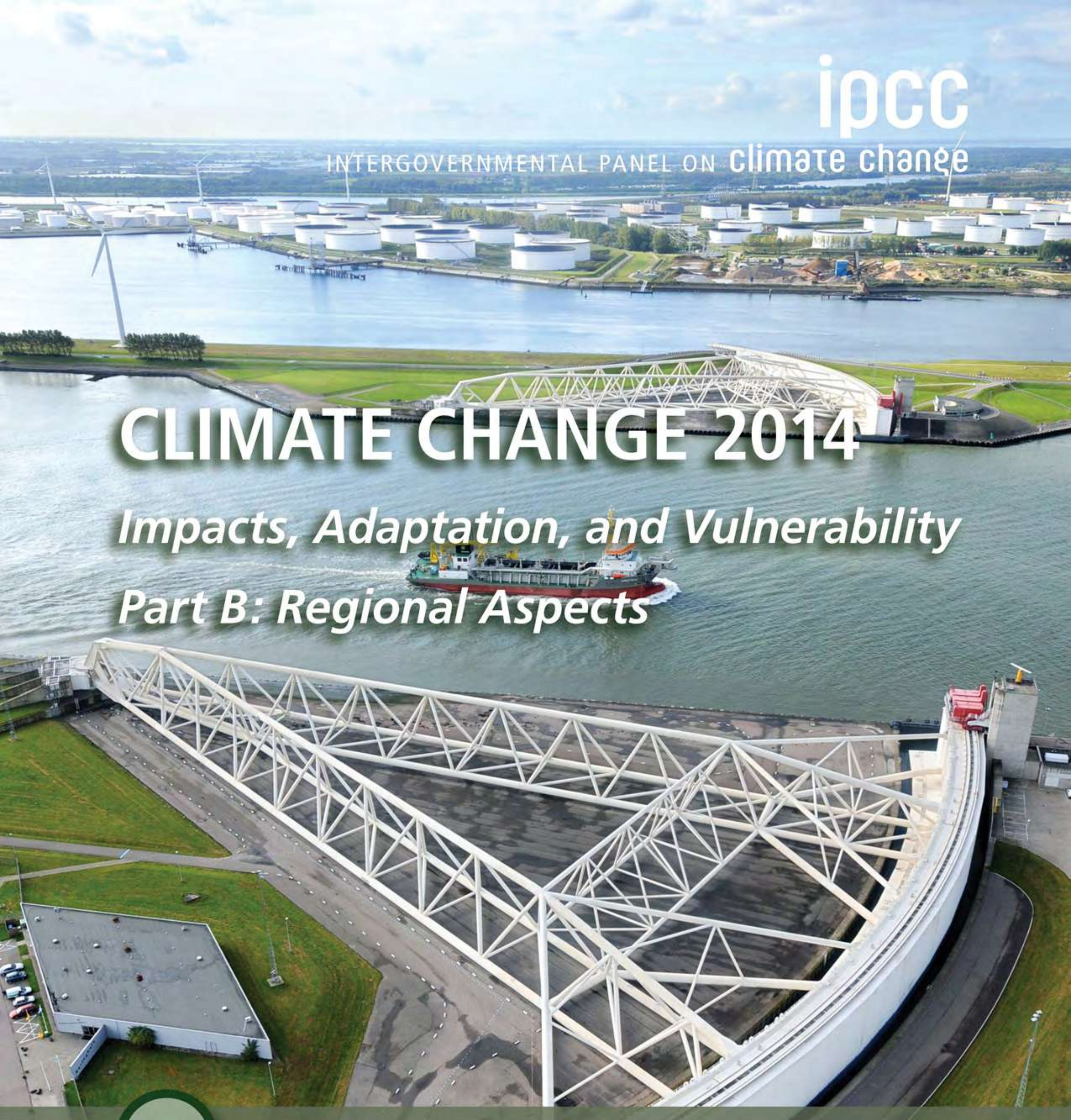

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INTERGOVERNMENTAL PANEL ON climate change

CLIMATE CHANGE 2014

Impacts, Adaptation, and Vulnerability

Part B: Regional Aspects

WG II

WORKING GROUP II CONTRIBUTION TO THE
FIFTH ASSESSMENT REPORT OF THE
INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

Climate Change 2014
Impacts, Adaptation, and Vulnerability
Part B: Regional Aspects

Working Group II Contribution to the
Fifth Assessment Report of the
Intergovernmental Panel on Climate Change

Edited by

Vicente R. Barros
Working Group II Co-Chair
Centro de Investigaciones del Mar y la Atmósfera
Universidad de Buenos Aires

Christopher B. Field
Working Group II Co-Chair
Department of Global Ecology
Carnegie Institution for Science

David Jon Dokken
Executive Director

Michael D. Mastrandrea
Co-Director of Science

Katharine J. Mach
Co-Director of Science

T. Eren Bilir **Monalisa Chatterjee** **Kristie L. Ebi** **Yuka Otsuki Estrada** **Robert C. Genova** **Betelhem Girma**
Eric S. Kissel **Andrew N. Levy** **Sandy MacCracken** **Patricia R. Mastrandrea** **Leslie L. White**

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Coordinating Lead Authors:
Bruce Hewitson (South Africa), Anthony C. Janetos (USA)

Lead Authors:
Timothy R. Carter (Finland), Filippo Giorgi (Italy), Richard G. Jones (UK), Won-Tae Kwon (Republic of Korea), Linda O. Mearns (USA), E. Lisa F. Schipper (Sweden), Maarten K. van Aalst (Netherlands)

Contributing Authors:
Eren Bilir (USA), Monalisa Chatterjee (USA/India), Katharine J. Mach (USA), Carol McSweeney (UK), Grace Redmond (UK), Vanessa Schweizer (USA), Luke Wirth (USA), Claire van Wyk (South Africa)

Review Editors:
Thomas Downing (USA), Phil Duffy (USA)

Volunteer Chapter Scientist:
Kristin Kuntz-Duriseti (USA)

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Executive Summary

There has been an evolution in the treatment of regional aspects of climate change in IPCC reports from a patchwork of case examples in early assessments toward recent attempts at a more systematic coverage of regional issues at continental and sub-continental scales. {21.2.2} Key topics requiring a regional treatment include changes in the climate itself and in other aspects of the climate system (such as the cryosphere, oceans, sea level, and atmospheric composition), climate change impacts on natural resource sectors and on human activities and infrastructure, factors determining adaptive capacity for adjusting to these impacts, emissions of greenhouse gases and aerosols and their cycling through the Earth system, and human responses to climate change through mitigation and adaptation.

A good understanding of decision-making contexts is essential to define the type and scale of information on climate change-related risks required from physical climate science and impacts, adaptation, and vulnerability (IAV) assessments (*high confidence*). {21.2.1} This is a general issue for all IAV assessments, but is especially important in the context of regional issues. Many studies still rely on global data sets, models, and assessment methods to inform regional decisions. However, tailored regional approaches are often more effective in accounting for variations in transnational, national, and local decision-making contexts, as well as across different groups of stakeholders and sectors. There is a growing body of literature offering guidance on how to provide the most relevant climate risk information to suit specific decision-making scales and processes.

A greater range of regional scale climate information is now available that provides a more coherent picture of past and future regional changes with associated uncertainties. {21.3.3} More targeted analyses of reference and projected climate information for impact assessment studies have been carried out. Leading messages include:

- Significant improvements have been made in the amount and quality of climate data that are available for establishing baseline reference states of climate-sensitive systems. {21.5.3.1} These include new and improved observational data sets, rescue and digitization of historical data sets, and a range of improved global reconstructions of weather sequences.
- A larger set of global and regional (both dynamical and statistical) model projections allow a better characterization of ranges of plausible climate futures than in the Fourth Assessment Report (AR4) {21.3.3}, and more methods are available to produce regional probabilistic projections of changes for use in IAV assessment work. {21.5.3}
- Better process understanding would strengthen the emerging messages on future climate change where there remains significant regional variation in their reliability. {21.3.3}
- Confidence in past climate trends has different regional variability, and in many regions there is higher confidence in future changes, often owing to a lack of evidence on observed changes. {21.3; Box 21-4}

In spite of improvements, the available information is limited by the lack of comprehensive observations of regional climate, or analyses of these, and different levels of confidence in projected climate change (*high confidence*). Some trends that are of particular significance for regional impacts and adaptation include: {21.3.3.1; WGI AR5 SPM}

- The globally averaged combined land and ocean surface temperature data show a warming of 0.85 (0.65 to 1.06) °C, over the period 1880–2012. There is regional variation in the global trend, but overall the entire globe has warmed during the period 1901–2012. {WGI AR5 SPM} Future warming is *very likely* to be larger over land areas than over oceans. {WGI AR5 SPM}
- Averaged over mid-latitude land areas, precipitation has increased since 1901(*medium confidence* before and *high confidence* after 1951), but for other regions there is *low confidence* in the assessment of precipitation trends. {WGI AR5 SPM}
- There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most *medium*. The frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa and *likely* decreased in central North America and northwest Australia.
- The annual mean Arctic sea ice extent decreased over the period 1979–2012 with a rate that was *very likely* in the range 3.5 to 4.1% per decade. Climate models indicate a nearly ice-free Arctic Ocean in September before mid-century is *likely* under the high forcing scenario Representative Concentration Pathway 8.5 (RCP8.5) (*medium confidence*).
- The average rate of ice loss from glaciers worldwide, excluding those near the Greenland and Antarctic ice sheets, was *very likely* 275 (140 to 410) Gt yr^{-1} over the period 1993–2009. By the end of the 21st century, the volume of glaciers (excluding those near the Antarctic ice sheet) is projected to decrease by 15 to 55% for RCP2.6, and by 35 to 85% for RCP8.5, relative to 1986–2005 (*medium confidence*).

- The rate of global mean sea level rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010, under all RCP scenarios. {21.3.3.5; WGI AR5 SPM} By the end of the 21st century it is *very likely* that sea level will rise in more than about 95% of the ocean area, with about 70% of the global coastlines projected to experience a sea level change within 20% of the global mean change. Sea level rise along coasts will also be a function of local and regional conditions, including land subsidence or uplift and patterns of development near the coast.

There is substantial regional variation in observations and projections of climate change impacts, both because the impacts themselves vary and because of unequal research attention. {21.3.1} Evidence linking observed impacts on biological, physical, and increasingly) human systems to recent and ongoing regional temperature and (in some cases) precipitation changes have become more compelling since the Fourth Assessment Report (AR4). This is due both to the greater availability of statistically robust, calibrated satellite records, and to improved reporting from monitoring sites in hitherto under-represented regions, though the disparity still remains large between data-rich and data-poor regions. Regional variations in physical impacts such as vegetation changes, sea level rise, and ocean acidification are increasingly well documented, though their consequences for ecosystems and humans are less well studied or understood. Projections of future impacts rely primarily on a diverse suite of biophysical, economic, and integrated models operating from global to site scales, though some physical experiments are also conducted to study processes in altered environments. New research initiatives are beginning to exploit the diversity of impact model projections, through cross-scale model intercomparison exercises.

There are large variations in the degree to which adaptation processes, practices, and policy have been studied and implemented in different regions (*high confidence*). {21.3.2} Europe and Australia have had extensive research programs on climate change adaptation, while research in Africa and Asia has been dominated by international partners and relies heavily on case studies of community-based adaptation. National adaptation strategies are common in Europe, and adaptation plans are in place in some cities in Europe, the Americas, and Australasia, with agriculture, water, and land use management the primary sectors of activity. However, it is still the case that implementation lags behind planning in most regions of the world.

Contested definitions and alternative approaches to describing regional vulnerability to climate change pose problems for interpreting vulnerability indicators. {21.3.1.2, 21.5.1.1} There are numerous studies that use indicators to define aspects of vulnerability, quantifying these across regional units (e.g., by country or municipality), often weighting and merging them into vulnerability indices and presenting them regionally as maps. However, methods of constructing indices are subjective, often lack transparency, and can be difficult to interpret. Moreover, indices commonly combine indicators reflecting current conditions (e.g., of socioeconomic capacity) with other indicators describing projected changes (e.g., of future climate or population), and have failed to reflect the dynamic nature of the different indicator variables.

Hotspots draw attention, from various perspectives and often controversially, to locations judged to be especially vulnerable to climate change. {21.5.1.2} Identifying hotspots is an approach that has been used to indicate locations that stand out in terms of IAV capacity (or combinations of these). The approach exists in many fields and the meaning and use of the term hotspots differs, though their purpose is generally to set priorities for policy action or for further research. Hotspots can be very effective as communication tools, but may also suffer from methodological weaknesses. They are often subjectively defined, relationships between indicator variables may be poorly understood, and they can be highly scale dependent. In part due to these ambiguities, there has been controversy surrounding the growing use of hotspots in decision making, particularly in relation to prioritizing regions for climate change funding.

Cross-regional phenomena can be crucial for understanding the ramifications of climate change at regional scales, and its impacts and policies of response (*high confidence*). {21.4} These include global trade and international financial transactions, which are linked to climate change as a direct or indirect cause of anthropogenic emissions; as a predisposing factor for regional vulnerability, through their sensitivity to climate trends and extreme climate events; and as an instrument for implementing mitigation and adaptation policies. Migration is also a cross-regional phenomenon, whether of people or of ecosystems, both requiring transboundary consideration of their causes, implications, and possible interventions to alleviate human suffering and promote biodiversity.

Downscaling of global climate reconstructions and models has advanced to bring the climate data to a closer match for the temporal and spatial resolution requirements for assessing many regional impacts, and the application of downscaled climate

data has expanded substantially since AR4. {21.3.3, 21.5.3} This information remains weakly coordinated, and current results indicate that high-resolution downscaled reconstructions of the current climate can have significant errors. The increase in downscaled data sets has not narrowed the uncertainty range. Integrating these data with historical change and process-based understanding remains an important challenge.

Characterization of uncertainty in climate change research on regional scales has advanced well beyond quantifying uncertainties in regional climate projections alone, to incorporating uncertainties in simulations of future impacts as well as considering uncertainties in projections of societal vulnerability. {21.3.3, 21.5} In particular, intercomparison studies are now examining the uncertainties in impacts models (e.g., Agricultural Model Intercomparison and Improvement Project (AgMIP) and Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP)) and combining them with uncertainties in regional climate projections. Some results indicate that a larger portion of the uncertainty in estimates of future impacts can be attributed to the impact models applied rather than to the climate projections assumed. In addition, the deeper uncertainties associated with aspects of defining societal vulnerability to climate change related to the alternative approaches to defining vulnerability are becoming appreciated. As yet there has been little research actively to quantify these uncertainties or to combine them with physical impact and climate uncertainties.

Studies of multiple stressors and assessments of potential global and regional futures using scenarios with multiple, non-climate elements are becoming increasingly common. {21.5.3.2-3} Non-climatic factors relevant to assessing a system's vulnerability generally involve a complex mix of influences such as environmental changes (e.g., in air, water, and soil quality; sea level; resource depletion), land use and land cover changes, and socioeconomic changes (e.g., in population, income, technology, education, equity, governance). All of these non-climate factors have important regional variations. There is significant variation in vulnerability owing to variability in these factors.

21.1. Introduction

This chapter serves as an introduction to Part B of this volume. It provides context for an assessment of regional aspects of climate change in different parts of the world, which are presented in the following nine chapters. While the main focus of those chapters is on the regional dimensions of impacts, adaptation, and vulnerability (IAV), this chapter also offers links to regional aspects of the physical climate reported by Working Group I (WGI) and of mitigation analysis reported by Working Group III (WGIII). The chapter frames the discussion of both global and regional issues in a decision-making context. This context identifies different scales of decisions that are made (e.g., global, international, regional, national, subnational, local) and the different economic or impact sectors that are often the objects of decision making (e.g., agriculture, water resources, energy).

Within this framing, the chapter then provides three levels of synthesis. First there is an evaluation of the state of knowledge of changes in the physical climate system, and associated impacts and vulnerabilities, and the degree of confidence that we have in understanding those on a regional basis as relevant to decision making. Second, the regional context of the sectoral findings presented in Part A of this volume is discussed. Third, there is an analysis of the regional variation revealed in subsequent chapters of Part B. In so doing, the goal is to examine how the chapters reflect differences or similarities in how decision making is being addressed by policy and informed by research in different regions of the world, and whether there is commonality of experience among regions that could be useful for enhancing decisions in the future.

Having analyzed similarities and differences among IPCC regions, the chapter then discusses trans-regional and cross-regional issues that affect both human systems (e.g., trade and financial flows) and natural systems (e.g., ecosystem migration). Finally, the chapter evaluates methods of assessing regional vulnerabilities and adaptation, impact analyses, and the development and application of baselines and scenarios of the future. These evaluations provide guidance for understanding how such methods might ultimately be enhanced, so that the confidence in research about possible future conditions and consequences might ultimately improve.

21.2. Defining Regional Context

The climate system may be global in extent, but its manifestations—through atmospheric processes, ocean circulation, bioclimatic zones, daily weather, and longer-term climate trends—are regional or local in their occurrence, character, and implications. Moreover, the decisions that are or could be taken on the basis of climate change science play out on a range of scales, and the relevance and limitations of information on both biophysical impacts and social vulnerability differ strongly from global to local scale, and from one region to another. Explicit recognition of geographical diversity is therefore important for any scientific

Table 21-1 | Dimensions of the institutions and actors involved in climate change decision making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decision-making domains are illustrative. Modified and extended from Mickwitz et al. (2009).

	Level	Coherent policies and decision making across domains					
		Economy	**Energy**	**Food/fiber**	**Technology**	**Environment**	…
Multi-level organization and governance	Global	• International Monetary Fund • World Bank • World Trade Organization • Millennium Development Goals • NGOs	• International Energy Agency • NGOs	• UN Food and Agriculture Organization • World Trade Organization • UN Convention on the Law of the Sea (fisheries) • NGOs	• World Intellectual Property Organization • NGOs	• UN Framework Convention on Climate Change • Convention on Biological Diversity • Montreal Protocol • NGOs	
	Transnational	• Multilateral Financial Institutions/Multilateral Development Banks • Bilateral Financial Institutions • Organisation for Economic Cooperation and Development • EU • UN Convention on the Law of the Sea (transport)	• Organization of the Petroleum Exporting Countries • Electric grid operators • Oil/gas distributors	• Association of Southeast Asian Nations Free Trade Area • Common Market for Eastern and Southern Africa • Mercado Común del Sur (Southern Common Market) • EU Common Agricultural/Fisheries Policies	• Multi-nationals' research and development • EU Innovation Union	• Convention on Long-range Transboundary Air Pollution (Europe, North America, Central Asia) • Mekong River Commission for Sustainable Development • Lake Victoria Basin Commission • EU Directives	
	National	• Ministries/governments • Departments/agencies • Banks • Taxation	• Ministries/governments • Departments/agencies • Energy providers • Energy regulators	• Ministries/governments • Departments/agencies • Tariffs, quotas, regulations	• Ministries/governments • Departments/agencies • Education • Innovation • Research and development	• Ministries/governments • Departments/agencies • Environmental law	
	Subnational	• States/provinces/counties/ cIties • Taxation	• States/provinces/counties/ cities • Public/private energy providers	• States/provinces/counties/ cities • Extension services • Land use planning	• States/provinces/counties/ cities • Incentives • Science parks	• States/provinces/counties/ cities • Protected areas • Regional offices	
	Local	• Microfinance • Cooperatives • Employers • Voters • Consumers	• Renewables • Producers • Voters • Consumers	• Farmers • Foresters • Fishers • Landowners • Voters • Consumers	• Entrepreneurs • Investors • Voters • Consumers	• Environmentalists • Landowners • Voters • Consumers	

Notes: EU = European Union; NGO = Non-governmental Organization; UN = United Nations.

assessment of anthropogenic climate change. The following sections emphasize some of the crucial regional issues to be pursued in Part B of this report.

21.2.1. Decision-Making Context

A good understanding of decision-making contexts is essential to define the type and resolution and characteristics of information on climate change-related risks required from physical climate science and impacts, adaptation, and vulnerability assessments (IAV; e.g., IPCC, 2012). This is a general issue for all IAV assessments (cf. the chapters in Part A), but is especially important in the context of regional issues. Many studies still rely on global data sets, models, and assessment methods to inform regional decisions. However, tailored regional approaches are often more effective in accounting for variations in transnational, national, and local decision-making contexts, as well as across different groups of stakeholders and sectors. There is a growing body of literature offering guidance on how to provide the most relevant climate risk information to suit specific decision-making scales and processes (e.g., Willows and Connell, 2003; ADB, 2005; Kandlikar et al., 2011).

Table 21-1 illustrates the range of actors involved in decision making to be informed by climate information at different scales in different sectors, ranging from international policymakers and agencies, to national and local government departments, to civil society organizations and the private sector at all levels, all the way to communities and individual households. The table illustrates how policymakers face a dual challenge in achieving policy integration—vertically, through multiple levels of governance, and horizontally, across different sectors (policy coherence).

Many climate change risk assessments have traditionally been undertaken either in the context of international climate policy making (especially United Nations Framework Convention on Climate Change (UNFCCC)), or by (or for) national governments (e.g., Roshydromet, 2008; SEI, 2009; Watkiss et al., 2011; DEFRA, 2012). In those cases, climate risk information commonly assumes a central role in the decision making, for instance to inform mitigation policy, or for plans or projects designed specifically to adapt to a changing climate. In recent years, increasing attention has been paid to more sector- or project-specific risk assessments, intended to guide planning and practice by a range of actors (e.g., Liu et al., 2008; Rosenzweig et al., 2011). In those contexts, climate may often be considered as only one contributor among a much wider set of considerations for a particular decision. In such cases, there is uncertainty about not only the future climate, but also many other aspects of the system at risk. Moreover, while analysts will seek the best available climate risk information to inform the relative costs and benefits of the options available to manage that risk, they will also need to consider the various constraints to action faced by the actors involved.

Some of these decision-making contexts, such as the design of large infrastructure projects, may require rigorous quantitative information to feed formal evaluations, often including cost-benefit analysis (e.g., PriceWaterHouseCoopers, 2010; see also Chapter 17). Others, especially at the local level, such as decision making in traditional communities, are often made more intuitively, with a much greater role for a wide range of social and cultural aspects. These may benefit much more from experience-based approaches, participatory risk assessments, or story-telling to evaluate future implications of possible decisions (e.g., van Aalst et al., 2008; World Bank, 2010a). Multi-criteria analysis, scenario planning, and flexible decision paths offer options for taking action when faced with large uncertainties or incomplete information, and can help bridge adaptation strategies across scales (in particular between the national and local levels). In most cases, an understanding of the context in which the risk plays out, and the alternative options that may be considered to manage it, are not an afterthought, but a defining feature of an appropriate climate risk analysis, which requires a much closer interplay between decision makers and providers of climate risk information than often occurs in practice (e.g., Hellmuth et al., 2011; Cardona et al., 2012; Mendler de Suarez et al., 2012).

The different decision-making contexts also determine the types of climate information required, including the climate variables of interest and the geographic and time scales on which they need to be provided. Many climate change impact assessments have traditionally focused on changes over longer time horizons (often out to 2100, though recently studies have begun to concentrate more on mid-century or earlier). In contrast, most decisions taken today have a planning horizon ranging from a few months to about 2 decades (e.g., Wilby et al., 2009). For many such shorter term decisions, recent climate variability and observed trends are commonly regarded as sufficient to inform adaptation (e.g., Hallegatte, 2009). However, in so doing, there is often scope to make better use of observed climatological information as well as seasonal and maybe also decadal climate forecasts (e.g., Wang et al., 2009; Ziervogel et al., 2010; HLT, 2011; Mehta et al., 2011; Kirtman et al., 2014). For longer term decisions, such as decisions with irreversible long-term implications and investments with a long investment horizon and substantial vulnerability to changing climate conditions, longer term climate risk information is needed (e.g., Reeder and Ranger, 2010). However, while that longer term information is often used simply to plan for a best-guess scenario to optimize for most probable conditions, there is increasing attention for informing concerns about maladaptation (Barnett and O'Neill, 2010) and sequencing of potential adaptation options in a wider range of possible outcomes, requiring a stronger focus on ranges of possible outcomes and guidance on managing uncertainties, especially at regional, national, and sub-national levels (Hall et al., 2012; Gersonius et al., 2013).

Section 21.3 summarizes different approaches that have been applied at different scales, looking at IAV and climate science in a regional context and paying special attention to information contained in the regional chapters.

21.2.2. Defining Regions

There has been an evolution in the treatment of regional aspects of climate change in IPCC reports (Table 21-2) from a patchwork of case examples in the First Assessment Report (FAR) and its supplements, through to attempts at a more systematic coverage of regional issues following a request from governments, beginning with the *Special Report on the Regional Impacts of Climate Change* in 1998. That report distilled information from the Second Assessment Report (SAR) for 10 continental scale regions, and the subsequent Third (TAR) and Fourth (AR4) assessments each contained comparable chapters on IAV in the WGII volumes. WGI and WGIII reports have also addressed regional issues in various chapters, using different methods of mapping, statistical aggregation, and spatial averaging to provide regional information.

Part B of this WGII contribution to the Fifth Assessment Report (AR5) is the first to address regional issues treated in all three WGs. It consists of chapters on the six major continental land regions, polar regions, small islands, and the ocean. These are depicted in Figure 21-1.

Table 21-2 | Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SRs). Major assessments are subdivided into three Working Group reports, each described by generic titles.

IPCC report	Treatment of regions
First Assessment Report (IPCC, 1990a–c)	Climate: Climate projections for 2030 in 5 subcontinental regions; observations averaged for Northern/Southern Hemisphere, by selected regions, and by 20° latitude × 60° longitude grid boxes
	Impacts: Agriculture by continent (7 regions); ecosystem impacts for 4 biomes; water resources for case study regions; oceans and coastal zones treated separately
	Responses: Emissions scenarios by 5 economic groupings; energy and industry by 9 regions; coastal zone and wetlands by 20 world regions
Supplements to First Assessment Report (IPCC, 1992a–b)	Climate: IS92 emissions scenarios by 7 world regions
	Impacts: Agriculture by continent (6 regions); ocean ecology by 3 latitude zones; questionnaire to governments on current activities on impacts by 6 World Meteorological Organization regions
SR: Climate Change 1994 (IPCC, 1994a)	Evaluation of IS92 emissions scenarios by 4 world regions: OECD, USSR/Eastern Europe, China/Centrally Planned Asia, and Other
Second Assessment Report (IPCC, 1996a–c)	Climate: Gridded proportional circle maps for observed climate trends (5° latitude/longitude); climate projections for 7 subcontinental regions
	Impacts, Adaptations, and Mitigation: Energy production statistics by 10 world regions; forests, wood production and management by three zones (tropical, temperate, boreal); separate chapters by physiographic types (deserts, mountain regions, wetlands, cryosphere, oceans, and coastal zones and small islands); country case studies, agriculture by 8 continental-scale regions; energy supply by 8 world regions
	Economic and social dimensions: Social costs and response options by 6 economic regions
SR: Regional Impacts (IPCC, 1998)	10 continental-scale regions: Africa, Arctic and Antarctic, Australasia, Europe, Latin America, Middle East and Arid Asia, North America, Small Island States, Temperate Asia, Tropical Asia. Subdivisions applied in some regions; vegetation shifts mapped by 9 biomes; reference socioeconomic data for 1990 provided by country and for all regions except polar
SR: Land-Use Change and Forestry (IPCC, 1998a)	9 biomes; 15 land use categories; national and regional case studies
SR: Aviation (IPCC, 1999)	Observed and projected emissions by 22 regional air routes; inventories by 5 economic regions
SR: Technology Transfer (IPCC, 2000b)	Country case studies; indicators of technology transfer by 6 or 7 economic regions
SR: Emissions Scenarios (IPCC, 2000a)	4 SRES world regions defined in common across integrated assessment models; 11 sub-regions; driving factors by 6 continental regions
Third Assessment Report (TAR) (IPCC, 2001a–c)	Climate: Gridded observations of climate trends; 20 example glaciers; 9 biomes for carbon cycle; Circulation Regimes for model evaluation; 23 "Giorgi-type" regions for regional climate projections
	Impacts, Adaptation, and Vulnerability: Example projections from 32 "Giorgi-type" regions; basins by continent; 5 coastal types; urban/rural settlements; insurance by economic region; 8 continental-scale regions equivalent to 1998 Special Report but with single chapter for Asia; subdivisions used for each region (Africa, Asia, and Latin America by climate zones; North America by 6 core regions and 3 border regions)
	Mitigation: Country examples; developed (Annex I) and developing (non-Annex I); various economic regions; policies, measures, and instruments by 4 blocs: OECD, Economies in Transition, China and Centrally Planned Asia, and Rest of the World
SR: Ozone Layer (IPCC/TEAP, 2005)	Various economic regions/countries depending on sources and uses of chemicals
SR: Carbon Capture and Storage (IPCC, 2005)	CO_2 sources by 9 economic regions; potential storage facilities by geological formation, by oil/gas wells, by ocean depth; costs by 4 economic groupings
Fourth Assessment Report (AR4) (IPCC, 2007a–c)	Climate: Land use types for surface forcing of climate; observations by 19 Giorgi regions; modes of variability for model evaluation; attribution of climate change by 22 "Giorgi-type" regions and by 6 ocean regions; climate statistics for 30 "Giorgi-type" regions; probability density functions of projections for 26 regions; summary graphs for 8 continental regions
	Impacts, Adaptation, and Vulnerability: Studies reporting observed impacts by 7 IPCC regions; comparison of TAR and AR4 climate projections for 32 "Giorgi-type" regions; ecosystems by 11 biomes; agriculture by latitudinal zone; examples of coastal mega-deltas; industry and settlement by continental region; 8 continental regions, as in TAR, but Small Islands not Small Island States; sub-regional summary maps for each region, using physiographic, biogeographic, or geographic definitions; example vulnerability maps at sub-national scale and globally by country
	Mitigation: 17 global economic regions for GDP; energy supply by continent, by economic region, by 3 UNFCCC groupings; trends in CO_2 emissions (and projections), waste and carbon balance by economic region
SR: Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011)	Global maps showing potential resources for renewable energy: land suitability for bioenergy production, global irradiance for solar, geothermal, hydropower, ocean waves/tidal range, wind; various economic/continental regions: installed capacity (realized vs. potential), types of technologies, investment cost, cost effectiveness, various scenario-based projections; country comparisons of deployment and uptake of technologies, share of energy market
SR: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012)	Trends in observed (tables) and projected (maps and tables) climate extremes (T_{max}, T_{min}, heat waves, heavy precipitation and dryness) by 26 sub-continental regions covering most land areas of the globe; attribution studies of return periods of extreme temperatures for 15 "Giorgi-type" regions; gridded global maps of projected extremes of temperature, precipitation, wind speed, dry spells, and soil moisture anomalies; continental-scale estimates of projected changes in impacts of extremes (floods, cyclones, coastal inundation) as well as frequencies of observed climate extremes and their estimated costs); distinctions drawn between local, country and international/global actors with respect to risk management and its financing

Continued next page →

Table 21-2 (continued)

IPCC report	Treatment of regions
Fifth Assessment Report (IPCC, 2013a, 2014, and this volume)	Climate: Gridded global maps of observed changes in climate; cryosphere observations from 19 glacierized regions and 3 Arctic permafrost zones; paleoclimatic reconstructions for 7 continental regions; CO_2 fluxes for 11 land and 10 ocean regions; observed aerosol concentrations for 6 continental regions and projections for 9 regions; detection and attribution of changes in mean and extreme climate for 7 continental and 8 ocean regions; climate model evaluation and multi-model projections of extremes for 26 sub-continental regions; maps and time series of seasonal and annual multi-model simulated climate changes for 19 sub-continental regions and global over 1900–2100
	Impacts, Adaptation, and Vulnerability, Part A: Global and sectoral aspects: Gridded global maps of water resources, species distributions, ocean productivity; global map of 51 ocean biomes; detection and attribution of observed impacts, key risks, and vulnerabilities and adaptation synthesis by IPCC regions. Part B: Regional aspects: 9 continental-scale regions, 8 as in AR4 plus the ocean; sub-regions in Africa (5), Europe (5), Asia (6), Central and South America (5 or 7); Polar (2); Small Islands (4), Oceans (7); Other disaggregation by gridded maps or countries
	Mitigation: Economic statistics by development (3 or 5 categories) or by income; 5 country groupings (plus international transport) for emission-related scenario analysis (RCP5: OECD 1990 countries, Reforming Economies, Latin America and Caribbean, Middle East and Africa, Asia) with further disaggregation to 10 regions (RCP10) for regional development; land use regions for forest (13) and agriculture (11); Most other analyses by example countries

Notes: IS92 = IPCC Scenarios, 1992; OECD = Organisation for Economic Cooperation and Development; RCP = Representative Concentration Pathway; SRES = Special Report on Emission Scenarios; UNFCCC = United Nations Framework Convention on Climate Change.

Some of the main topics benefiting from a regional treatment are:

- *Changes in climate*, typically represented over sub-continental regions, a scale at which global climate models simulate well the pattern of observed surface temperatures, though more modestly the pattern of precipitation (Flato et al., 2014). While maps are widely used to represent climatic patterns, regional aggregation of this (typically gridded) information is still required to summarize the processes and trends they depict. Examples, including information on climate extremes, are presented elsewhere in this chapter, with systematic coverage of all regions provided in on-line supplementary material. Selected time series plots of temperature and precipitation change from an atlas of global and regional climate projections accompanying the WGI report (Collins et al., 2014a) can also be found in several regional chapters of this volume. In Figure 21-1, the sub-continental regions used for summarizing climate information are overlaid on a map of the nine regions treated in Part B.
- *Changes in other aspects of the climate system*, such as cryosphere, oceans, sea level, and atmospheric composition. A regional treatment of these phenomena is often extremely important to gauge real risks, for example, when regional changes in land movements and local ocean currents counter or reinforce global sea level rise (Nicholls et al., 2013).
- *Climate change impacts* on natural resource sectors, such as agriculture, forestry, ecosystems, water resources, and fisheries, and on human activities and infrastructure, often with regional treatment according to biogeographical characteristics (e.g., biomes; climatic zones; physiographic features such as mountains, river basins, coastlines, or deltas; or combinations of these).
- *Adaptive capacity*, which is a measure of society's ability to adjust to the potential impacts of climate change, sometimes characterized in relation to social vulnerability (Füssel, 2010b) and represented in regional statistics through the use of socioeconomic indicators.

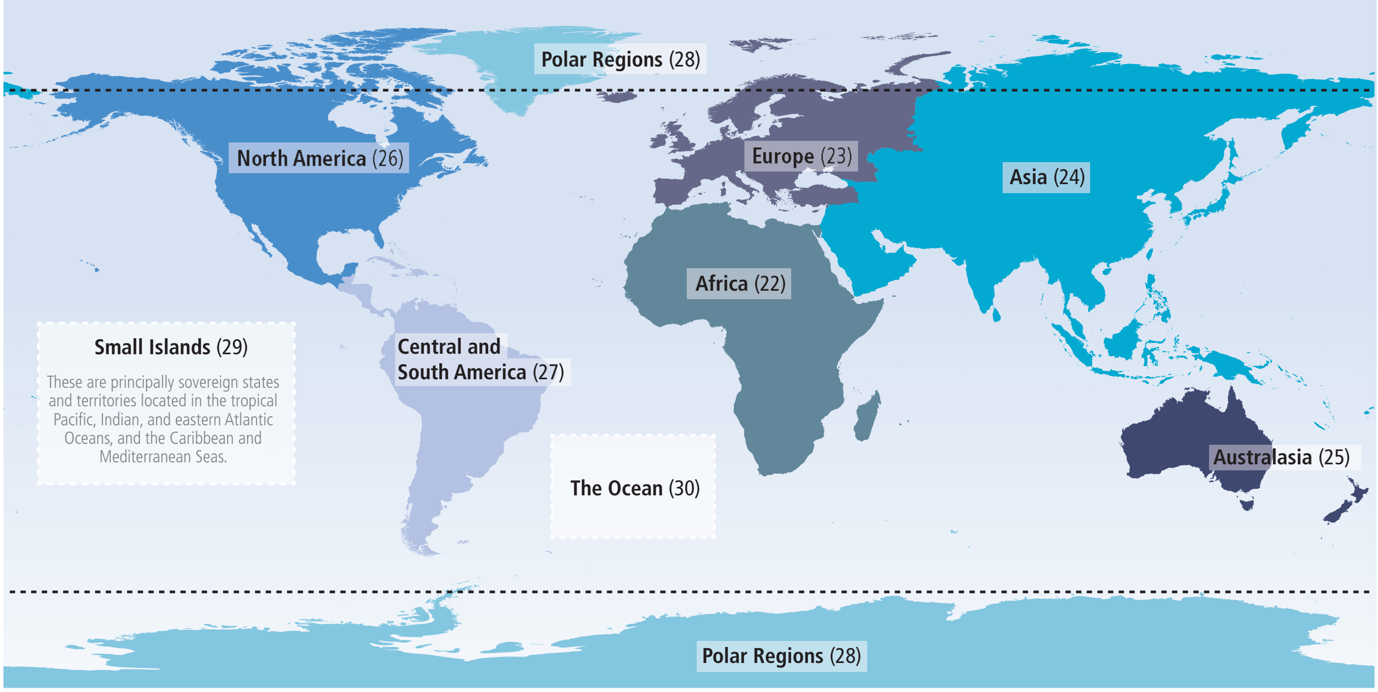

Figure 21-1 | Specification of the world regions described in Chapters 22 to 30 of this volume. Chapter numbers are given in parentheses after each region's name.

Box 21-1 | A New Framework of Global Scenarios for Regional Assessment

The major socioeconomic driving factors of future emissions and their effects on the global climate system were characterized in the TAR and AR4 using scenarios derived from the IPCC *Special Report on Emissions Scenarios* (SRES; IPCC, 2000a). However, these scenarios are becoming outdated in terms of their data and projections, and their scope is too narrow to serve contemporary user needs (Ebi et al., 2013). More recently a new approach to developing climate and socioeconomic scenarios has been adopted in which concentration trajectories for atmospheric greenhouse gases (GHGs) and aerosols were developed first (Representative Concentration Pathways (RCPs); Moss et al., 2010), thereby allowing climate modeling work to proceed much earlier in the process than for SRES. Different possible Shared Socioeconomic Pathways (SSPs), intended for shared use among different climate change research communities, were to be determined later, recognizing that more than one socioeconomic pathway can lead to the same concentrations of GHGs and aerosols (Kriegler et al., 2012).

Four different RCPs were developed, corresponding to four different levels of radiative forcing of the atmosphere by 2100 relative to preindustrial levels, expressed in units of W m^{-2}: RCP8.5, 6.0, 4.5, and 2.6 (van Vuuren et al., 2012). These embrace the range of scenarios found in the literature, and all except RCP8.5 also include explicit stabilization strategies, which were missing from the SRES set. An approximate mapping of the SRES scenarios onto the RCPs on the basis of a resemblance in radiative forcing by 2100 is presented in Chapter 1, pairing RCP8.5 with SRES A2 and RCP 4.5 with B1 and noting that RCP6.0 lies between B1 and B2. No SRES scenarios result in forcing as low as RCP2.6, though mitigation scenarios developed from initial SRES trajectories have been applied in a few climate model experiments (e.g., the E1 scenario; Johns et al., 2011).

In addition, five SSPs have been proposed, representing a wide range of possible development pathways (van Vuuren et al., 2013). An inverse approach is applied, whereby the SSPs are constructed in terms of outcomes most relevant to IAV and mitigation analysis, depicted as challenges to mitigation and adaptation. Narrative storylines for the SSPs have been outlined and preliminary quantifications of the socioeconomic variables are underway (O'Neill et al., 2013). Priority has been given to a set of *basic* SSPs with the minimum detail and comprehensiveness needed to provide inputs to impacts, adaptation, and vulnerability (IAV), and integrated assessment models, primarily at global or large regional scales. Building on the basic SSPs, a second stage will construct *extended* SSPs, designed for finer-scale regional and sectoral applications (O’Neill et al., 2013).

An overall scenario architecture has been designed for integrating RCPs and SSPs (Ebi et al., 2013; van Vuuren et al., 2013), for considering mitigation and adaptation policies using Shared Policy Assumptions (SPAs; Kriegler et al., 2013) and for providing relevant socioeconomic information at the scales required for IAV analysis (van Ruijven et al., 2013). Additional information on these scenarios can be found in Section 1.1.3 and elsewhere in the assessment (Blanco et al., 2014; Collins et al., 2014a; Kunreuther et al., 2014). However, owing to the time lags that still exist between the generation of RCP-based climate change projections in the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) and the development of SSPs, few of the IAV studies assessed in this report actively use these scenarios. Instead, most of the scenario-related studies in the assessed literature still rely on the SRES.

- *Emissions* of greenhouse gases (GHGs) and aerosols and their cycling through the Earth system (Blanco et al., 2014; Ciais et al., 2014).
- *Human responses to climate change through mitigation and adaptation*, which can require both global and regional approaches (e.g., Agrawala et al., 2014; Somanathan et al., 2014; Stavins et al., 2014; see also Chapters 14 to 16).

Detailed examples of these elements are referred to throughout this chapter and the regional ones that follow. Some of the more important international political groupings that are pertinent to the climate change issue are described and cataloged in on-line supplementary material (Section SM21.1). Table SM21-1 lists United Nations member states and other territories, their status in September 2013 with respect to some illustrative groupings of potential relevance for international climate change policy making, and the regional chapters in which they are considered in this report.

Finally, new global socioeconomic and environmental scenarios for climate change research have emerged since the AR4 that are richer and more diverse and offer a higher level of regional detail than previous scenarios taken from the IPCC *Special Report on Emissions Scenarios* (SRES). These are introduced in Box 21-1.

21.2.3. Introduction to Methods and Information

There has been significant confusion and debate about the definitions of key terms (Janssen and Ostrom, 2006), such as vulnerability (Adger, 2006), adaptation (Stafford Smith et al., 2011), adaptive capacity (Smit and Wandel, 2006), and resilience (Klein et al., 2003). One explanation is that the terms are not independent concepts, but defined by each other, thus making it impossible to remove the confusion around the definitions (Hinkel, 2011). The differences in the definitions relate to the different entry points for looking at climate change risk (IPCC, 2012).

Table 21-3 shows two ways to think about vulnerability, demonstrating that different objectives (e.g., improving well-being and livelihoods or reducing climate change impacts) lead to different sets of questions being asked. This results in the selection of different methods to arrive at the answers. The two approaches portrayed in the middle and righthand columns of Table 21-3 have also been characterized in terms of top-down (middle column) and bottom-up (right column) perspectives, with the former identifying physical vulnerability and the latter social vulnerability (Dessai and Hulme, 2004). In the middle column, the climate change impacts are the starting point for the analysis, revealing that people and/or ecosystems are vulnerable to climate change. This approach commonly applies global-scale scenario information and seeks to refine this to the region of interest through downscaling procedures. For the approach illustrated on the right, the development context is the starting point (i.e., social vulnerability), commonly focusing on local scales, on top of which climate change occurs. The task is then to identify what changes are needed in the broader scale development pathways to reduce vulnerability to climate change. Another difference is a contrast in time frames, where a climate change-focused approach tends to look to the future to see how to adjust to expected changes, whereas a vulnerability-focused approach is centered on addressing the drivers of current vulnerability. A similar approach is described by McGray et al. (2009).

The information assessed in this chapter stems from different entry points, framings, and conceptual frameworks for thinking about risk. They merge social and natural science perspectives with transdisciplinary ones. There is no single "best" conceptual model: the approaches change as scientific thinking evolves. The IPCC itself is an example of this: The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; IPCC, 2012) presented an approach that has been adjusted and adapted in Chapter 19 of this volume. Chapter 2 describes other conceptual models for decision making in the context of risk. Though this diversity in approaches enriches our understanding of climate change, it can also create difficulties in comparisons. For instance, findings that are described as vulnerabilities in some studies may be classified as impacts in others; lack of adaptive capacity in one setting might be described as social vulnerability in another.

21.3. Synthesis of Key Regional Issues

This section presents information on IAV and climate science in a regional context. To illustrate how these different elements play out in actual decision-making contexts, Table 21-4 presents examples drawn from the regional and thematic chapters, which illustrate how information about vulnerability and exposure, and climate science at different scales, inform adaptation (implemented in policy and practice as part of a wider decision-making context). These show that decision making is informed by a combination of different types of information. However, this section is organized by the three constituent elements: vulnerabilities and impacts, adaptation, and climate science.

The following two subsections offer a brief synopsis of the approaches being reported in the different regional chapters on impacts and vulnerability studies (Section 21.3.1) and adaptation studies (Section 21.3.2), aiming particularly to highlight similarities and differences among regions. Table 21-5 serves as a rough template for organizing this discussion, which is limited to the literature that has been assessed by the regional chapters. It is organized according to the broad research approach applied, distinguishing impacts and vulnerability approaches from adaptation approaches, and according to scales of application ranging from global to local.

Table 21-3 | Two possible entry points for thinking about vulnerability to climate change (illustrative and adapted from Füssel, 2007).

Context	Climate change impacts perspective	Vulnerability perspective
Root problem	Climate change	Social vulnerability
Policy context	Climate change mitigation, compensation, technical adaptation	Social adaptation, sustainable development
Illustrative policy question	What are the benefits of climate change mitigation?	How can the vulnerability of societies to climatic hazards be reduced?
Illustrative research question	What are the expected net impacts of climate change in different regions?	Why are some groups more affected by climatic hazards than others?
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to current climate variability
Starting point of analysis	Scenarios of future climate change	Current vulnerability to climatic variability
Analytical function	Descriptive, positivist	Explanatory, normative
Main discipline	Natural science	Social science
Meaning of "vulnerability"	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors
Vulnerability approach	Integrated, risk-hazard	Political economy
Reference	IPCC (2001a)	Adger (1999)

Section 21.3.3 then provides an analysis of advances in understanding of the physical climate system for the different regions covered in Chapters 22 to 30, introducing new regional information to complement the large-scale and process-oriented findings presented by WGI AR5. Understanding the reliability of this information is of crucial importance. In the context of IAV studies it is relevant to a very wide range of scales and it comes with a similarly wide range of reliabilities. Using a classification of spatial scales similar to that presented in Table 21-5,

Table 21-4 | Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.

Early warning systems for heat	
Exposure and vulnerability	Factors affecting exposure and vulnerability include age, preexisting health status, level of outdoor activity, socioeconomic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, urban heat island effects, and urban infrastructure. [8.2.3, 8.2.4, 11.3.3, 11.3.4, 11.4.1, 11.7, 13.2.1, 19.3.2, 23.5.1, 25.3, 25.8.1, SREX Table SPM.1]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] **Projected:** *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3]
Climate information at the regional scale	**Observed:** • *Likely* that heat wave frequency has increased since 1950 in large parts of Europe, Asia, and Australia. [WGI AR5 2.6.1] • *Medium confidence* in overall increase in heat waves and warm spells in North America since 1960. Insufficient evidence for assessment or spatially varying trends in heat waves or warm spells for South America and most of Africa. [SREX Table 3-2; WGI AR5 2.6.1] **Projected:** • *Likely* that, by the end of the 21st century under Representative Concentration Pathway 8.5 (RCP8.5) in most land regions, a current 20-year high-temperature event will at least double its frequency and in many regions occur every 2 years or annually, while a current 20-year low-temperature event will become exceedingly rare. [WGI AR5 12.4.3] • *Very likely* more frequent and/or longer heat waves or warm spells over most land areas. [WGI AR5 12.4.3]
Description	Heat-health early warning systems are instruments to prevent negative health impacts during heat waves. Weather forecasts are used to predict situations associated with increased mortality or morbidity. Components of effective heat wave and health warning systems include identifying weather situations that adversely affect human health, monitoring weather forecasts, communicating heat wave and prevention responses, targeting notifications to vulnerable populations, and evaluating and revising the system to increase effectiveness in a changing climate. Warning systems for heat waves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia. [11.7.3, 24.4.6, 25.8.1, 26.6, Box 25-6]
Broader context	• Heat health warning systems can be combined with other elements of a health protection plan, for example building capacity to support communities most at risk, supporting and funding health services, and distributing public health information. • In Africa, Asia, and elsewhere, early warning systems have been used to provide warning of and reduce a variety of risks related to famine and food insecurity; flooding and other weather-related hazards; exposure to air pollution from fire; and vector-borne and food-borne disease outbreaks. [7.5.1, 11.7, 15.4.2, 22.4.5, 24.4.6, 25.8.1, 26.6.3, Box 25-6]
Mangrove restoration to reduce flood risks and protect shorelines from storm surge	
Exposure and vulnerability	Loss of mangroves increases exposure of coastlines to storm surge, coastal erosion, saline intrusion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, can be particularly vulnerable. [5.4.3, 5.5.6, 29.7.2, Box CC-EA]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] **Projected:** • *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] • In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]
Climate information at the regional scale	**Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** • *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] • Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] • *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
Description	Mangrove restoration and rehabilitation has occurred in a number of locations (e.g., Vietnam, Djibouti, and Brazil) to reduce coastal flooding risks and protect shorelines from storm surge. Restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion. [2.4.3, 5.5.4, 8.3.3, 22.4.5, 27.3.3]
Broader context	• Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, saline intrusion, wave damage, and erosion. Restoration and rehabilitation of mangroves, as well as of wetlands or deltas, is ecosystem-based adaptation that enhances ecosystem services. • Synergies with mitigation given that mangrove forests represent large stores of carbon. • Well-integrated ecosystem-based adaptation can be more cost effective and sustainable than non-integrated physical engineering approaches. [5.5, 8.4.2, 14.3.1, 24.6, 29.3.1, 29.7.2, 30.6.1, 30.6.2, Table 5-4, Box CC-EA]

Continued next page →

Table 21-4 (continued)

Community-based adaptation and traditional practices in small island contexts	
Exposure and vulnerability	With small land area, often low elevation coasts, and concentration of human communities and infrastructure in coastal zones, small islands are particularly vulnerable to rising sea levels and impacts such as inundation, saltwater intrusion, and shoreline change. [29.3.1, 29.3.3, 29.6.1, 29.6.2, 29.7.2]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] • Singe 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] **Projected:** • *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] • In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** • *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] • Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% and 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] • *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
Description	Traditional technologies and skills can be relevant for climate adaptation in small island contexts. In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after Cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. [29.6.2]
Broader context	• Perceptions of self-efficacy and adaptive capacity in addressing climate stress can be important in determining resilience and identifying useful solutions. • The relevance of community-based adaptation principles to island communities, as a facilitating factor in adaptation planning and implementation, has been highlighted, for example, with focus on empowerment and learning-by-doing, while addressing local priorities and building on local knowledge and capacity. Community-based adaptation can include measures that cut across sectors and technological, social, and institutional processes, recognizing that technology by itself is only one component of successful adaptation. [5.5.4, 29.6.2]
Adaptive approaches to flood defense in Europe	
Exposure and vulnerability	Increased exposure of persons and property in flood risk areas has contributed to increased damages from flood events over recent decades. [5.4.3, 5.4.4, 5.5.5, 23.3.1, Box 5-1]
Climate information at the global scale	**Observed:** • *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] **Projected:** • *Very likely* that the time-mean rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971–2010 for all RCP scenarios. [WGI AR5 13.5.1] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • *Likely* increase in the frequency or intensity of heavy precipitation in Europe, with some seasonal and/or regional variations. [WGI AR5 2.6.2] • Increase in heavy precipitation in winter since the 1950s in some areas of northern Europe (*medium confidence*). Increase in heavy precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*). [SREX Table 3-2] • Increasing mean sea level with regional variations, except in the Baltic Sea where the relative sea level is decreasing due to vertical crustal motion. [5.3.2, 23.2.2] **Projected:** • Over most of the mid-latitude land masses, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world. [WGI AR5 12.4.5] • Overall precipitation increase in northern Europe and decrease in southern Europe (*medium confidence*). [23.2.2] • Increased extreme precipitation in northern Europe during all seasons, particularly winter, and in central Europe except in summer (*high confidence*). [23.2.2; SREX Table 3.3]
Description	Several governments have made ambitious efforts to address flood risk and sea level rise over the coming century. In the Netherlands, government recommendations include "soft" measures preserving land from development to accommodate increased river inundation; maintaining coastal protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. Through a multi-stage process, the British government has also developed extensive adaptation plans to adjust and improve flood defenses to protect London from future storm surges and river flooding. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions. [5.5.4, 23.7.1, Box 5-1]
Broader context	• The Dutch plan is considered a paradigm shift, addressing coastal protection by "working with nature" and providing "room for river." • The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise with numerous and diverse measures possible over the next 50 to 100 years to reduce risk to acceptable levels. • In cities in Europe and elsewhere, the importance of strong political leadership or government champions in driving successful adaptation action has been noted. [5.5.3, 5.5.4, 8.4.3, 23.7.1, 23.7.2, 23.7.4, Boxes 5-1 and 26-3]

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Table 21-4 (continued)

Index-based insurance for agriculture in Africa	
Exposure and vulnerability	Susceptibility to food insecurity and depletion of farmers' productive assets following crop failure. Low prevalence of insurance due to absent or poorly developed insurance markets or to amount of premium payments. The most marginalized and resource-poor especially may have limited ability to afford insurance premiums. [10.7.6, 13.3.2, Box 22-1]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] • *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** • *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3] • Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with medium confidence by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • *Medium confidence* in increase in frequency of warm days and decrease in frequency of cold days and nights in southern Africa. [SREX Table 3-2] • *Medium confidence* in increase in frequency of warm nights in northern and southern Africa. [SREX Table 3-2] **Projected:** • *Likely* surface drying in southern Africa by the end of the 21st century under RCP8.5 (*high confidence*). [WGI AR5 12.4.5] • *Likely* increase in warm days and nights and decrease in cold days and nights in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*). [Table SREX 3-3] • Likely more frequent and/or longer heat waves and warm spells in Africa (*high confidence*). [Table SREX 3-3]
Description	A recently introduced mechanism that has been piloted in a number of rural locations, including in Malawi, Sudan, and Ethiopia, as well as in India. When physical conditions reach a particular predetermined threshold where significant losses are expected to occur—weather conditions such as excessively high or low cumulative rainfall or temperature peaks—the insurance pays out. [9.4.2, 13.3.2, 15.4.4, Box 22-1]
Broader context	• Index-based weather insurance is considered well suited to the agricultural sector in developing countries. • The mechanism allows risk to be shared across communities, with costs spread over time, while overcoming obstacles to traditional agricultural and disaster insurance markets. It can be integrated with other strategies such as microfinance and social protection programs. • Risk-based premiums can help encourage adaptive responses and foster risk awareness and risk reduction by providing financial incentives to policyholders to reduce their risk profile. • Challenges can be associated with limited availability of accurate weather data and difficulties in establishing which weather conditions cause losses. Basis risk (i.e., farmers suffer losses but no payout is triggered based on weather data) can promote distrust. There can also be difficulty in scaling up pilot schemes. • Insurance for work programs can enable cash-poor farmers to work for insurance premiums by engaging in community-identified disaster risk reduction projects. [10.7.4 to 10.7.6, 13.3.2, 15.4.4, Table 10-7, Box 22-1, Box 25-7]

Continued next page →

Table 21-6 provides a summary assessment of the reliability of information on two basic climate variables of relevance, surface temperature and precipitation. It is drawn from the extensive assessment and supporting literature from the IPCC SREX (IPCC, 2012) and the WGI AR5 reports. Some discussion of relevant methodologies and related issues and results is also presented in Section 21.5.

Table 21-6 shows there are significant variations in reliability, with finer scaled information generally less reliable given the need for a greater density of observations and/or for models to maintain accuracy at high resolutions. The reliability of information on past climate depends on the availability and quality of observations, which are higher for temperature than precipitation as observations of temperature are easier to make and generally more representative of surrounding areas than is the case for precipitation. Future climate change reliability depends on the performance of the models used for the projections in simulating the processes that lead to these changes. Again, information on temperature is generally more reliable owing to the models' demonstrated ability to simulate the relevant processes when reproducing past changes. The significant geographical variations, in the case of the observations, result from issues with availability and/or quality of data in many regions, especially for precipitation. For future climate change, data availability is less of an issue with the advent of large ensembles of climate model projections but quality is a significant problem in some regions where the models perform poorly and there is little confidence that processes driving the projected changes are accurately captured. A framework for summary information on model projections of future climate change placed in the context of observed changes is presented in Box 21-2.

21.3.1. Vulnerabilities and Impacts

21.3.1.1. Observed Impacts

The evidence linking observed impacts on biological, physical, and (increasingly) human systems to recent and ongoing regional climate changes has become more compelling since the AR4 (see Chapter 18). One reason for this is the improved reporting of published studies from hitherto under-represented regions of the world, especially in the tropics (Rosenzweig and Neofotis, 2013). That said, the disparity is still large between the copious evidence being presented from Europe and North America, as well as good quality data emerging from Australasia, polar regions, many ocean areas, and some parts of Asia and South America, compared to the much sparser coverage of studies from Africa, large parts of Asia, Central and South America, and many small islands. On the other hand, as the time series of well-calibrated satellite observations

Table 21-4 (continued)

Relocation of agricultural industries in Australia	
Exposure and vulnerability	Crops sensitive to changing patterns of temperature, rainfall, and water availability. [7.3, 7.5.2]
Climate information at the global scale	**Observed:** • *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] • *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] • *Medium confidence* in precipitation change over global land areas since 1950. [WGI AR5 2.5.1] • Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] • *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** • *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal time scales. [WGI AR5 12.4.3] • *Virtually certain* increase in global precipitation as global mean surface temperature increases. [WGI AR5 12.4.1] • Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] • Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
Climate information at the regional scale	**Observed:** • Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand, since 1950 (*high confidence*). [Table 25-1] • *Likely* increase in heat wave frequency since 1950 in large parts of Australia. [WGI AR5 2.6.1] • Late autumn/winter decreases in precipitation in southwestern Australia since the 1970s and southeastern Australia since the mid-1990s, and annual increases in precipitation in northwestern Australia since the 1950s (*very high confidence*). [Table 25-1] • Mixed or insignificant trends in annual daily precipitation extremes, but a tendency to significant increase in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). [Table 25-1] **Projected:** • Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). [Table 25-1] • Annual decline in precipitation over southwestern Australia (*high confidence*) and elsewhere in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). [Table 25-1] • Increase in most regions in the intensity of rare daily rainfall extremes and in sub-daily extremes (*medium confidence*) in Australia and New Zealand. [Table 25-1] • Drought occurrence to increase in southern Australia (*medium confidence*). [Table 25-1] • Snow depth and snow area to decline in Australia (*very high confidence*). [Table 25-1] • Freshwater resources projected to decline in far southeastern and far southwestern Australia (*high confidence*). [25.5.2]
Description	Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use *in situ* in response to recent climate change or expectations of future change. For example, there has been some switching from grazing to cropping in southern Australia. Adaptive movement of crops has also occurred elsewhere. [7.5.1, 25.7.2, Table 9-7, Box 25-5]
Broader context	• Considered transformational adaptation in response to impacts of climate change. • Positive or negative implications for the wider communities in origin and destination regions. [25.7.2, Box 25-5]

become longer in duration, and hence statistically more robust, these are increasingly providing a near global coverage of changes in surface characteristics such as vegetation, hydrology, and snow and ice conditions that can usefully complement or substitute for surface observations (see Table 21-4 and Chapter 18 for examples). Changes in climate variables other than temperature, such as precipitation, evapotranspiration, and carbon dioxide (CO_2) concentration, are also being related to observed impacts in a growing number of studies (Rosenzweig and Neofotis, 2013; see also examples from Australia in Table 25-3 and southeastern South America in Figure 27-7).

Other regional differences in observed changes worth pointing out include trends in relative sea level, which is rising on average globally (Church et al., 2014), but displays large regional variations in magnitude, or even sign, due to a combination of influences ranging from El Niño/La Niña cycles to local tectonic activity (Nicholls et al., 2013), making general conclusions about ongoing and future risks of sea level change very difficult to draw across diverse regional groupings such as small islands (see Chapter 29). There are also regional variations in another ongoing effect of rising CO_2 concentration—ocean acidification, with a greater pH decrease at high latitudes consistent with the generally lower buffer capacities of the high latitude oceans compared to lower latitudes (Rhein et al., 2014; Section 3.8.2). Calcifying organisms are expected to show responses to these trends in future, but key uncertainties remain at organismal to ecosystem levels (Chapter 30, Box CC-OA).

21.3.1.2. Future Impacts and Vulnerability

21.3.1.2.1. Impact models

The long-term monitoring of environmental variables, as well as serving a critical role in the detection and attribution of observed impacts, also provides basic calibration material used for the development and testing of impact models. These include process-based or statistical models used to simulate the biophysical impacts of climate on outcomes such as crop yield, forest productivity, river runoff, coastal inundation, or human mortality and morbidity (see Chapters 2 to 7, 11). They also encompass various types of economic models that can be applied to evaluate the costs incurred by biophysical impacts (see, e.g., Chapters 10 and 17).

There are also Integrated Assessment Models (IAMs), Earth system models, and other more loosely linked integrated model frameworks that represent multiple systems and processes (e.g., energy, emissions, climate, land use change, biophysical impacts, economic effects, global trade) and the various interactions and feedbacks between them. For examples of these, see Section 17.6.3 and Flato et al. (2014).

Table 21-5 | Dimensions of assessments of impacts and vulnerability and of adaptation drawn on to serve different target fields (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to original studies and to chapters in which similar studies are cited. Aspects of some of the studies in this table are also alluded to in Section 21.5.

Scale	Approach/field		
	Impacts/vulnerability	**Adaptation**	**Target field**
Global	• Resource availability[1,2,3] • Impact costs[4,5,6,7] • Vulnerability/risk mapping[8,9,10] • Hotspots analysis[11]	• Adaptation costs[4,5,6,7,12]	• Policy negotiations • Development aid • Disaster planning • Capacity building
Continental/biome	• Observed impacts[13,14,15] • Future biophysical impacts[16,17] • Impact costs[5,16] • Vulnerability/risk mapping[18]	• Adaptation costs[5] • Modeled adaptation[19]	• Capacity building • International law • Policy negotiations • Regional development
National/state/province	• Observed impacts[20,21,22] • Future impacts/risks[23,24] • Vulnerability assessment[24] • Impact costs[25]	• Observed adaptation[26] • Adaptation assessment[24,27]	• National adaptation plan/strategy • National communication • Legal requirement • Regulation
Municipality/basin/patch/delta/farm	• Hazard/risk mapping[28] • Pest/disease risk mapping[29] • Urban risks/vulnerabilities[30]	• Adaptation cost[28] • Urban adaptation[30,31]	• Spatial planning • Extension services • Water utilities • Private sector
Site/field/tree/floodplain/household	• Field experiments[32]	• Coping studies[33,34] • Economic modeling[35] • Agent-based modeling[36]	• Individual actors • Local planners

1. Global terrestrial water balance in the Water Model Intercomparison Project (Haddeland et al., 2011); see 3.4.1.
2. Global dynamic vegetation model intercomparison (Sitch et al., 2008); see 4.3.2.
3. Impacts on agriculture, coasts, water resources, ecosystems, and health in the Inter-Sectoral Impact Model Intercomparison Project (Schiermeier, 2012); see 19.6.2.
4. UNFCCC study to estimate the aggregate cost of adaptation (UNFCCC, 2007), which is critiqued by Parry (2009) and Fankhauser (2010)
5. The Economics of Adaptation to Climate Change study (World Bank, 2010).
6. A thorough evaluation of global modeling studies is provided in 17.4.2. (See also 14.5.2 and 16.3.2.)
7. Impacts on agriculture and costs of adaptation (e.g., Nelson et al., 2009b); see 7.4.4.
8. Can we avoid dangerous climate change? (AVOID) program and Quantifying and Understanding the Earth System (QUEST) Global-scale impacts of climate change (GSI) project (Arnell et al., 2013); see 19.7.1.
9. OECD project on Cities and Climate Change (Hanson et al., 2011); see 5.4.3, 23.3.1, 24.4.5, and 26.8.3.
10. For critical reviews of global vulnerability studies, see Füssel (2010b) and Preston et al. (2011).
11. A discussion of hotspots can be found in Section 21.5.1.2.
12. Adaptation costs for climate change-related human health impacts (Ebi, 2008); see 17.4.2.
13. Satellite monitoring of sea ice over polar regions (Comiso and Nishio, 2008); see also Vaughan et al. (2013).
14. Satellite monitoring of vegetation growth (e.g., Piao et al., 2007) and phenology (e.g., Heumann et al., 2011); see 4.3.2, 4.3.3, and 18.3.2.
15. Meta-analysis of range shifts in terrestrial organisms (e.g., Chen et al., 2011); see 4.3.2 and 18.3.2.
16. Physical and economic impacts of future climate change in Europe (Ciscar et al., 2011); see 23.3.1 and 23.4.1.
17. Impacts on crop yields in West Africa (Roudier et al., 2011); see Chapter 22.3.4.
18. Climate change integrated methodology for cross-sectoral adaptation and vulnerability in Europe (CLIMSAVE) project (Harrison et al., 2012); see 23.2.1.
19. Modeling agricultural management under climate change in sub-Saharan Africa (Waha et al., 2013).
20. Satellite monitoring of lake levels in China (Wang et al., 2013).
21. Satellite monitoring of phenology in India (Singh et al., 2006) and in other regions (18.3.2).
22. UK Climate Change Risk Assessment (CCRA, 2012); see Table 15-2.
23. United States Global Change Research Program second (Karl et al., 2009) and third (in review) national climate change impact assessments; see 26.1.
24. The Global Environment Facility-funded Assessments of Impacts and Adaptations to Climate Change program addressed impacts and vulnerability (Leary et al., 2008b) and adaptation (Leary et al., 2008a) in developing countries; for example, see 27.3.5.
25. Economics of Climate Change national studies in Kenya and Tanzania (SEI, 2009; GCAP, 2011); see 22.3.6.
26. Sowing dates of various crops in Finland (Kaukoranta and Hakala, 2008); and see 23.4.1.
27. Finnish Climate Change Adaptation Research Programme (ISTO) Synthesis Report (Ruuhela, 2012).
28. Urban flood risk and adaptation cost, Finland (Perrels et al., 2010).
29. See Garrett (2013) for a specific example of a risk analysis, or Sutherst (2011) for a review; and see 25.7.2.
30. New York City coastal adaptation (Rosenzweig et al., 2011); and see 8.2 and Box 26-3.
31. Bangkok Assessment Report of Climate Change (BMA/GLF/UNEP, 2009); see 8.3.3.
32. Field, chamber and laboratory plant response experiments (e.g., Long et al., 2006; Hyvönen et al., 2007; Wittig et al., 2009; Craufurd et al., 2013); see 4.2.4 and 7.3.1.
33. Farming response to irrigation water scarcity in China (Liu et al., 2008); and see 13.2.2.
34. Farmers' mechanisms for coping with hurricanes in Jamaica (Campbell and Beckford, 2009); and see 29.6.
35. Modeling micro-insurance of subsistence farmers for drought losses in Ethiopia (Meze-Hausken et al., 2009); see 14.3.1.
36. Simulating adaptive behavior of farming communities in the Philippines (Acosta-Michlik and Espaldon, 2008); see 24.4.6.

Table 21-6 | Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to Very Low (VL).

Spatial scale	Era	Temporal scale					
		Annual		Seasonal		Daily	
		Temperature	Precipitation	Temperature	Precipitation	Temperature	Precipitation
Global	Past	VH	H	VH	H	N/A	N/A
	Future change	VH (direction) H (amount)	H (direction) MH (amount)	VH (direction) H (amount)	H (direction) MH (amount)	N/A	N/A
Regional, large river basin	Past	VH–H (depends on observation availability)	H–L (depends on observation availability)	VH–H (depends on observation availability)	H–L (depends on observation availability)	VH–H (depends on observation availability)	H–L (depends on observation availability)
	Future change	VH (direction) H (amount)	H–L (depends on capture of processes)	VH (direction) MH (amount)	H–L (depends on capture of processes)	VH (direction) MH (amount)	H–L (depends on capture of processes)
National, state	Past	VH–H (depends on observation availability)	H–L (depends on observation availability)	VH–H (depends on observation availability)	H–L (depends on observation availability)	VH–H (depends on observation availability)	H–VL (depends on observation availability)
	Future change	VH (direction) MH (amount)	H–L (depends on capture of processes)	VH (direction) MH (amount)	H–L (depends on capture of processes)	H (direction) MH (amount)	H–VL (depends on capture of processes)
City, county	Past	VH–M (depends on observation availability)	H–VL (depends on observation availability)	VH–M (depends on observation availability)	H–VL (depends on observation availability)	H–ML (depends on observation availability)	H–VL (depends on observation availability)
	Future change	H (direction) MH (amount)	H–VL (depends on capture of processes)	H (direction) MH (amount)	H–VL (depends on capture of processes)	H (direction) M (amount)	M–VL (depends on capture of processes)
Village, site/field	Past	VH–ML (depends on observation availability)	H–VL (depends on observation availability)	VH–ML (depends on observation availability)	H–VL (depends on observation availability)	H–ML (depends on observation availability)	H–VL (depends on observation availability)
	Future change	H (direction) MH (amount)	H–VL (depends on capture of processes)	H (direction) MH (amount)	H–VL (depends on capture of processes)	H (direction) M (amount)	M–VL (depends on capture of processes)

Frequently Asked Questions

FAQ 21.1 | How does this report stand alongside previous assessments for informing regional adaptation?

The five major Working Group II assessment reports produced since 1990 all share a common focus that addresses the environmental and socioeconomic implications of climate change. In a general sense, the earlier assessments are still valid, but the assessments have become much more complete over time, evolving from making very simple, general statements about sectoral impacts, through greater concern with regions regarding observed and projected impacts and associated vulnerabilities, through to an enhanced emphasis on sustainability and equity, with a deeper examination of adaptation options. Finally, in the current report there is a much improved appreciation of the context for regional adaptation and a more explicit treatment of the challenges of decision making within a risk management framework.

Obviously one can learn about the latest understanding of regional impacts, vulnerability, and adaptation in the context of climate change by looking at the most recent report. This builds on the information presented in previous reports by reporting developments in key topics. New and emergent findings are given prominence, as these may present fresh challenges for decision makers. Differences with the previous reports are also highlighted—whether reinforcing, contradicting, or offering new perspectives on earlier findings—as these too may have a bearing on past and present decisions. Following its introduction in the TAR, uncertainty language has been available to convey the level of confidence in key conclusions, thus offering an opportunity for calibrated comparison across successive reports. Regional aspects have been addressed in dedicated chapters for major world regions, first defined following the SAR and used with minor variations in the three subsequent assessments. These consist of the continental regions of Africa, Europe, Asia, Australasia, North America, Central and South America, Polar Regions, and Small Islands, with a new chapter on The Oceans added for the present assessment.

21.3.1.2.2. Vulnerability mapping

A second approach to projecting potential future impacts is to construct vulnerability maps. These usually combine information on three components: exposure to a hazard (commonly defined by the magnitude of climate change, sensitivity to that hazard), the magnitude of response for a given level of climate change, and adaptive capacity (describing the social and economic means to withstand the impacts of climate change (IPCC, 2001b)). Key indicators are selected to represent each of the three components, which are sometimes combined into a single index of vulnerability. Indicators are usually measured quantities taken from statistical sources (e.g., income, population), or have been modeled separately (e.g., key climate variables). Vulnerability indices have received close scrutiny in several recent reviews (Füssel, 2010b; Hinkel, 2011; Malone and Engle, 2011; Preston et al., 2011; Kienberger et al., 2012), and a number of global studies have been critiqued by Füssel (2010b).

A variant of vulnerability mapping is risk mapping (e.g., Ogden et al., 2008; Tran et al., 2009). This commonly identifies a single indicator of hazard (e.g., a level of flood expected with a given return period), which can be mapped accurately to define those regions at risk from such an event (e.g., in a flood plain). Combined with information on changing return periods of such events under a changing climate would enable some estimate of altered risk to be determined.

21.3.1.2.3. Experiments

A final approach for gaining insights on potential future impacts concerns physical experiments designed to simulate future altered environments of climate (e.g., temperature, humidity, and moisture) and atmospheric composition (e.g., CO_2, surface ozone, and sulfur dioxide concentrations). These are typically conducted to study responses of crop plants, trees, and natural vegetation, using open top chambers, greenhouses, or free air gas release systems (e.g., Craufurd et al., 2013), or responses of aquatic organisms such as plankton, macrophytes, or fish, using experimental water enclosures known as mesocosms (e.g., Sommer et al., 2007; Lassen et al., 2010).

21.3.1.2.4. Scale issues

Impact models operate at a range of spatial and temporal resolutions, and while their outputs are sometimes presented as fine-resolution maps, key model findings are rarely produced at the finest resolution

Frequently Asked Questions

FAQ 21.2 | Do local and regional impacts of climate change affect other parts of the world?

Local and regional impacts of climate change, both adverse and beneficial, may indeed have significant ramifications in other parts of the world. Climate change is a global phenomenon, but often expresses itself in local and regional shocks and trends impacting vulnerable systems and communities. These impacts often materialize in the same place as the shock or trend, but also much farther afield, sometimes in completely different parts of the world. Regional interdependencies include both the global physical climate system as well as economic, social, and political systems that are becoming increasingly globalized.

In the physical climate system, some geophysical impacts can have large-scale repercussions well beyond the regions in which they occur. A well-known example of this is the melting of land-based ice, which is contributing to sea level rise (and adding to the effects of thermal expansion of the oceans), with implications for low-lying areas far beyond the polar and mountain regions where the melting is taking place.

Other local impacts can have wider socioeconomic and geopolitical consequences. For instance, extreme weather events in one region may impact production of commodities that are traded internationally, contributing to shortages of supply and hence increased prices to consumers, influencing financial markets and disrupting food security worldwide, with social unrest a possible outcome of food shortages. Another example, in response to longer term trends, is the potential prospect of large-scale migration due to climate change. Though hotly contested, this link is already seen in the context of natural disasters, and could become an issue of increasing importance to national and international policymakers. A third example is the shrinkage of Arctic sea ice, opening Arctic shipping routes as well as providing access to valuable mineral resources in the exclusive economic zones of countries bordering the Arctic, with all the associated risks and opportunities. Other examples involving both risks and opportunities include changes of investment flows to regions where future climate change impacts may be beneficial for productivity.

Finally, some impacts that are entirely local and may have little or no direct effect outside the regions in which they occur still threaten values of global significance, and thus trigger international concern. Examples include humanitarian relief in response to local disasters or conservation of locally threatened and globally valued biodiversity.

Box 21-2 | Summary Regional Climate Projection Information

Summary figures on observed and projected changes in temperature and precipitation are presented in the following regional chapters. These provide some context to the risks associated with climate change vulnerability and impacts and the decision making on adaptations being planned and implemented in response to these risks. Figure 21-2 provides an example for Africa. The information is identical to that displayed in Box CC-RC.

These figures provide a very broad overview of the projected regional climate changes, but in dealing with only annual averages they are not able to convey any information about projected changes on seasonal time scales or shorter, such as for extremes. In addition, they are derived solely from the Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) and do not display any information derived from CMIP3 data, which are widely used in many of the studies assessed within the WGII AR5. To provide additional context, two additional sets of figures are presented here and in Box 21-4 that display temperature and precipitation changes at the seasonal and daily time scales respectively.

Figure 21-3 displays projected seasonal and annual changes averaged over the regions defined in the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), for Central and South America for the four RCP scenarios and three of the SRES scenarios. The temperature and precipitation changes for the period 2071–2100 compared to a baseline of 1961–1990 are plotted for the four standard 3-month seasons with the changes from each CMIP3 or CMIP5 represented by a symbol. Symbols showing the CMIP3 model projections are all gray but differ in shape depending on the driving SRES concentrations scenario and those showing the CMIP5 projections differ in color depending on the driving RCP emissions/concentrations scenario (see figure legend for details and Box 21-1 for more information on the SRES and RCP scenarios). The 30-year periods were chosen for consistency with the figures displayed in Box 21-4 (Figures 21-7 and 21-8) showing changes in daily temperatures and precipitation. Figures presenting similar information for the SREX regions contained in the other inhabited continents are presented in Figures SM21-1 to SM21-7.

of the simulations (i.e., they are commonly aggregated to political or topographic units of interest to the target audience, e.g., watershed, municipality, national, or even global). Aggregation of data to coarse-scale units is also essential for allowing comparison of outputs from models operating at different resolutions, but it also means that sometimes quite useful detail may be overlooked when model outputs are presented at the scale of the coarsest common denominator. Conversely, if outputs from impact models are required as inputs to other models, the outputs may need to be harmonized to a finer grid than the original data. In such cases, downscaling methods are commonly applied. This was the case, for example, when providing spatially explicit projections of future land use from different IAMs (Hurtt et al., 2011) for climate modelers to apply in the CMIP5 process (Collins et al., 2014a). It is also a common procedure used in matching climate model outputs to impact models designed to be applied locally (e.g., over a river basin or an urban area; see Section 21.3.3.2).

Even if the same metrics are being used to compare aggregate model results (e.g., developed versus developing country income under a given future scenario) estimates may have been obtained using completely different types of models operating at different resolutions. Moreover, many models that have a large-scale coverage (e.g., continental or global) may nonetheless simulate processes at a relatively fine spatial resolution, offering a potentially useful source of spatially explicit information that is unfamiliar to analysts working in specific regions, who may defer to models more commonly applied at the regional scale. Examples include comparison of hydrological models with a global and regional scope (Todd et al., 2011) and bioclimatic models of vascular plant distributions with a European and local scope (Trivedi et al., 2008).

Vulnerability mapping exercises can also be undermined by inappropriate merging of indicator data sets that resolve information to a different level of precision (e.g., Tzanopoulos et al., 2013). There is scope for considerably enhanced cross-scale model intercomparison work in the future, and projects such as the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2013) and Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP; Schiermeier, 2012; see also Section 21.5) have provision for just such exercises.

21.3.2. Adaptation

This section draws on material from the regional chapters (22 to 30) as well as the examples described in Table 21-4. Material from Chapters 14 to 17 is also considered. See also Table 16-4 for a synthesis from the perspective of adaptation constraints and limits.

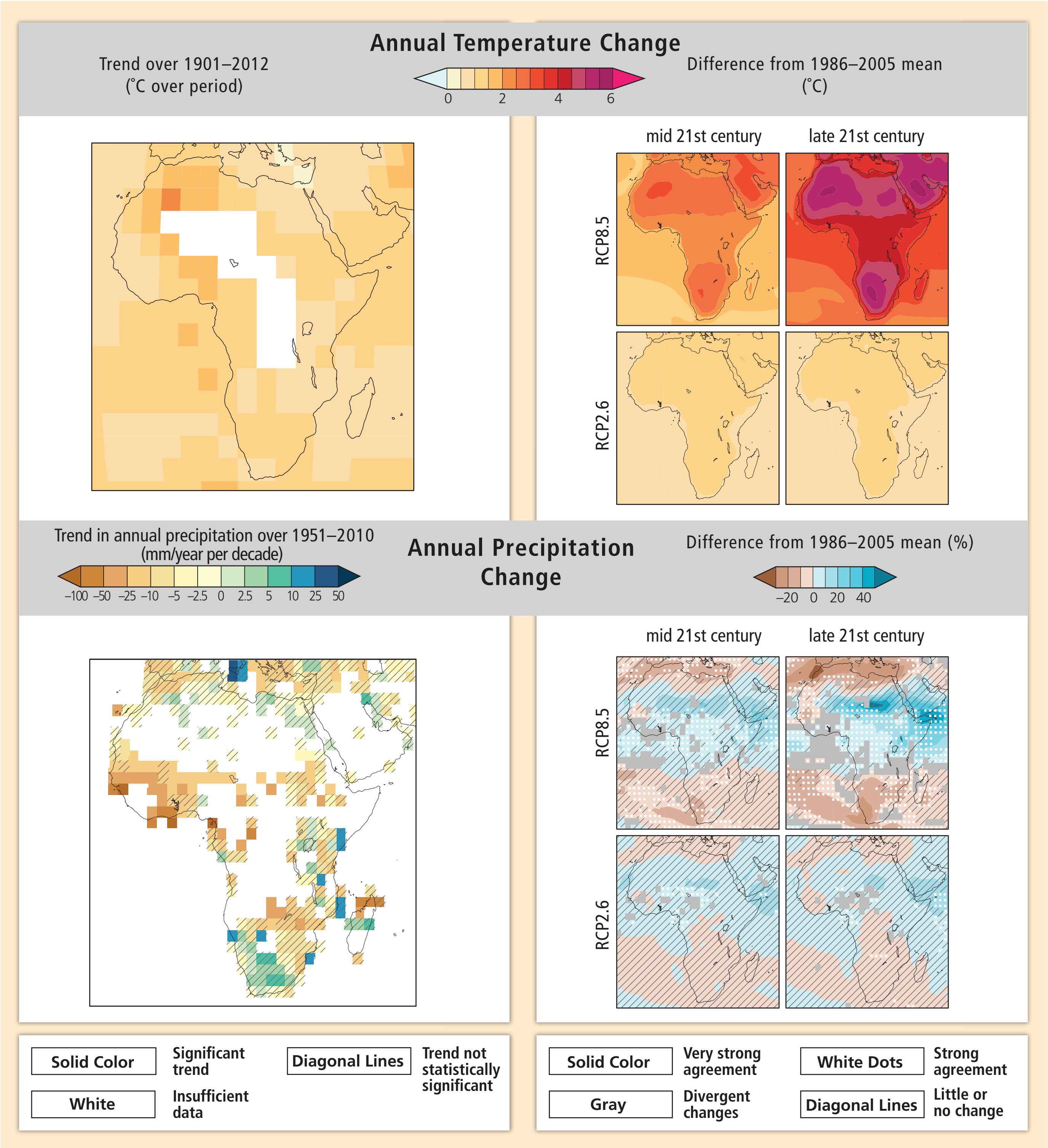


Figure 21-2 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5 Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

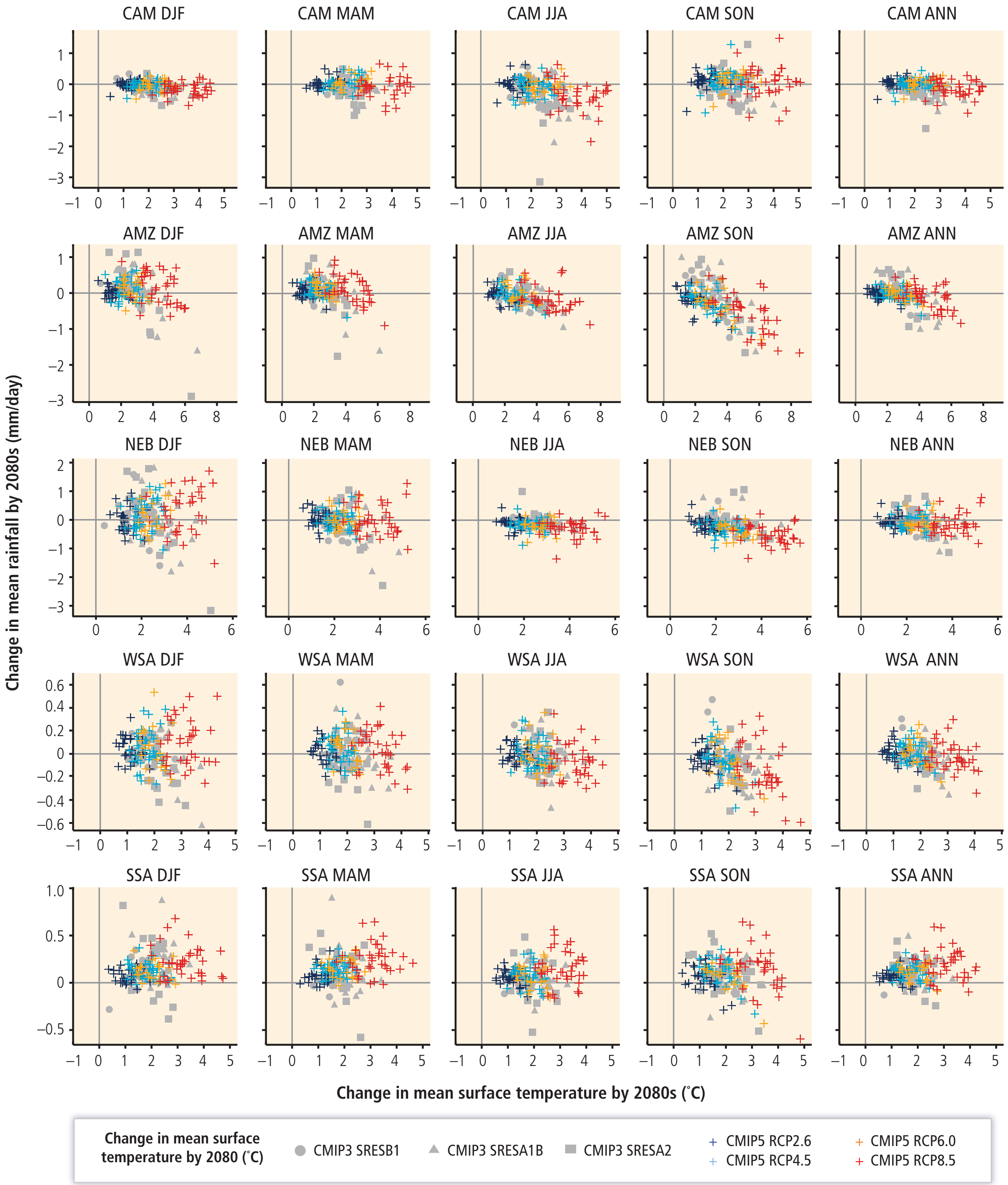


Figure 21-3 | Regional average change in seasonal and annual mean temperature and precipitation over five sub-regions covering South and Central America for the period 2071–2100 relative to 1961–1990 in General Circulation Model (GCM) projections from 35 Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble under four Representative Concentration Pathway (RCP) scenarios (van Vuuren et al., 2011) compared with GCM projections from 22 CMIP3 ensemble under three Special Report on Emission Scenarios (SRES) scenarios (IPCC, 2000a); see Table 21-1 for details of the relationship between the SRES and RCP scenarios. Regional averages are based on SREX region definitions (IPCC, 2012; see also Figure 21-4). Temperature changes are given in °C and precipitation changes in mm day^{-1} with axes scaled relative to the maximum changes projected across the range of models. The models that generated the data displayed are listed in Table SM21-3.

21.3.2.1. Similarities and Differences in Regions

As described in the regional chapters, a large portion of adaptation knowledge is based on conclusions drawn from case studies in specific locations, with the conceptual findings typically being applied globally (Chapters 14 to 17). It is this empirical knowledge on adaptation that guides understandings in the different regions. This is especially the case for developing regions. Thus, regional approaches to adaptation vary in their degree of generality. One of the most striking differences between regions in terms of adaptation is the extent to which it has been studied and implemented. Australia and Europe have invested heavily in research on adaptation since the AR4, and the result is a rich body of literature published by local scientists. The ability to advance in adaptation knowledge may be related to the amount and quality of reliable climate information, the lack of which has been identified as a constraint to developing adaptation measures in Africa (Section 22.4.2). Many case studies, especially of community-based adaptation, stem from Asia, Africa, Central and South America, and small islands but the majority of this work has been undertaken and authored by international non-governmental organizations, as well as by other non-local researchers. In Africa, most planned adaptation work is considered to be pilot and seen as part of learning about adaptation, although there has been significant progress since the AR4 (Section 22.4.4.2).

Most regional chapters report lags in policy work on adaptation (see also Section 16.5.2). While most European countries have adaptation strategies, few have been implemented (Section 23.1.2). Lack of implementation of plans is also the case for Africa (Section 22.4). In North (Section 26.8.4.1.2) and Central and South America (Section 27.5.3.2), adaptation plans are in place for some cities. In Australasia, there are few adaptation plans (Section 25.4.2). In the Arctic, they are in their infancy (Section 28.4). At the same time, civil society and local communities have the opportunity to play a role in decision making about adaptation in Europe and Asia (Sections 23.7.2, 24.4.6.5). In Africa, social learning and collective action are used to promote adaptation (Section 22.4.5.3). Adaptation is observed as mostly autonomous (spontaneous) in Africa, although socio-ecological changes are creating constraints for autonomous adaptation (Section 22.4.5.4). There is a disconnect in most parts of Africa between policy and planning levels, and the majority of work is still autonomous and unsupported (Section 22.4.1). In the case of UNFCCC-supported activities, such as National Adaptation Programmes of Action, few projects from the African (Section 22.4.4.2) least developed countries have been funded, thus limiting the effectiveness of these investments. Several chapters (Africa, Europe, North America, Central and South America, and Small Islands) explicitly point out that climate change is only one of multiple factors that affect societies and ecosystems and drives vulnerability or challenges adaptation (Sections 22.4.2, 23.10.1, 26.8.3.1, 27.3.1.2, 29.6.3). For example, North America reports that for water resources, most adaptation actions are “no-regrets,” meaning that they have benefits beyond just adaptation to climate change (Section 26.3.4). In Australasia, the limited role of socioeconomic information in vulnerability assessments restricts confidence regarding the conclusions about future vulnerability and adaptive capacity (Section 25.3.2).

Some chapters (Polar Regions, North America, Australasia) emphasize the challenges faced by indigenous peoples and communities in dealing with climate change (Sections 25.8.2, 26.8.2.2, 28.4.1). Although they are described as having some degree of adaptive capacity to deal with climate variability, shifts in lifestyles combined with a loss of traditional knowledge leave many groups more vulnerable to climate change (Section 28.2.4.2). Also, traditional responses have been found to be maladaptive because they are unable to adjust to the rate of change, or the broader context in which the change is taking place, as seen in the Arctic (28.4.1). In response to changing environmental conditions, people are taking on maladaptive behavior—for instance, by going further to hunt because of changed fish stocks and thus exposing themselves to greater risk, or changing to different species and depleting stocks (Section 28.4.1). Limits to traditional approaches for responding to changing conditions have also been observed in several Small Island States (29.8).

Most populated regions have experience with adaptation strategies in agriculture, where exposure to the impacts of climate variability over centuries provides a starting point for making adjustments to new changes in climate. Water and land use management strategies stand out in the literature in common across all of the main continental regions.

The link between adaptation and development is explicit in Africa, where livelihood diversification has been key to reducing vulnerability (Section 22.4.5.2). At the same time, there is evidence that many short-term development initiatives have been responsible for increasing vulnerability (Section 22.4.4.2). Other chapters mention constraints or barriers to adaptation in their regions. For example, the low priority accorded to adaptation in parts of Asia, compared to more pressing issues of employment and education, is attributed in part to a lack of awareness of the potential impacts of climate change and the need to adapt, a feature common to many regions (Section 22.5.4). All developing regions cite insufficient financial resources for implementing adaptation as a significant limitation.

21.3.2.2. Adaptation Examples in Multiple Regions

Across regions, similar responses to climate variability and change can be noted. Heat waves are an interesting example (Table 21-4), as early warning systems are gaining use for helping people reduce exposure to heat waves. At the global scale, the length and frequency of warm spells, including heat waves, has increased since 1950 (*medium confidence*) and, over most land areas on a regional scale, more frequent and/or longer heat waves or warm spells are *likely* by 2016–2035 and *very likely* by 2081–2100 (IPCC, 2013a). Warning systems are now planned and implemented in Europe, the USA, Canada, Asia, and Australia.

Use of mangroves to reduce flood risks and protect coastal areas from storm surges is a measure promoted in Asia, Africa, the Pacific, and South America (Table 21-4). Often, mangroves have been cut down to provide coastal access, so there is a need to restore and rehabilitate them. This is an example that is considered low-regrets because it brings multiple benefits to communities besides protecting them from storm surges, such as providing food security and enhancing ecosystem services. Mangrove forests also store carbon, offering synergies with mitigation.

Frequently Asked Questions

FAQ 21.3 | What regional information should I take into account for climate risk management for the 20-year time horizon?

The fundamental information required for climate risk management is to understand the climate events that put the system being studied at risk and what is the likelihood of these arising. The starting point for assembling this information is a good knowledge of the climate of the recent past including any trends in aspects of these events (e.g., their frequency or intensity). It is also be important to consider that many aspects of the climate are changing, to understand how the future projected changes may influence the characteristics of these events and that these changes will, in general, be regionally variable. However, it should be noted that over the coming 20 years the magnitude of projected changes may not be sufficient to have a large influence on the frequency and intensity of these events. Finally, it is also essential to understand which other factors influence the vulnerability of the system. These may be important determinants in managing the risks; also, if they are changing at faster rates than the climate, then changes in the latter become a secondary issue.

For managing climate risks over a 20-year time horizon it is essential to identify the climate variables to which the system at risk is vulnerable. It could be a simple event such as extreme precipitation or a tropical cyclone or a more complex sequence of a late onset of the monsoon coupled with prolonged dry spells within the rainy season.

The current vulnerability of the system can then be estimated from historical climate data on these variables, including any information on trends in the variables. These historical data would give a good estimate of the vulnerability assuming the record was long enough to provide a large sample of the relevant climate variables and that the reasons for any trends, for example, clearly resulting from climate change, were understood. It should be noted that in many regions sufficiently long historical records of the relevant climate variables are often not available.

It is also important to recognize that many aspects of the climate of the next 20 years will be different from the past. Temperatures are continuing to rise with consequent increases in evaporation and atmospheric humidity and reductions in snow amount and snow season length in many regions. Average precipitation is changing in many regions, with both increases and decreases, and there is a general tendency for increases in extreme precipitation observed over land areas. There is a general consensus among climate projections that further increases in heavy precipitation will be seen as the climate continues to warm and more regions will see significant increases or decreases in average precipitation. In all cases the models project a range of changes for all these variables that are generally different for different regions.

Many of these changes may often be relatively small compared to their natural variations but it is the influence of these changes on the specific climate variables that the system is at risk from that is important. Thus information needs to be derived from the projected climate changes on how the characteristics of these variables, for example, the likelihood of their occurrence or magnitude, will change over the coming 20 years. These projected future characteristics in some cases may be indistinguishable from those historically observed but in other cases some or all models will project significant changes. In the latter situation, the effect of the projected climate changes will then result in a range of changes in either the frequency or magnitude of the climate event, or both. The climate risk management strategy would then need to adapt to accounting for either a greater range or changed magnitude of risk. This implies that in these cases a careful analysis of the implications of projected changes for the specific temporal and spatial characteristic of the climate variables relevant to the system at risk is required.

In several African countries, as well as in India, index-based insurance for agriculture has been used to address food insecurity and loss of crops resulting from more hot and fewer cold nights, an increase in heavy precipitation events, and longer warm spells (Table 21-4). A predetermined weather threshold typically associated with high loss triggers an insurance pay-out. The mechanism shares risk across communities and can help encourage adaptive responses and foster risk awareness and risk reduction. However, limited availability of accurate weather data means that establishing which weather conditions causes losses can be challenging. Furthermore, if there are losses but not enough to trigger pay-out, farmers may lose trust in the mechanism.

21.3.2.3. Adaptation Examples in Single Regions

Although conditions are distinct in each region and location, practical lessons can often be drawn from looking at examples of adaptation in different locations. Experience with similar approaches in different

Box 21-3 | Developing Regional Climate Information Relevant to Political and Economic Regions

In many world regions, countries form political and/or economic groupings that coordinate activities to further the interests of the constituent nations and their peoples. For example, the Intergovernmental Authority on Development (IGAD) of the countries of the Greater Horn of Africa recognizes that the region is prone to extreme climate events such as droughts and floods that have severe negative impacts on key socioeconomic sectors in all its countries. In response it has set up the IGAD Climate Prediction and Applications Centre (ICPAC). ICPAC provides and supports application of early warning and related climate information for the management of climate-related risks (for more details see http://www.icpac.net/). In addition it coordinates the development and dissemination of seasonal climate forecasts for the IGAD countries as part of a World Meteorological Organization (WMO)-sponsored Regional Climate Outlook Forum process (Ogallo et al., 2008) which perform the same function in many regions. A more recent WMO initiative, the Global Framework for Climate Services (Hewitt et al., 2012), aims to build on these and other global, regional, and national activities and institutions to develop climate information services for all nations.

As socioeconomic factors are important contributors to both the vulnerability and adaptability of human and natural systems, it clearly makes sense to summarize and assess available climate and climate change information for these regions, as this will be relevant to policy decisions taken within these groupings on their responses to climate change. For example, Figure 22-2 illustrates the presentation of observed and projected climate changes of two summary statistics for five political/economic regions covering much of Africa. It conveys several important pieces of information: the models are able to reproduce the observed trends in temperature; they simulate significantly lower temperatures without the anthropogenic forcings and significantly higher future temperatures under typical emissions paths; and for most regions the models project that future variations in the annual average will be similar to those simulated for the past. However, for a more comprehensive understanding additional information needs to be included on other important aspects of climate, for example, extremes (see Box 21-4).

regions offers additional lessons that can be useful when deciding whether an approach is appropriate.

Community-based adaptation is happening and being planned in many developing regions, especially in locations that are particularly poor. In small islands, where a significant increase in the occurrence of future sea level extremes by 2050 and 2100 is anticipated, traditional technologies and skills may still be relevant for adapting (Table 21-4). In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji, after Cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. These actions provide more than just the immediate benefits; they empower people to feel in control of their situations.

In Europe, several governments have made ambitious efforts to address risks of inland and coastal flooding due to higher precipitation and sea level rise during the coming century (Table 21-4). Efforts include a multitude of options. One of the key ingredients is strong political leadership or government champions. In The Netherlands, government recommendations include “soft” measures preserving land from development to accommodate increased river inundation; raising the level of lakes to ensure continuous freshwater supply; restoring natural estuary and tidal regimes; maintaining coastal protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. The British government has also developed extensive adaptation plans to adjust and improve flood defenses and restrict development in flood risk areas to protect London from future storm surges and river flooding. They undertook a multi-stage process, engaging stakeholders and using multi-criteria analysis. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions.

In Australia, farmers and industries are responding to experienced and expected changes in temperature, rainfall, and water availability by relocating parts of their operations, such as for rice, wine, or peanuts, or changing land use completely (Table 21-4). In South Australia, for instance, there has been some switching from grazing to cropping. The response is transformational adaptation, and can have positive or negative implications for communities in both origin and destination regions. This type of adaptation requires a greater level of commitment, access to more resources and greater integration across decision-making levels because it spans regions, livelihoods, and economic sectors.

21.3.3. Climate System

This section places the regional chapters in a broader context of regional climate information, particularly regarding cross-regional aspects, but does not provide a detailed region-by-region assessment. Boxes 21-2 and 21-4 introduce examples of regional information for continental/sub-continental regions but other regional definitions are often relevant (see Box 21-3). The focus in this section is on the summary of new and emerging knowledge since the AR4 relevant to IAV research, with emphasis on material deriving from dynamical and statistical downscaling work which is often of greater relevance for IAV applications than the coarser resolution global climate model data. In a regional context, WGI AR5 Chapter 14 is particularly relevant for the projections and evaluation of confidence in models' ability to simulate temperature, precipitation, and phenomena, together with an assessed implication for the general level of confidence in projections for 2080–2099 of regional temperature and precipitation (see WGI AR5 Table 14.2).

21.3.3.1. Global Context

21.3.3.1.1. Observed changes

Temperature and precipitation

New estimates of global surface air temperatures give a warming of about 0.89ºC (0.69ºC–1.08ºC) for the period of 1901–2012 and about 0.72ºC (0.49ºC–0.79ºC) for the period 1951–2012 (WGI AR5 Section 2.4.3). Positive annual temperature trends are found over most land areas, particularly since 1981. Over the period 1981–2012, relatively large trends have occurred over areas of Europe, the Sahara and Middle East, central and northern Asia, and northeastern North America (WGI AR5 Section 2.4.3).

For precipitation, the Northern Hemisphere mid- to high latitudes show a *likely* increasing trend (*medium confidence* prior to 1950, *high confidence* afterwards; WGI AR5 Section 2.5.1). Observed precipitation trends show a high degree of spatial and temporal variability, with both positive and negative values (WGI AR5 Section 2.5). The human influence on warming since the middle of the 20th century is *likely* over every continental region, except Antarctica (WGI AR5 Section 10.3.1), while the attribution of changes in hydrological variables is less confident (WGI AR5 Section 10.3.2).

Cryosphere

New data have become available since the AR4 to evaluate changes in the cryosphere (WGI AR5 Section 4.1) showing that the retreat of annual Arctic sea ice extent has continued, at a *very likely* rate of 3.5 to 4.1% per decade during the period 1979–2012. The perennial sea ice extent (sea ice area at summer minimum) decreased at a rate of 11.5 ± 2.1% per decade (*very likely*) over the same period 1979–2012 (WGI AR5 Section 4.2.2). The thickness, concentration, and volume of Arctic ice have also decreased. Conversely, the total annual extent of Antarctic ice has increased slightly (*very likely* 1.2 to 1.8% per decade between 1979 and 2011), with strong regional differences (WGI AR5 Section 4.2.3).

Almost all glaciers worldwide have continued to shrink since the AR4, with varying rates across regions (WGI AR5 Sections 4.3.1, 4.3.3). In particular, during the last decade most ice loss has been observed from glaciers in Alaska, the Canadian Arctic, the Southern Andes, the Asian mountains, and the periphery of the Greenland ice sheet. Several hundred glaciers globally have completely disappeared in the last 30 years (WGI AR5 Section 4.3.3).

Because of better techniques and more data, confidence has increased in the measurements of Greenland and Antarctica ice sheets. These indicate that parts of the Antarctic and Greenland ice sheets have been losing mass over the last 2 decades (*high confidence*), mostly due to changes in ice flow in Antarctica, and a mix of changes in ice flow and increases in snow/ice melt in Greenland. Ice shelves in the Antarctic Peninsula are continuing a long-term trend of thinning and partial collapse started some decades ago (WGI AR5 Sections 4.4.2-3, 4.4.5).

21.3.3.1.2. Near-term and long-term climate projections

The uncertainty in near-term CMIP5 projections is dominated by internal variability of the climate system (see 'Climate Variability' in Glossary), initial ocean conditions, and inter-model response, particularly at smaller spatial and temporal scales (Hawkins and Sutton, 2009, 2011). In the medium and long term, emission profiles may affect the climate response. Global warming of 0.3ºC to 0.7ºC is *likely* for the period of 2016–2035 compared to 1986–2005 based on the CMIP5 multi-model ensemble, and spatial patterns of near-term warming are generally consistent with the AR4 (WGI AR5 Section 11.3.6). For precipitation (2016–2035 vs. 1986–2005), zonal mean precipitation will *very likely* increase in high and some of the mid-latitudes, and will *more likely than not* decrease in the subtropics (WGI AR5 Section 11.3.2). Results from multi-decadal near-term prediction experiments (up to 2035) with initialized ocean state show that there is some evidence of predictability of yearly to decadal temperature averages both globally and for some geographical regions (WGI AR5 Section 11.2.3).

Moving to long-term projections (up to 2100), analyses of the CMIP5 ensemble have shown that, in general, the mean temperature and precipitation regional change patterns are similar to those found for CMIP3, with a pattern correlation between CMIP5 and CMIP3 ensemble mean late 21st century change greater than 0.9 for temperature and greater than 0.8 for precipitation (WGI AR5 Section 12.4). Given the increased comprehensiveness and higher resolution of the CMIP5 models, this adds robustness to the projected regional change patterns.

Some of the main characteristics of the projected late 21st century regional temperature and precipitation changes derived from the CMIP5 ensemble can be broadly summarized as follows (from WGI AR5 Chapter 12 and the WGI AR5 Atlas) with further details provided in Box 21-2 and accompanying on-line supplementary material.

Temperature

Regions that exhibit relatively high projected temperature changes (often greater than the global mean by 50% or more) are high-latitude

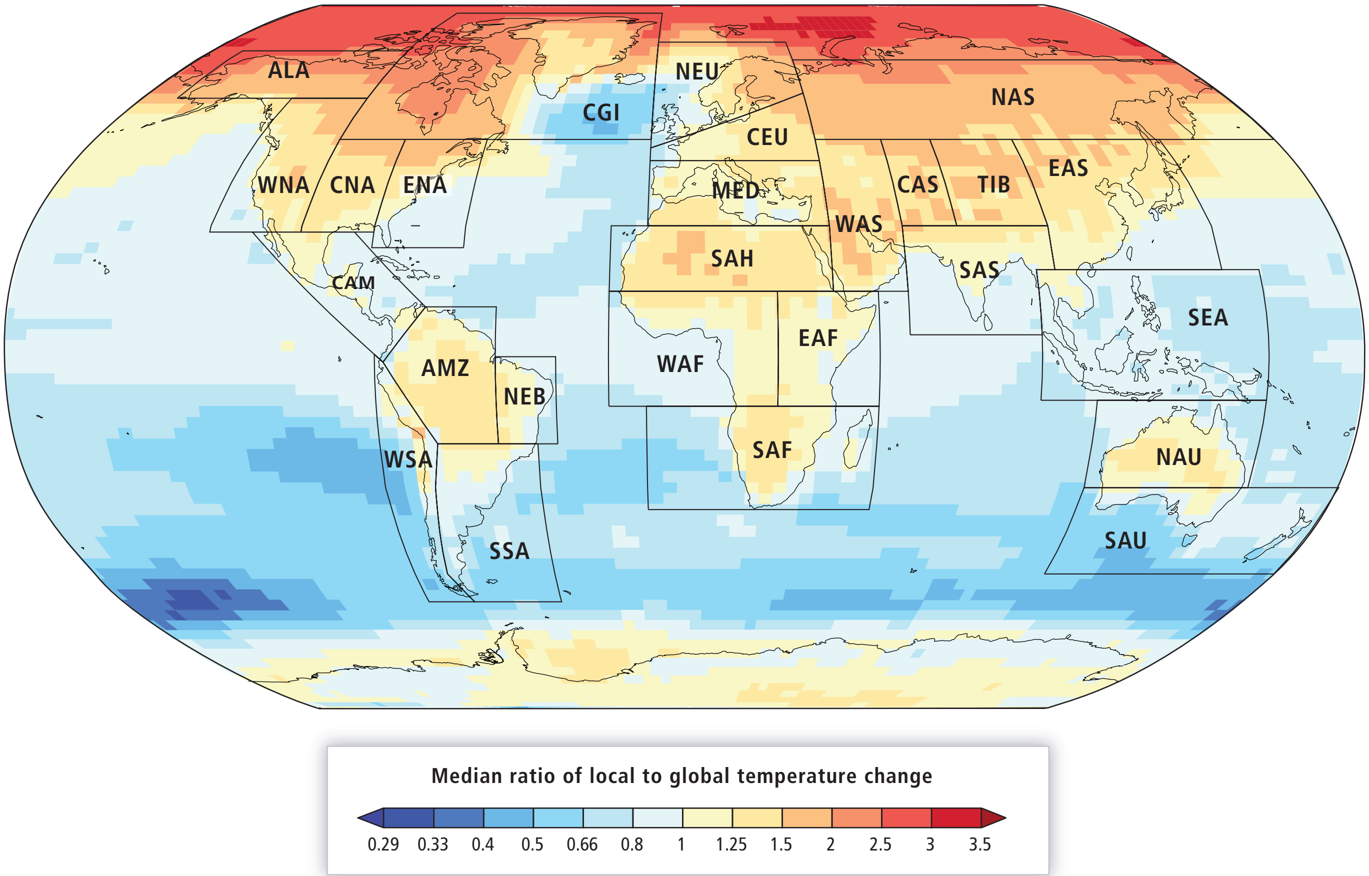


Figure 21-4 | Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble median ratio of local to global average temperature change in the period 2071–2100 relative to 1961–1990 under the Representative Concentration Pathway 8.5 (RCP8.5) emissions/concentrations scenario. The values are displayed on a common 2.5° × 3.75° grid onto which each models' data were re-gridded and they were calculated as follows: (1) for each model the local change was calculated between 1961 and 1990 at each grid cell, and is divided by the global average change in that model projection over the same period; (2) the median ratio value across all models at each grid cell is identified and shown. Data used are from the 35 CMIP5 models for which monthly projections were available under RCP8.5, as listed in Table SM21-3. Over-plotted polygons indicate the SREX regions (IPCC, 2012) used to define the sub-regions used to summarize information in Chapters 21 and some of the subsequent regional chapters.

Northern Hemisphere land areas and the Arctic, especially in December–January–February, and Central North America, portions of the Amazon, the Mediterranean, and Central Asia in June–July–August (Figure 21-4).

Precipitation

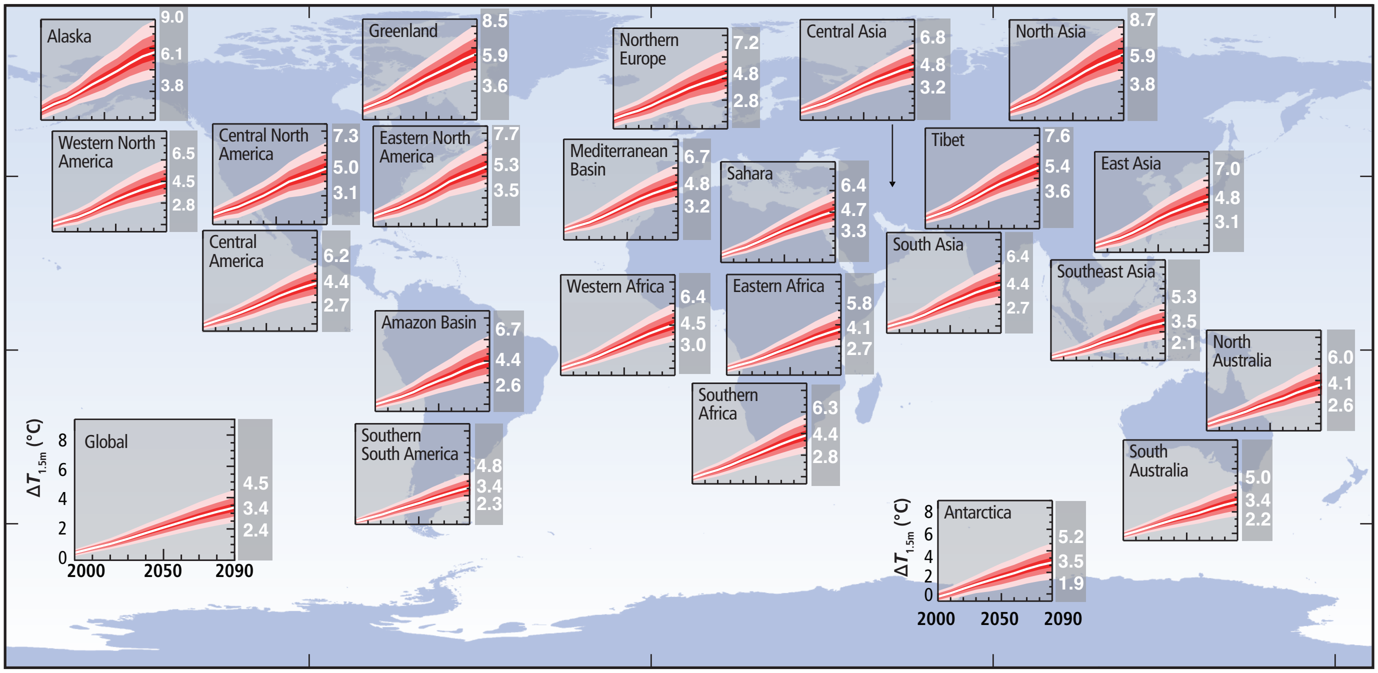
Changes in precipitation are regionally highly variable, with different areas projected to experience positive or negative changes (Box 21-2). By the end of the century in the RCP8.5 scenario, the high latitudes will *very likely* experience greater amounts of precipitation, some mid-latitude arid and semiarid regions will *likely* experience drying, while some moist mid-latitude regions will *likely* experience increased precipitation (WGI AR5 Section 12.4.5).

Studies have also attempted to obtain regional information based on pattern scaling techniques in which regional temperature and precipitation changes are derived as a function of global temperature change (e.g., Giorgi, 2008; Watterson, 2008, 2011; Watterson and Whetton, 2011; Ishizaki et al., 2012). Figure 21-5 from Harris et al. (2013) provides an example of Probability Density Functions (PDFs) of temperature and precipitation change over sub-continental scale regions obtained using a Bayesian method complemented by pattern scaling and performance-based model weighting.

21.3.3.2. Dynamically and Statistically Downscaled Climate Projections

Dynamical and statistical downscaling techniques have been increasingly applied to produce regional climate change projections, often as part of multi-model intercomparison projects (Görgen et al, 2010). A large number of Regional Climate Model (RCM)-based climate projections for the European region were produced as part of the European projects PRUDENCE (Christensen et al., 2007; Deque et al., 2007) and ENSEMBLES (Hewitt 2005; Deque and Somot, 2010). High-resolution projections (grid interval of ~12 km) were also produced as part of Euro-Coordinated Regional Downscaling Experiment (CORDEX; Jacob et al 2013). All these studies provide a generally consistent picture of seasonally and latitudinally varying patterns of change, which Giorgi and Coppola (2007) summarized with the term "European Climate Change Oscillation (ECO)." The ECO consists of a dipole pattern of precipitation change, with decreased precipitation to the south (Mediterranean) and increased to the north (Northern Europe) following a latitudinal/seasonal oscillation.

(a) Giorgi-Francisco regions, temperature change (°C), annual, A1B scenario



(b) Giorgi-Francisco regions, precipitation change (%), JJA, A1B scenario

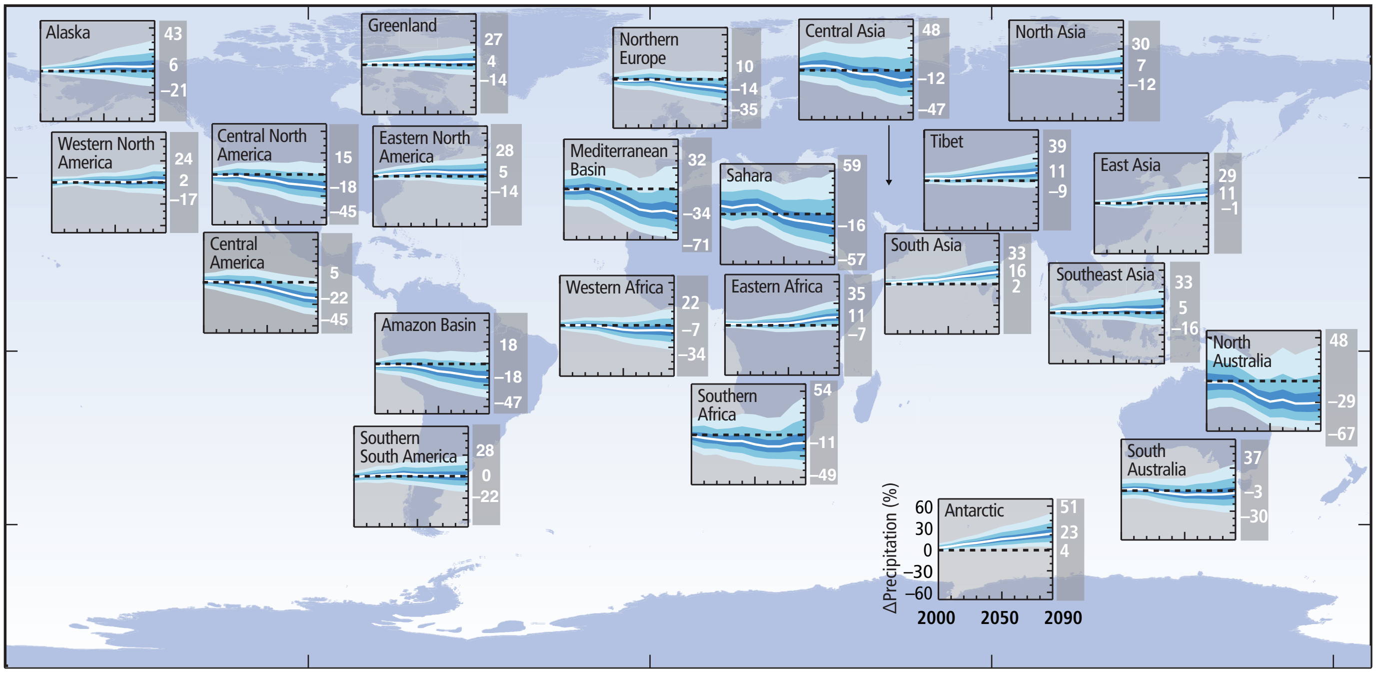


Figure 21-5 | Evolution of the 5%, 17%, 33%, 50%, 67%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (panel a) and JJA percentage precipitation changes (panel b) for the Giorgi-Francisco (2000) regions and the globe with the SRES A1B forcing scenario (IPCC, 2000) combining results from a perturbed physics ensemble and the Coupled Model Intercomparison Project Phase 3 (CMIP3) ensemble. Twenty year means relative to the 1961–1990 baseline are plotted in decadal steps using a common *y*-axis scale. The 5%, 50%, and 95% percentile values for the period 2080–2099 are displayed for each region (From Harris et al. 2012).

As a result, the Mediterranean region is projected to be much drier and hotter than today in the warm seasons (Giorgi and Lionello, 2008), and central/northern Europe much warmer and wetter in the cold seasons (Kjellstrom and Ruosteenoja, 2007). An increase of interannual variability of precipitation and summer temperature is also projected throughout Europe, with a decrease in winter temperature variability over Northern Europe (Schar et al., 2004; Giorgi and Coppola, 2007; Lenderink et al., 2007). This leads to broader seasonal anomaly distributions and a higher frequency and intensity of extreme hot and dry summers (e.g., Schar et al., 2004; Seneviratne et al., 2006; Beniston et al., 2007; Coppola and

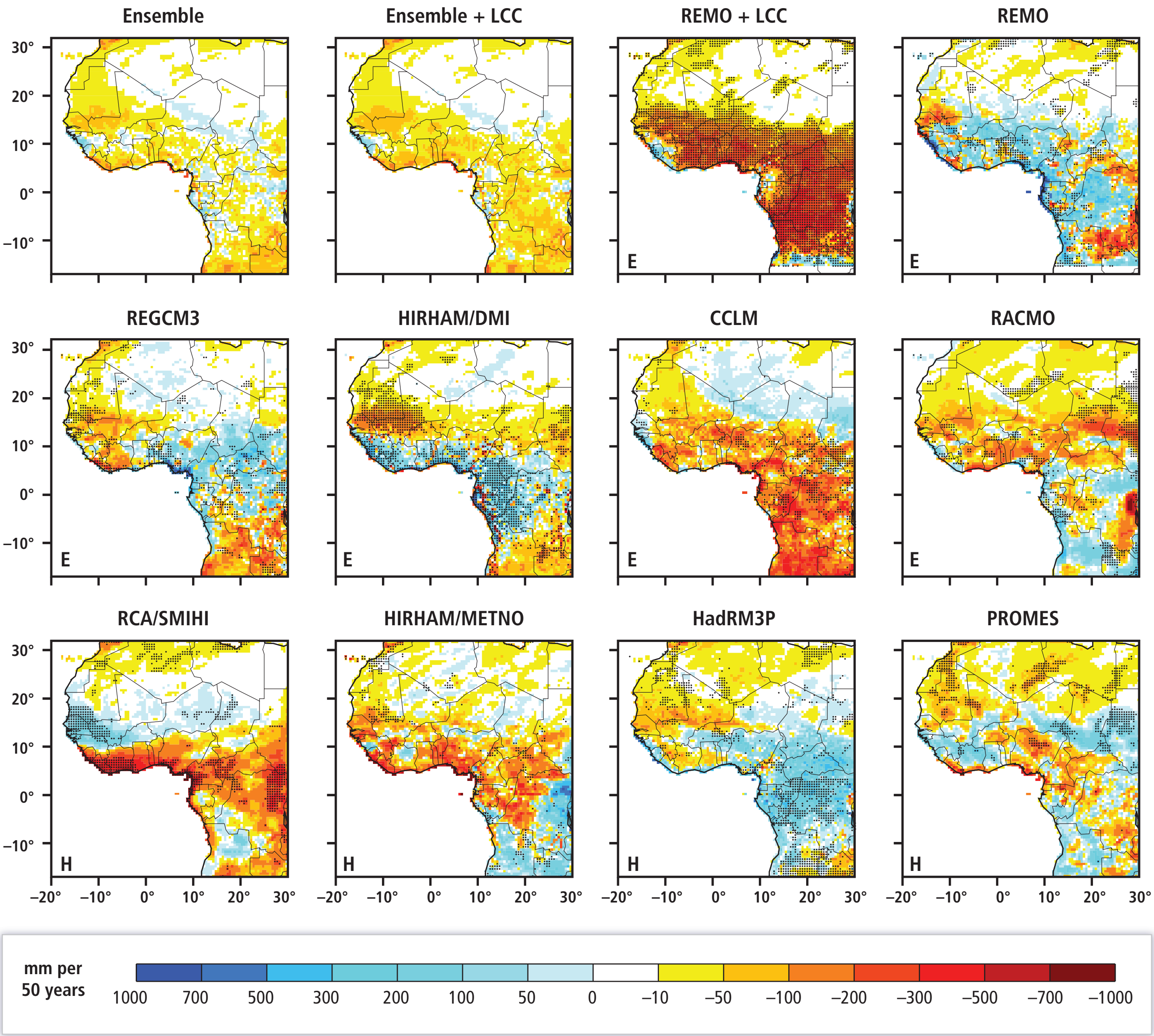


Figure 21-6 | Linear changes (i.e., changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001–2050 period from 10 individual Regional Climate Model (RCM) experiments and the Multi-Model Ensemble (MME) mean under the A1B emission scenario. The top middle panels also account for projected land cover changes. Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 95% level are marked by black dots (Paeth et al., 2011).

Giorgi, 2010), for which a substantial contribution is given by land-atmosphere feedbacks (Seneviratne et al., 2006; Fischer et al., 2007; Seneviratne et al., 2010; Hirschi et al., 2011; Jaeger and Seneviratne, 2011). The broad patterns of change in regional model simulations generally follow those of the driving global models (Christensen and Christensen, 2007; Deque et al., 2007; Zanis et al., 2009); however, fine scale differences related to local topographical, land use, and coastline features are produced (e.g., Gao et al., 2006; Coppola and Giorgi, 2010; Tolika et al., 2012).

As part of the ENSEMBLES and AMMA projects, multiple RCMs were run for the period 1990–2050 (A1B scenario) over domains encompassing the West Africa region with lateral boundary conditions from different GCMs. The RCM-simulated West Africa monsoon showed a wide range of response in the projections, even when the models were driven by the same GCMs (Paeth et al., 2011; see Figure 21-6). Although at least some of the response patterns may be within the natural variability, this result suggests that for Africa, and probably more generally the tropical regions, local processes and how they are represented in models play a key factor in determining the precipitation change signal, leading to a relatively high uncertainty (Engelbrecht et al., 2009; Haensler et al., 2011; Mariotti et al., 2011; Diallo et al., 2012). Statistical downscaling techniques have also been applied to the Africa region (Hewitson and Crane, 2006; Lumsden et al., 2009; Goergen et al., 2010; Benestad, 2011; Paeth and Diederich, 2011). In this regard, methodological developments since the AR4 have been limited (see, e.g., reviews in Brown et al., 2008;

Paeth et al., 2011) and activities have focused more on the applications (e.g., Mukheibir, 2007; Gerbaux et al., 2009) for regional specific activities in the context of IAV work.

Several RCM and time-slice high resolution GCM experiments have been conducted or analyzed for the South America continent (Marengo et al., 2009, 2010; Nunez et al., 2009; Cabre et al., 2010; Menendez et al., 2010; Sorensson et al., 2010; Kitoh et al., 2011). Overall, these studies revealed varied patterns of temperature and precipitation change, depending on the global and regional models used; however, a consistent change found in many of these studies was an increase in both precipitation intensity and extremes, especially in areas where mean precipitation was projected to also increase. The Central American region has emerged as a prominent climate change hotspot since the AR4, especially in terms of a consistent decrease of precipitation projected by most models, particularly in June to July (Rauscher et al., 2008, 2011). Regional model studies focusing specifically on Central America projections are, however, still too sparse to provide robust conclusions (e.g., Campbell et al., 2011).

Since the AR4 there has been considerable attention to producing higher resolution climate change projections over North America based on RCMs and high-resolution global time slices (e.g., Salathe et al., 2008, 2010; DominGuez et al., 2010; Subin et al., 2011), in particular as part of the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009, 2012, 2013). Results indicate variations (and thus uncertainty) in future climate based on the different RCMs, even when driven by the same GCM in certain subdomains (De Elia and Cote, 2010; Bukovsky et al., 2013; Mearns et al., 2013). However, in the NARCCAP suite of simulations there were also some important commonalities in the climate changes produced by the RCMs. For example, they produced larger and more consistent decreases in precipitation throughout the Great Plains in summer than did the driving GCMs or the full suite of CMIP3 GCM simulations as well as larger increases in precipitation in the northern part of the domain in winter. In the realm of statistical downscaling and spatial disaggregation, considerable efforts have been devoted to applying different statistical models for the entire USA and parts of Canada (e.g., Maurer et al., 2007; Hayhoe et al., 2010; Schoof et al., 2010).

Numerous high-resolution RCM projections have been carried out over the East Asia continent. While some of these find increases in monsoon precipitation over South Asia in agreement with the driving GCMs (Kumar et al., 2013), others also produce results that are not in line with those from GCMs. For example, both Ashfaq et al. (2009) and Gao et al. (2011) found in high-resolution RCM experiments (20- and 25-km grid spacing, respectively) decreases in monsoon precipitation over areas of India and China in which the driving GCMs projected an increase in monsoon rain. Other high-resolution (20-km grid spacing) projections include a series of double-nested RCM scenario runs for the Korean peninsula (Im et al., 2007, 2008a,b, 2010, 2011; Im and Ahn, 2011), indicating a complex fine-scale structure of the climate change signal in response to local topographical forcing. Finally, very high resolution simulations were also performed. Using a 5-km mesh non-hydrostatic RCM nested within a 20-km mesh Atmosphere General Circulation Model (AGCM), Kitoh et al. (2009) and Kanada et al. (2012) projected a significant increase in intense daily precipitation around western Japan during the late Baiu season.

Finally, a range of RCM, variable resolution, and statistical downscaling 21st century projections have been conducted over the Australian continent or some of its sub-regions (Nunez and Mc Gregor, 2007; Song et al., 2008, Timbal et al., 2008; Watterson et al., 2008; Yin et al., 2010; Bennett et al., 2012; Grose et al., 2012a,b), showing that a local fine-scale modulation of the large-scale climate signal occurs in response to topographical and coastal forcings.

21.3.3.3. Projected Changes in Hydroclimatic Regimes, Major Modes of Variability, and Regional Circulations

By modifying the Earth's energy and water budgets, climate change may possibly lead to significant changes in hydroclimatic regimes and major modes of climate variability (Trenberth et al., 2003). For example, Giorgi et al. (2011) defined an index of hydroclimatic intensity (HY-INT) incorporating a combined measure of precipitation intensity and mean dry spell length. Based on an analysis of observations and global and regional climate model simulations, they found that a ubiquitous global and regional increase in HY-INT was a strong hydroclimatic signature in model projections consistent with observations for the late decades of the 20th century. This suggests that global warming may lead to a hydroclimatic regime shift toward more intense and less frequent precipitation events, which would increase the risk of both flood and drought associated with global warming.

El Niño-Southern Oscillation (ENSO) is a regional mode of variability that substantially affects human and natural systems (McPhaden et al., 2006). Although model projections indicate that ENSO remains a major mode of tropical variability in the future, there is little evidence to indicate changes forced by GHG warming that are outside the natural modulation of ENSO occurrences (WGI AR5 Sections 14.4, 14.8).

The North Atlantic Oscillation (NAO) is a major mode of variability for the Northern Hemisphere mid-latitude climate. Model projections indicate that the NAO phase is *likely* to become slightly more positive (WGI AR5 Chapter 14 ES) due to GHG forcing, but the NAO will be dominated by its large natural fluctuations. Model projections indicate that the Southern Annular Mode (SAM), a major mode of variability for the Southern Hemisphere, is *likely* going to weaken as ozone concentrations recover through the mid-21st century (WGI AR5 Sections 14.5, 14.8).

Regional circulations, such as the monsoon, are expected to change. The global monsoon precipitation, aggregated over all monsoon systems, is *likely* to strengthen in the 21st century with increases in its area and intensity, while the monsoon circulation weakens. Different regional monsoon systems, however, exhibit different responses to GHG forcing in the 21st century (WGI AR5 Section 14.2.1).

21.3.3.4. Projected Changes in Extreme Climate Events

CMIP5 projections confirm results from the CMIP3; a decrease in the frequency of cold days and nights, an increase in the frequency of warm days and nights, an increase in the duration of heat waves, and an increase in the frequency and intensity of high precipitation events, both in the near term and far future (IPCC, 2012, Sections 3.3.2, 3.4.4; WGI

AR5 Section 12.4.5). Increases in intensity of precipitation (thus risk of flood) and summer drought occurrence over some mid-continental land areas is a robust signature of global warming, both in observations for recent decades and in model projections (Trenberth, 2011; WGI AR5 Section 12.4.5). For tropical cyclones there is still little confidence in past trends and near-term projections (Seneviratne et al., 2012). Globally, tropical cyclone frequency is projected to either not change or decrease and, overall, wind speed and precipitation is *likely* to increase though basin scale specific conclusions are still unclear (Knutson et al., 2010). A summary of observed and projections extremes, along with some statistics on CMIP5 projections of changes in daily temperature and precipitation extremes over the main continents and the SREX regions

Box 21-4 | Synthesis of Projected Changes in Extremes Related to Temperature and Precipitation

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), or SREX for short, provides an in-depth assessment of observed and projected changes in climate extremes. Owing to the relevance of this material for assessing risks associated with climate change vulnerability and impacts and responses to these risks, summary information is presented here both drawing from and building on the material in the SREX report, including additional analyses of Coupled Model Intercomparison Project Phase 5 (CMIP5) data (only CMIP3 data were used in SREX).

Summaries of SREX findings relevant to three continents—South America (including the Caribbean), Asia, and Africa (CDKN, 2012a,b,c; available from http://cdkn.org/srex/)—have been developed using material from SREX Chapter 3. A synthesis of this material for all SREX regions, along with additional material from WGI AR5, is presented in Table 21-7. This demonstrates that in many areas of the world there is higher confidence in future changes in extreme events than there is in past trends, often owing to a lack of evidence on observed changes.

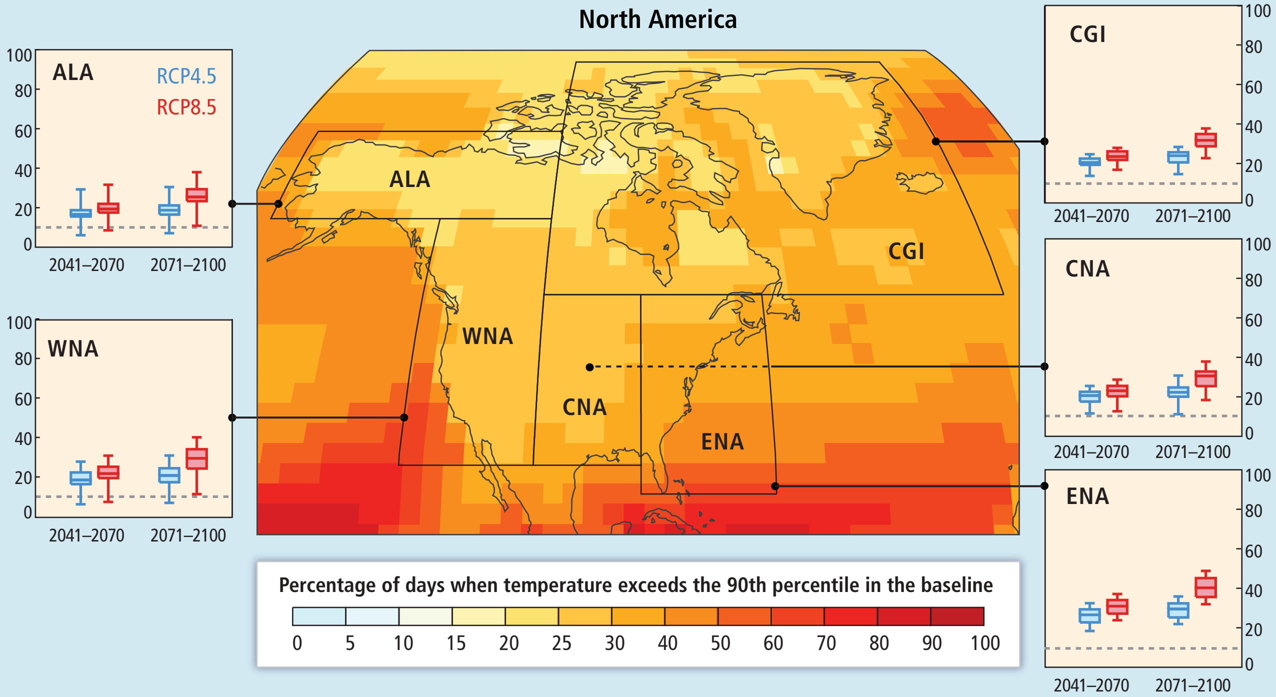


Figure 21-7 | The frequency of "warm days" (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961–1990) projected for the 2071–2100 period by 26 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) for North America. Map: Ensemble median frequency of "warm days" during 2071–2100 under Representative Concentration Pathway 8.5 (RCP8.5). Graphs: Box-and-whisker plots indicate the range of regionally averaged "hot-day" frequency by 2041–2070 and 2071–2100 under RCP4.5 and RCP8.5 across the 26 CMIP5 models for each SREX sub-region in North America. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of "warm days" of 10% is represented on the graphs by the dashed line. A full list of CMIP5 models for which data is shown here can be found in Table SM21-4.

Continued next page →

Box 21-4 (continued)

In the SREX report, the only coordinated global multi-model ensemble information available was from CMIP3. To provide information consistent with the projections assessed elsewhere in WGI and WGII AR5, changes in daily temperature and precipitation projected by the CMIP5 models are presented here for two example indices, the 90th percentiles of the daily maximum temperature and daily precipitation amounts on wet days. Changes in these indices were calculated over 30-year periods (1961–1990 for the baseline and two future periods, 2041–2070 and 2071–2100) and the analysis was focused on the less extreme daily events to reduce problems with the number needed to be sampled to generate robust statistics (Kendon et al., 2008). Projected changes were calculated for Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 and the results are displayed as a map for a given continental region and also regional averages over the SREX regions within that continent. Two examples are provided: for temperature changes over North America (Figure 21-7) and precipitation changes over Asia (Figure 21-8). A full set can be found in Figures SM21-8 to SM21-19.

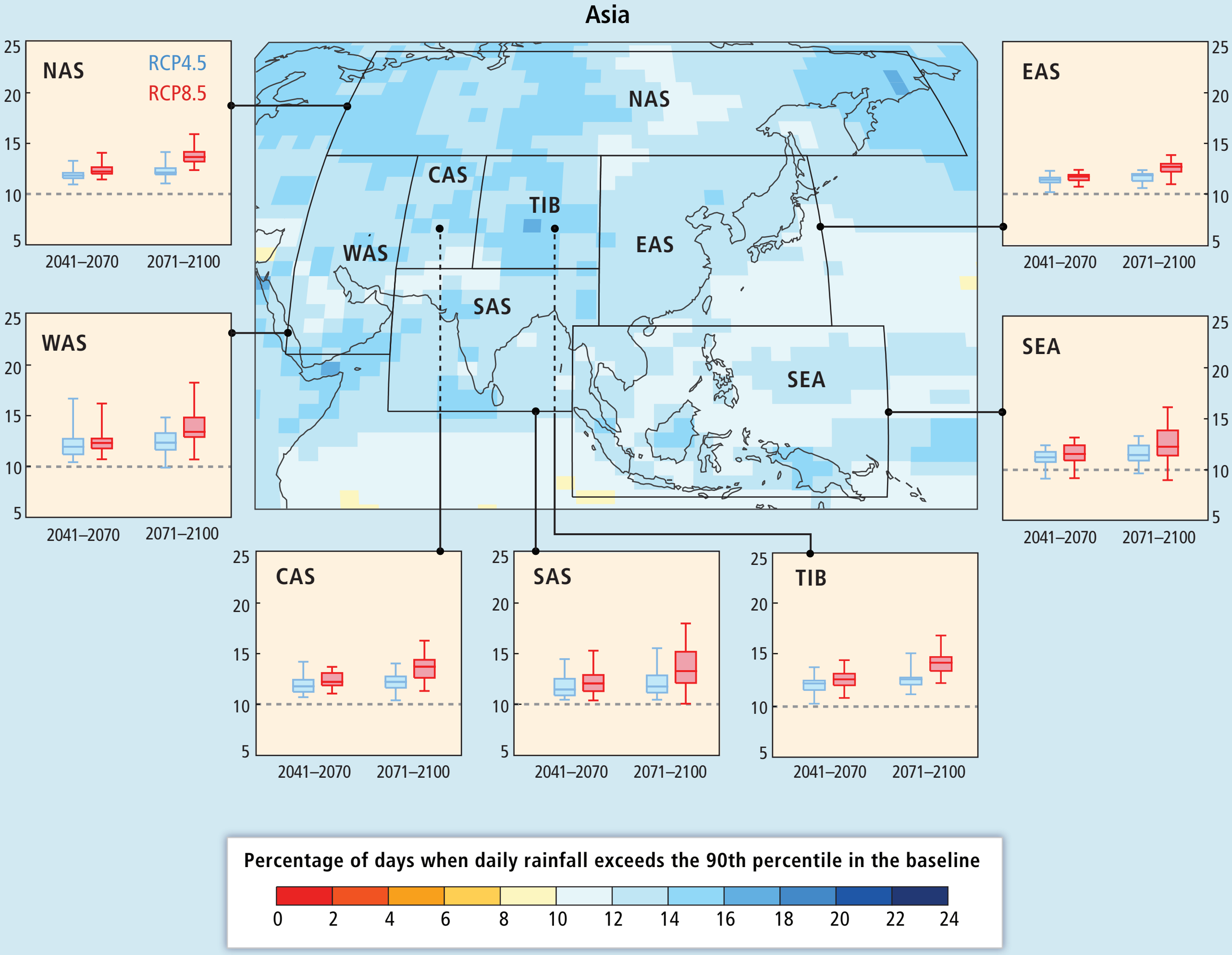


Figure 21-8 | The frequency of "very wet days" (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961–1990 with wet days defined as days with 1 mm of precipitation or more) projected for the 2071–2100 period by 26 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) or Asia. Map: Ensemble median frequency of "very wet days" during 2071–2100 under Representative Concentration Pathway 8.5 (RCP8.5). Graphs: Box-and-whisker plots indicate the range of regionally averaged "very wet day" frequency by 2041–2070 and 2071–2100 under RCP4.5 and RCP8.5 across the 26 CMIP5 models for each SREX sub-region in Asia. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of "very wet days" of 10% is represented on the graphs by the dashed line. A full list of CMIP5 models for which data are shown here can be found in Table SM21-4. Note that the World Meteorological Organization (WMO) Expert Team on Climate Change Detection Indices defines "very wet days" threshold as the 95th percentile daily precipitation event.

Table 21-7 | An assessment of observed and projected future changes in temperature and precipitation extremes over 26 sub-continental regions as defined in the SREX report (IPCC 2012); these regions are also displayed in Figure 21.4 and Table SM21.2. Confidence levels are indicated by color coding of the symbols. Likelihood terms are given only for high confidence statements and are specified in the text. Observed trends in temperature and precipitation extremes, including dryness, are generally calculated from 1950, using the period 1961-1990 as a baseline (see Box 3.1 of IPCC, 2012). The future changes are derived from global and regional climate model projections of the climate of 2071-2100 compared with 1961-1990 or 2080-2100 compared with 1980-2000. Table entries are summaries of information in Tables 3-2 and 3-3 of IPCC (2012) supplemented with or superseded by material from Chapters 2 (Section 2.6 and Table 2.13) and 14 (Section 14.4) of IPCC (2013a) and Table 25-1 of this volume. The source(s) of information for each entry are indicated by the superscripts a (Table 3-2 of IPCC, 2012), b (Table 3-3 of IPCC, 2012), c (Section 2.6 and Table 2.13 of IPCC, 2013a), d (Section 14.4 of IPCC, 2013a), and e (Table 25-1 of this volume).

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
West North America WNA, 3	🔴⌃ *Very likely* large increases in hot days (large decreases in cool days)[a]	🔴⌃ *Very likely* increase in hot days (decrease in cool days)[b]	🔴⌃ *Very likely* large decreases in cold nights (large increases in warm nights)[a]	🔴⌃ *Very likely* increase in warm nights (decrease in cold nights)[b]	🟠⌃ Increase in warm spell duration[a]	🔴⌃ *Likely* more frequent, longer, and/or more intense heat waves and warm spells[b]	🟠◇ Spatially varying trends. General increase, decrease in some areas[a]	🟠⌃ Increase in 20-year return value of annual maximum daily precipitation and other metrics over northern part of the region (Canada)[b] 🟡∿ Less confidence in southern part of the region, due to inconsistent signal in these other metrics[b]	🟠⊖ No change or overall slight decrease in dryness[a]	🟡∿ Inconsistent signal[b]
Central North America CNA, 4	🟠◇ Spatially varying trends: small increases in hot days in the north, decreases in the south[a]	🔴⌃ *Very likely* increase in hot days (decrease in cool days)[b]	🟠◇ Spatially varying trends: small increase in cold nights (and decreases in warm nights) in south and vice versa in the north[a]	🔴⌃ *Very likely* increase in warm nights (decrease in cold nights[b]	🟠◇ Spatially varying trends[a]	🔴⌃ *Likely more* frequent, longer, and/or more intense heat waves and warm spells[b]	🔴⌃ *Very likely* increase since 1950[a]	🟠⌃ Increase in 20-year return value of annual maximum daily precipitation[b] 🟡∿ Inconsistent signal in other heavy precipitation days metrics[b]	🔴⌄ *Likely* decrease[a, c]	🟠◇ Increase in consecutive dry days and soil moisture in southern part of central North America[b] 🟡∿ Inconsistent signal in the rest of the region[b]

Symbols

⌃ Increasing trend or signal

⌄ Decreasing trend or signal

◇ Both increasing and decreasing trend or signal

∿ Inconsistent trend or signal or insufficient evidence

⊖ No change or only slight change

Level of confidence in findings

🟡 *Low confidence*

🟠 *Medium confidence*

🔴 *High confidence*

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Table 21-7 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
East North America ENA, 5	↕ Spatially varying trends. Overall increases in hot days (decreases in cool days), opposite or insignificant signal in a few areas[a]	↑ *Very likely* increase in hot days (decrease in cool days)[b]	∼ Weak and spatially varying trends[a]	↑ *Very likely* increase in warm nights (decrease in cold nights[b]	↕ Spatially varying trends, many areas with increase in duration, some areas with decrease[a]	↑ *Likely* more frequent, longer and/or more intense heat waves and warm spells[b]	↑ *Very likely* increase since 1950[a]	↑ Increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation over northern part of the region.[b] ∼ No signal or inconsistent signal in these other metrics in the southern part of the region[b]	↓ Slight decrease in dryness since 1950[a]	∼ Inconsistent signal in consecutive dry days, some consistent decrease in soil moisture[b]
Alaska/ Northwest Canada ALA, 1	↑ *Very likely* large increases in warm days (decreases in cold days)[a]	↑ *Very likely* increase in hot days (decrease in cool days)[b]	↑ *Very likely* large decreases in cold nights, increases in warm nights[a]	↑ *Very likely* increase in warm nights (decrease in cold nights)[b]	∼ Insufficient evidence[a]	↑ *Likely* more frequent, and/or longer heat waves and warm spells[b]	↑ Slight tendency for increase[a] — No significant trend in southern Alaska[a]	↑ *Likely* increase in heavy precipitation[b]	∼ Inconsistent trends[a] ↑ Increases in dryness in part of the region[a]	∼ Inconsistent signal[b]
East Canada, Greenland, Iceland CGI, 2	↕ *Likely* increases in hot days (decreases in cool days) in some areas, decrease in hot days (increase in cool days) in others[a]	↑ *Very likely* increase in warm days (decrease in cold days)[b]	↓ Small increases in unusually cold nights and decreases in warm nights in northeastern Canada[a] ↑ Small decrease in cold nights and increase in warm nights in south-eastern/central Canada[a]	↑ *Very likely* increase in warm nights (decrease in cold nights)[b]	↕ Some areas with warm spell duration increase, some with decrease[a]	↑ *Likely* more frequent, and/or longer heat waves and warm spells[b]	↑ Increase in a few areas[a]	↑ *Likely* increase in heavy precipitation[b]	∼ Insuffcient evidence[a]	∼ Inconsistent signal[b]
Northern Europe NEU, 11	↑ Increase in hot days (decrease in cool days), but generally not significant at the local scale[a]	↑ *Very likely* increase in hot days (decrease in cool days) [but smaller trends than in central and southern Europe][b]	↑ Increase in warm nights (decrease in cold nights) over the whole region, but generally not significant at the local scale[a]	↑ *Very likely* increase in warm nights (decrease in cold nights)[b]	↑ Increase in heat waves. Consistent tendency for increase in heat wave duration and intensity, but no significant trend[a]	↑ *Likely* more frequent, longer and/or more intense heat waves/ warm spells, but summer increases smaller than in southern Europe[b] — Little change over Scandinavia[b]	↑ Increase in winter in some areas, but often insignificant or inconsistent trends at sub-regional scale, particularly in summer[a]	↑ *Likely* increase in 20-year return value of annual maximum daily precipitation. *Very likely* increases in heavy preciptation intensity and frequency in winter in the north[b]	↕ Spatially varying trends. Overall only slight or no increase in dryness, slight decrease in dryness in part of the region[a]	— No major changes in dryness[b]

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Table 21-7 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
Central Europe CEU, 12	▲ *Likely* overall increase in hot days (decrease in cool days) since 1950 in most regions. *Very likely* increase in hot days (*likely* decrease in cool days) in west-central Europe[a] ∿ Lower confidence in trends in east-central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	▲ *Very likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* overall increase in warm nights (decrease in cold nights) at the yearly time scale. Some regional and seasonal variations in significance and in a few cases sign of trends. *Very likely* increase in warm nights (decrease in cold nights)in west-central Europe[a] ∿ Lower confidence in trends in east-central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	▲ *Very likely* increase in warm nights (decrease in cold nights)[b]	▲ Increase in heat waves. Consistent increase in heat wave duration and intensity, but no significant trend. Significant increase in maximum heat wave duration in west-central Europe in summer[a]	▲ *Likely* more frequent, longer and/or more intense heat waves/ warm spells[b]	▲ Increase in part of the region, in particular central western Europe and European Russia, especially in winter.[a] ∿ Insignificant or inconsistent trends elsewhere, in particular in summer[a]	▲ *Likely* increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation in large part of the region over winter.[b] ∿ Less confidence in summer, due to inconsistent evidence[b]	◆ Spatially varying trends. Increase in dryness in part of the region but some regional variation in dryness trends and dependence of trends on studies considered (index, time period)[a]	▲ Increase in dryness in central Europe and increase in short-term droughts[b]
Southern Europe and Mediterranean MED, 13	▲ *Likely* increase in hot days (decrease in cool days) in most of the region. Some regional and temporal variations in the significance of the trends. *Likely* strongest and most significant trends in Iberian peninsula and southern France[a] ▲ Smaller or less significant trends in southeastern Europe and Italy due to change point in trends, strongest increase in hot days since 1976[a]	▲ *Very likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* increase in warm nights (decrease in cold nights) in most of the region. Some regional variations in the significance of the trends. *Very likely* overall increase in warm nights (decrease in cold nights in southwest Europe/west Mediterranean[a]	▲ *Very likely* increase in warm nights (decrease in cold nights)[b]	▲ *Likely* increase in most regions[a]	▲ *Likely* more frequent, longer and/ or more intense heat waves and warm spells (likely largest increases in southwest south, and east of the region)[b]	∿ Inconsistent trends across the region and across studies[a]	∿ Inconsistent changes and/ or regional variations[b]	▲ Overall increase in dryness, *likely* increase in the Mediterranean[a, c]	▲ Increase in dryness. Consistent increase in area of drought[b, d]
West Africa WAF, 15	▲ Significant increase in temperature of hottest day and coolest day in some parts[a] ∿ Insufficient evidence in other parts[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ Increasing frequency of warm nights. Decrease in cold nights in western central Africa, Nigeria, and Gambia[a] ∿ Insufficient evidence on trends in cold nights in other parts[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	∿ Insufficient evidence for most of the region[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	▲ Rainfall intensity increased[a]	− Slight or no change in heavy precipitation indicators in most areas[b] ∿ Low model agreement in northern areas[b]	▲ *Likely* increase but 1970s Sahel drought dominates the trend; greater inter-annual variation in recent years[a, c]	∿ Inconsistent signal[b]

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Table 21-7 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
East Africa EAF, 16	∿ Lack of evidence due to lack of literature and spatially non-uniform trends[a] ∧ Increases in hot days in southern tip (decrease in cool days)[a]	∧ *Likely* increase in hot days (decrease in cool days)[b]	◇ Spatially varying trends in most areas[a] ∧ Increases in warm nights in southern tip (decrease in cold nights)[a]	∧ *Likely* increase in warm nights (decrease in cold nights)[b]	∿ Insufficient evidence[a] ∧ Increase in warm spell duration in southern tip of the region[a]	∧ *Likely* more frequent and/or longer heat waves and warm spells[b]	∿ Insufficient evidence[a]	∧ *Likely* increase in heavy precipitation[b]	∿ Spatially varying trends in dryness[a]	∨ Decreasing dryness in large areas[b]
Southern Africa SAF, 17	∧ *Likely* increase in hot days (decrease in cool days)[a, c]	∧ *Likely* increase in hot days (decrease in cool days)[b]	∧ *Likely* increase in warm nights (decrease in cold nights)[a, c]	∧ *Likely* increase in warm nights (decrease in cold nights)[b]	∧ Increase in warm spell duration[a]	∧ *Likely* more frequent and/or longer heat waves and warm spells[b]	◇ Increases in more regions than decreases but spatially varying trends[a]	∿ Lack of agreement in signal for region as a whole[b] ∿ Some evidence of increase in heavy precipitation in southeast regions[b]	∧ General increase in dryness[a]	∧ Increase in dryness, except eastern part[b, d] ∧ Consistent increase in area of drought[b]
Sahara SAH, 14	∿ Lack of literature[a]	∧ *Likely* increase in hot days (decrease in cool days)[b]	∧ Increase in warm nights[a] ∿ Lack of literature on trends in cold nights[a]	∧ *Likely* increase in warm nights (decrease in cold nights)[b]	∿ Insufficient evidence[a]	∧ *Likely* more frequent and/or longer heat waves and warm spells[b]	∿ Insufficient evidence[a]	∿ *Low agreement*[b]	∿ Limited data, spatial variation of the trends[a]	∿ Inconsistent signal of change[b]
Central America and Mexico CAM, 6	∧ Increases in the number of hot days, decreases in the number of cool days[a]	∧ *Likely* increase in hot days (decrease in cool days)[b]	∧ Increases in number of warm nights (decrease in number of cold nights)[a]	∧ *Likely* increase in warm nights (*likely* decrease in cold nights)[b]	◇ Spatially varying trends (increases in some areas, decreases in others)[a]	∧ *Likely* more frequent, longer and/or more intense heat waves/ warm spells in most of the region[b]	◇ Spatially varying trends. Increase in many areas, decrease in a few others[a]	∿ Inconsistent trends[b]	∿ Varying and inconsistent trends[a]	∧ Increase in dryness in Central America and Mexico, with less confidence in trend in extreme south of region[b]
Amazon AMZ, 7	∿ Insufficient evidence to identify trends[a]	∧ Hot days *likely* to increase (cool days *likely* to decrease)[b]	∿ Insufficient evidence to identify trends[a]	∧ *Very likely* increase in warm nights (*likely* decrease in cold nights)[b]	∿ Insufficient evidence[a]	∧ *Likely* more frequent and longer heat waves and warm spells[b]	◇ Increases in many areas, decreases in a few[a]	∧ Tendency for increases in heavy precipitation events in some metrics[b]	◇ Decrease in dryness for much of the region. Some opposite trends and inconsistencies[a]	∿ Inconsistent signals[b]
Northeastern Brazil NEB, 8	∧ Increases in the number of hot days[a]	∧ Hot days *likely* to increase (cool days *likely* to decrease)[b]	∧ Increases in the number of warm nights[a]	∧ *Likely* increase in warm nights (*likely* decrease in cold nights)[b]	∿ Insufficient evidence[a]	∧ *Likely* more frequent and longer heat waves and warm spells in some studies[b]	◇ Increases in many areas, decreases in a few[a]	— Slight or no change[b]	∿ Varying and inconsistent trends[a]	∧ Increase in dryness[b]

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Table 21-7 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
Southeastern South America SSA, 10	◆ Spatially varying trends (increases in some areas, decreases in others)[a]	▲ Hot days *likely* to increase (cool days *likely* to decrease)[b]	▲ Increases in number of warm nights (decreases in number of cold nights)[a]	▲ *Very likely* increase in warm nights (*likely* decrease in cold nights)[b]	◆ Spatially varying trends (increases in some areas, decreases in others)[a]	▲ Tendency for more frequent and longer heat waves and warm spells[b]	▲ Increases in northern areas[a] ∿ Insufficient evidence in southern areas[a]	▲ Increases in northern areas[b] ∿ Insufficient evidence in southern areas[b]	∿ Varying and inconsistent trends[a]	∿ Inconsistent signals[b]
West Coast South America WSA, 9	◆ Spatially varying trends (increases in some areas, decreases in others)[a]	▲ Hot days *likely* to increase (cool days *likely* to decrease)[b]	▲ Increases in number of warm nights (decreases in number of cold nights)[a]	▲ *Likely* increase in warm nights (*likely* decrease in cold nights)[b]	∿ Insufficient evidence[a]	▲ *Likely* more frequent and longer heat waves and warm spells[b]	◆ Increases in many areas, decrease in a few areas[a]	▲ Increases in tropics[b] ∿ *Low confidence* in extratropics[b]	∿ Varying and inconsistent trends[a]	◆ Decrease in consecutive dry days in the tropics, and increase in the extratropics[b] ◆ Increase in consecutive dry days and soil moisture in southwest South America[b]
North Asia NAS, 18	▲ *Likely* increase in hot days (decrease in cool days)[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* increase in warm nights (decrease in cold nights)[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	◆ Spatially varying trends[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[a]	▲ Increase in some regions, but spatial variation[a]	▲ *Likely* increase in heavy precipitation for most regions[b]	◆ Spatially varying trends[a]	∿ Inconsistent signal of change[b]
Central Asia CAS, 20	▲ *Likely* increase in hot days (decrease in cool days)[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* increase in warm nights (decrease in cold nights)[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	▲ Increase in warm spell duration in a few areas[a] ∿ Insufficient evidence in others[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	◆ Spatially varying trends[a]	∿ Inconsistent signal in models[b]	◆ Spatially varying trends[a]	∿ Inconsistent signal of change[b]
East Asia EAS, 22	▲ *Likely* increase in hot days (decrease in cool days)[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ Increase in warm nights (decrease in cold nights)[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	▲ Increased heat waves in China[a] ◆ Increase in warm spell duration in northern China, decrease in southern China[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	◆ Spatially varying trends[a]	▲ Increase in heavy precipitation across the region[b]	▲ Tendency for increased dryness[a]	∿ Inconsistent signal of change[b]

Continued next page →

Table 21-7 (continued)

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
Southeast Asia SEA, 24	▲ Increase in hot days (decrease in cool days) for northern areas[a] ∿ Insufficient evidence for Malay Archipelago[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ Increase in warm nights (decrease in cold nights) for northern areas[a] ∿ Insufficient evidence for Malay Archipelago[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	∿ Insufficient evidence[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells over continental areas[b] ∿ *Low confidence* in changes for some areas[b]	◇ Spatially varying trends, partial lack of evidence[a]	▲ Increases in most metrics over most (especially non-continental) regions. One metric shows inconsistent signals of change.[b]	◇ Spatially varying trends[a]	∿ Inconsistent signal of change[b]
South Asia SAS, 23	▲ Increase in hot days (decrease in cool days)[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ Increase in warm nights (decrease in cold nights)[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	∿ Insufficient evidence[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	∿ Mixed signal in India[a]	∿ More frequent and intense heavy precipitation days over parts of South Asia. Either no change or some consistent increases in other metrics[b]	∿ Inconsistent signal for different studies and indices[a]	∿ Inconsistent signal of change[b]
West Asia WAS, 19	▲ *Very likely* increase in hot days (decrease in cool days *more likely than not*)[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* increase in warm nights (decrease in cold nights)[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	▲ Increase in warm spell duration[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	▼ Decrease in heavy precipitation events[a]	∿ Inconsistent signal of change[b]	∿ Lack of studies, mixed results[a]	∿ Inconsistent signal of change[b]
Tibetan Plateau TIB, 21	▲ *Likely* increase in hot days (decrease cool days)[a]	▲ *Likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* increase in warm nights (decrease in cold nights)[a]	▲ *Likely* increase in warm nights (decrease in cold nights)[b]	◇ Spatially varying trends[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	∿ Insufficient evidence[a]	▲ Increase in heavy precipitation[b]	∿ Insufficient evidence. Tendency to decreased dryness[a]	∿ Inconsistent signal of change[b]
North Australia NAU, 25	▲ *Likely* increase in hot days (decrease in cool days). Weaker trends in northwest[a]	▲ *Very likely* increase in hot days (decrease in cool days)[b]	▲ *Likely* increase in warm nights (decrease in cold nights)[a]	▲ *Very likely* increase in warm nights (decrease of cold nights)[b]	∿ Insufficient literature[a]	◇ *Likely* more frequent and/or longer heat waves and warm spells[b]	◇ Spatially varying trends, which mostly reflect changes in mean rainfall[e]	▲ Increase in most regions in the intensity of extreme (i.e., current 20-year return period) heavy rainfall events[e]	∿ No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e]	∿ Inconsistent signal[b]
South Australia/ New Zealand SAU, 26	▲ *Very likely* increase in hot days (decrease in cool days)[a]	▲ *Very likely* increase in hot days (decrease in cool days)[b]	▲ *Very likely* increase in warm nights (decrease in cold nights)[a]	▲ *Very likely* increase in warm nights (decrease in cold nights)[b]	▲ Increase in warm spells across southern Australia[a]	▲ *Likely* more frequent and/or longer heat waves and warm spells[b]	◇ Spatially varying trends in southern Australia, which mostly reflect changes in mean rainfall[e] ◇ Spatially varying trends in New Zealand, which mostly reflect changes in mean rainfall[e]	▲ Increase in most regions in the intensity of extreme (i.e., current 20-year return period) heavy rainfall events[e]	∿ No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e] ∿ No trend in drought occurrence over New Zealand (defined using a soil–water balance model) since 1972[e]	▲ Increase in drought frequency in southern Australia, and in many regions of New Zealand[e]

(Figure 21-4), are introduced in Box 21-4 and accompanying on-line supplementary material.

21.3.3.5. Projected Changes in Sea Level

Projections of regional sea level changes, based both on the CMIP3 and CMIP5 models, indicate a large regional variability of sea level rise (even more than 100% of the global mean sea level rise) in response to different regional processes (WGI AR5 Section 13.6.5). However, by the end of the 21st century it is *very likely* that more than about 95% of the oceans will undergo sea level rise, with about 70% of coastlines experiencing a sea level rise within 20% of the global value and most regions experiencing sea level fall being located near current and former glaciers and ice sheets (WGI AR5 Section 13.6.5). Some preliminary analysis of the CMIP5 ensembles indicates areas of maximum steric sea level rise in the Northern Atlantic, the northwestern Pacific off the East Asia coasts, the eastern coastal oceanic regions of the Bay of Bengal, and the western coastal regions of the Arabian Sea (WGI AR5 Section 13.6.5).

21.3.3.6. Projected Changes in Air Quality

Since the AR4 more studies have become available addressing the issue of the effects of both climate and emission changes on air quality. Most of these studies focused on the continental USA and Europe, and utilized both global and regional climate and air quality models run in off-line or coupled mode. Regional modeling studies over the USA or some of its sub-regions include, for example, those of Hogrefe et al. (2004), Knowlton et al. (2004), Dawson et al. (2007), Steiner et al. (2006), Lin et al. (2008), Zhang et al. (2008), and Weaver et al. (2009), while examples of global modeling studies include Doherty et al. (2006), Murazaki and Hess (2006), Shindell et al. (2006), and Stevenson et al. (2006). Weaver et al. (2009) provide a synthesis of simulated effects of climate change on ozone concentrations in the USA using an ensemble of regional and global climate and air quality models, indicating a predominant increase in near-surface ozone concentrations, particularly in the eastern USA (Figure 21-9) mostly tied to higher temperatures and corresponding biogenic emissions. An even greater increase was found in the frequency and intensity of extreme ozone concentration events, which are the most dangerous for human health. Examples of regional studies of air quality changes in response to climate change over Europe include Langner et al. (2005), Forkel and Knocke (2006), Meleux et al. (2007), Szopa and Hauglustaine (2007), Kruger et al. (2008), Engardt et al. (2009), Andersson and Engardt (2010), Athanassiadou et al. (2010), Carvalho et al. (2010), Katragkou et al. (2010, 2011), Huszar et al. (2011), Zanis et al. (2011), and Juda-Rezler et al. (2012). All of these studies indicated the potential of large increases in near-surface summer ozone concentrations especially in Central and Southern Europe due to much warmer and drier projected summer seasons.

21.4. Cross-Regional Phenomena

Thus far, this chapter has covered climate change-related issues that have a regional expression in one part of the world or another. In principle, these issues can be studied and described, *in situ*, in the regions in which they occur. However, there is a separate class of issues that transcends regional boundaries and demands a different treatment. To understand such cross-regional phenomena, knowledge is required of critical but geographically remote associations and of dynamic cross-boundary flows.

The following sections consider some examples of these phenomena, focusing on trade and financial flows and migration. Though these issues are treated in more detail in Part A of this report, they are restated here in Part B to stress the importance of a global perspective in appreciating climate change challenges and potential solutions at the regional scale.

21.4.1. Trade and Financial Flows

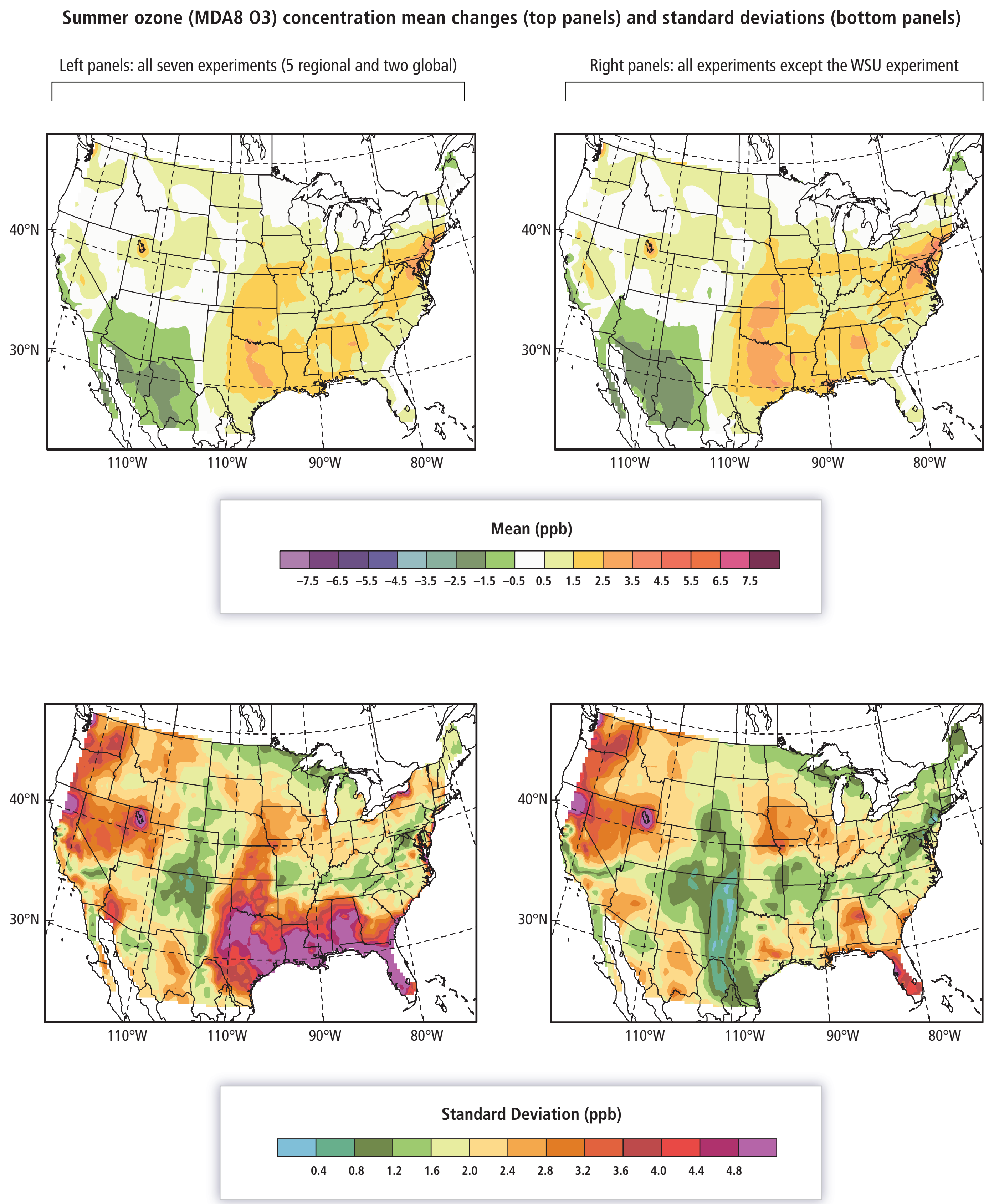
Global trade and international financial transactions are the motors of modern global economic activity. Their role as key instruments for implementing mitigation and adaptation policies is explored in detail in Chapters 14 to 17 and in the WGIII AR5 (Gupta et al., 2014; Stavins et al., 2014).

They are also inextricably linked to climate change (WTO and UNEP, 2009) through a number of other interrelated pathways that are expanded here: (1) as a direct or indirect cause of anthropogenic emissions (e.g., Peters et al., 2011), (2) as contributory factors for regional vulnerability to the impacts of climate change (e.g., Leichenko and O'Brien, 2008), and (3) through their sensitivity to climate trends and extreme climate events (e.g., Nelson et al., 2009a; Headey, 2011).

21.4.1.1. International Trade and Emissions

The contemporary world is highly dependent on trading relationships between countries in the import and export of raw materials, food and fiber commodities, and manufactured goods. Bulk transport of these products, whether by air, sea, or over land, is now a significant contributor to emissions of GHGs and aerosols (Stavins et al., 2014). Furthermore, the relocation of manufacturing has transferred net emissions via international trade from developed to developing countries (see Figure 21-10), and most developed countries have increased their consumption-based emissions faster than their domestic (territorial) emissions (Peters et al., 2011).

This regional transfer of emissions is commonly referred to in climate policy negotiations as "carbon leakage" (Barker et al., 2007)—though only a very small portion of this can be attributed to climate policy ("strong carbon leakage"), a substantial majority being due to the effect of non-climate policies on international trade ("weak carbon leakage"; Peters, 2010). A particular example of strong carbon leakage concerns the conversion of land use from the production of food to bioenergy crops. These crops sequester carbon otherwise extracted from the ground as fossil fuels, but in the process displace demand for food production to land in other regions, often inducing land clearance and hence an increase in emissions (Searchinger et al., 2008), though the empirical basis for this latter assertion is disputed (see Kline and Dale, 2008).



Summer ozone (MDA8 O3) concentration mean changes (top panels) and standard deviations (bottom panels)

Left panels: all seven experiments (5 regional and two global)

Right panels: all experiments except the WSU experiment

Figure 21-9 | Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2050s minus 1990s) MDA8 summer ozone concentrations across (lefthand panels) all seven experiments (five regional and two global) and for comparison purposes (righthand panels), not including the WSU experiment (which simulated July-only conditions). The different experiments use different pollutant emission and Special Report on Emission Scenarios (SRES) greenhouse gas (GHG) emission scenarios. The pollutant emissions are the same in the present and future simulations (Weaver et al., 2009).

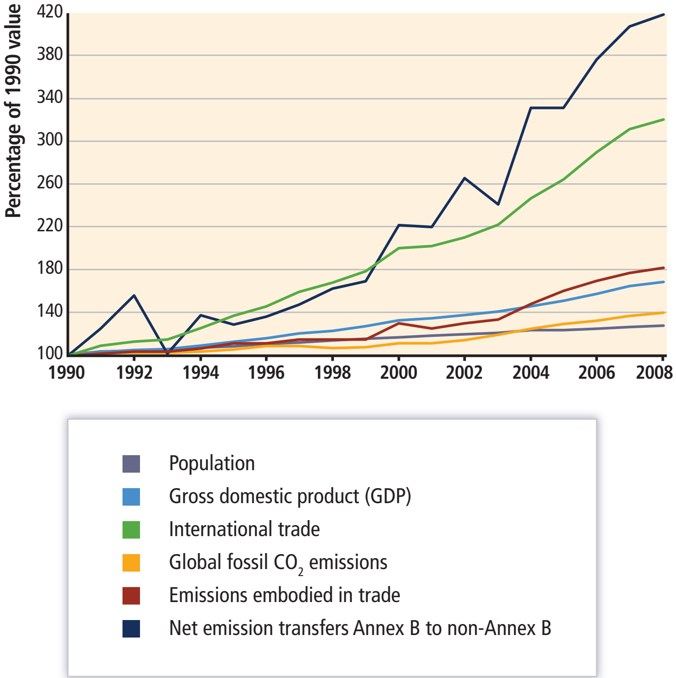


Figure 21-10 | Growth rates from 1990–2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macro-variables, all indexed to 1990 (Peters et al., 2011). Annex B and non-Annex B Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are listed in Table SM21-1.

21.4.1.2. Trade and Financial Flows as Factors Influencing Vulnerability

The increasingly international nature of trade and financial flows (commonly referred to as globalization), while offering potential benefits for economic development and competitiveness in developing countries, also presents high exposure to climate-related risks for some of the populations already most vulnerable to climate change (Leichenko and O'Brien, 2008). Examples of these risks, explored further in Chapters 7 to 9, 12, 13, and 19, include:

- Severe impacts of food price spikes in many developing countries (including food riots and increased incidence of child malnutrition) such as occurred in 2008 following shortfalls in staple cereals, due to a coincidence of regional weather extremes (e.g., drought) in producer countries, the reallocation of food crops by some major exporters for use as biofuels (an outcome of climate policy; see previous section), and market speculation (Ziervogel and Ericksen, 2010). Prices subsequently fell back as the world economy went into recession, but spiked again in early 2011 for many of the same reasons (Trostle et al., 2011), with some commentators predicting a period of rising and volatile prices due to increasing demand and competition from biofuels (Godfray et al., 2010).
- A growing dependence of the rural poor on supplementary income from seasonal urban employment by family members and/or on international financial remittances from migrant workers (Davies et al., 2009). These workers are commonly the first to lose their jobs in times of economic recession, which automatically decreases the resilience of recipient communities in the event of adverse climate conditions. On the other hand, schemes to provide more effective communication with the diaspora in times of severe weather and other extreme events can provide rapid access to resources to aid recovery and reduce vulnerability (Downing, 2012).
- Some aspects of international disaster relief, especially the provision of emergency food aid over protracted periods, has been cited as an impediment to enhancing adaptive capacity to cope with climate-related hazards in many developing countries (Schipper and Pelling, 2006). Here, international intervention, while well-intentioned to relieve short-term stress, may actually be counterproductive in regard to the building of long-term resilience.

21.4.1.3. Sensitivity of International Trade to Climate

Climate trends and extreme climate events can have significant implications for regional resource exploitation and international trade flows. The clearest example of an anticipated, potentially major impact of climate change concerns the opening of Arctic shipping routes as well as exploitation of mineral resources in the exclusive economic zones (EEZs) of Canada, Greenland/Denmark, Norway, the Russian Federation, and the USA (Figure 21-11, see also Section 28.3.4).

For instance, the Community Climate System Model 4 (CCSM4) climate and sea ice model has been used to provide projections under RCP4.5, RCP6.0, and RCP8.5 forcing (see Box 21-1) of future accessibility for shipping to the sea ice hazard zone of the Arctic marine environment defined by the International Maritime Organization (IMO) (Stephenson et al., 2013; Figure 21-11, central map). Results suggest that moderately ice-strengthened ships (Polar Class 6), which are estimated under baseline (1980–1999) conditions to be able to access annually about 36% of the IMO zone, would increase this access to 45 to 48% by 2011–2030, 58 to 69% by 2046–2065, and 68 to 93% by 2080–2099, with almost complete accessibility projected for summer (90 to 98% in July to October) by the end of the century (Stephenson et al., 2013). The robustness of those findings was confirmed using seven sea ice models in an analysis of optimal sea routes in peak season (September) for 2050–2069 under RCP4.5 and RCP8.5 forcing (Smith and Stephenson, 2013). All studies imply increased access to the three major cross Arctic routes: the Northwest Passage, Northern Sea Route (part of the Northeast Passage), and Trans-Polar Route (Figure 21-11), which could represent significant distance savings for trans-continental shipping currently using routes via the Panama and Suez Canals (Stephenson et al., 2011).

Indeed, in 2009, two ice-hardened cargo vessels—the Beluga Fraternity and Beluga Foresight—became the first to successfully traverse the Northeast Passage from South Korea to The Netherlands, a reduction of 5500 km and 10 days compared to their traditional 20,000-km route via the Suez Canal, translating into an estimated saving of some US$300,000 per ship, including the cost of standby icebreaker assistance (Smith, 2009; Det Norsk Veritas, 2010). A projection using an earlier version of the CCSM sea ice model under the SRES A1B scenario, but offering similar results (with forcing by mid-century lying just below RCP8.5; Figure 1-5a), is presented in Figure 21-11 (peripheral maps), which also portrays winter transportation routes on frozen ground. These routes are heavily relied on for supplying remote communities and for activities such as forestry and, in contrast to the shipping routes, are projected to decline in many regions.

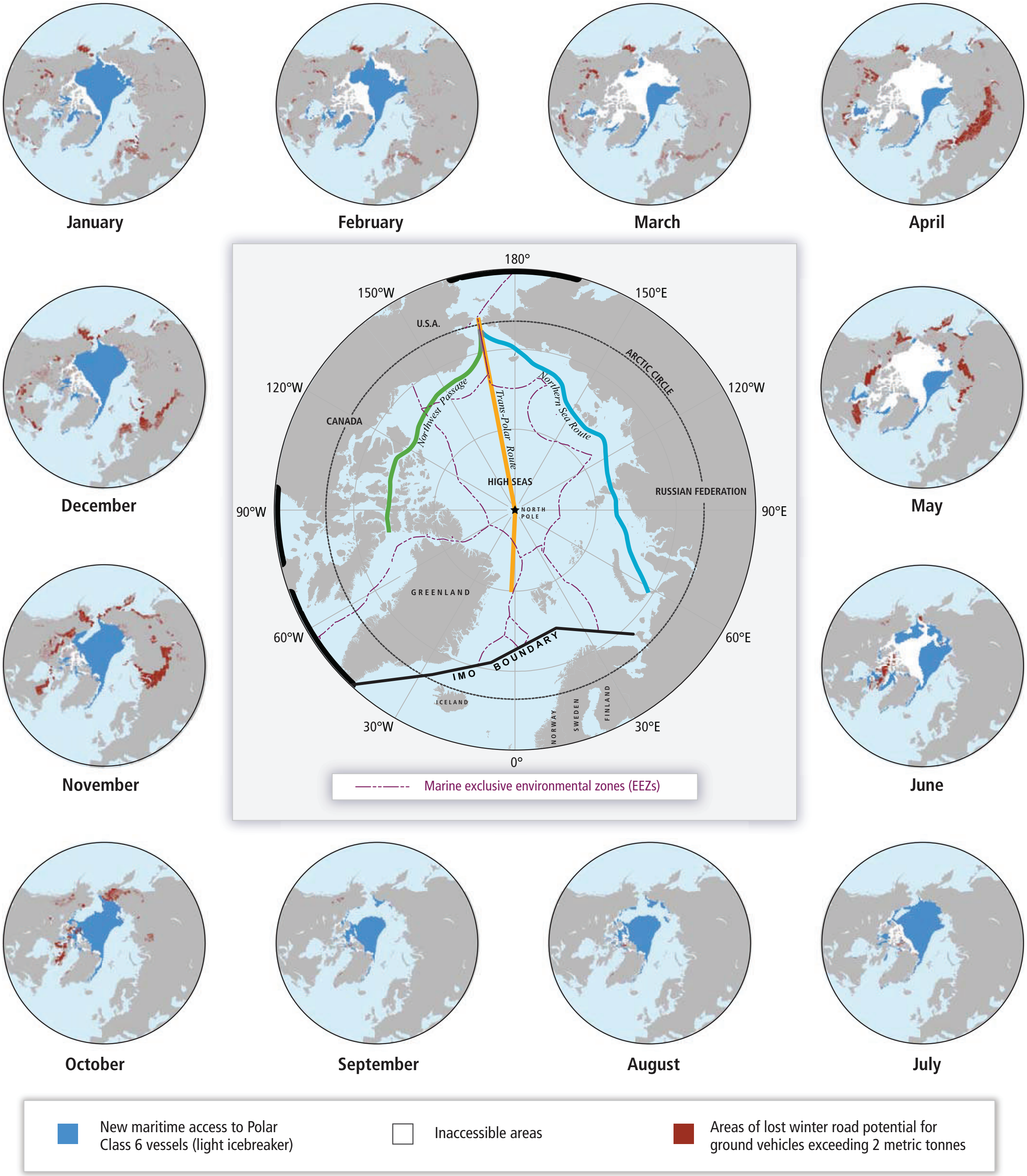


Figure 21-11 | Central map: Marine exclusive environmental zones (EEZs, dashed lines) of Canada, Greenland/Denmark, Norway, Russian Federation, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the International Maritime Organization (IMO) Guidelines Boundary for Arctic shipping (thick black border) (after Stephenson et al., 2013). Peripheral monthly maps: Projected change in accessibility of maritime and land-based transportation by mid-century (2045–2059 relative to 2000–2014) using the Arctic Transport Accessibility Model and Community Climate System Model 3 (CCSM3) climate and sea ice estimates assuming a Special Report on Emission Scenarios (SRES) A1B scenario. Dark blue areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).

A second illustration of how the risk of adverse climate changes may have contributed to anticipatory adaptive actions affecting countries in other regions of the world and potentially influencing commodity markets relates to the purchase or renting of large tracts of productive land in parts of Africa, South America and the Caribbean, Central Asia, and Southeast Asia by countries in Europe, Africa, the Gulf, and South and East Asia (De Schutter, 2009; Cotula et al., 2011; Zoomers, 2011). While there is clearly a profit motive in many of these purchases (i.e., cheap and fertile land and the opportunity to cultivate high value food or biofuel crops), there is also a concern that domestic agricultural production in some countries will be unable to keep pace with rapid growth in domestic demand and changing dietary preferences, especially in agricultural regions affected by frequent shortfalls due to droughts, floods, and cyclones (Cotula et al., 2011), or threatened by sea level rise (Zoomers, 2011). Land acquisition on such a large scale raises a number of ethical issues relating to local access to food and the appropriate and sustainable management of the land (Deininger and Byerlee, 2012). These issues have led the UN Special Rapporteur on the right to food to recommend a list of 11 principles for ensuring informed participation of local communities, adequate benefit sharing, and the respect of human rights (De Schutter, 2009). This issue is elaborated with respect to livelihoods and poverty in Section 13.4.3.4, and land dispossession is categorized as a key risk in Section 19.6.2.

Extreme climate phenomena that may be harbingers of similar and more frequent events in a warmer world, already exact devastating consequences in some regions that extend well beyond country boundaries. A recent event that disrupted international trade and commodity flows was the severe 2010/2011 flooding in eastern Australia (Giles, 2011; Queensland Floods Commission of Inquiry, 2012; see also Box 25-8), which, combined with damaging cyclones in Queensland and western Australia, curtailed numerous mining operations and damaged transportation networks, leading to declines in both thermal and metallurgical coal exports (by 31 and 19%, respectively, relative to the previous quarter; ABARES, 2011), with a sharp rise in their monthly price between November 2010 and January 2011 (Index Mundi, 2012). The severe weather was the primary factor contributing to a fall in Australian GDP of 1.2% during January to March 2011 compared with a rise of 0.7% in the preceding 3-month period (Australian Bureau of Statistics, 2011). Other examples of how extreme climate events can affect international trade are reported by Oh and Reuveny (2010) and Handmer et al. (2012).

21.4.2. Human Migration

There has been considerable debate in recent years around the postulate that anthropogenic climate change and environmental degradation could lead to mass migration (Perch-Nielsen et al., 2008; Feng et al., 2010; Warner, 2010; Black et al., 2011; Foresight, 2011; Assan and Rosenfeld, 2012). The issue is treated at length in Chapters 9, 12, and 19, so only a few aspects are touched on here, to highlight the growing significance of migration in all regions of the world. Four possible pathways through which climate change could affect migration are suggested by Martin (2009):

1) Intensification of natural disasters
2) Increased warming and drought that affects agricultural production and access to clean water
3) Sea level rise, which makes coastal areas and some island states increasingly uninhabitable
4) Competition over natural resources, which leads to conflict and displacement of inhabitants.

Abundant historical evidence exists to suggest that changes in climatic conditions have been a contributory factor in migration, including large population displacements in the wake of severe events such as Hurricane Katrina in New Orleans, Louisiana, USA, in 2005 (Cutter et al., 2012), Hurricane Mitch in Central America in 1998, and the northern Ethiopian famines of the 1980s (McLeman and Smit, 2006). Other examples are provided in Table 12-3. However, the evidence is not clear cut (Black, 2001), with counterexamples also available of migration being limited due to economic hardship (e.g., during the Sahel drought of the mid-1980s in Mali; Findley, 1994).

The spatial dimension of climate-related migration is most commonly internal to nations (e.g., from affected regions to safer zones; Naik, 2009). In this context it is also worth pointing out that internal migration for other (predominantly economic) reasons may actually expose populations to increased climate risk. For instance, there are large cities in developing countries in low-elevation coastal zones that are vulnerable to sea level rise. Increased migration to these cities could exacerbate the problems, with the migrants themselves being especially vulnerable (Nordås and Gleditsch, 2007; UNFPA, 2007).

Migration can also be international, though this is less common in response to extreme weather events, and where it does happen it usually occurs along well established routes. For example, emigration following Hurricane Mitch tripled from Honduras and increased from Nicaragua by 40%, mainly to the southern states of the USA (already a traditional destination for migrants), and was aided by a relaxation of temporary residency requirements by the USA (Naik, 2009).

The causal chains and links between climate change and migration are complex and can be difficult to demonstrate (e.g., Perch-Nielsen et al., 2008; Piguet, 2010; Tänzler et al., 2010; ADB, 2012; Oliver-Smith, 2012; Sections 9.3.3.3.1,12.4, 19.4.2.1), though useful insights can be gained from studying past abandonment of settlements (McLeman, 2011). Thus projecting future climate-related migration remains a challenging research topic (Feng et al., 2010). There are also psychological, symbolic, cultural, and emotional aspects to place attachment, which are well documented from other non-climate causes of forced migration, and are also applicable to cases of managed coastal retreat due to sea level rise (e.g., Agyeman et al., 2009).

Forced migration appears to be an emerging issue requiring more scrutiny by governments in organizing development cooperation, and to be factored into international policy making as well as international refugee policies. For example, it has been suggested that the National Adaptation Plans of Action (NAPAs) under the UNFCCC, by ignoring transboundary issues (such as water scarcity) and propounding nationally orientated adaptation actions (e.g., upstream river management, to the detriment of downstream users in neighboring countries), could potentially be a trigger for conflict, with its inevitable human consequences. Currently there is no category in the United Nations High Commission for Refugees classification system for environmental refugees, but it is possible that this group of refugees will increase in the future and their needs and rights will need to be taken into consideration (Brown, 2008). The Nansen Initiative, put forward jointly by Norway and Switzerland at a 2011 ministerial meeting, pledges "to cooperate with interested states and relevant actors, including UNHCR, to obtain a better understanding of cross-border movements provoked by new factors such as climate change, identify best practices and develop a consensus on how best to protect and assist those affected," and may eventually result in a soft law or policy framework (Kolmannskog, 2012). However, migration should not always be regarded as a problem; in those circumstances where it contributes to adaptation (e.g., through remittances) it can be part of the solution (Laczko and Aghazarm, 2009).

21.4.3. Migration of Natural Ecosystems

One of the more obvious consequences of climate change is the displacement of biogeographical zones and the natural migration of species (see Chapters 4, 6, 19). General warming of the climate can be expected to result in migration of ecosystems toward higher latitudes and upward into higher elevations (Section 4.3.2.5) or downward to cooler depths in marine environments (Section 6.3.2.1). Species shifts are already occurring in response to recent climate changes in many parts of the world (Rosenzweig et al., 2008), with average poleward shifts in species' range boundaries of 6 km per decade being reported (Parmesan et al., 2011).

Study of the estimated shifts of climatic zones alone can provide insights into the types of climatic regimes to anticipate under projected future anthropogenic climate change. By grouping different combinations and levels of climatic variables it is possible not only to track the shifts in the zones in which they occur, but also to identify newly emerging combinations of conditions not found at the present day as well as combinations that may not survive global climate change (known respectively as novel and disappearing climates; Williams et al., 2007; see also Section 19.5.1). These analyses can help define what types of climatic niches may be available in the future and where they will be located. Such a spatial analog approach can delimit those regions that might currently or potentially (in the future) be susceptible to invasion by undesirable aquatic (e.g., EPA, 2008) or terrestrial (e.g., Mainka and Howard, 2010) alien species or alternatively might be candidates for targeting translocation (assisted colonization) of species endangered in their native habitats (e.g., Brooker et al., 2011; Thomas, 2011). However, there are many questions about the viability of such actions, including genetic implications (e.g., Weeks et al., 2011), inadvertent transport of pests or pathogens with the introduced stock (e.g., Brooker et al., 2011), and risk of invasiveness (e.g., Mueller and Hellmann, 2008).

The ability of species to migrate with climate change must next be judged, in the first instance, against the rate at which the climatic zones shift over space (e.g., Loarie et al., 2009; Burrows et al., 2011; Diffenbaugh and Field, 2013; see also Section 4.3.2.5). For projecting potential future species shifts, this is the most straightforward part of the calculation. In contrast, the ecological capacity of species to migrate is a highly complex function of factors, including their ability to:

- Reproduce, propagate, or disperse
- Compete for resources
- Adapt to different soils, terrain, water quality, and day length
- Overcome physical barriers (e.g., mountains, water/land obstacles)
- Contend with obstacles imposed by human activity (e.g., land use, pollution, or dams).

Conservation policy under a changing climate is largely a matter of promoting the natural adaptation of ecosystems, if this is even feasible for many species given the rapidity of projected climate change. Studies stress the risks of potential mismatching in responses of co-dependent species to climate change (e.g., Schweiger et al., 2012) as well as the importance of maintaining species diversity as insurance for the provision of basic ecosystem services (e.g., Traill et al., 2010; Isbell et al., 2011). Four priorities have been identified for conservation stakeholders to apply to climate change planning and adaptation (Heller and Zavaleta, 2009): (1) regional institutional coordination for reserve planning and management and to improve landscape connectivity; (2) a broadening of spatial and temporal perspectives in management activities and practice, and actions to enhance system resilience; (3) mainstreaming of climate change into all conservation planning and actions; and (4) holistic treatment of multiple threats and global change drivers, also accounting for human communities and cultures. The regional aspects of conservation planning transcend political boundaries, again arguing for a regional (rather than exclusively national) approach to adaptation policy. This issue is elaborated in Sections 4.4.2 and 19.4.2.3.

21.5. Analysis and Reliability of Approaches to Regional Impacts, Adaptation, and Vulnerability Studies

Assessing climate vulnerability or options for adapting to climate impacts in human and natural systems requires an understanding of all factors influencing the system and how change may be effected within the system or applied to one or more of the external influencing factors. This will require, in general, a wide range of climate and non-climate information and methods to apply this to enhance the adaptive capacity of the system.

There are both areas of commonality across and differences between regions in the information and methods, and these are explored in this section. It initially focuses on advances in methods to study vulnerability and adaptive capacity and to assess impacts (studies of practical adaptation and the processes of adaptation decision making are treated in detail in Chapters 14 to 17, so not addressed here). This is followed by assessments of new information on, and thinking related to, baseline and recent trends in factors needed to assess vulnerability and define impacts baselines, and future scenarios used to assess impacts, changes in vulnerability, and adaptive capacity; and then assessment of the credibility of the various types of information presented.

21.5.1. Analyses of Vulnerability and Adaptive Capacity

Multiple approaches exist for assessing vulnerability and for exploring adaptive capacity (UNFCCC, 2008; Schipper et al., 2010). The choice of method is influenced by objectives and starting point (see Table 21-3) as well as the type of information available. Qualitative assessments usually draw on different methods and inputs from quantitative assessments. Qualitative information cannot always be translated to quantitative information, or vice versa, yet both approaches can sometimes be used to answer the same questions. Indicators, indices, and mapping are the most common ways to aggregate the resulting vulnerability and adaptive capacity information to compare across regions (Section 21.5.1.1) or to identify "hotspots" (Section 21.5.1.2).

21.5.1.1. Indicators and Indices

Several attempts have been made to develop vulnerability indicators and indices (Atkins et al., 2000; Downing et al., 2001; Moss et al., 2001; Villa and McLeod, 2002; Lawrence et al., 2003; Luers et al., 2003; Cardona, 2007; Barr et al., 2010; Birkmann, 2011; Chen et al., 2011). Representation on a map or through an index is a common way to depict global vulnerability information and requires quantification of selected variables in order to measure them against a selected baseline, even though quantification of some qualitative information may not be possible (Luers et al., 2003; Edwards et al., 2007; Hinkel, 2011). Vulnerability is differentiated according to factors such as gender, age, livelihood, or access to social networks, among many other factors (Wisner et al., 2004; Cardona et al., 2012), which may not be represented accurately through some indicators.

One approach used to create regional comparisons is to use indices, which are composites of several indicators thought to contribute to vulnerability, each normalized and sometimes weighted so they can be combined (Adger et al., 2004; Rygel et al., 2006). The approach has been critiqued extensively because the weights assigned the indicators depend on expert opinion which can result in different regions appearing more or less vulnerable, as Füssel (2010b) found in reviewing global vulnerability maps based on different indices.

Vulnerability indices developed to date have failed to reflect the dynamic nature of component indicator variables. This is illustrated by the (in)ability to characterize how the selected indicators contribute to determining vulnerability over time. Significantly, the relative importance of the indicator may change from season-to-season (e.g., access to irrigation water) or may gradually or rapidly become obsolete. Hinkel's (2011) review of literature on vulnerability indicators suggests that vulnerability has been confused as a proxy for unsustainable or insufficient development so that simple measurements are seen as sufficient to tell a story about vulnerability. Hinkel (2011) suggests that the simplification of information to create vulnerability indicators is what limits their utility.

Indicator systems have also been developed to improve understanding of adaptive capacity. These are used both to measure adaptive capacity and identify entry points for enhancing it (Adger and Vincent, 2005; Eriksen and Kelly, 2007; Swanson et al., 2007; Lioubimtseva and Henebry, 2009; Adaptation Sub-Committee, 2011). For example, the Global Adaptation Index, developed by the Global Adaptation Alliance (GAIN, n.d.), uses a national approach to assess vulnerability to climate change and other global challenges and compare this with a country's "Readiness to improve resilience" (GAIN, n.d.) to assist public and private sectors to prioritize financial investments in adaptation activities.

21.5.1.2. Hotspots

A special case of the use of indicators concerns the identification of hotspots, a term originally used in the context of biodiversity, where a "biodiversity hotspot" is a biologically diverse region typically under threat from human activity, climate change, or other drivers (Myers, 1988). The term typically relates to a geographical location, which emerges as a concern when multiple layers of information are compiled to define it. In climate change analysis, hotspots are used to indicate locations that stand out in terms of impacts, vulnerability, or adaptive capacity (or all three). Examples of hotspot mapping include how climate change can influence disease risk (de Wet et al., 2001), extinctions of endemic species (Malcolm et al., 2006), and disaster risk (Dilley, 2006). Hotspots analysis is used to serve various purposes, such as setting priorities for policy action, identifying focal regions for further research (Dilley, 2006; Ericksen et al., 2011; de Sherbinin, 2013; see also www.climatehotmap.org), or, increasingly, helping distinguish priority locations for funding. Examples of the latter purpose include guiding the allocation of global resources to pre-empt, or combat, disease emergence (Jones et al., 2008) or funding for disaster risk management (Arnold et al., 2005). Because identifying hotspots raises important methodological issues about the limitation of using indicators to integrate quantitative impacts with qualitative dimensions of vulnerability, their use to compare regions leads to a subjective ranking of locations as having priority for climate change investment. This can be controversial and considered politically motivated (Klein, 2009).

Certain locations are considered hotspots because of their regional or global importance. These can be defined by population size and growth rate, contributions to regional or global economies, productive significance (e.g., food production) as well as by disaster frequency and magnitude, and projected climate change impacts. The choice of variables may result in different locations being identified as hotspots (Füssel, 2009). For example, the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change Agriculture and Food Security (CCAFS) mapped hotspots of food insecurity and climate change in the tropics (Ericksen et al, 2011) using stunted growth as a proxy for food security, but other variables could also have been selected. Scale matters in representing hotspots and they will look different on a global scale than on a finer scale (Arnold et al., 2006).

The rationale for identifying such hotspots is that they may gradually evolve into locations of conflict or disaster, where a combination of factors leads to the degradation of resources and social fabric. Climate change hotspots have been defined as locations where impacts of climate change are "well pronounced and well documented" (UCS, 2011). A climate change hotspot can describe (1) a region for which potential climate change impacts on the environment or different activity sectors can be particularly pronounced or (2) a region whose climate is especially responsive to global change (Giorgi, 2006). An example of the former is given by Fraser et al. (2013), combining hydrological modeling with quantitatively modeled adaptive capacity (defined as the inverse of sensitivity to drought) to identify vulnerability hotspots for wheat and maize. Examples of the latter are given by Giorgi (2006), Diffenbaugh et al. (2008), Giorgi and Bi (2009), Xu et al. (2009), Diffenbaugh and Scherer (2011), and Diffenbaugh and Giorgi (2012), who used different regional climate change indices, including changes in mean and interannual variability of temperature and precipitation and metrics of seasonal extremes, to identify the Mediterranean Basin, Central America, Central and West Africa, the Northern high latitude regions, the Amazon, the southwestern USA, Southeast Asia, and the Tibetan Plateau as prominent hotspots.

21.5.2. Impacts Analyses

In recent years, there has been increased scrutiny of the methods and tools applied in impact assessment, especially quantitative models that are used to project the biophysical and socioeconomic impacts of future climate change (see Section 2.3.2.1), but also encompassing qualitative methods, including studies of indigenous knowledge (Section 12.3.3). In an advance from previous assessments, different types of impact models are now being applied for the first time in many regions of the world. This is largely due to burgeoning international development support for climate change vulnerability and adaptation studies (Fankhauser, 2010). It is also related to a surge of interest in regional economic assessments in the wake of the Stern review (Stern, 2007) as well as to the evolution of climate models into Earth system models that incorporate a more realistic representation of land surface processes (Flato et al., 2014) and their increased application to study hydrological (Section 3.4.1), ecophysiological (Section 4.3.3), and cryospheric (Vaughan et al., 2014) impacts.

Potential impacts have been simulated for single as well as multiple sectors, at spatial scales ranging from site or household to global, and over a range of temporal scales and time horizons (Table 21-5). A majority of impact studies still follow the conventional approach where future impacts are modelled based on a set of assumptions (scenarios) about future climate and socioeconomic conditions (see Section 21.2.3, lefthand side of Table 21-3). However, an increasing number are being undertaken that follow a "socio-institutional" approach to adaptation planning (Downing, 2012), righthand side of Table 21-3, which emphasizes the importance of adaptive flexibility and climate resilience given the often intractable, "deep" uncertainties implicit in many projections of future change (Donley et al., 2012; Garrett et al., 2013; Gersonius et al., 2013).

Impact modeling studies also commonly treat aspects of adaptation, either explicitly as modeled options or implicitly as built-in autonomous responses (Dickinson, 2007; White et al., 2011). Furthermore, as an anthropogenic signature is attributed to ongoing climate changes in many regions (Bindoff et al., 2014), and with growing evidence that these changes are having impacts on natural and human systems in many more regions than reported in the AR4 (Chapter 18; Rosenzweig and Neofotis, 2013), it is now possible in some regions and sectors to test impact models' projections against observed impacts of recent climate change (e.g., Araújo et al., 2005; Barnett et al., 2008; Lobell et al., 2011). This is also an essential element in the attribution of observed impacts (Sections 18.3-5).

Uncertainties in and Reliability of Impacts Analyses

Literature on uncertainty in impacts analyses has focused mainly on the uncertainties in impacts that result from the uncertainties in future climate (Mearns et al., 2001; Carter et al., 2007), and this literature continues to grow since AR4, particularly in the realm of agriculture and water resources (e.g., Ferrise et al., 2011; Littell et al., 2011; Wetterhall et al., 20011; Ficklin et al., 2012; Osborne et al., 2013), but also in other areas such as flood risk (Ward et al., 2013). Furthermore, research has advanced to establish which future climate uncertainties are most important to the resultant uncertainties about crop yields (e.g., Lobell and Burke, 2008) and to apply future resource uncertainties to adaptation studies (Howden et al., 2007). Use of multiple global or regional model scenarios is now found in many more studies (e.g., Arnell, 2011; Bae et al., 2011; Gosling et al., 2011; Olsson et al., 2011), and the use of probabilistic quantification of climate uncertainties has produced estimates of probabilities of changes in future resources such as agriculture and water (e.g., Tebaldi and Lobell, 2008; Watterson and Whetton, 2011). Some studies have developed probability distributions of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009). Nobrega et al. (2011) apply six different GCMs and four different SRES emissions scenarios to study the impacts of climate change on water resources in the Rio Grande Basin in Brazil and found that choice of GCM was the major source of uncertainty in terms of river discharge.

With an ever-increasing number of impacts' projections appearing in the literature and the unprecedented rate and magnitude of climate change projected for many regions, some authors have begun to question both the robustness of the impacts models being applied (e.g., Heikkinen et al., 2006; Fitzpatrick and Hargrove, 2009; Watkiss, 2011a) as well as the methods used to represent key uncertainties in impacts' projections (e.g., Arnell, 2011; Rötter et al., 2011; White et al., 2011). This is being addressed through several prominent international research efforts: AgMIP, involving crop and economic models at different scales (Rosenzweig et al., 2013), the Carbon Cycle Model Intercomparison Project (C4MIP; Friedlingstein et al., 2006; Sitch et al., 2008; Arora et al., 2013), and the Water Model Intercomparison Project (WaterMIP; Haddeland et al., 2011). Modeling groups from these projects are also participating in the ISI-MIP, initially focusing on intercomparing global impact models for agriculture, ecosystems, water resources, health, and coasts under RCP- and SSP-based scenarios (see Box 21-1) with regional models being considered in a second phase of work (Schiermeier, 2012). AgMIP results for 27 wheat models run at contrasting sites worldwide indicate that projections of yield to the mid-21st century are more sensitive to crop model differences than to global climate model scenario differences (Asseng et al., 2013; Carter, 2013). WaterMIP's analysis of runoff and evapotranspiration from five global hydrologic and six land surface models indicate substantial differences in the models' estimates in these key parameters (Haddelenad et al., 2011). Finally, as in climate modeling, researchers are now applying multiple impact model and perturbed parameter ensemble approaches to future projections (e.g., Araújo and New, 2007; Jiang et al., 2007; Palosuo et al., 2011), usually in combination with ensemble climate projections treated discretely (e.g., New et al., 2007; Graux et al., 2013; Tao and Zhang, 2013) or probabilistically (e.g., Luo et al., 2007; Fronzek et al., 2009, 2011; Børgesen and Olesen, 2011; Ferrise et al., 2011; Wetterhall et al., 2011).

These new impact MIPs, and similar initiatives, have the common purpose of mobilizing the research community to address some long-recognized but pervasive problems encountered in impact modeling. A sample of recent papers illustrate the variety of issues being highlighted, for example, forest model typology and comparison (Medlyn et al., 2011), crop pest and disease modeling and evaluation (Sutherst et al., 2011; Garrett et al., 2013), modeling responses to extreme weather events (Lobell et al., 2010; Asseng et al., 2013), field experimentation for model calibration and testing (Long et al., 2006; Craufurd et al., 2013), and data quality considerations for model input and calibration (Lobell, 2013). Greater attention is also being paid to methods of economic evaluation of the costs of impacts and adaptation at scales ranging from global (e.g., UNFCCC, 2007; Nelson et al., 2009b; Parry et al., 2009; Fankhauser, 2010; Füssel, 2010a; Patt et al., 2010), through regional (e.g., EEA, 2007; World Bank, 2010b; Ciscar et al., 2011; Watkiss, 2011b), to national (SEI, 2009; Watkiss et al., 2011) and local levels (e.g., Perrels et al., 2010).

21.5.3. Development and Application of Baseline and Scenario Information

21.5.3.1. Baseline Information: Context, Current Status, and Recent Advances

This section deals with defining baseline information for assessing climate change IAV. The baseline refers to a reference state or behavior of a system, for example, current biodiversity of an ecosystem, or a reference state of factors (e.g., agricultural activity, climate) that influence that system (see Glossary). For example, the UNFCCC defines the preindustrial baseline climate, prior to atmospheric composition changes from its baseline preindustrial state, as a reference for measuring global average temperature rises. A baseline may be used to characterize average conditions and/or variability during a reference period, or may allude to a single point in time, such as a reference year. It may provide information on physical factors such as climate, sea level, or atmospheric composition, or on a range of non-climate factors, such as technological, land use, or socioeconomic conditions. In many cases a baseline needs to capture much of a system's variability to enable assessment of its vulnerability or to test whether significant changes have taken place. Thus the information used to establish this baseline must account for the variability of the factors influencing the system. In the case of climate factors often this requires 30 years of data (e.g., Jones et al., 1997) and sometimes substantially more (e.g., Kendon et al., 2008). In addition, temporal and spatial properties of systems will influence the information required. Many depend on high-resolution information, for example, urban drainage systems (high spatial scales) or temperature-sensitive organisms (sub-daily time scales). This section assesses methods to derive relevant climatic and non-climatic information and its reliability.

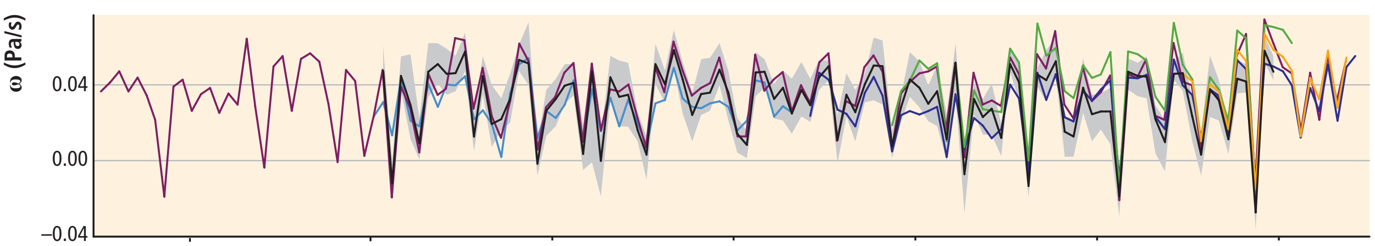
21.5.3.1.1. Climate baselines and their credibility

Observed weather data are generally used as climate baselines, for example, with an impacts model to form a relevant impacts baseline, though downscaled climate model data are now being used as well. For example, Bell et al. (2012) use dynamically and statistically downscaled hourly rainfall data with a 1-km river flow model to generate realistic high-resolution baseline river flows. These were then compared with future river flows derived used corresponding downscaled future climate projections to generate projected impacts representing realistic responses to the imposed climate perturbations. This use of high-resolution data was important to ensure that changes in climate variability that the system was sensitive to were taken into account (see also Hawkins et al., 2013). Underscoring the importance of including the full spectrum of climate variability when assessing climate impacts, Kay and Jones (2012) showed a greater range of projected changes in UK river flows resulted when using high time resolution (daily rather than monthly) climate data.

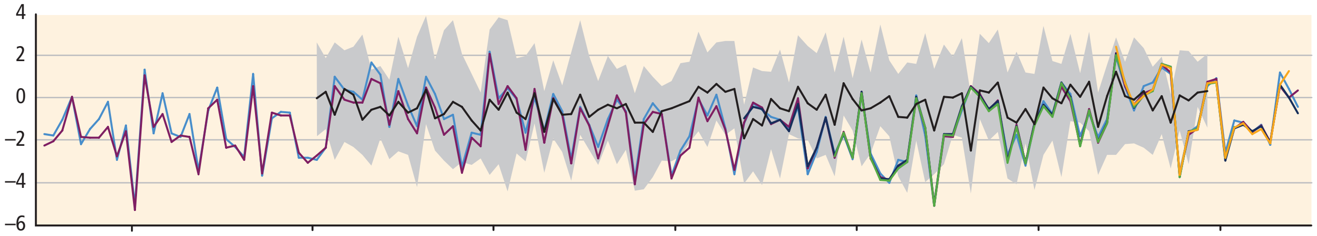
Thus to develop the baseline of a climate-sensitive system it is important to have a good description of the baseline climate, thus including information on its variability on time scales of days to decades. This has motivated significant efforts to enhance the quality, length, and homogeneity of, and make available, observed climate records (also important for monitoring, detecting, and attributing observed climate change; Bindoff et al., 2014; Hartmann et al., 2014; Masson-Delmotte et al., 2014; Rhein et al., 2014; Vaughan et al., 2014). This has included generating new data sets such as Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE, a gridded rain-gauge based data set for Asia; Yatagai, et al., 2012), coordinated analyses of regional climate indices and extremes by Climate Variability and Predictability Programme (CLIVAR)'s Expert Team on Climate Change Detection and Indices (ETCCDI) (see, e.g., Zhang et al., 2011), and data rescue work typified by the Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (Allan et al., 2011), resulting in analysis and digitization of many daily or sub-daily weather records from all over the world. Also, estimates of uncertainty in the observations are either being directly calculated, for example, for the Hadley Centre/climatic research unit gridded surface temperature data set 4 (HadCRUT4) near-surface temperature record (Morice et al., 2012), or can be generated from multiple data sets, for example, for precipitation using data sets such as Global Precipitation Climatology Centre (GPCC; Rudolf et al., 2011), Tropical Rainfall Measuring Mission (TRMM; Huffman et al., 2010), and APHRODITE (Yatagi et al., 2012).

Significant progress has also been made in developing improved and new global reanalyses. These use climate models constrained by long time series of observations from across the globe to reconstruct the temporal evolution of weather patterns during the period of the observations. An important new development has been the use of digitized surface pressure data from ACRE by the 20th Century Reanalysis (20CR) project (Compo et al., 2011) covering 1871 to the present day. 20CR provides the basis for estimating historical climate variability from the sub-daily to the multi-decadal time scale (Figure 21-12) at any location. It can be used directly, or via downscaling, to develop estimates of the baseline sensitivity of a system to climate and addressing related issues such as establishing links between historical climate events and their impacts. Other advances in reanalyses (http://reanalyses.org) have focused on developing higher quality reconstructions for the recent past. They include a new European Centre for Medium Range Weather Forecasts Reanalyses (ERA) data set, ERA-Interim (Dee et al., 2011), and the NASA Modern Era Reanalysis for Research and Applications (MERRA; Rienecker et al., 2011), 1979 to the present, the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR), 1979 to January 2010 (Saha et al., 2010), and regional reanalyses

(a) The tropical September to January Pacific Walker Circulation (PWC)



(b) The December to March North Atlantic Oscillation (NAO)



(c) The December to March Pacific North American (PNA) pattern

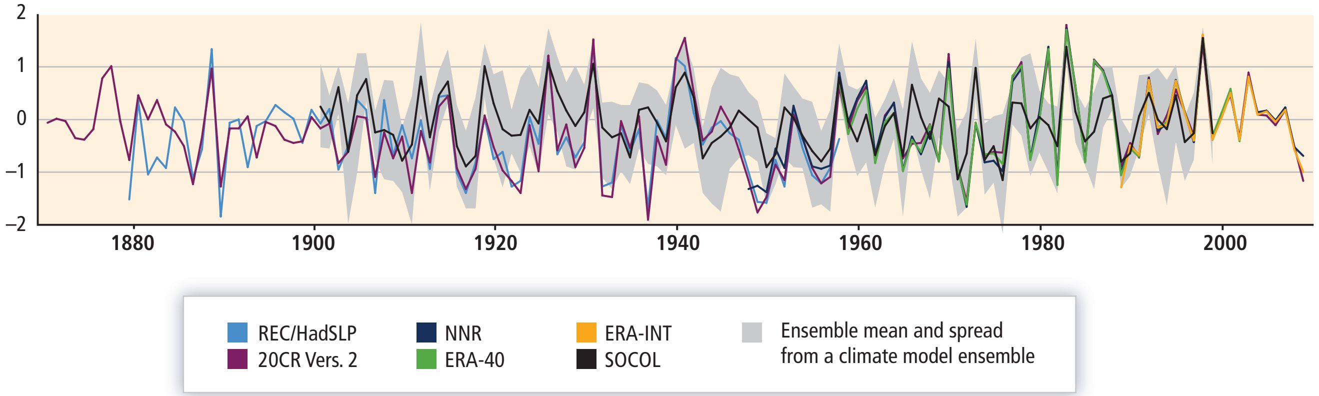


Figure 21-12 | Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); and (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann et al., 2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis, and model sources: statistical reconstructions of the PWC, the PNA, and the NAO (blue); 20th Century Reanalysis (20CR, purple); National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (NNR, dark blue); European Centre for Medium Range Weather Forecasts 40-Year Reanalysis (ERA-40, green); and ERA-Interim (orange). The black line and gray shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed sea surface temperatures and sea ice from the Hadley Centre Interpolated sea surface temperature (HadISST) data set (Rayner et al., 2003); see Brönnimann et al. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea surface temperature and sea ice alone and demonstrate that the reanalyses have significantly higher skill in reproducing these modes of variability.

such as the North American Regional Reanalysis (NARR; Mesinger et al., 2006) and European Reanalysis and Observations for Monitoring (EURO4M; http://www.euro4m.eu/).

In many regions high temporal and spatial resolution baseline climate information is not available (e.g., World Weather Watch, 2005; Washington et al., 2006). Recent reanalyses may provide globally complete and temporally detailed reconstructions of the climate of the recent past but generally lack the spatial resolution or have significant biases (Thorne and Vose, 2010; Cerezo-Mota et al., 2011; Dee et al., 2011). Downscaling the reanalyses can be used with available observations to estimate the error in the resulting reconstructions, which can often be significant (Duryan et al., 2010; Mearns et al., 2012). Advances in this area are expected through the World Climate Research Programme (WCRP)-sponsored Coordinated Regional Downscaling Experiment (CORDEX) project (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html; Giorgi et al., 2009), which includes downscaling ERA-Interim over all land and enclosed sea areas (e.g., Nikulin et al. 2012).

21.5.3.1.2. Non-climatic baselines and their credibility

Climate-sensitive systems can be influenced by many non-climatic factors, so information on the baseline state of these factors is also commonly required (Carter et al., 2001, 2007). Examples of physical non-climatic factors include availability of irrigation systems, effectiveness of disease prevention, or flood protection. Examples of socioeconomic factors include levels of social, educational, and economic development, political/governance background, and available technology. Significant work has been undertaken to collect and make this information available. Local and national governments and international agencies (e.g., UN agencies, World Bank) have been collecting data (http://data.worldbank.org/data-catalog) on the human-related factors for many decades and similarly information on technological developments is widely available. Often these factors are evolving quickly and the baseline is taken as the reference state at a particular point in time rather than aggregated over a longer period. In the case of the physical factors, information on many of these have been refined and updated as they are critical inputs to deriving the climate forcings in the RCPs (van Vuuren et al., 2011) used in CMIP5 (Taylor et al., 2012). This includes updated information on land use change (Hurtt et al., 2011), atmospheric composition (Meinshausen et al., 2011) and aerosols (Grainer et al., 2011; Lamarque et al., 2011).

The importance of establishing an appropriate physical baseline is illustrated in a study of potential climate change impacts on flow in the River Thames in the UK over a 126-year period. No long-term trend is seen in annual maximum flows despite increases in temperature and a major change in the seasonal partitioning of rainfall, winter rainfall becoming larger than summer (Marsh, 2004). An investigation of the physical environment found that it had been significantly modified as part of river management activities, with increases in channel capacity of 30% over 70 years leading to fewer floods. Thus establishing a baseline for river channel capacity explained the current reduced vulnerability of the Thames to flooding. In a study of the potential for crop adaptation (Challinor et al., 2009), the relevant non-climatic factor identified was technological. Detailed field studies demonstrated that the current germplasm included varieties with a wide range of tolerance to higher temperatures (Badigannavar et al., 2002). This established an agricultural technology baseline, current crop properties, which demonstrated the potential to reduce vulnerability in the system to compensate for the projected climate change impact.

21.5.3.2. Development of Projections and Scenarios

Since the AR4 there have been several new developments in the realm of scenarios and projections: (1) a new approach to the construction of global scenarios for use in climate change analysis, initiated with the development of RCPs (see Box 21-1 for a full description); (2) the development and application of a greater number of higher resolution climate scenarios (Section 21.3.3.2); and (3) further use of multiple scenario elements as opposed to use of climate change scenarios only and greater focus on multiple stressors.

21.5.3.2.1. Application of high-resolution future climate information

There are now many examples of the generation and application of high-resolution climate scenarios for assessing impacts and adaptation planning. These provide information at resolutions relevant for many impacts and adaptation studies but also, particularly with regard to dynamical downscaling, account for higher resolution forcings, such as complex topography (e.g., Salathé et al., 2010) or more detailed land-atmosphere feedbacks such as in West Africa (Taylor et al., 2011). In an analysis of climate impacts including possible adaptations in the Pacific Northwest of North America (Miles et al., 2010) application of two dynamically downscaled scenarios was particularly useful for the assessment of effects of climate change on stormwater infrastructure (Rosenberg et al., 2010). More widely in North America results from NARCCAP have been used to assess impacts of climate change on available wind energy (Pryor and Barthelmie, 2011), road safety (Hambly et al., 2012), hydrology (Burger et al., 2011; Shrestha et al., 2012), forest drought (Williams et al., 2013), and human health (Li et al., 2012).

Several European-led projects have generated and applied high-resolution climate scenarios to investigate the impacts of climate change over Europe for agriculture, river flooding, human health, and tourism (Christensen et al., 2012) and on energy demand, forest fire risk, wind storms damage, crop yields, and water resources (Morse et al., 2009). The UK developed new UK Climate Projections in 2009 (UKCP09) combining the CMIP3, a perturbed physics GCM, and a regional climate model ensemble to develop probabilities of changes in temperature and precipitation at a 25-km resolution (Murphy et al., 2009) to determine probabilities of different impacts of climate change and possible adaptations. In general, with all of this work, a range of different techniques have been used with little assessment or guidance on the relative merits of each.

21.5.3.2.2. Use of multiple scenario elements and focus on multiple stressors

Many more impacts and adaptation studies now use multiple scenario elements, and focus on multiple stressors as opposed to climate change scenarios and effects alone (e.g., Sections 3.3.2, 4.2.4, 7.1.2). Good examples of use of multiple scenario elements involve studies of climate change and human health considering additional factors such as urban heat island (e.g., Knowlton et al., 2008; Rosenzweig et al., 2009), population increase and expanded urban areas (McCarthy et al., 2010), and population and socioeconomic conditions (Watkiss and Hunt, 2012). As these studies are often undertaken at small scales, local scale information on relevant factors may be inconsistent with larger scale scenario elements used in quantifying other stressors. In recognition of this, efforts have been or are being made to downscale the large-scale scenario elements, for example, the SRES scenarios were downscaled for Europe (van Vuuren and O'Neill, 2006), and economic activity information has been downscaled to 0.5° grids in some regions (Gaffin et al., 2004; Grübler et al., 2007; van Vuuren et al., 2010). However, this information is far from comprehensive and has not yet been examined carefully in the impacts and vulnerability literature (van Ruijven et al., 2013).

Typical non-climate stressors include changes in population, migration, land use, economic factors, technological development, social capital, air pollution, and governance structures. They can have independent, synergistic, or antagonistic effects and their importance varies regionally. Land use and socioeconomic changes are stressors of equal importance to climate change for some studies in Latin America (Section 27.2.2.1); numerous changes in addition to climate strongly affect ocean ecosystem health (Section 6.6.1); and in Asia rapid urbanization, industrialization, and economic development are identified as major stressors expected to be compounded by climate change in (Sections 24.4.1-7). Most multiple stressor studies are regional or local in scope. For example, Ziervogel and Taylor (2008) examined two different villages in South Africa and found that a suite of stressors are present such as high unemployment, health status (e.g., increased concern about AIDs), and access to education, with climate change concerns present only in the context of other impacts such as availability of water. In a study on the Great Lakes region, additional stressors included land use change, population increase, and point source pollution (Danz et al., 2007). Mawdesly et al. (2009) considered wildlife management and biodiversity conservation and noted that reducing pressure from other stressors can maximize flexibility for adaptation to climate change. This increased focus on multiple stressors obviously increases the need for a much wider range of data and wider range of projections for the wide range of stressors, across multiple spatial scales.

21.5.3.3. Credibility of Projections and Scenarios

21.5.3.3.1. Credibility of regional climate projections

Obtaining robust regional projections of climate change (i.e., at least a clear indication of the direction of change), requires combining projections with detailed analysis and understanding of the drivers of the changes. The most successful example of this is the application of the attribution of observed global and regional temperature changes using global models incorporating known natural and anthropogenic climate forcing factors (Flato et al., 2014; see also WGI AR5 Section 10.3). The ability of GCMs to reproduce the observed variations in temperature and the quantification of the influence of the different forcings factors and how well these influences are captured in the models provide confidence that models capture correctly the physical processes driving the changes. This can also provide confidence in projections of precipitation when physically linked to changes in temperature (Rowell and Jones, 2006; Kendon et al., 2010). It is important, especially with precipitation where regional change may appear to differ in direction from one model to another, to distinguish when changes are significant (Tebaldi et al., 2011; Collins et al., 2014b; see also WGI AR5 Box 12.1). Significant future projections of opposite direction are found, with neither possibility able to be excluded on the basis of our physical understanding of the drivers of these changes. For example, McSweeney et al. (2012) found that in an ensemble of GCM projections over Southeast Asia, all models simulated the important monsoon processes and rainfall well but projected both positive and negative changes in monsoon precipitation and significantly different patterns of change.

Model trends or projections may also be inconsistent with trends in available observations and in these cases, their projections are less credible. For example, the magnitude of the significant drying trend seen in the Sahel from the 1960s to the 1990s is not captured by models driven by observed sea surface temperatures (SSTs) (e.g., Held et al. 2005) despite statistical analysis demonstrating the role of SSTs in driving Sahel rainfall variability. Thus our understanding of the system and its

Frequently Asked Questions

FAQ 21.4 | Is the highest resolution climate projection the best to use for performing impacts assessments?

A common perception is that higher resolution (i.e., more spatial detail) equates to more useable and robust information. Unfortunately data does not equal information, and more high-resolution data does not necessarily translate to more or better information. Hence, while high-resolution Global Climate Models (GCMs) and many downscaling methods can provide high-resolution data, and add value in, for example, regions of complex topography, it is not a given that there will be more value in the final climate change message. This partially depends on how the higher resolution data were obtained. For example, simple approaches such as spatial interpolation or adding climate changes from GCMs to observed data fields do increase the spatial resolution but add no new information on high-resolution climate change. Nonetheless, these data sets are useful for running impacts models. Many impacts settings are somewhat tuned to a certain resolution, such as the nested size categorizations of hydrologic basins down to watershed size, commonly used in hydrologic modeling. Using dynamical or statistical downscaling methods will add a new high-resolution component, providing extra confidence that sub-GCM scale processes are being represented more accurately. However, there are new errors associated with the additional method applied that need to be considered. More importantly, if downscaling is applied to only one or two GCMs then the resulting high-resolution scenarios will not span the full range of projected changes that a large GCM ensemble would indicate are plausible futures. Spanning that full range is important in being able to properly sample the uncertainty of the climate as it applies in an impacts context. Thus, for many applications, such as understanding the full envelope of possible impacts resulting from our current best estimates of regional climate change, lower resolution data may be more informative. At the end of the day, no one data set is best, and it is through the integration of multiple sources of information that robust understanding of change is developed. What is important in many climate change impacts contexts is appropriately sampling the full range of known uncertainties, regardless of spatial resolution. It is through the integration of multiple sources of information that robust understanding of change is developed.

drivers, and their representation in the models, is incomplete, which complicates the interpretation of future projected changes in this region (e.g., Biasutti et al., 2008; Druyan, 2011). It implies that other processes are important and so research is required to identify these and ensure they are correctly represented in the models, without which projections of rainfall changes over this region cannot be considered reliable.

21.5.3.3.2. Credibility regarding socioeconomic scenario elements

Cash et al. (2003) distinguish three criteria for linking scientific knowledge to policy action: credibility (scientific adequacy of a policy-relevant study), salience (relevance of a study's findings to the needs of decision makers), and legitimacy (the perception that the study is respectful of divergent values and beliefs). Studies examining the performance of scenarios in climate change research across all three of these criteria are rare, but a general conclusion has been that much less attention is paid to salience and legitimacy (Garb et al., 2008; Hulme and Dessai, 2008; Girod et al., 2009). Recognizing this, a new framework for global scenarios has been developed (Box 21-1), providing researchers greater freedom than hitherto for customizing information provided by global scenarios. These innovations may pose challenges for scientific credibility, and it is unclear how difficult it will be to bring independently developed climate and socioeconomic projections together as scenarios in an internally consistent manner, especially when some of these may include fine-scale regional detail (O'Neill and Schweizer, 2011; O'Neill et al., 2013).

Owing to the common practice for scenario development of using narrative descriptions of alternative futures as the inspiration for socioeconomic simulations (the Story and Simulation approach; Alcamo, 2009) it has been suggested that the exclusion of some details in socioeconomic scenario studies can affect the internal consistency and therefore the overall credibility of a study (e.g., Schweizer and Kriegler, 2012; Lloyd and Schweizer, 2013). Storylines can offer a point of entry for multi-scalar scenario analyses (Rounsevell and Metzger, 2010), and such sub-global scenario studies have been on the rise (Kok et al., 2011; Preston et al., 2011; Sietz et al., 2011; van Ruijven et al., 2013).

Table 21-8 | Leading knowledge gaps and related research needs.

Knowledge gap	Research need
There is no clear understanding of how to integrate the diversity of climate change projections data. The full associated uncertainty is weakly characterized and quantifying how much of an observed or simulated climate change is due to internal variability or external forcings is difficult in many situations. Collectively this results in data products with differing time and space resolution and differing dependencies and assumptions that can have conflicting messages. At present, individual products are plausible and mostly defensible insofar as they have a physical basis within the assumptions of the method. However, at decision-relevant scales, understanding where (or whether) the true outcome will lie within the range of the products collectively is often not possible and thus the products are often not strongly actionable.	Research is needed to distinguish the relative stochastic and deterministic sources of variability and change as a function of scale, variable, and application. The need is to develop further and build on physical understanding of the drivers of climate variability and change and to represent these realistically within models to understand the source of the spread and any contradictions in the regional projections at scales relevant to users, and then to provide guidance on a likely range of outcomes within which the true response would be expected to lie. Similarly, there is a need is to articulate the real inherent uncertainty within climate projection data and to understand when climate information is useful at the scales of need. This also requires stronger dialogues with users of climate information to inform choices of variables and ways to characterize envelopes of risk and uncertainties.
The growth of multi-model, multi-method, and multi-generational data for climate projections creates confusion for the Impacts, Adaptation, and Vulnerability (IAV) community. The lack of a clear approach to handling this diversity leads to choosing one or another subset, where one choice may substantially alter the IAV conclusion compared to a different subset.	Methodological and conceptual advances are needed to facilitate the synthesis of diverse data sets on different scales from methods with different assumptions, and to integrate these into cohesive and defensible understanding of projected regional change.
The attributes of regional climate change through which impacts are manifest, such as the intensity, persistence, distribution, recurrence, and frequency of weather events, is poorly understood. The information conveyed to the adaptation community is dominated by aggregates in time and space (e.g., IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) regional averages, or time averages), which hide the important attributes underlying these aggregated changes. In part this is a consequence of the first row above.	The research need is to be able to demonstrate how to unpack the regional projections into terms relevant for impacts and adaptation. For example, how is the shape of the distribution of weather events changing (not just the extremes), or how stable are the critical global teleconnection patterns that contribute to the variability of a region?
The historical record for many regions, especially those regions most vulnerable to climate change, is poor to the extent that the historical record is at best an estimate with unknown uncertainty. This severely undermines the development of regional change analysis, limits the evaluation of model skill, and presents a weak baseline against which to assess change signals or to develop impacts, adaptation, or vulnerability baselines.	The research need is to integrate the multiplicity of historical data as represented by the raw observations into processed gridded products (e.g., climate research unit and Global Precipitation Climatology Project), satellite data, and reanalysis data sets. Involving national scientists with their inherent local knowledge and rescue and digitization of the many national archives still inaccessible to the wider research community would significantly enhance this research activity.
Impact model sensitivity studies and intercomparison exercises are beginning to reveal fundamental flaws and omissions in some impact models in the representation of key processes that are expected to be important under projected climate changes. For example, high temperature constraints and CO_2 and drought effects on agricultural yields are poorly represented in many crop models.	Intensified efforts are needed to refine, test, and intercompare impact models over a wider range of sectors and environments than hitherto. These should be supported, where applicable, by targeted field, chamber, and laboratory experiments under controlled atmospheric composition and climate conditions, to improve understanding of key physical, biological, and chemical processes operating in changed environments. Such experiments are needed across a range of terrestrial and aquatic biogeographical zones in different regions of the world.
New global scenarios are under development, based on climate projections for different Representative Concentration Pathways (RCPs) and socioeconomic scenarios based on shared socioeconomic pathways (SSPs). However, there is currently little or no guidance on how these projections are to be accessed or applied in IAV studies. Moreover, as yet, quantitative SSPs are available only for large regions (basic SSPs), and regional SSPs that are consistent with the global SSPs (extended SSPs) along with scenarios that include mitigation and adaptation policies (shared policy assumptions (SPAs)) have not yet been developed.	Extended SSPs for major subcontinental regions of the world, including variables that define aspects of adaptive capacity and guidance on how to combine RCP-based regional climate projections with regional SSPs and SPAs to form plausible regional scenarios for application in IAV analysis.
The determinants and regional variability of vulnerability, exposure, and adaptive capacity are not well understood, and methods for projecting changes in them are underdeveloped. Furthermore, given these lacks of understanding, uncertainties of these three elements are poorly characterized and quantified.	Case studies and underlying theory of these features of societies, and documentation of the effectiveness of actions taken, are needed in conjunction with methods development for projections. More attention needs to be placed on determining their uncertainties in national and regional assessments.

Environmental scenario exercises crossing geographical scales suggests that linkages between scenarios at different scales can be hard or soft (Zurek and Henrichs, 2007), where downscaling (van Vuuren et al., 2010) would be an example of a hard linkage while other similarities between scenarios would be soft linkages. How to apply flexible interpretations of scientific adequacy and maintain scenario credibility is relatively unexplored, and there is thus a need for studies to document best practices in this respect.

21.6. Knowledge Gaps and Research Needs

Understanding of the regional nature of climate change, its impacts, regional and cross-regional vulnerabilities, and options for adaptation is still at a rudimentary level. There are both fundamental and methodological research issues in the physical sciences concerned with the projection of regional changes in the climate system and the potential impacts of those changes on various resource sectors and natural systems. Of equal importance, there are also fundamental gaps in our understanding of the determinants of vulnerability and adaptive capacity, thus presenting methodological challenges for projecting how societal vulnerability might evolve as the climate system changes. While development of new scenarios is a part of the underlying research agenda, they will inevitably be limited without further progress in our knowledge of the determinants of vulnerability.

Table 21-8 summarizes major research gaps in the physical, ecological, and social sciences that impede the scientific communities' progress in understanding the regional context of climate changes, their consequences, and societies' responses.

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22

Africa

Coordinating Lead Authors:
Isabelle Niang (Senegal), Oliver C. Ruppel (Namibia)

Lead Authors:
Mohamed A. Abdrabo (Egypt), Ama Essel (Ghana), Christopher Lennard (South Africa), Jonathan Padgham (USA), Penny Urquhart (South Africa)

Contributing Authors:
Ibidun Adelekan (Nigeria), Sally Archibald (South Africa), Michael Balinga (Cameroon), Armineh Barkhordarian (Germany), Jane Battersby (South Africa), Eren Bilir (USA), Marshall Burke (USA), Mohammed Chahed (Tunisia), Monalisa Chatterjee (USA/India), Chineke Theo Chidiezie (Nigeria), Katrien Descheemaeker (Netherlands), Houria Djoudi (Algeria), Kristie L. Ebi (USA), Papa Demba Fall (Senegal), Ricardo Fuentes (Mexico), Rebecca Garland (South Africa), Fatou Gaye (The Gambia), Karim Hilmi (Morocco), Emiloa Gbobaniyi (Nigeria), Patrick Gonzalez (USA), Blane Harvey (UK), Mary Hayden (USA), Andreas Hemp (Germany), Guy Jobbins (UK), Jennifer Johnson (USA), David Lobell (USA), Bruno Locatelli (France), Eva Ludi (UK), Lars Otto Naess (UK), Mzime R. Ndebele-Murisa (Zimbabwe), Aminata Ndiaye (Senegal), Andrew Newsham (UK), Sirra Njai (The Gambia), Johnson Nkem (Cameroon), Jane Mukarugwiza Olwoch (South Africa), Pieter Pauw (Netherlands), Emilia Pramova (Bulgaria), Marie-Louise Rakotondrafara (Madagascar), Clionadh Raleigh (Ireland), Debra Roberts (South Africa), Carla Roncoli (USA), Aissa Toure Sarr (Senegal), Michael Henry Schleyer (South Africa), Lena Schulte-Uebbing (Germany), Roland Schulze (South Africa), Hussen Seid (Ethiopia), Sheona Shackleton (South Africa), Mxolisi Shongwe (South Africa), Dáithí Stone (Canada/South Africa/USA), David Thomas (UK), Okoro Ugochukwu (Nigeria), Dike Victor (Nigeria), Katharine Vincent (South Africa), Koko Warner (Germany), Sidat Yaffa (The Gambia)

Review Editors:
Pauline Dube (Botswana), Neil Leary (USA)

Volunteer Chapter Scientist:
Lena Schulte-Uebbing (Germany)

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Executive Summary

Evidence of warming over land regions across Africa, consistent with anthropogenic climate change, has increased (*high confidence*). Decadal analyses of temperatures strongly point to an increased warming trend across the continent over the last 50 to 100 years. {22.2.1.1}

Mean annual temperature rise over Africa, relative to the late 20th century mean annual temperature, is *likely* to exceed 2°C in the *Special Report on Emissions Scenarios* (SRES) A1B and A2 scenarios by the end of this century (*medium confidence*). Warming projections under medium scenarios indicate that extensive areas of Africa will exceed 2°C by the last 2 decades of this century relative to the late 20th century mean annual temperature and all of Africa under high emission scenarios. Under a high Representative Concentration Pathway (RCP), that exceedance could occur by mid-century across much of Africa and reach between 3°C and 6°C by the end of the century. It is *likely* that land temperatures over Africa will rise faster than the global land average, particularly in the more arid regions, and that the rate of increase in minimum temperatures will exceed that of maximum temperatures. {22.2.1.2}

A reduction in precipitation is *likely* over Northern Africa and the southwestern parts of South Africa by the end of the 21st century under the SRES A1B and A2 scenarios (*medium* to *high confidence*). Projected rainfall change over sub-Saharan Africa in the mid- and late 21st century is uncertain. In regions of high or complex topography such as the Ethiopian Highlands, downscaled projections indicate *likely* increases in rainfall and extreme rainfall by the end of the 21st century. {22.2.2.2, 22.2.3}

African ecosystems are already being affected by climate change, and future impacts are expected to be substantial (*high confidence*). There is emerging evidence on shifting ranges of some species and ecosystems due to elevated carbon dioxide (CO_2) and climate change, beyond the effects of land use change and other non-climate stressors (*high confidence*). Ocean ecosystems, in particular coral reefs, will be affected by ocean acidification and warming as well as changes in ocean upwellings, thus negatively affecting economic sectors such as fisheries (*medium confidence*). {22.3.2, Table 22-3}

Climate change will amplify existing stress on water availability in Africa (*high confidence*). Water resources are subjected to high hydro-climatic variability over space and time, and are a key constraint on the continent's continued economic development. The impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical sociopolitical and economic footprint. Strategies that integrate land and water management, and disaster risk reduction, within a framework of emerging climate change risks would bolster resilient development in the face of projected impacts of climate change. {22.3.2.2, 22.3.3}

Climate change will interact with non-climate drivers and stressors to exacerbate vulnerability of agricultural systems, particularly in semi-arid areas (*high confidence*). Increasing temperatures and changes in precipitation are *very likely* to reduce cereal crop productivity. This will have strong adverse effects on food security. New evidence is also emerging that high-value perennial crops could also be adversely affected by temperature rise (*medium confidence*). Pest, weed, and disease pressure on crops and livestock is expected to increase as a result of climate change combined with other factors (*low confidence*). Moreover, new challenges to food security are emerging as a result of strong urbanization trends on the continent and increasingly globalized food chains, which require better understanding of the multi-stressor context of food and livelihood security in both urban and rural contexts in Africa. {22.3.4.3, 22.3.4.5}

Progress has been achieved on managing risks to food production from current climate variability and near-term climate change but these will not be sufficient to address long-term impacts of climate change (*high confidence*). Livelihood-based approaches for managing risks to food production from multiple stressors, including rainfall variability, have increased substantially in Africa since the IPCC's Fourth Assessment Report (AR4). While these efforts can improve the resiliency of agricultural systems in Africa over the near term, current adaptations will be insufficient for managing risks from long-term climate change, which will be variable across regions and farming system types. Nonetheless, processes such as collaborative, participatory research that includes scientists and farmers, strengthening of communication systems for anticipating and responding to climate risks, and increased flexibility in livelihood options, which serve to strengthen coping strategies in agriculture for near-term risks from climate variability, provide potential pathways for strengthening adaptive capacities for climate change. {22.4.5.4, 22.4.5.7, 22.4.6, 22.6.2}

Climate change may increase the burden of a range of climate-relevant health outcomes (*medium confidence*). Climate change is a multiplier of existing health vulnerabilities (*high confidence*), including insufficient access to safe water and improved sanitation, food insecurity, and limited access to health care and education. {22.3.5.1} Detection and attribution of trends is difficult because of the complexity of disease transmission, with many drivers other than weather and climate, and short and often incomplete data sets. Evidence is growing that highland areas, especially in East Africa, could experience increased malaria epidemics due to climate change (*medium evidence*, *very high agreement*). The strong seasonality of meningococcal meningitis and associations with weather and climate variability suggest the disease burden could be negatively affected by climate change (*medium evidence*, *high agreement*). The frequency of leishmaniasis epidemics in sub-Saharan Africa is changing, with spatial spread to peri-urban areas and to adjacent geographic regions, with possible contributions from changing rainfall patterns (*low confidence*). Climate change is projected to increase the burden of malnutrition (*medium confidence*), with the highest toll expected in children. {22.3.5.3}

In all regions of the continent, national governments are initiating governance systems for adaptation and responding to climate change, but evolving institutional frameworks cannot yet effectively coordinate the range of adaptation initiatives being implemented (*high confidence*). Progress on national and subnational policies and strategies has initiated the mainstreaming of adaptation into sectoral planning. {22.4.4} However, incomplete, under-resourced, and fragmented institutional frameworks and overall low levels of adaptive capacity, especially competency at local government levels, to manage complex socio-ecological change translate into a largely ad hoc and project-level approach, which is often donor driven. {22.4.2, 22.4.4.3-4} Overall adaptive capacity is considered to be low. {22.4.2} Disaster risk reduction, social protection, technological and infrastructural adaptation, ecosystem-based approaches, and livelihood diversification are reducing vulnerability, but largely in isolated initiatives. {22.4.5} Most adaptations remain autonomous and reactive to short-term motivations. {22.4.3, 22.4.4.5}

Conservation agriculture provides a viable means for strengthening resilience in agroecosystems and livelihoods that also advance adaptation goals (*high confidence*). A wide array of conservation agriculture practices, including agroforestry and farmer-managed natural tree regeneration, conservation tillage, contouring and terracing, and mulching, are being increasingly adopted in Africa. These practices strengthen resilience of the land base to extreme events and broaden sources of livelihoods, both of which have strongly positive implications for climate risk management and adaptation. Moreover, conservation agriculture has direct adaptation-mitigation co-benefits. Addressing constraints to broader adoption of these practices, such as land tenure/usufruct stability, access to peer-to-peer learning, gender-oriented extension and credit and markets, as well as identification of perverse policy incentives, would help to enable larger scale transformation of agricultural landscapes. {22.4.5.6, 22.4.5.7, 22.4.6, 22.6.2}

Despite implementation limitations, Africa's adaptation experiences nonetheless highlight valuable lessons for enhancing and scaling up the adaptation response, including principles for good practice and integrated approaches to adaptation (*high confidence*). Five common principles for adaptation and building adaptive capacity can be distilled: (1) supporting autonomous adaptation through a policy that recognizes the multiple-stressor nature of vulnerable livelihoods; (2) increasing attention to the cultural, ethical, and rights considerations of adaptation by increasing the participation of women, youth, and poor and vulnerable people in adaptation policy and implementation; (3) combining "soft path" options and flexible and iterative learning approaches with technological and infrastructural approaches and blending scientific, local, and indigenous knowledge when developing adaptation strategies; (4) focusing on building resilience and implementing low-regrets adaptation with development synergies, in the face of future climate and socioeconomic uncertainties; and (5) building adaptive management and social and institutional learning into adaptation processes at all levels. {22.4} Ecosystem-based approaches and pro-poor integrated adaptation-mitigation initiatives hold promise for a more sustainable and system-oriented approach to adaptation, as does promoting equity goals, key for future resilience, through emphasizing gender aspects and highly vulnerable groups such as children. {22.4.2, 22.4.5.6, 22.6.2, Table 22-5}

Strengthened interlinkages between adaptation and development pathways and a focus on building resilience would help to counter the current adaptation deficit and reduce future maladaptation risks (*high confidence*). {22.4.3} Development strategies are currently not able to counter current climate risks, as highlighted by the impacts of recent extreme events; national policies that disregard cultural, traditional, and context-specific factors can act as barriers to local adaptation; and there is increased knowledge of maladaptation risks from narrowly conceived development interventions and sectoral adaptation strategies that decrease resilience in other sectors or ecosystems.

{22.4.4, 22.4.6} Given multiple uncertainties in the African context, successful adaptation will depend on building resilience. {22.4-6} Options for pro-poor adaptation/resilient livelihoods include improved social protection, social services, and safety nets; better water and land governance and tenure security over land and vital assets; enhanced water storage, water harvesting, and post-harvest services; strengthened civil society and greater involvement in planning; and more attention to urban and peri-urban areas heavily affected by migration of poor people. {22.4.2, 22.4.4-6}

Growing understanding of the multiple interlinked constraints on increasing adaptive capacity is beginning to indicate potential limits to adaptation in Africa (*medium confidence*). Climate change combined with other external changes (environmental, social, political, technological) may overwhelm the ability of people to cope and adapt, especially if the root causes of poverty and vulnerability are not addressed. Evidence is growing for the effectiveness of flexible and diverse development systems that are designed to reduce vulnerability, spread risk, and build adaptive capacity. These points indicate the benefits of new development trajectories that place climate resilience, ecosystem stability, equity, and justice at the center of development efforts. {22.4.6}

There is increased evidence of the significant financial resources, technological support, and investment in institutional and capacity development needed to address climate risk, build adaptive capacity, and implement robust adaptation strategies (*high confidence*). Funding and technology transfer and support is needed to both address Africa's current adaptation deficit and to protect rural and urban livelihoods, societies, and economies from climate change impacts at different local scales. {22.4, 22.6.4} Strengthening institutional capacities and governance mechanisms to enhance the ability of national governments and scientific institutions in Africa to absorb and effectively manage large amounts of funds allocated for adaptation will help to ensure the effectiveness of adaptation initiatives (*medium confidence*). {22.6.4}

Climate change and climate variability have the potential to exacerbate or multiply existing threats to human security including food, health, and economic insecurity, all being of particular concern for Africa (*medium confidence*). {22.6.1} Many of these threats are known drivers of conflict (*high confidence*). Causality between climate change and violent conflict is difficult to establish owing to the presence of these and other interconnected causes, including country-specific sociopolitical, economic, and cultural factors. For example, the degradation of natural resources as a result of both overexploitation and climate change will contribute to increased conflicts over the distribution of these resources. {22.6.1.1} Many of the interacting social, demographic, and economic drivers of observed urbanization and migration in Africa are sensitive to climate change impacts. {22.6.1.2}

A wide range of data and research gaps constrain decision making in processes to reduce vulnerability, build resilience, and plan and implement adaptation strategies at different levels in Africa (*high confidence*). Overarching data and research gaps identified include data management and monitoring of climate parameters and development of climate change scenarios; monitoring systems to address climate change impacts in the different sectors; research and improved methodologies to assess and quantify the impact of climate change on different sectors and systems; and socioeconomic consequences of the loss of ecosystems, of economic activities, of certain mitigation choices such as biofuels, and of adaptation strategies. {22.7}

Of nine climate-related key regional risks identified for Africa, eight pose medium or higher risk even with highly adapted systems, while only one key risk assessed can be potentially reduced with high adaptation to below a medium risk level, for the end of the 21st century under 2°C global mean temperature increase above preindustrial levels (*medium confidence*). Key regional risks relating to shifts in biome distribution, loss of coral reefs, reduced crop productivity, adverse effects on livestock, vector- and water-borne diseases, undernutrition, and migration are assessed as either medium or high for the present under current adaptation, reflecting Africa's existing adaptation deficit. {22.3.1-2, 22.3.4-5, 22.6.1.2} The assessment of significant residual impacts in a 2°C world at the end of the 21st century suggests that, even under high levels of adaptation, there could be very high levels of risk for Africa. At a global mean temperature increase of 4°C, risks for Africa's food security (see key risks on livestock and crop production) are assessed as very high, with limited potential for risk reduction through adaptation. {22.3.4, 22.4.5, 22.5, Table 22-6}

22.1. Introduction

Africa as a whole is one of the most vulnerable continents due to its high exposure and low adaptive capacity. Given that climatic and ecological regions transcend national political boundaries, we have used the divisions of Africa's Regional Economic Communities (RECs) to structure the assessment within this chapter.

22.1.1. Structure of the Regions

The African continent (including Madagascar) is the world's second largest and most populous continent (1,031,084,000 in 2010) behind Asia (UN DESA Population Division, 2013). The continent is organized at the regional level under the African Union (AU).[1] The AU's Assembly of Heads of State and Government has officially recognized eight RECs (Ruppel, 2009). Except for the Sahrawi Arab Democratic Republic,[2] all AU member states are affiliated with one or more of these RECs. These RECs include the Arab Maghreb Union (AMU), with 5 countries in Northern Africa; the Community of Sahel-Saharan States (CEN-SAD), grouping 27 countries; the Common Market for Eastern and Southern Africa (COMESA), grouping 19 countries in Eastern and Southern Africa; the East African Community (EAC), with 5 countries; the Economic Community of Central African States (ECCAS), with 10 countries; the Economic Community of West African States (ECOWAS), with 15 countries; the Intergovernmental Authority on Development (IGAD) with 8 countries; and the Southern African Development Community (SADC), with 15 countries. The regional subdivision of African countries into RECs is a structure used by the AU and the New Partnership for Africa (NEPAD).

22.1.2. Major Conclusions from Previous Assessments

22.1.2.1. Regional Special Report and Assessment Reports

Major concluions related to Africa from previous assessments are summarized in Table 22-1.

22.1.2.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; IPCC, 2012) is of particular relevance to the African continent. There is *low* to *medium confidence* in historical extreme temperature and heavy rainfall trends over most of Africa because of partial lack of data, literature, and consistency of reported patterns in the literature (Seneviratne et al., 2012). However, most regions within Africa for which data are available have recorded an increase in extreme temperatures (Seneviratne et al., 2012). For projected temperature extreme there is *high confidence* that heat waves and warm spell durations will increase, suggesting an increased persistence of hot days (90th percentile) toward the end of the century

Table 22-1 | Major conclusions from previous IPCC assessments.

Report	Major conclusions	Reference
Special Report on the Regional Impacts of Climate Change	• Sensitivity of water resources and coastal zones to climatic parameters • Identification of climate change as an additional burden on an already stressful situation • Major challenges for Africa: lack of data on energy sources; uncertainties linked to climate change scenarios (mainly for precipitation); need for integrated studies; and the necessary links between science and decision makers	Zinyowera et al. (1997)
Third Assessment Report	• Impacts of climate change on and vulnerability of six sectors: water resources; food security; natural resources and biodiversity management; health; human settlements and infrastructure; desertification • Adaptation strategies for each of the sectors • Threats of desertification and droughts to the economy of the continent • Suggestion of adaptation options: mainly linked with better resource management • Identification of research gaps and needs: capacity building; data needs; development of integrated analysis; consideration of literature in other languages	Desanker et al. (2001)

Fourth Assessment Report	• Vulnerability of Africa due mainly to its low adaptive capacity
	• Sources of vulnerability mainly socioeconomic causes (demographic growth, governance, conflicts, etc.)
	• Impacts of climate change on various sectors: energy, tourism, and coastal zones considered separately
	• Potential impacts of extreme weather events (droughts and floods)
	• Adaptation costs
	• Need for mainstreaming climate change adaptation into national development policies
	• Two case studies:
	  • Food security: Climate change could affect the three main components of food security.
	  • Traditional knowledge: African communities have prior experience with climate variability, although this knowledge will not be sufficient to face climate change impacts.
	• Research needs: better knowledge of climate variability; more studies on the impacts of climate change on water resources, energy, biodiversity, tourism, and health; the links between different sectors (e.g., between agriculture, land availability, and biofuels); developing links with the disaster reduction community; increasing interdisciplinary analysis of climate change; and strengthening institutional capacities
		Boko et al. (2007)

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[1] Owing to controversies regarding the Sahrawi Arab Democratic Republic, Morocco withdrew from the Organization of African Unity (OAU) in protest in 1984 and, since South Africa's admittance in 1994, remains the only African nation not within what is now the AU.

[2] Although the Sahrawi Arab Democratic Republic has been a full member of the OAU since 1984 and remains a member of the AU, the Republic is not generally recognized as a sovereign state and has no representation in the United Nations.

(Tebaldi et al., 2006; Orlowsky and Seneviratne, 2012). There is *high confidence* for projected shorter extreme maximum temperature return periods across the SRES B1, A1B, and A2 scenarios for the near and far future as well as a reduction of the number of cold extremes (Seneviratne et al., 2012). In East and southern Africa, there is *medium confidence* that droughts will intensify in the 21st century in some seasons, due to reduced precipitation and/or increased evapotranspiration. There is *low confidence* in projected increases of heavy precipitation over most of Africa except over East Africa, where there is a *high confidence* in a projected increase in heavy precipitation (Seneviratne et al., 2012).

22.2. Observed Climate Trends and Future Projections

22.2.1. Temperature

22.2.1.1. Observed Trends

Near surface temperatures have increased by 0.5°C or more during the last 50 to 100 years over most parts of Africa, with minimum temperatures warming more rapidly than maximum temperatures (Hulme et al., 2001; Jones and Moberg, 2003; Kruger and Shongwe, 2004; Schreck and Semazzi, 2004; New et al., 2006; IPCC, 2007; Rosenzweig et al., 2007; Trenberth et al., 2007; Christy et al., 2009; Collins 2011; Grab and Craparo, 2011; Hoffman et al., 2011; Mohamed, 2011; Stern et al., 2011; Funk et al., 2012; Nicholson et al., 2013). Near surface air temperature anomalies in Africa were significantly higher for the period 1995–2010 compared to the period 1979–1994 (Collins, 2011). Figure 22-1 shows that it is *very likely* that mean annual temperature has increased over the past century over most of the African continent, with the exception of areas of the interior of the continent, where the data coverage has been determined to be insufficient to draw conclusions about temperature trends (Figure 22-1; Box CC-RC). There is strong evidence of an anthropogenic signal in continent-wide temperature increases in the 20th century (WGI AR5 Section 10.3.1; Stott, 2003; Min and Hense, 2007; Stott et al., 2010, 2011).

In recent decades, North African annual and seasonal observed trends in mean near surface temperature indicate an overall warming that is significantly beyond the range of changes due to natural (internal) variability (Barkhordarian et al., 2012a). During the warm seasons (March-April-May, June-July-August) an increase in near surface temperature is shown over northern Algeria and Morocco that is *very unlikely* due to natural variability or natural forcing alone (Barkhordarian et al., 2012b). The region has also experienced positive trends in annual minimum and maximum temperature (Vizy and Cook, 2012).

Over West Africa and the Sahel near surface temperatures have increased over the last 50 years. Using indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI), New et al. (2006) show the number of cold days and cold nights have decreased and the number of warm days and warm nights have increased between 1961 and 2000. Many of these trends are statistically significant at the 90% level, and they find similar trends in extreme temperature indices. Collins (2011) shows statistically significant warming of between 0.5°C and 0.8°C between 1970 and 2010 over the region using remotely sensed data with a greater magnitude of change in the latter 20 years of the period compared to the former.

The equatorial and southern parts of eastern Africa have experienced a significant increase in temperature since the beginning of the early 1980s (Anyah and Qiu, 2012). Similarly, recent reports from the Famine Early Warning Systems Network (FEWS NET) indicate that there has been an increase in seasonal mean temperature in many areas of Ethiopia, Kenya, South Sudan, and Uganda over the last 50 years (Funk et al., 2011, 2012). In addition, warming of the near surface temperature and an increase in the frequency of extreme warm events has been observed for countries bordering the western Indian Ocean between 1961 and 2008 (Vincent et al., 2011b).

In recent decades, most of southern Africa has also experienced upward trends in annual mean, maximum, and minimum temperature over large extents of the sub-region during the last half of the 20th century, with the most significant warming occurring during the last 2 decades (Zhou et al., 2010; Collins, 2011; Kruger and Sekele, 2012). Minimum temperatures have increased more rapidly relative to maximum temperatures over inland southern Africa (New et al., 2006).

22.2.1.2. Projected Trends

Temperatures in Africa are projected to rise faster than the global average increase during the 21st century (Christensen et al., 2007; Joshi et al., 2011; Sanderson et al., 2011; James and Washington, 2013). Global average near surface air temperature is projected to move beyond 20th century simulated variability by 2069 (±18 years) under Representative Concentration Pathway 4.5 (RCP4.5) and by 2047 (±14 years) under RCP8.5 (Mora et al., 2013). However, in the tropics, especially tropical West Africa, these unprecedented climates are projected to occur 1 to 2 decades earlier than the global average because the relatively small natural climate variability in this region generates narrow climate bounds that can be easily surpassed by relatively small climate changes. Figure 22-1 shows projected temperature increases based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble. Increases in mean annual temperature over all land areas are *very likely* in the mid- and late 21st-century periods for RCP2.6 and RCP8.5 (Figure 22-1; Box CC-RC). Ensemble mean changes in mean annual temperature exceed 2°C above the late 20th-century baseline over most land areas of the continent in the mid-21st century for RCP8.5, and exceed 4°C over most land areas in the late 21st century for RCP8.5. Changes in mean annual temperature for RCP8.5 follow a pattern of larger changes in magnitude over northern and southern Africa, with (relatively) smaller changes in magnitude over central Africa. The ensemble mean changes are less than 2°C above the late 20th century baseline in both the mid- and late 21st century for RCP2.6.

Over North Africa under the SRES A1B scenario, both annual minimum and maximum temperature are *likely* to increase in the future, with greater increase in minimum temperature (Vizy and Cook, 2012). The faster increase in minimum temperature is consistent with greater warming at night, resulting in a decrease in the future extreme temperature range (Vizy and Cook, 2012). Higher temperature increases are projected during boreal summer by CMIP5 General Circulation Models (GCMs)

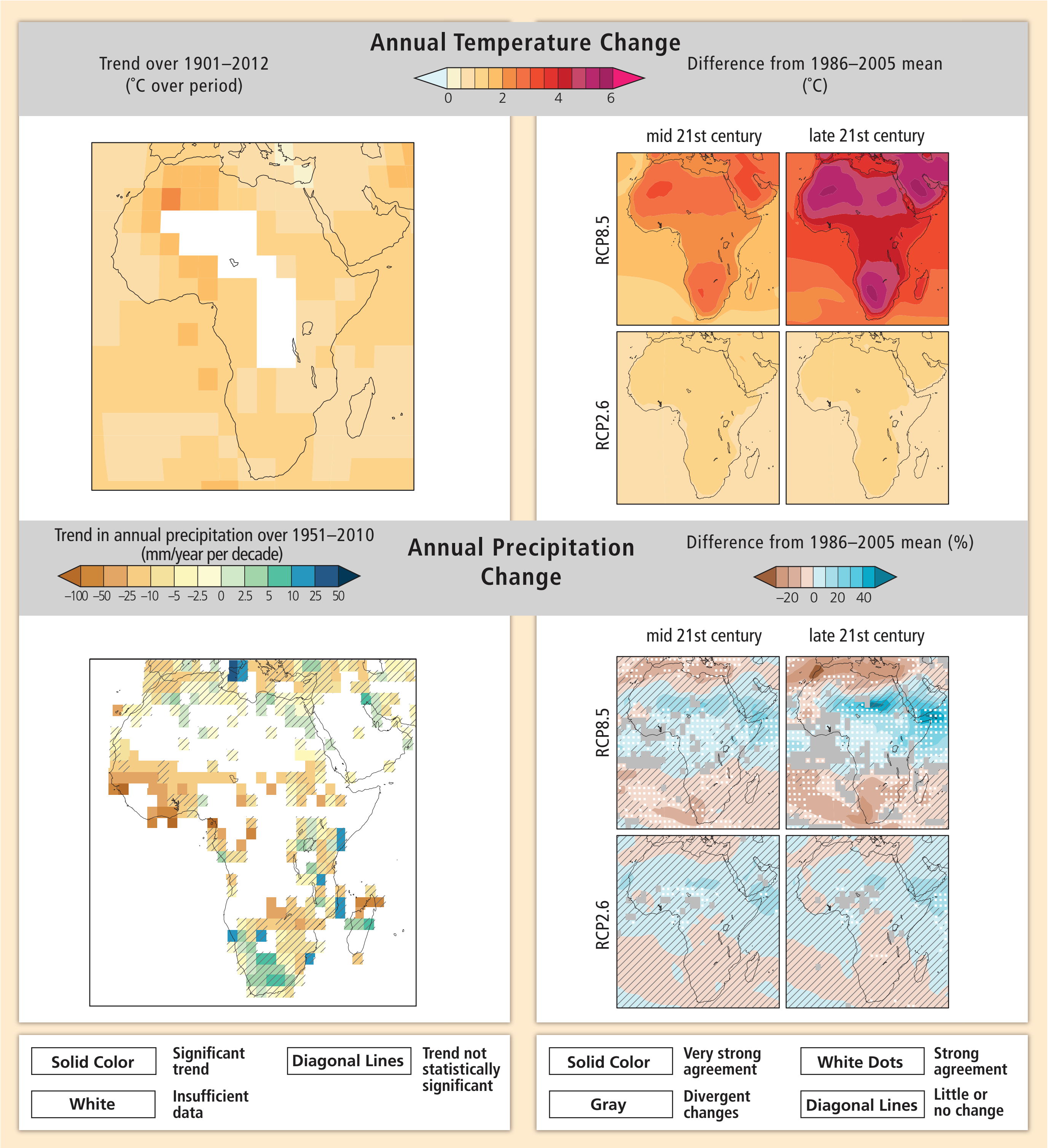

Figure 22-1 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5 Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

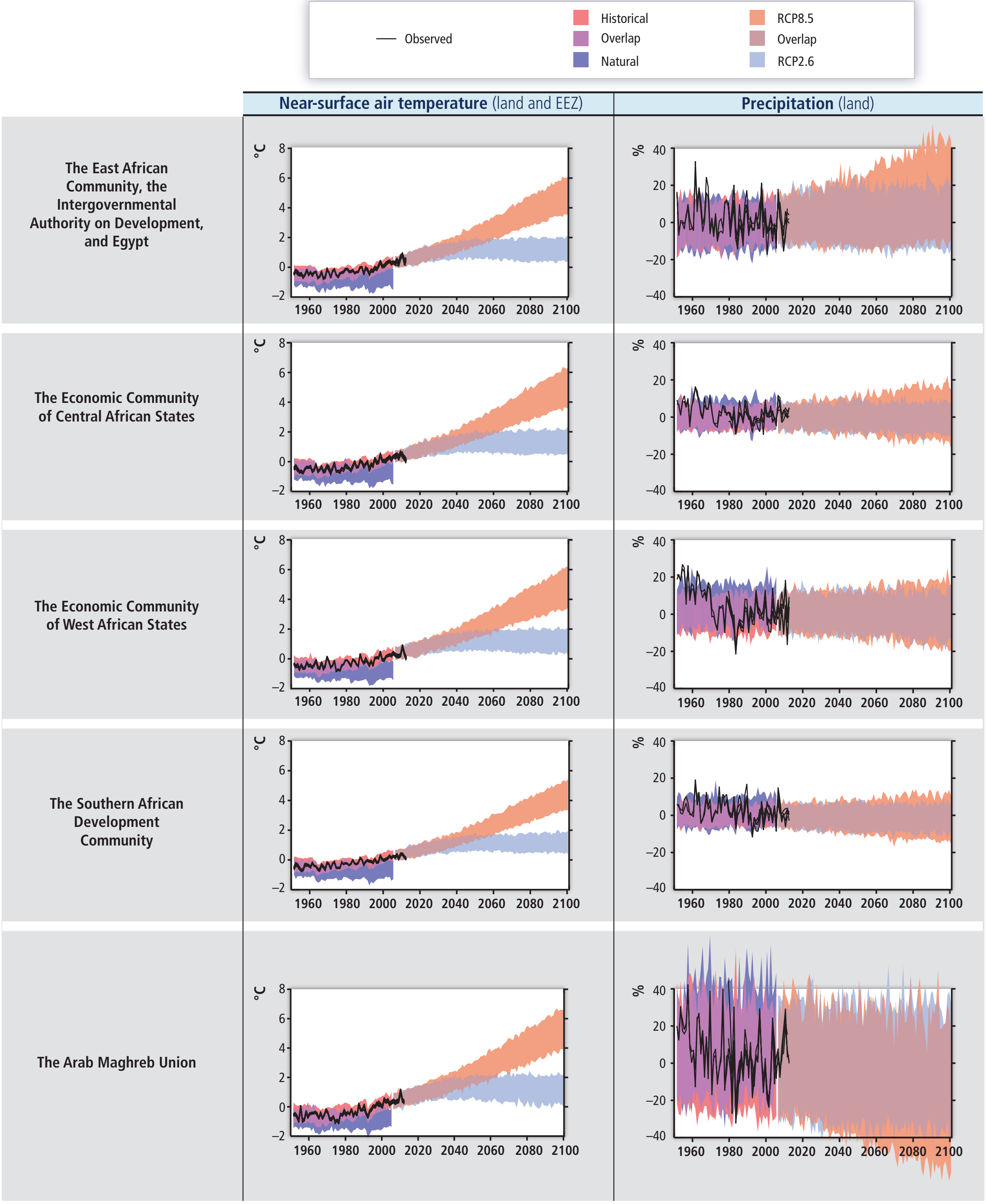

Figure 22-2 | Observed and simulated variations in past and projected future annual average temperature over East African Community–Intergovernmental Authority on Development–Egypt (EAC–IGAD–Egypt), Economic Community of Central African States (ECCAS), Economic Community of West African States (ECOWAS), Southern African Development Community (SADC), and the Arab Maghreb Union (AMU). Black lines show various estimates from observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the RCP2.6 emissions scenario (63), and RCP8.5 (63). Data are anomalies from the 1986–2005 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.

(WGI AR5 Annex 1). A strengthening of the North African thermal low in the 21st century is associated with a surface temperature increase (Paeth et al., 2009; Patricola and Cook, 2010; Barkhordarian et al., 2012a; Cook and Vizy, 2012).

Temperature projections over West Africa for the end of the 21st century from both the CMIP3 GCMs (SRES A2 and A1B scenarios) and CMIP5 GCMs (RCP4.5 and RCP8.5) range between 3°C and 6°C above the late 20th century baseline (Meehl et al., 2007; Fontaine et al., 2011; Diallo et al., 2012; Monerie et al., 2012; Figures 22-1, 22-2). Regional downscalings produce a similar range of projected change (Patricola and Cook, 2010, 2011; Mariotti et al., 2011; Vizy et al., 2013). Diffenbaugh and Giorgi (2012) identify the Sahel and tropical West Africa as hotspots of climate change for both RCP4.5 and RCP8.5 pathways, and unprecedented climates are projected to occur earliest (late 2030s to early 2040s) in these regions (Mora et al., 2013).

Climate model projections under the SRES A2 and B1 scenarios over Ethiopia show warming in all four seasons across the country, which may cause a higher frequency of heat waves as well as higher rates of evaporation (Conway and Schipper, 2011). Projected maximum and minimum temperatures over equatorial eastern Africa show a significant increase in the number of days warmer than 2°C above the 1981–2000 average by the middle and end of the 21st century under the A1B and A2 scenarios (Anyah and Qiu, 2012). Elshamy et al. (2009) show a temperature increase over the upper Blue Nile of between 2°C and 5°C at the end of the 21st century under the A1B scenario compared to a 1961–1990 baseline.

Mean land surface warming in Southern Africa is likely to exceed the global mean land surface temperature increase in all seasons (Sillmann and Roeckner, 2008; Watterson, 2009; Mariotti et al., 2011; Orlowsky and Seneviratne, 2012; James and Washington, 2013). Furthermore, towards the end of the 21st century the projected warming of between 3.4ºC and 4.2ºC above the 1981–2000 average under the A2 scenario far exceeds natural climate variability (Moise and Hudson, 2008). High warming rates are projected over the semi-arid southwestern parts of the sub-region covering northwestern South Africa, Botswana, and Namibia (WGI AR5 Annex 1; Moise and Hudson, 2008; Engelbrecht et al., 2009; Shongwe et al., 2009; Watterson, 2009). Observed and simulated variations in past and projected future annual average temperature over five African regions (EAC-IGAD-Egypt, ECCAS, ECOWAS, SADC, and AMU) are captured in Figure 22-2, which indicates the projected temperature rise is *very likely* to exceed the 1986–2005 baseline by between 3°C and 6°C across these regions by the end of the 21st century under RCP8.5.

22.2.2. Precipitation

22.2.2.1. Observed Changes

Most areas of the African continent lack sufficient observational data to draw conclusions about trends in annual precipitation over the past century (Figure 22-1; Box CC-RC). In addition, in many regions of the continent discrepancies exist between different observed precipitation data sets (Nikulin et al., 2012; Sylla et al., 2012; Kalognomou et al., 2013; Kim et al., 2013). Areas where there are sufficient data include *very likely* decreases in annual precipitation over the past century over parts of the western and eastern Sahel region in northern Africa, along with *very likely* increases over parts of eastern and southern Africa.

Over the last few decades the northern regions of North Africa (north of the Atlas Mountains and along the Mediterranean coast of Algeria and Tunisia) have experienced a strong decrease in the amount of precipitation received in winter and early spring (Barkhordarian et al., 2013). The observed record also indicates greater than 330 dry days (with less than 1 mm day^{-1} rainfall) per year over the 1997–2008 time period (Vizy and Cook, 2012). However, in autumn (September-October-November) observations show a positive trend in precipitation in some parts of northern Algeria and Morocco (Barkhordarian et al., 2013). The Sahara Desert, which receives less than 25 mm yr^{-1}, shows little seasonal change (Liebmann et al., 2012).

Rainfall over the Sahel has experienced an overall reduction over the course of the 20th century, with a recovery toward the last 20 years of the century (WGI AR5 Section 14.3.7.1; Nicholson et al., 2000; Lebel and Ali, 2009; Ackerley et al., 2011; Mohamed, 2011; Biasutti, 2013). The occurrence of a large number of droughts in the Sahel during the 1970s and 1980s is well documented and understood (Biasutti and Giannini, 2006; Biasutti et al., 2008; Greene et al., 2009). The recovery of the rains may be due to natural variability (Mohino et al., 2011) or a forced response to increased greenhouse gases (Haarsma et al., 2005; Biasutti, 2013) or reduced aerosols (Ackerley et al., 2011).

Precipitation in eastern Africa shows a high degree of temporal and spatial variability dominated by a variety of physical processes (Rosell and Holmer, 2007; Hession and Moore, 2011). Williams and Funk (2011) and Funk et al. (2008) indicate that over the last 3 decades rainfall has decreased over eastern Africa between March and May/June. The suggested physical link to the decrease in rainfall is rapid warming of the Indian Ocean, which causes an increase in convection and precipitation over the tropical Indian Ocean and thus contributes to increased subsidence over eastern Africa and a decrease in rainfall during March to May/June (Funk et al., 2008; Williams and Funk, 2011). Similarly, Lyon and DeWitt (2012) show a decline in the March-May seasonal rainfall over eastern Africa. Summer (June-September) monsoonal precipitation has declined throughout much of the Great Horn of Africa over the last 60 years (during the 1948–2009 period; Williams et al., 2012) as a result of the changing sea level pressure (SLP) gradient between Sudan and the southern coast of the Mediterranean Sea and the southern tropical Indian Ocean region (Williams et al., 2012).

Over southern Africa a reduction in late austral summer precipitation has been reported over its western parts, extending from Namibia, through Angola, and toward the Congo during the second half of the 20th century (Hoerling et al., 2006; New et al., 2006). The drying is associated with an upward trend in tropical Indian Ocean sea surface temperatures (SSTs). Modest downward trends in rainfall are found in Botswana, Zimbabwe, and western South Africa. Apart from changes in total or mean summer rainfall, certain intra-seasonal characteristics of seasonal rainfall such as onset, duration, dry spell frequencies, and rainfall intensity as well as delay of rainfall onset have changed (Tadross et al., 2005, 2009; Thomas et al., 2007; Kniveton et al., 2009). An increasing frequency of dry spells is accompanied by an increasing trend in daily rainfall intensity, which has implications for run-off characteristics (New et al., 2006).

22.2.2.2. Projected Changes

Precipitation projections are more uncertain than temperature projections (Rowell, 2012) and exhibit higher spatial and seasonal dependence than temperature projections (Orlowsky and Seneviratne, 2012). The CMIP5 ensemble projects *very likely* decreases in mean annual precipitation over the Mediterranean region of northern Africa in the mid- and late 21st century periods for RCP8.5 (Figure 22-1; Box CC-RC). CMIP5 also projects *very likely* decreases in mean annual precipitation over areas of southern Africa beginning in the mid-21st century for RCP8.5 and expanding substantially in the late 21st century for RCP8.5. In contrast, CMIP5 projects *likely* increases in mean annual precipitation over areas of central and eastern Africa beginning the mid-21st century for RCP8.5. Most areas of the African continent do not exhibit changes in mean annual precipitation that exceed the baseline variability in more than 66% of the models in either the mid- or late 21st-century periods for RCP2.6. Observed and simulated variations in past and projected future annual average precipitation over five African regions (EAC-IGAD-Egypt, ECCAS, ECOWAS, SADC, and AMU) are captured in Figure 22-2.

A reduction in rainfall over northern Africa is *very likely* by the end of the 21st century. The annual and seasonal drying/warming signal over the northern African region (including North of Morocco, Algeria, Libya, Egypt, and Tunisia) is a consistent feature in the global (Giorgi and Lionello, 2008; Barkhordarian et al., 2013) and the regional (Lionello and Giorgi, 2007; Gao and Giorgi, 2008; Paeth et al., 2009; Patricola and Cook, 2010) climate change projections for the 21st century under the A1B and A2 scenarios. Furthermore, over the northern basin of Tunisia, climate models under the A1B scenario project a significant decrease in the median and 10th and 90th percentile values of precipitation in winter and spring seasons (Bargaoui et al., 2013).

West African precipitation projections in the CMIP3 and CMIP5 archives show inter-model variation in both the amplitude and direction of change that is partially attributed to the inability of GCMs to resolve convective rainfall (WGI AR5 Section 14.8.7; Biasutti et al., 2008; Druyan, 2011; Fontaine et al., 2011; Roehrig et al., 2013). Many CMIP5 models indicate a wetter core rainfall season with a small delay to rainy season by the end of the 21st century (WGI AR5 Section 14.8.7; Biasutti, 2013). However, Regional Climate Models (RCMs) can alter the sign of rainfall change of the driving GCM, especially in regions of high or complex topography (WGI AR5 Sections 9.6.4, 14.3.7.1; Sylla et al., 2012; Cook and Vizy, 2013; Saeed et al., 2013). There is therefore *low* to *medium confidence* in the robustness of projected regional precipitation change until a larger body of regional results become available through, for example, the Coordinated Regional Downscaling Experiment (CORDEX; Giorgi et al., 2009, Jones et al., 2011, Hewitson et al., 2012).

An assessment of 12 CMIP3 GCMs over eastern Africa suggests that by the end of the 21st century there will be a wetter climate with more intense wet seasons and less severe droughts during October-November-December (OND) and March-April-May (MAM) (WGI AR5 Section 14.8.7; Moise and Hudson, 2008; Shongwe et al., 2011). These results indicate a reversal of historical trend in these months (Funk et al., 2008; Williams and Funk, 2011). Lyon and DeWitt (2012) ascribe this reversal to recent cooling in the eastern equatorial Pacific that offsets the equatorial Pacific SST warming projected by CMIP3 GCMs in future scenarios. However, GCM projections over Ethiopia indicate a wide range of rainfall spatial pattern changes (Conway and Schipper, 2011) and in some regions GCMs do not agree on the direction of precipitation change, for example, in the upper Blue Nile basin in the late 21st century (Elshamy et al., 2009). Regional climate model studies suggest drying over most parts of Uganda, Kenya, and South Sudan in August and September by the end of the 21st century as a result of a weakening Somali jet and Indian monsoon (Patricola and Cook, 2011). Cook and Vizy (2013) indicate truncated boreal spring rains in the mid-21st century over eastern Ethiopia, Somalia, Tanzania, and southern Kenya while the boreal fall season is lengthened in the southern Kenya and Tanzania (Nakaegawa et al., 2012). These regional studies highlight the importance of resolving both regional scale atmospheric processes and local effects such as land surface on rainfall simulation across the region (WGI AR5 Section 14.8.7).

Over southern Africa CMIP3 GCM projections show a drying signal in the annual mean over the climatologically dry southwest, extending northeastward from the desert areas in Namibia and Botswana (Moise and Hudson, 2008; Orlowsky and Seneviratne, 2012; James and Washington, 2013). This pattern is replicated by CMIP5 GCMs (see Figure 22-1). During the austral summer months, dry conditions are projected in the southwest while downscaled projections indicate wetter conditions in the southeast of South Africa and the Drakensberg mountain range (Hewitson and Crane, 2006; Engelbrecht et al., 2009). Consistent with the AR4, drier winters are projected over a large area in southern Africa by the end of the century as a result of the poleward displacement of mid-latitude storm tracks (WGI AR5 Section 14.8.7; Moise and Hudson, 2008; Engelbrecht et al., 2009; Shongwe et al., 2009; Seth et al., 2011; James and Washington, 2013). Rainfall decreases are also projected during austral spring months, implying a delay in the onset of seasonal rains over a large part of the summer rainfall region of southern Africa (Shongwe et al., 2009; Seth et al., 2011). The sign, magnitude, and spatial extent of projected precipitation changes are dependent on the Coupled General Circulation Model (CGCM) employed, due primarily to parameterization schemes used and their interaction with model dynamics (Hewitson and Crane, 2006; Rocha et al., 2008). Changes in the parameterization schemes of a single regional climate model produced opposite rainfall biases over the region (Crétat et al., 2012) so multiple ensemble downscalings, such as those being produced through CORDEX, are important to more fully describe the uncertainty associated with projected rainfall changes across the African continent (WGI AR5 Section 9.6.5; Laprise et al., 2013).

22.2.3. Observed and Projected Changes in Extreme Temperature and Rainfall

In northern Africa, the northwestern Sahara experienced 40 to 50 heat wave days per year during the 1989–2009 time period (Vizy and Cook, 2012). There is a projected increase in this number of heat wave days over the 21st century (Patricola and Cook, 2010; Vizy and Cook, 2012).

Over West Africa there is *low* to *medium confidence* in projected changes of heavy precipitation by the end of the 21st century based on CMIP3 GCMs (Seneviratne et al., 2012). Regional model studies suggest an increase in the number of extreme rainfall days over West Africa and the Sahel during May and July (Vizy and Cook, 2012) and more intense and more frequent occurrences of extreme rainfall over the Guinea Highlands and Cameroun Mountains (Sylla et al., 2012; Haensler et al., 2013). The ability of RCMs to resolve complex topography captures the amplifying role of topography in producing extreme rainfall that GCMs cannot.

Extreme precipitation changes over eastern Africa such as droughts and heavy rainfall have been experienced more frequently during the last 30 to 60 years (Funk et al., 2008; Williams and Funk, 2011; Shongwe et al., 2011; Lyon and DeWitt, 2012). A continued warming in the Indian-Pacific warm pool has been shown to contribute to more frequent East African droughts over the past 30 years during the spring and summer seasons (Williams and Funk, 2011). It is unclear whether these changes are due to anthropogenic influences or multi-decadal natural variability (Lyon and DeWitt, 2012; Lyon et al., 2013). Projected increases in heavy precipitation over the region have been reported with high certainty in the SREX (Seneviratne et al., 2012), and Vizy and Cook (2012) indicate an increase in the number of extreme wet days by the mid-21st century.

Over southern Africa an increase in extreme warm ETCCDI indices (hot days, hot nights, hottest days) and a decrease in extreme cold indices (cold days and cold nights) in recent decades is consistent with the general warming trend (New et al., 2006; Tebaldi et al., 2006; Aguilar et al., 2009; Kruger and Sekele, 2012). The probability of austral summer heat waves over South Africa increased over the last 2 decades of the 20th century compared to 1961 to 1980 (Lyon, 2009). Enhanced heat wave probabilities are associated with deficient rainfall conditions that tend to occur during El Niño events. The southwestern regions are projected to be at a high risk to severe droughts during the 21st century and beyond (Hoerling et al., 2006; Shongwe et al., 2011). Large uncertainties surround projected changes in tropical cyclone landfall from the southwest Indian Ocean that have resulted in intense floods during the 20th century. Future precipitation projections show changes in the scale of the rainfall probability distribution, indicating that extremes of both signs may become more frequent in the future (Kay and Washington, 2008).

22.3. Vulnerability and Impacts

This section highlights Africa's vulnerability to climate change, as well as the main observed and potential impacts on natural resources, ecosystems, and economic sectors. Figure 22-3 summarizes the main conclusions regarding observed changes in regional climate and their relation to anthropogenic climate change (described in Section 22.2) as well as regarding observed changes in natural and human systems and their relation to observed regional climate change (described in this section). Confidence in detection and attribution of anthropogenically driven climate change is highest for temperature measures. In many regions of Africa, evidence is constrained by limited monitoring. However, impacts of observed precipitation changes are among the observed impacts with the highest assessment of confidence, implying that some of the potentially more significant impacts of anthropogenic climate change for Africa are of a nature that challenges detection and attribution analysis (Section 18.5.1).

22.3.1. Socioeconomic and Environmental Context Influencing Vulnerability and Adaptive Capacity

Equitable socioeconomic development in Africa may strengthen its resilience to various external shocks, including climate change. In 2009, the Human Rights Council adopted Resolution 10/4,[3] which noted the effects of climate change on the enjoyment of human rights, and reaffirmed the potential of human rights obligations and commitments to inform and strengthen international and national policymaking.

The impacts of climate change on human rights have been explicitly recognized by the African Commission on Human and Peoples' Rights (hereafter African Commission) in its Resolution on Climate Change and Human Rights and the Need to Study Its Impact in Africa (ACHPR/Res 153 XLV09). The 1981 African (Banjul) Charter on Human and Peoples' Rights (hereafter African Charter) protects the right of peoples to a "general satisfactory environment favorable to their development" (Article 24). The recognition of this right and the progressive jurisprudence by the African Commission in environmental matters underline the relevance of potential linkages between climate change and human rights (Ruppel, 2012).

The link between climate change and humans is not only associated with human rights. Rather, strong links exist between climate change and the Millennium Development Goals (MDGs): climate change may adversely affect progress toward attaining the MDGs, as climate change can not only increase the pressure on economic activities, such as agriculture (Section 22.3.4) and fishing (Section 22.3.4.4), but also adversely affect urban areas located in coastal zones (Section 22.3.6). Slow progress in attaining most MDGs may, meanwhile, reduce the resilience and adaptive capabilities of African individuals, communities, states, and nations (UNECA et al., 2009, 2012; UNDP et al., 2011).

The African continent has made significant progress on some MDGs; however, not all MDGs have been achieved, with high levels of spatial and group disparities. In addition, progress on all MDG indicators is skewed in favor of higher-income groups and urban populations, which means further marginalization of already excluded groups (MDG Africa Steering Group, 2008; AfDB et al., 2010; World Bank and IMF, 2010). As a whole, the continent is experiencing a number of demographic and economic constraints, with the population having more than doubled since 1980, exceeding 1 billion in 2010 and expected to reach 3 billion by the year 2050, should fertility rates remain constant (Muchena et al., 2005; Fermont et al., 2008; UN DESA Population Division, 2011). The global economic crisis is adding additional constraints on economic development efforts, leading to increased loss of livelihood and widespread poverty (Easterly, 2009; Moyo, 2009; Adesina, 2010). The percent of the population below the poverty line has decreased from 56.5% in 1990 to 47.5% in 2008 (excluding North Africa); however, a significant proportion of the population living below the poverty line remains

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[3] U.N. Doc. A/HRC/10/L.11.

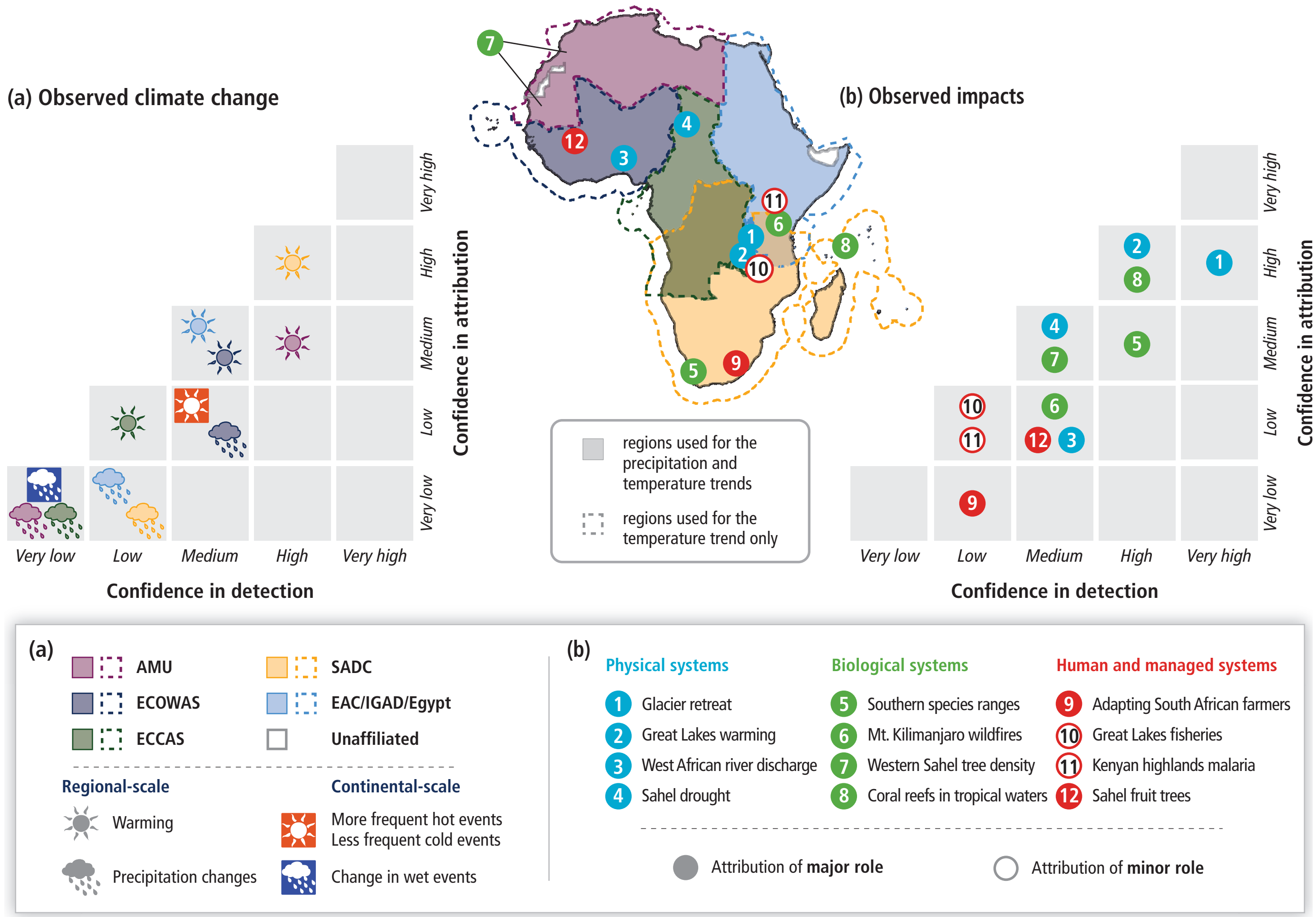

Figure 22-3 | (a) Confidence in detection and in attribution of observed climate change over Africa to anthropogenic emissions. All detection assessments are against a reference of no change, while all attribution assessments concern a major role of anthropogenic emissions in the observed changes. See 22.2, SREX Chapter 3 (Seneviratne et al., 2012), and WGI AR5 Chapter 10 for details. The regions used for analyses are: Arab Maghreb Union (AMU), Economic Community of West African States (ECOWAS), Economic Community of Central African States (ECCAS), Southern African Development Community (SADC), combined East African Community, Intergovernmental Authority on Development, and Egypt (EAC/IGAD/Egypt). (b) Confidence in detection and in attribution of the impacts of observed regional climate change on various African systems. All detection assessments are against a reference of no change, except "9. Adapting South African farmers" (economic changes), "10. Great Lakes fisheries" (changes due to fisheries management and land use), and "11. Kenyan highlands malaria" (changes due to vaccination, drug resistance, demography, and livelihoods). Attribution is to a major role or a minor role of observed climate change, as indicated. See 22.2.2, 22.2.3, 22.3.2, 22.3.3, 22.3.5.4, 22.4.5.7 and Tables 18-5 through 18-9 for details. Assessments follow the methods outlined in 18.2.

chronically poor (UNECA et al., 2012). Although poverty in rural areas in sub-Saharan Africa has declined from 64.9% in 1998 to 61.6% in 2008, it is still double the prevailing average in developing countries in other regions (IFAD, 2010).

Agriculture, which is the main economic activity in terms of employment share, is 98% rainfed in the sub-Saharan region (FAO, 2002).[4] Stagnant agricultural yields, relative to the region's population growth, have led to a fall in per capita food availability since the 1970s (MDG Africa Steering Group, 2008).[5] Such stagnation was reversed with an improved performance of the agricultural sector in sub-Saharan Africa during 2000–2010. However, most of this improvement was the result of countries recovering from the poor performance of the 1980s and 1990s, along with favorable domestic prices (Nin-Pratt et al., 2012).

In addition, recent increases in global food prices aggravate food insecurity among the urban poor, increasing the risk of malnutrition and its consequences (MDG Africa Steering Group, 2008). For example, it was estimated that the global rise in food prices has contributed to the deaths of an additional 30,000 to 50,000 children suffering from malnutrition in 2009 in sub-Saharan Africa (Friedman and Schady, 2009); see Table 22-2. This situation may be complicated further by changes in rainfall variability and extreme weather events affecting the agriculture sector (Yabi and Afouda, 2012).

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[4] However, mining and energy sectors, where active, are undergoing expansion, stimulating growth and adding potentially to state revenues but are also highly vulnerable to global recession. Overall, the limited production and export structures of the continent are likely to maintain its historical vulnerability to external shocks (UNECA and AUC, 2011).

[5] Lack of extension services for farmers in Africa can also contribute to low utilization and spread of innovations and technologies that can help mitigate climate change.

Table 22-2 | Undernourishment in Africa, by number and percentage of total population.

Undernourished	1990–1992	1999–2001	2004–2006	2007–2009	2010–2012
Million	175	205	210	220	239
Percentage of total population	27.3	25.3	23.1	22.6	22.9

Source: IFAD et al. (2012).

In response, the New Partnership for Africa's Development (NEPAD) was founded in 2001, for Africans to take the lead in efforts to achieve the development vision espoused in the AU Constitutive Act as well as the MDGs and to support regional integration as a mechanism for inclusive growth and development in Africa (NEPAD et al., 2012; Ruppel, 2013). Furthermore, the Comprehensive Africa Agriculture Development Program (CAADP), which works under the umbrella of NEPAD, was established in 2003 to help African countries reach a higher path of economic growth through agriculture-led development. For this to happen, it focuses on four pillars for action: land and water management, market access, food supply and hunger, and agricultural research (NEPAD, 2010).

Africa has made much progress in the achievement of universal primary education; however, the results are unevenly distributed. Nevertheless, a considerable number of children, especially girls from poor backgrounds and rural communities, still do not have access to primary education (MDG Africa Steering Group, 2008).

From the livelihood perspective, African women are vulnerable to the impacts of climate change because they shoulder an enormous but imprecisely recorded portion of responsibility for subsistence agriculture, the productivity of which can be expected to be adversely affected by climate change and overexploited soil (Viatte et al., 2009; see also Section 22.4.2 and Table 22-5).[6] Global financial crises, such as the one experienced in 2007–2008, as well as downturn economic trends at the national level, may cause job losses in the formal sector and men may compete for jobs in the informal sector that were previously undertaken by women, making them more vulnerable (AfDB et al., 2010).

Significant efforts have been made to improve access to safe drinking water and sanitation in Africa, with access to safe drinking water increasing from 56 to 65% between 1990 and 2008 (UNDP et al., 2011), with sub-Saharan Africa nearly doubling the number of people using an improved drinking water source—from 252 to 492 million over the same period (UN, 2011). Despite such progress, significant disparities in access to safe water and sanitation, between not only urban and rural but also between large- and medium- and small-sized cities, still exist (UNDP et al., 2011). Use of improved sanitation facilities, meanwhile, is generally low in Africa, reaching 41% in 2010 compared to 36% in 1990 (UNDP et al., 2011).

22.3.2. Ecosystems

It is recognized that interactions between different drivers of ecosystem structure, composition, and function are complex, which makes the prediction of the impacts of climate change more difficult (see Chapter 4). In AR4, the chapter on Africa indicated that extensive pressure is exerted on different ecosystems by human activities (deforestation, forest degradation, biomass utilization for energy) as well as processes inducing changes such as fires or desertification (see WGII AR4 Section 9.2.2.7). Even if the trend is toward better preservation of ecosystems and a decrease in degradation (such as deforestation), pressures linked, for example, to agriculture and food security, energy demand, and urbanization are increasing, putting these ecosystems at risk. This chapter emphasizes new information since AR4 regarding the vulnerability to and impacts of climate change for some terrestrial, freshwater, and coastal/ocean ecosystems.

22.3.2.1. Terrestrial Ecosystems

Changes are occurring in the distribution and dynamics of all types of terrestrial ecosystems in Africa, including deserts, grasslands and shrublands, savannas and woodlands, and forests (*high confidence*) (see also Section 4.3.2.5). Since AR4, three primary trends have been observed at the continental scale. The first is a small overall expansion of desert and contraction of the total vegetated area (*low confidence*; Brink and Eva, 2009). The second is a large increase in the extent of human influence within the vegetated area, accompanied by a decrease in the extent of natural vegetation (*high confidence*; Brink and Eva, 2009; Potapov et al., 2012; Mayaux et al., 2013). The third is a complex set of shifts in the spatial distribution of the remaining natural vegetation types, with net decreases in woody vegetation in western Africa (Vincke et al., 2010; Ruelland et al., 2011; Gonzalez et al., 2012) and net increases in woody vegetation in central, eastern, and southern Africa (*high confidence*; Wigley et al., 2009, 2010; Buitenwerf et al., 2012; Mitchard and Flintrop, 2013).

Overall, the primary driver of these changes is anthropogenic land use change, particularly the expansion of agriculture, livestock grazing, and fuelwood harvesting (*high confidence*; Brink and Eva, 2009; Kutsch et al., 2011; Bond and Midgley, 2012; Gonzalez et al., 2012). Natural climate variability, anthropogenic climate change, and interactions between these drivers and anthropogenic land use change have important additional and interacting effects (*high confidence*; Foden et al., 2007; Touchan et al., 2008; Brink and Eva, 2009; Bond and Midgley, 2012; Gonzalez et al., 2012). Owing to these interactions, it has been difficult to determine the role of climate change in isolation from the other drivers (Malhi et al., 2013). In general, while there are already many examples of changes in terrestrial ecosystems that are consistent with a climate change signal and have been detected with *high confidence*, attribution to climate change has tended to be characterized by *low confidence* (see Table 22-3). New observations and approaches are improving confidence in

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[6] For instance, 84% of women in sub-Saharan Africa, compared with 69.5% of men, are engaged in such jobs. In northern Africa, even though informal or self-employment is less predominant, the gender gap is stark, with a much higher proportion of women compared to men in the more vulnerable informal and self-employed status (56.7% of women compared with 34.9% of men) (UN DESA Population Division, 2011).

Table 22-3 | Examples of detected changes in species, natural ecosystems, and managed ecosystems in Africa that are both consistent with a climate change signal and published since the AR4. Confidence in detection of change is based on the length of study and on the type, amount, and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate being a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and found insufficient to explain the observed change.

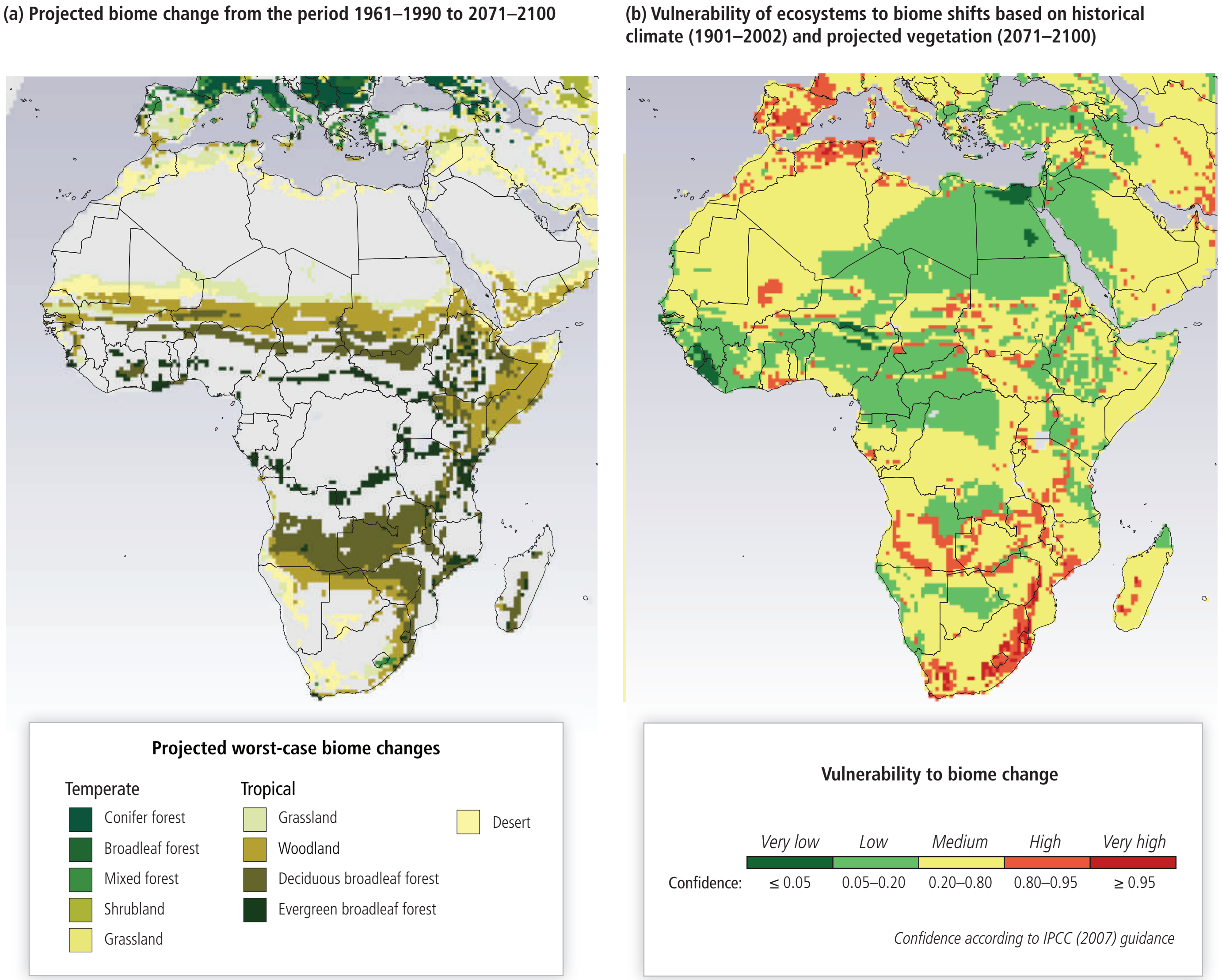
Type of change and nature of evidence	Examples	Time scale of observations	Confidence in the detection of change	Potential climate change driver(s)	Confidence in the role of climate vs. other drivers
Changes in ecosystem types *Robust evidence*	Across sub-Saharan Africa, 57% increase in agricultural areas and 15% increase in barren (largely desert) areas was accompanied by 16% decrease in total forest cover and 5% decrease in total non-forest cover (Brink and Eva, 2009).	~25 years (1975–2000)	*Medium*	Increasing CO_2, changing precipitation patterns, increasing temperatures	*Low*
	On Mt. Kilimanjaro, increased vulnerability to anthropogenic fires has driven 9% decreases in montane forest and 83% decreases in subalpine forest (Hemp, 2009).	~25 years (1976–2000)	*High*	Increasing temperatures, decreasing precipitation	*Low*
	In the Democratic Republic of Congo, total forest cover declined by 2.3%, with most losses in secondary humid forest (Potapov et al., 2012).	~10 years (2000–2010)	*High*	None proposed	*Low*
	Dieback of seaward edge of mangroves in Cameroon at rates up to 3 m yr^{-1} (Ellison and Zouh, 2012)	~35 years (1975–2010)	*High*	Sea level rise	*Medium*
	Across western Africa, central Africa, and Madagascar, net deforestation was 0.28% yr^{-1} for 1990–2000 and 0.14% yr^{-1} for 2000–2010 (Mayaux et al., 2013).	~20 years (1990–2010)	*High*	None proposed	*Low*
Changes in ecosystem structure *Robust evidence*	Surveys of coral reefs in northern Tanzania indicate relative stability in the abundance and diversity of species, despite climate and non-climate stressors (McClanahan et al., 2009).	~9 years (1996–2005)	*High*	None proposed	*Low*
	Analysis of sediment cores from Lake Victoria indicates current community structure (i.e., dominated by cyanobacteria and invasive fish) was established rapidly, during the 1980s (Hecky et al., 2010).	~100 years (1900–2000)	*High*	Increasing temperatures	*Low*
	Long-term declines in density of trees and shrubs in the Sahel zone of Senegal (Vincke et al., 2010) and Mali (Ruelland et al., 2011)	~20–50 years (Senegal, 1976–1995; Mali, 1952–2003)	*High*	Drought stress induced by decreasing precipitation	*Low*
	Southward shift in the Sahel, Sudan, and Guinean savanna vegetation zones inferred from declines in tree density in Senegal and declines in tree species richness and changes in species composition in Mauritania, Mali, Burkina Faso, Niger, and Chad (Gonzalez et al., 2012)	~40–50 years (density, 1954–2002; diversity, 1960–2000)	*Medium*	Increasing temperatures, decreasing precipitation	*Medium*
	Long-term increase in shrub and tree cover across mesic savanna sites (700–1000 mm mean annual precipitation (MAP)) with contrasting land use histories in South Africa (Wigley et al., 2009; 2010)	~67 years (1937–2004)	*High*	Increasing CO_2	*Low*
	In long-term field experiments (between 1970s and 1990s) in South Africa where disturbance from fire and herbivory was controlled, density of trees and shrubs increased almost threefold in mesic savannas (from original MAP of more than 700 mm yr^{-1} in 1970s) but showed no change in a semi-arid savanna (original MAP of over 500 mm yr^{-1} in 1970s) (Buitenwerf et al., 2012).	~30–50 years (1980–2010 for 600-mm MAP site; 1954–2004 for 550- and 750-mm MAP sites)	*High*	In mesic site, increasing CO_2; but lack of response in semi-arid site surprising and unexplained	*Medium*
Changes in ecosystem physiology *Moderate evidence*	A reconstruction of drought history in Tunisia and Algeria based on tree ring records from *Cedrus atlantica* and *Pinus halepensis* indicates that a 1999–2002 drought was the most severe since the 15th century (Touchan et al., 2008).	~550 years (1456–2002)	*High*	Increasing temperatures, decreasing precipitation	*Low*
	Across 79 African tropical forest plots, above-ground carbon storage in live trees increased by 0.63 $\text{Mg C ha}^{-1}\ \text{yr}^{-1}$ (Lewis et al., 2009).	~40 years (1968–2007)	*High*	Increasing CO_2	*Medium*
	Increased stratification and reduced nutrient fluxes and primary productivity in Lake Tanganyika (Verburg and Hecky, 2009)	~90 years (1913–2000)	*High*	Increasing temperatures	*High*
	Recent increases in surface temperatures and decreases in productivity of Lake Tanganyika exceed the range of natural variability (Tierney et al., 2010).	~1500 years (500–2000)	*High*	Increasing temperatures	*High*
Changes in species distributions, physiology, or behavior *Moderate evidence*	The range of *Aloe dichotoma*, a Namib Desert tree, is shifting poleward, but extinction along trailing edge exceeds colonization along leading edge (Foden et al., 2007).	~100 years (1904–2002)	*High*	Increasing temperatures, decreasing precipitation	*Medium*
	On Tsaratanana Massif, the highest mountain in Madagascar, reptiles and amphibians are moving upslope (Raxworthy et al., 2008).	~10 years (1993–2003)	*High*	Increasing temperatures	*Medium*
	Pomacentrus damselfish species vary in avoidance of predation-related mortality under elevated CO_2 (Ferrari et al., 2011).	Minutes to days (Nov.–Dec. 2009)	*High*	Increasing CO_2	*Low*
	In greenhouse experiments, growth of seedlings of woody savanna species (*Acacia karoo* and *Terminalia sericea*) was enhanced at elevated CO_2 levels (Bond and Midgley, 2012).	~1–2 years	*High*	Increasing CO_2	*Medium*

attribution (e.g., Buitenwerf et al., 2012; Gonzalez et al., 2012; Pettorelli et al., 2012; Otto et al., 2013).

There is *high agreement* that continuing changes in precipitation, temperature, and carbon dioxide (CO_2) associated with climate change are *very likely* to drive important future changes in terrestrial ecosystems throughout Africa (*high confidence*; see examples in Sections 4.3.3.1-2). Modeling studies focusing on vegetation responses to climate have projected a variety of biome shifts, related primarily to the extent of woody vegetation (Delire et al., 2008; Gonzalez et al., 2010; Bergengren et al., 2011; Zelazowski et al., 2011; Midgley, 2013). For an example of such projections, see Figure 22-4. However, substantial uncertainties are inherent in these projections because vegetation across much of the continent is not deterministically driven by climate alone (*high confidence*). Advances in understanding how vegetation dynamics are affected by fire, grazing, and the interaction of fire and grazing with climate are expected to enable more sophisticated representations of these processes in coupled models (Scheiter and Higgins, 2009; Staver et al., 2011a,b). Improvements in forecasting vegetation responses to climate change should reduce the uncertainties that are currently associated with vegetation feedbacks to climate forcing, as well as the uncertainties about impacts on water resources, agriculture, and health (Alo and Wang, 2008; Sitch et al., 2008; see also Section 4.5).

22.3.2.2. Freshwater Ecosystems

Freshwater ecosystems in Africa are at risk from anthropogenic land use change, over-extraction of water and diversions from rivers and lakes, and increased pollution and sedimentation loading in water bodies (Vörösmarty et al., 2005; Vié et al., 2009; Darwall et al., 2011). Climate change is also beginning to affect freshwater ecosystems (see



(a) Projected biome change from the period 1961–1990 to 2071–2100

(b) Vulnerability of ecosystems to biome shifts based on historical climate (1901–2002) and projected vegetation (2071–2100)

Figure 22-4 | (a) Projected biome change from the periods 1961–1990 to 2071–2100 using the MC1 Dynamic Vegetation Model. Change is indicated if any of nine combinations of three General Circulation Models (GCMs: Commonwealth Scientific and Industrial Research Organisation (CSIRO Mk3), Met Office Hadley Centre climate prediction model 3 (HadCM3), Model for Interdisciplinary Research on Climate (MIROC) 3.2 medres) and three emissions scenarios (B1, A1B, A2) project change and is thus a worst-case scenario. Colors represent the future biome predicted. (b) Vulnerability of ecosystems to biome shifts based on historical climate (1901–2002) and projected vegetation (2071–2100), where all nine GCM emissions scenario combinations agree on the projected biome change. Source: Gonzalez et al., 2010.

also Section 3.5.2.4, as evident by elevated water temperatures reported in surface waters of Lakes Kariba, Kivu, Tanganyika, Victoria, and Malawi (Odada et al., 2006; Marshall et al., 2009; Verburg and Hecky, 2009; Hecky et al., 2010; Magadza, 2010, 2011; Olaka et al., 2010; Tierney et al., 2010; Ndebele-Murisa, 2011; Woltering et al., 2011; Osborne, 2012; Ndebele-Murisa et al., 2012) (*medium confidence*).

Small variations in climate cause wide fluctuations in the thermal dynamics of freshwaters (Odada et al., 2006; Stenuite et al., 2007; Verburg and Hecky, 2009; Moss, 2010; Olaka et al., 2010). Thermal stratification in the regions' lakes, for instance, isolates nutrients from the euphotic zone, and is strongly linked to hydrodynamic and climatic conditions (Sarmento et al., 2006; Ndebele-Murisa et al., 2010). Moderate warming may be contributing to reduced lake water inflows and therefore nutrients, which subsequently destabilizes plankton dynamics and thereby adversely affects food resources for higher trophic levels of mainly planktivorous fish (*low confidence*) (Magadza, 2008, 2010; Verburg and Hecky, 2009; Ndebele-Murisa et al., 2011). However, the interacting drivers of fisheries decline in African lakes are uncertain, given the extent to which other factors, such as overfishing, pollution, and invasive species, also impact lake ecosystems and fisheries production (Phoon et al., 2004; Sarvala et al., 2006; Verburg et al., 2007; Tumbare, 2008; Hecky et al., 2010; Marshall, 2012).

22.3.2.3. Coastal and Ocean Systems

Coastal and ocean systems are important for the economies and livelihoods of African countries, and climate change will increase challenges from existing stressors, such as overexploitation of resources, habitat degradation, loss of biodiversity, salinization, pollution, and coastal erosion (Arthurton et al., 2006; UNEP and IOC-UNESCO, 2009; Diop et al., 2011). Coastal systems will experience impacts through sea level rise (SLR). They will also experience impacts through high sea levels combined with storm swells, for example, as observed in Durban in March 2007, when a storm swell up to 14 m due to winds generated by a cyclone combined with a high astronomic tide at 2.2 m, leading to damages estimated at US$100 million (Mather and Stretch, 2012). Other climate change impacts, such as flooding of river deltas or an increased migration toward coastal towns due to increased drought induced by climate change (Rain et al., 2011), will also affect coastal zones.

Some South African sea bird species have moved farther south over recent decades, but land use change may also have contributed to this migration (Hockey and Midgley, 2009; Hockey et al., 2011). However, it is considered that South African seabirds could be a valuable signal for climate change, particularly of the changes induced on prey species related to changes in physical oceanography, if we are able to separate the influences of climate parameters from other environmental ones (Crawford and Altwegg, 2009).

Upwellings, including Eastern Boundary Upwelling Ecosystems (EUBEs) and Equatorial Upwelling Systems (EUSs) are the most biologically active systems in the oceans (Box CC-UP). In addition to equatorial upwelling, the primary upwelling systems that affect Africa are the Benguela and Canary currents along the Atlantic coast (both EBUEs).The waters of the Benguela current have not shown warming over the period 1950–2009 (Section 30.5.5.1.2), whereas most observations suggest that the Canary current has warmed since the early 1980s, and there is *medium evidence* and *medium agreement* that primary production in the Canary current has decreased over the past 2 decades (Section 30.5.5.1.1). Changing temperatures in the Canary current has resulted in changes to important fisheries species (e.g., Mauritanian waters have become increasingly suitable for *Sardinella aurita*) (Section 30.5.5.1.1). Upwellings are areas of naturally low pH and high CO_2 concentrations, and, consequently, may be vulnerable to ocean acidification and its impacts (Boxes CC-OA, CC-UP; Section 30.5.5). Warming is projected to continue in the Canary current, and the synergies between this increase in water temperature and ocean acidification could influence a number of biological processes (Section 30.5.5.2). Regarding the Benguela current upwelling, there is *medium agreement* despite *limited evidence* that the Benguela system will experience changes in upwelling intensity as a result of climate change (Section 30.5.5.1.2). There is considerable debate as to whether or not climate change will drive an intensification of upwelling (e.g., Bakun et al., 2010; Narayan et al., 2010) in all regions. Discussion of the various hypotheses for how climate change may affect coastal upwelling is presented in Box 30-1.

Ocean acidification (OA) is the term used to describe the process whereby increased CO_2 in the atmosphere, upon absorption, causes lowering of the pH of seawater (Box CC-OA). Projections indicate that severe impairment of reef accretion by organisms such as corals (Hoegh-Guldberg et al., 2007) and coralline algae (Kuffner et al., 2008) are substantial potential impacts of ocean acidification, and the combined effects of global warming and ocean acidification have been further demonstrated to lower both coral reef productivity (Anthony et al., 2008) and resilience (Anthony et al., 2011). These effects will have consequences for reef biodiversity, ecology, and ecosystem services (Sections 6.3.1-2, 6.3.5, 6.4.1, 30.3.2; Box CC-CR).

Coral vulnerability to heat anomalies is high in the Western Indian Ocean (Section 30.5.6.1.2). Corals in the southwestern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, Réunion, and Rodrigues) appeared to be more resilient than those in eastern locations (Section 30.5.6.1.2). Social adaptive capacity to cope with such change varies, and societal responses (such as closures to fishing) can have a positive impact on reef recovery, as observed in Tanzania (McClanahan et al., 2009). In Africa, fisheries mainly depend on either coral reefs (on the eastern coast) or coastal upwelling (on the western coast). These two ecosystems will be affected by climate change through ocean acidification, a rise in sea surface temperatures, and changes in upwelling (see Boxes CC-OA, CC-CR, CC-UP).

22.3.3. Water Resources

Knowledge has advanced since the AR4 regarding current drivers of water resource abundance in Africa, and in understanding of potential future impacts on water resources from climate change and other drivers. However, inadequate observational data in Africa remains a systemic limitation with respect to fully estimating future freshwater availability (Neumann et al., 2007; Batisani, 2011). Detection of and attribution to climate change are difficult given that surface and groundwater hydrology are governed by multiple, interacting drivers and factors, such as land use change, water withdrawals, and natural climate variability (see also Section 3.2.1 and Box CC-WE). There is poor understanding in Africa of how climate change will affect water quality. This is an important knowledge gap.

A growing body of literature generated since the AR4 suggests that climate change in Africa will have an overall modest effect on future water scarcity relative to other drivers, such as population growth, urbanization, agricultural growth, and land use change (*high confidence*) (Alcamo et al., 2007; Calow and MacDonald, 2009; Carter and Parker, 2009; MacDonald et al., 2009; Taylor et al., 2009; Abouabdillah et al., 2010; Beck and Bernauer, 2011; Droogers et al., 2012; Notter et al., 2012; Tshimanga and Hughes, 2012). However, broad-scale assumptions about drivers of future water shortages can mask significant sub-regional variability of climate impacts, particularly in water-stressed regions that are projected to become drier, such as northern Africa and parts of southern Africa. For example, rainfed agriculture in northern Africa is highly dependent on winter precipitation and would be negatively impacted if total precipitation and the frequency of wet days decline across North Africa, as has been indicated in recent studies (Born et al., 2008; Driouech et al., 2010; Abouabdillah et al., 2010; García-Ruiz et al., 2011). Similarly, climate model predictions based on average rainfall years do not adequately capture interannual and interdecadal variability that can positively or negatively influence surface water runoff (Beck and Bernauer, 2011; Notter et al., 2012; Wolski et al., 2012). Key challenges for estimating future water abundance in Africa lie in better understanding relationships among evapotranspiration, soil moisture, and land use change dynamics under varying temperature and precipitation projections (Goulden et al., 2009a) and to understand how compound risks such as heat waves and seasonal rainfall variability might interact in the future to impact water resources.

Several studies from Africa point to a future decrease in water abundance due to a range of drivers and stresses, including climate change in southern and northern Africa (*medium confidence*). For example, all countries within the Zambezi River Basin could contend with increasing water shortages (A2 scenario) although non-climate drivers (e.g., population and economic growth, expansion of irrigated agriculture, and water transfers) are expected to have a strong influence on future water availability in this basin (Beck and Bernauer, 2011). In Zimbabwe, climate change is estimated to increase water shortages for downstream users dependent on the Rozva dam (Ncube et al., 2011). Water shortages are also estimated for the Okavango Delta, from both climate change and increased water withdrawals for irrigation (Murray-Hudson et al., 2006; Milzow et al., 2010; Wolski et al., 2012), and the Breede River in South Africa (Steynor et al., 2009).

For North Africa, Droogers et al. (2012) estimated that in 2050 climate change will account for 22% of future water shortages in the region while 78% of increased future water shortages can be attributed to socioeconomic factors. Abouabdillah et al. (2010) estimated that higher temperatures and declining rainfall (A2 and B1 scenarios) would reduce water resources in Tunisia. Reduced snowpack in the Atlas Mountains from a combination of warming and reduced precipitation, combined with more rapid springtime melting is expected to reduce supplies of seasonal meltwater for lowland areas of Morocco (García-Ruiz et al., 2011).

In eastern Africa, potential climate change impacts on the Nile Basin are of particular concern given the basin's geopolitical and socioeconomic importance. Reduced flows in the Blue Nile are estimated by late century due to a combination of climate change (higher temperatures and declining precipitation) and upstream water development for irrigation and hydropower (Elshamy et al., 2009; McCartney and Menker Girma, 2012). Beyene et al. (2010) estimated that streamflow in the Nile River will increase in the medium term (2010–2039) but will decline in the latter half of this century (A2 and B1 scenarios) as a result of both declining rainfall and increased evaporative demand, with subsequent diminution of water allocation for irrigated agriculture downstream from the High Aswan Dam. Kingston and Taylor (2010) reached a similar conclusion about an initial increase followed by a decline in surface water discharge in the Upper Nile Basin in Uganda. Seasonal runoff volumes in the Lake Tana Basin are estimated to decrease by the 2080s under the A2 and B2 scenarios (Abdo et al., 2009), while Taye et al. (2011) reported inconclusive findings as to changes in runoff in this basin. The Mara, Nyando, and Tana Rivers in eastern Africa are projected to have increased flow in the second half of this century (Taye et al., 2011; Dessu and Melesse, 2012; Nakaegawa et al., 2012).

Estimating the influence of climate change on water resources in West Africa is limited by the significant climate model uncertainties with regard to the region's future precipitation. For example, Itiveh and Bigg (2008) estimate higher future rainfall in the Niger River Basin (A1, A2, and B1 scenarios), whereas Oguntunde and Abiodun (2013) report a strong seasonal component with reduced precipitation in the basin during the rainy season and increased precipitation during the dry season (A1B scenario). The Volta Basin is projected to experience a slight mean increase in precipitation (Kunstmann et al., 2008), and the Bani River Basin in Mali is estimated to experience substantial reductions in runoff (A2 scenario) due to reduced rainfall (Ruelland et al., 2012). The impact of climate change on total runoff in the Congo Basin is estimated to be minimal (A2 scenario) (Tshimanga and Hughes, 2012). Continental wide studies (e.g., De Wit and Stankiewicz, 2006) indicate that surface drainage in dry areas is more sensitive to, and will be more adversely affected by, reduced rainfall than would surface drainage in wetter areas that experience comparable rainfall reductions.

The overall impact of climate change on groundwater resources in Africa is expected to be relatively small in comparison with impacts from non-climatic drivers such as population growth, urbanization, increased reliance on irrigation to meet food demand, and land use change (Calow and MacDonald, 2009; Carter and Parker, 2009; MacDonald et al., 2009; Taylor et al., 2009). Climate change impacts on groundwater will vary across climatic zones. (See also Section 3.4.6.) An analysis by MacDonald et al. (2009) indicated that changes in rainfall would not be expected to impact the recharge of deep aquifers in areas receiving below 200 mm rainfall per year, where recharge is negligible due to low rainfall. Groundwater recharge may also not be significantly affected by climate change in areas that receive more than 500 mm per year, where sufficient recharge would remain even if rainfall diminished, assuming current groundwater extraction rates. By contrast, areas receiving between 200 and 500 mm per year, including the Sahel, the Horn of Africa, and southern Africa, may experience a decline in groundwater recharge with climate change to the extent that prolonged drought and other precipitation anomalies become more frequent with climate change, particularly in shallow aquifers, which respond more quickly to seasonal and yearly changes in rainfall than do deep aquifers (Barthel et al., 2009).

Coastal aquifers are additionally vulnerable to climate change because of high rates of groundwater extraction, which leads to saltwater intrusion in aquifers, coupled with increased saltwater ingression resulting from SLR (Bouchaou et al., 2008; Moustadraf et al., 2008; Al-Gamal and Dodo, 2009; Kerrou et al., 2010). Some studies have shown additional impacts of SLR on aquifer salinization with salinity potentially reaching very high levels (Carneiro et al., 2010; Niang et al., 2010; Research Institute for Groundwater, 2011). Although these effects are expected to be localized, in some cases they will occur in densely populated areas (Niang et al., 2010). The profitability of irrigated agriculture in Morocco is expected to decline (under both B1 and A1B scenarios) owing to increased pumping of groundwater and increased salinization risk for aquifers (Heidecke and Heckelei, 2010).

The capacity of groundwater delivery systems to meet demand may take on increasing importance with climate change (Calow and MacDonald, 2009). Where groundwater pumping and delivery infrastructure are poor, and the number of point sources limited, prolonged pumping can lead to periodic drawdowns and increased failure of water delivery systems or increased saline intrusion (Moustadraf et al., 2008). To the extent that drought conditions become more prevalent in Africa with climate change, stress on groundwater delivery infrastructures will increase.

Future development of groundwater resources to address direct and indirect impacts of climate change, population growth, industrialization, and expansion of irrigated agriculture will require much more knowledge of groundwater resources and aquifer recharge potentials than currently exists in Africa. Observational data on groundwater resources in Africa are extremely limited and significant effort needs to be expended to assess groundwater recharge potential across the continent (Taylor et al., 2009). A preliminary analysis by MacDonald et al. (2012) indicates that total groundwater storage in Africa is 0.66 million km^3, which is "more than 100 times the annual renewable freshwater resources, and 20 times the freshwater stored in African lakes." However, borehole yields are variable and in many places water yields are relatively low. Detailed analysis of groundwater conditions for water resource planning would need to consider these constraints.

22.3.4. Agriculture and Food Security

Africa's food production systems are among the world's most vulnerable because of extensive reliance on rainfed crop production, high intra- and inter-seasonal climate variability, recurrent droughts and floods that affect both crops and livestock, and persistent poverty that limits the capacity to adapt (Boko et al., 2007). In the near term, better managing risks associated with climate variability may help to build adaptive capacities for climate change (Washington et al., 2006; Cooper et al., 2008; Funk et al., 2008). However, agriculture in Africa will face significant challenges in adapting to climate changes projected to occur by mid-century, as negative effects of high temperatures become increasingly prominent under an A1B scenario (Battisti and Naylor, 2009; Burke et al., 2009a), thus increasing the likelihood of diminished yield potential of major crops in Africa (Schlenker and Lobell, 2010; Sultan et al., 2013). Changes in growing season length are possible, with a tendency toward reduced growing season length (Thornton et al., 2011), though with potential for some areas to experience longer growing seasons (Cook and Vizy, 2012). The composition of farming systems from mixed crop-livestock to more livestock dominated food production may occur as a result of reduced growing season length for annual crops and increases in the frequency and prevalence of failed seasons (Jones and Thornton, 2009; Thornton et al., 2010). Transition zones, where livestock keeping is projected to replace mixed crop-livestock systems by 2050, include the West African Sahel and coastal and mid-altitude areas in eastern and southeastern Africa (Jones and Thornton, 2009), areas that currently support 35 million people and are chronically food insecure.

22.3.4.1. Crops

Climate change is very likely to have an overall negative effect on yields of major cereal crops across Africa, with strong regional variability in the degree of yield reduction (see also Section 7.3.2.1) (Liu et al., 2008; Lobell et al., 2008, 2011; Walker and Schulze, 2008; Thornton et al., 2009a; Roudier et al., 2011; Berg et al., 2013) (*high confidence*). One exception is in eastern Africa where maize production could benefit from warming at high elevation locations (A1FI scenario) (Thornton et al., 2009a), although the majority of current maize production occurs at lower elevations, thereby implying a potential change in the distribution of maize cropping. Maize-based systems, particularly in southern Africa, are among the most vulnerable to climate change (Lobell et al., 2008). Estimated yield losses at mid-century range from 18% for southern Africa (Zinyengere et al., 2013) to 22% aggregated across sub-Saharan Africa, with yield losses for South Africa and Zimbabwe in excess of 30% (Schlenker and Lobell, 2010). Simulations that combine all regions south of the Sahara suggest consistently negative effects of climate change on major cereal crops in Africa, ranging from 2% for sorghum to 35% for wheat by 2050 under an A2 scenario (Nelson et al., 2009). Studies in North Africa by Eid et al. (2007), Hegazy et al. (2008), Drine (2011), and Mougou et al. (2011) also indicate a high vulnerability of wheat production to projected warming trends. In West Africa, temperature increases above 2°C (relative to a 1961–1990 baseline) are estimated to counteract positive effects on millet and sorghum yields of increased precipitation (for B1, A1B, and A2 scenarios; Figure 22-5), with negative effects stronger in the savannah than in the Sahel, and with modern cereal varieties compared with traditional ones (Sultan et al., 2013).

Several recent studies since the AR4 indicate that climate change will have variable impacts on non-cereal crops, with both production losses and gains possible (*low confidence*). Cassava yields in eastern Africa are estimated to moderately increase up to the 2030s assuming CO_2 fertilization and under a range of low to high emissions scenarios (Liu et al., 2008), findings that were similar to those of Lobell et al. (2008). Suitability for growing cassava is estimated to increase with the greatest improvement in suitability in eastern and central Africa (A1B scenario) (Jarvis et al., 2012). However, Schlenker and Lobell (2010) estimated negative impacts from climate change on cassava at mid-century, although with impacts estimated to be less than those for cereal crops. Given cassava's hardiness to higher temperatures and sporadic rainfall relative to many cereal crops, it may provide a potential option for crop

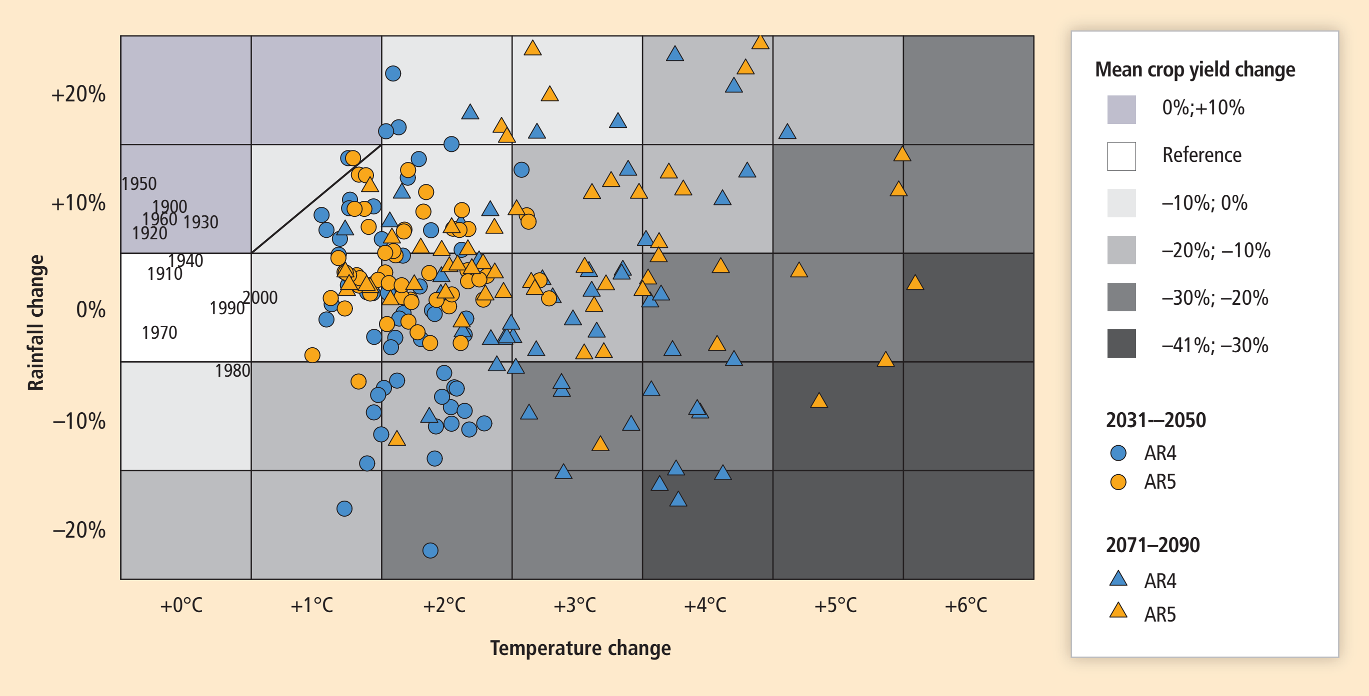


Figure 22-5 | The effect of rainfall and temperature changes on mean crop yield. Mean crop yield change (%) relative to the 1961–1990 baseline for 7 temperatures (x-axis) and 5 rainfall (y-axis) scenarios. Results are shown as the average over the 35 stations across West Africa and the 6 cultivars of sorghum and millet. Blue triangles and circles are the projected anomalies computed by several Coupled Model Intercomparison Project Phase 3 (CMIP3) General Circulation Models (GCMs) and three IPCC emission scenarios (B1, A1B, A2) for 2071–2090 and 2031–2050, respectively. Projections from CMIP5 GCMs and three Representative Concentration Pathways (RCPs: 4.5, 6.0, and 8.5) are represented by orange triangles and circles. Models and scenarios names are displayed in Figure S2 (available at stacks.iop.org/ERL/8/014040/mmedia). Past observed climate anomalies from CRU data are also projected by computing 10-year averages (e.g. 1940 is for 1941–1950). All mean yield changes are significant at a 5% level except boxes with a diagonal line. Source: Sultan et al., 2013.

substitution of cereals as an adaptation response to climate change (Jarvis et al., 2012; Rosenthal and Ort, 2012). Bean yields in eastern Africa are estimated to experience yield reductions by the 2030s under an intermediate emissions scenario (A1B) (Jarvis et al., 2012) and by the 2050s under low (B1) and high (A1FI) emissions scenarios (Thornton et al., 2011). For peanuts, some studies indicate a positive effect from climate change (A2 and B2 scenarios) (Tingem and Rivington, 2009) and others a negative one (Lobell et al., 2008; Schlenker and Lobell, 2010). Bambara groundnuts (*Vigna subterranea*) are estimated to benefit from moderate climate change (Tingem and Rivington, 2009) (A2 and B2 scenarios) although the effect could be highly variable across varieties (Berchie et al., 2012). Banana and plantain production could decline in West Africa and lowland areas of East Africa, whereas in highland areas of East Africa it could increase with temperature rise (Ramirez et al., 2011). Much more research is needed to better establish climate change impacts on these two crops.

Table 22-4 | Projected changes in agro-climatic suitability for perennial crops in Africa by mid-century under an A2 scenario.

Crop	Suitability change	Country	Source
Coffee	Increased suitability at high latitudes; decreased suitability at low latitudes	Kenya	Läderach et al. (2010)
Tea	Decreased suitability	Uganda	Eitzinger et al. (2011a,b)
	Increased suitability at high latitudes; decreased suitability at low latitudes	Kenya	
Cocoa	Constant or increased suitability at high latitudes; decreased suitability at low latitudes	Ghana, Côte d'Ivoire	Läderach et al. (2011c)
Cashew	Increased suitability	Ghana, Côte d'Ivoire	Läderach et al. (2011a)
Cotton	Decreased suitability	Ghana, Côte d'Ivoire	Läderach et al. (2011b)

Suitable agro-climatic zones for growing economically important perennial crops are estimated to significantly diminish, largely as a result of the effects of rising temperatures (Läderach et al., 2010, 2011a,b,c; Eitzinger et al., 2011a,b). Under an A2 scenario, by mid-century suitable agro-climatic zones that are currently classified as very good to good for perennial crops may become more marginal, and what are currently marginally suitable zones may become unsuitable; the constriction of crop suitability could be severe in some cases (see Table 22-4). Movement of perennial crops to higher altitudes would serve to mitigate the loss of suitability at lower altitudes but this option is limited. Loss of productivity of high-value crops such as tea, coffee, and cocoa would have detrimental impacts on export earnings.

22.3.4.2. Livestock

Livestock systems in Africa face multiple stressors that can interact with climate change and variability to amplify the vulnerability of livestock-keeping communities. These stressors include rangeland degradation; increased variability in access to water; fragmentation of grazing areas; sedentarization; changes in land tenure from communal toward private ownership; in-migration of non-pastoralists into grazing areas; lack of opportunities to diversify livelihoods; conflict and political crisis; weak social safety nets; and insecure access to land, markets, and other resources (Solomon et al., 2007; Smucker and Wisner, 2008; Galvin, 2009; Thornton et al., 2009b; Dougill et al., 2010; Ifejika Speranza, 2010). (See also Section 7.3.2.4.)

Loss of livestock under prolonged drought conditions is a critical risk given the extensive rangeland in Africa that is prone to drought. Regions that are projected to become drier with climate change, such as northern and southern Africa, are of particular concern (Solomon et al., 2007; Masike and Urich, 2008; Thornton et al., 2009b; Dougill et al., 2010; Freier et al., 2012; Schilling et al., 2012). Adequate provision of water for livestock production could become more difficult under climate change. For example, Masike and Urich (2009) estimated that the cost of supplying livestock water from boreholes in Botswana will increase by 23% by 2050 under an A2 scenario due to increased hours of groundwater pumping needed to meet livestock water demands under warmer and drier conditions. Although small in comparison to the water needed for feed production, drinking water provision for livestock is critical, and can have a strong impact on overall resource use efficiency in warm environments (Peden et al., 2009; Descheemaeker et al., 2010, 2011; van Breugel et al., 2010). Livestock production will be indirectly affected by water scarcity through its impact on crop production and subsequently the availability of crop residues for livestock feeding. Thornton et al. (2010) estimated that maize stover availability per head of cattle will decrease in several East African countries by 2050.

The extent to which increased heat stress associated with climate change will affect livestock productivity has not been well established, particularly in the tropics and subtropics (Thornton et al., 2009b), although a few studies point to the possibility that keeping heat-tolerant livestock will become more prevalent in response to warming trends. For example, higher temperatures in lowland areas of Africa could result in reduced stocking of dairy cows in favor of cattle (Kabubo-Mariara, 2008), a shift from cattle to sheep and goats (Kabubo-Mariara, 2008; Seo and Mendelsohn, 2008), and decreasing reliance on poultry (Seo and Mendelsohn, 2008). Livestock-keeping in highland areas of east Africa, which is currently cold-limited, would potentially benefit from increased temperatures (Thornton et al., 2010). Lunde and Lindtjørn (2013) challenge a finding in the AR4 that there is direct proportionality between range-fed livestock numbers and changes in annual precipitation in Africa. Their analysis indicates that this relationship may hold in dry environments but not in humid ones.

22.3.4.3. Agricultural Pests, Diseases, and Weeds

Since the AR4, understanding of how climate change will potentially affect crop and livestock pests and diseases and agricultural weeds in Africa is beginning to emerge. Climate change in interaction with other environmental and production factors could intensify damage to crops from pests, weeds, and diseases (Section 7.3.2.3).

Warming in highland regions of eastern Africa could lead to range expansion of crop pests into cold-limited areas (*low confidence*). For example, in highland Arabica coffee-producing areas of eastern Africa, warming trends may result in the coffee berry borer (*Hypothenemus hampei*) becoming a serious threat in coffee-growing regions of Ethiopia, Kenya, Uganda, Rwanda, and Burundi (Jaramillo et al., 2011). Temperature increases in highland banana-producing areas of eastern Africa enhance the risk of altitudinal range expansion of the highly destructive burrowing nematode, *Radopholus similis* (Nicholls et al., 2008); however, no detailed studies have assessed this risk. Ramirez et al. (2011) estimated that increasing minimum temperatures by 2020 would expand the suitable range of black leaf streak disease (*Mycosphaerella fijiensis*) of banana in Angola and Guinea.

Climate change may also affect the distribution of economically important pests in lowland and dryland areas of Africa (*low confidence*). Under A2A and B2A for 2020, Cotter et al. (2012) estimated that changes in temperature, rainfall, and seasonality will result in more suitable habitats for *Striga hermonthica* in central Africa, whereas the Sahel region may become less suitable for this weed. Striga weed infestations are a major cause of cereal yield reduction in sub-Saharan Africa. Climate change could also lead to an overall decrease in the suitable range of major cassava pests—whitefly, cassava brown streak virus, cassava mosaic geminivirus, and cassava mealybug (Jarvis et al., 2012)—although southeast Africa and Madagascar are estimated to experience increased suitability for cassava pests (Bellotti et al., 2012). In the case of livestock, Olwoch et al. (2008) estimated that the distribution of the main tick vector species (*Rhipicephalus appendiculatus*) of East Coast fever disease in cattle could be altered by a 2°C temperature increase over mean annual temperatures throughout the 1990s, and changes in mean precipitation resulting in the climatically suitable range of the tick shifting southward. However, a number of environmental and socioeconomic factors (e.g., habitat destruction, land use and cover change, and host density) in addition to climatic ones influence tick distribution and need to be considered in assigning causality (Rogers and Randolph, 2006).

22.3.4.4. Fisheries

Fisheries are an important source of food security in Africa. Capture fisheries (marine and inland) and aquaculture combined contribute more than one-third of Africa's animal protein intake (Welcomme, 2011), while in some coastal countries fish contribute up to two-thirds of total animal protein intake (Allison et al., 2009). Demand for fish is projected to increase substantially in Africa over the next few decades (De Silva and Soto, 2009). To meet fish food demand by 2020, De Silva and Soto (2009) estimated that aquaculture production in Africa would have to increase nearly 500%.

The vulnerability of national economies to climate change impacts on fisheries can be linked to exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries, and adaptive capacity within the country (Allison et al., 2009). In an analysis of fisheries in 132 countries, Allison et al. (2009) estimated that two-thirds of the most vulnerable countries were in Africa. Among these countries, the most vulnerable were Angola, Democratic Republic of Congo, Mauritania, and Senegal, due to the importance of fisheries to the poor and the close link between climate variability and fisheries production. Coastal countries of West Africa will experience a significant negative impact from climate change. Lam et al. (2012) projected that by 2050 (under an A1B scenario) the annual landed value of fish for that region is estimated to decline by 21%, resulting in a nearly 50% decline in fisheries-related employment and a total annual loss of US$311 million to the region's economy.

22.3.4.5. Food Security

Food security in Africa faces multiple threats stemming from entrenched poverty, environmental degradation, rapid urbanization, high population growth rates, and climate change and variability. The intertwined issues of markets and food security have emerged as an important issue in Africa and elsewhere in the developing world since the AR4. Price spikes for globally traded food commodities in 2007–2008 and food price volatility and higher overall food prices in subsequent years have undercut recent gains in food security across Africa (Brown et al., 2009; Hadley et al., 2011; Mason et al., 2011; Tawodzera, 2011; Alem and Söderbom, 2012; Levine, 2012). Among the most affected groups are the urban poor, who typically allocate more than half of their income to food purchases (Cohen and Garrett, 2010; Crush and Frayne, 2010). The proportion of smallholder farmers who are net food buyers of staple grains exceeds 50% in Mozambique, Kenya, and Ethiopia (Jayne et al., 2006); thus food security of rural producers is also sensitive to food spikes, particularly in the case of female-headed households, which generally have fewer assets than male-headed households (Kumar and Quisumbing, 2011). Although the recent spike in global food prices can be attributed to a convergence of several factors, the intensification of climate change impacts could become more important in the future in terms of exerting upward pressure on food prices of basic cereals (Nelson et al., 2009; Hertel et al., 2010), which would have serious implications for Africa's food security. As the recent wave of food price crises demonstrates, factors in other regions profoundly impact food security in Africa. Much more research is needed to understand better the potential interactions between climate change and other key drivers of food prices that act at national, regional, and global scales. (See also Section 7.2.2.)

Africa is undergoing rapid urbanization and subsequent transformation of its food systems to accommodate changes in food processing and marketing as well as in food consumption patterns. Considering the increasing reliance on purchased food in urban areas, approaches for addressing the impacts of climate change on food security will need to encompass a food systems approach (production as well as processing, transport, storage, and preparation) that moves food from production to consumption (Battersby, 2012). Weaknesses in the food system may be exacerbated by climate change in the region as high temperatures increase spoilage and the potential for increased flooding places food transportation infrastructure at higher risk of damage. In this respect, high post-harvest losses in Africa resulting in a large part from inadequate transport and storage infrastructure (Godfray et al., 2010; Parfitt et al., 2010) are an important concern.

22.3.5. Health

22.3.5.1. Introduction

Africa currently experiences high burdens of health outcomes whose incidence and geographic range could be affected by changing temperature and precipitation patterns, including malnutrition, diarrheal diseases, and malaria and other vector-borne diseases, with most of the impact on women and children (WHO, 2013a). In 2010, there were 429,000 to 772,000 deaths from malaria in Africa, continuing a slow decline since the early to mid-2000s (WHO, 2012). There are insufficient data series to assess trends in incidence in most affected countries in

Frequently Asked Questions

FAQ 22.1 | How could climate change impact food security in Africa?

Food security is composed of availability (is enough food produced?), access (can people get it, and afford it?), utilization (how local conditions bear on people's nutritional uptake from food), and stability (is the supply and access ensured?). Strong consensus exists that climate change will have a significantly negative impact on all these aspects of food security in Africa.

Food availability could be threatened through direct climate impacts on crops and livestock from increased flooding, drought, shifts in the timing and amount of rainfall, and high temperatures, or indirectly through increased soil erosion from more frequent heavy storms or through increased pest and disease pressure on crops and livestock caused by warmer temperatures and other changes in climatic conditions. Food access could be threatened by climate change impacts on productivity in important cereal-producing regions of the world, which, along with other factors, could raise food prices and erode the ability of the poor in Africa to afford purchased food. Access is also threatened by extreme events that impair food transport and other food system infrastructure. Climate change could impact food utilization through increased disease burden that reduces the ability of the human body to absorb nutrients from food. Warmer and more humid conditions caused by climate change could impact food availability and utilization through increased risk of spoilage of fresh food and pest and pathogen damage to stored foods (cereals, pulses, tubers) that reduces both food availability and quality. Stability could be affected by changes in availability and access that are linked to climatic and other factors.

Africa. Parasite prevalence rates in children younger than 5 years of age are highest in poorer populations and rural areas; factors increasing vulnerability include living in housing with little mosquito protection and limited access to health care facilities offering effective diagnostic testing and treatment. Of the 3.6 million annual childhood deaths in Africa, 11% are due to diarrheal diseases (Liu et al., 2012).

Drivers of these and other climate-relevant health outcomes include inadequate human and financial resources, inadequate public health and health care systems, insufficient access to safe water and improved sanitation, food insecurity, and poor governance. Although progress has been made on improving safe water and sanitation coverage, sub-Saharan Africa still has the lowest coverage, highlighting high vulnerability to the health risks of climate change (UNICEF and WHO, 2008, 2012). Vulnerabilities also arise from policies and measures implemented in other sectors, including adaptation and mitigation options. Collaboration between sectors is essential. For example, the construction of the Akosombo Dam in the 1960s to create Lake Volta in Ghana was associated with a subsequent increase in the prevalence of schistosomiasis (Scott et al., 1982).

22.3.5.2. Food- and Water-Borne Diseases

Cholera is primarily associated with poor sanitation, poor governance, and poverty, with associations with weather and climate variability suggesting possible changes in incidence and geographic range with climate change (Rodó et al., 2002; Koelle et al., 2005; Olago et al., 2007; Murray et al., 2012). The frequency and duration of cholera outbreaks are associated with heavy rainfall in Ghana, Senegal, other coastal West African countries, and South Africa, with a possible association with the El Niño-Southern Oscillation (ENSO) (de Magny et al., 2007, 2012; Mendelsohn and Dawson, 2008). In Zanzibar, Tanzania, and Zambia, an increase in temperature or rainfall increases the number of cholera cases (Luque Fernández et al., 2009; Reyburn et al., 2011). The worst outbreak of cholera in recent African history occurred in Zimbabwe from August 2008 to June 2009. The epidemic was associated with the rainy season and caused more than 92,000 cases and 4000 deaths. Contamination of water sources spread the disease (Mason, 2009). Poor governance, poor infrastructure, limited human resources, and underlying population susceptibility (high burden of malnutrition) contributed to the severity and extent of the outbreak (Murray et al., 2012). Other mechanisms for increases in cholera incidence are described in Section 11.5.2.1. As discussed in Section 22.2 there are projected increases in precipitation in areas in Africa, for example West Africa where cholera is already endemic. This possibly will lead to more frequent cholera outbreaks in the sub-regions affected. However, further research is needed to quantify the climatic impacts.

22.3.5.3. Nutrition

Detailed spatial analyses of climate and health dynamics among children in Mali and Kenya suggest associations between livelihoods and measures of malnutrition, and between weather variables and stunting (Grace et al., 2012; Jankowska et al., 2012). Projections of climate and demographic change to 2025 for Mali (based on 2010–2039 climatology from the Famine Early Warning System Network FCLIM method) suggest approximately 250,000 children will suffer stunting, nearly 200,000 will be malnourished, and more than 100,000 will become anemic, assuming constant morbidity levels; the authors conclude that climate change will cause a statistically significant proportion of stunted children (Jankowska et al., 2012).

Using a process-driven approach, Lloyd et al. (2011) projected future child malnutrition (as measured by severe stunting) in 2050 for four regions in sub-Saharan Africa, taking into consideration food and non-food (socioeconomic) causes, and using regional scenario data based on the A2 scenario. Current baseline prevalence rates of severe stunting were 12 to 20%. Considering only future socioeconomic change, the prevalence of severe stunting in 2050 would be 7 to 17% (e.g., a net decline). However, including climate change, the prevalence of severe stunting would be 9 to 22%, or an increase of 31 to 55% in the relative percent of children severely stunted. Western sub-Saharan Africa was projected to experience a decline in severe stunting from 16% at present to 9% in 2050 when considering socioeconomic and climate change. Projected changes for central, south, and east sub-Saharan Africa are close to current prevalence rates, indicating climate change would counteract the beneficial consequences of socioeconomic development. Local economic activity and food accessibility can reduce the incidence of malnutrition (Funk et al., 2008; Rowhani et al., 2011).

22.3.5.4. Vector-Borne Diseases and Other Climate-Sensitive Health Outcomes

A wide range of vector-borne diseases contribute to premature morbidity and mortality in Africa, including malaria, leishmaniasis, Rift Valley fever, as well as tick- and rodent-borne diseases.

22.3.5.4.1. Malaria

Weather and climate are among the environmental, social, and economic determinants of the geographic range and incidence of malaria (Reiter, 2008). The association between temperature and malaria varies regionally (Chaves and Koenraadt, 2010; Paaijmans et al., 2010a; Alonso et al., 2011; Gilioli and Mariani, 2011). Malaria transmission peaks at 25°C and declines above 28°C (Lunde et al., 2013; Mordecai et al., 2013). Total precipitation, rainfall patterns, temperature variability, and the water temperature of breeding sites are expected to alter disease susceptibility (Bomblies and Eltahir, 2010; Paaijmans et al., 2010b; Afrane et al., 2012; Blanford et al., 2013; Lyons et al., 2013). ENSO events also may contribute to malaria epidemics (Mabaso et al., 2007; Ototo et al., 2011). The complexity of the malaria transmission cycle makes it difficult to determine whether the distribution of the pathogen and vector are already changing due to climate change. Other factors such as the Indian Ocean Dipole have been proposed to affect malaria incidence (Hashizume et al., 2009; Chaves et al., 2012; Hashizume et al., 2012).

Climate change is expected to affect the geographic range and incidence of malaria, particularly along the current edges of its distribution, with contractions and expansions, and increasing and decreasing incidence

(Yé et al., 2007; Peterson, 2009; Parham and Michael, 2010; Paaijmans et al., 2010b, 2012; Alonso et al., 2011; Egbendewe-Mondzozo et al., 2011; Chaves et al., 2012; Ermert et al., 2012; Parham et al., 2012), depending on other drivers, such as public health interventions, factors influencing the geographic range and reproductive potential of malaria vectors, land use change (e.g., deforestation), and drug resistance, as well as the interactions of these drivers with weather and climate patterns (Chaves et al., 2008; Kelly-Hope et al., 2009; Paaijmans et al., 2009; Saugeon et al., 2009; Artzy-Randrup et al., 2010; Dondorp et al., 2010; Gething et al., 2010; Jackson et al., 2010; Kulkarni et al., 2010; Loha and Lindtjørn, 2010; Tonnang et al., 2010; Caminade et al., 2011; Omumbo et al., 2011; Stern et al., 2011; Afrane et al., 2012; Edlund et al., 2012; Ermert et al., 2012; Githeko et al., 2012; Himeidan and Kweka, 2012; Jima et al., 2012; Lyons et al., 2012; Stryker and Bomblies, 2012; Mordecai et al., 2013). Movement of the parasite into new regions is associated with epidemics with high morbidity and mortality. Because various *Anopheles* species are adapted to different climatic conditions, changing weather and climate patterns could affect species composition differentially, which could in turn affect malaria transmission (Afrane et al., 2012; Lyons et al., 2013).

Consensus is growing that highland areas, especially in East Africa, will experience increased malaria epidemics, with areas above 2000 m, where temperatures are currently too low to support malaria transmission, particularly affected (Pascual et al., 2006; Peterson, 2009; Gething et al., 2010; Lou and Zhao, 2010; Paaijmans et al., 2010a; Ermert et al., 2012). Reasons for different projections across models include use of different scenarios; use of global versus regional climate models (Ermert et al., 2012); the need for finer-scale and higher-resolution models of the sharp climate variations with altitude (Bouma et al., 2011); and the extent to malaria transmission and the drivers of its geographic range and incidence of malaria respond to and interact with climate change.

22.3.5.4.2. Leishmaniasis

Directly or indirectly, climate change may increase the incidence and geographic range of leishmaniasis, a highly neglected disease that has recently become a significant health problem in northern Africa (Postigo, 2010), with a rising concern in western Africa because of coinfection with HIV (Kimutai et al., 2006). The epidemiology of the disease appears to be changing (Dondji, 2001; Yiougo et al., 2007; WHO, 2009; Postigo, 2010). During the 20th century, zoonotic cutaneous leishmaniasis emerged as an epidemic disease in Algeria, Morocco, and Tunisia, and is now endemic (Salah et al., 2007; Aoun et al., 2008; Rhajaoui, 2011; Toumi et al., 2012; Bounoua et al., 2013). Previously an urban disease in Algeria, leishmaniasis now has a peri-urban distribution linked to changes in the distribution of the rodent host and of the vector since the early 1990s (Aoun et al., 2008). Cutaneous leishmaniasis has expanded its range from its historical focus at Biskra, Algeria, into the semi-arid steppe, with an associated upward trend in reported cases. In Morocco, sporadic cases of leishmania major (vector *Phlebotomus papatasi*) appeared early in the 21st century; since that time there have been occasional epidemics of up to 2000 cases, interspersed with long periods with few or no cases (Rhajaoui, 2011). Outbreaks of zoonotic cutaneous leishmaniasis have become more frequent in Tunisia (where it emerged as an epidemic disease in 1991) (Salah et al., 2007; Toumi et al., 2012). The disease has since spread to adjacent areas in West Africa and East Africa (Dondji, 2001; Yiougo et al., 2007; WHO, 2009). Disease incidence is associated with rainfall and minimum temperature (Toumi et al., 2012; Bounoua et al., 2013). Relationships between decadal shifts over 1990–2009 in northwest Algeria and northeast Morocco in the number of cases and climate indicators suggested increased minimum temperatures created conditions suitable for endemicity (Bounoua et al., 2013). Environmental modifications, such as construction of dams, can change the temperature and humidity of the soil and thus affect vegetation that may result in changes in the composition and density of sandfly species and rodent vectors. More research, however, is needed to quantify the climate related impacts because there are multiple underlying factors.

22.3.5.4.3. Rift Valley fever

Rift Valley fever (RVF) epidemics in the Horn of Africa are associated with altered rainfall patterns. Additional climate variability and change could further increase its incidence and spread. RVF is endemic in numerous African countries, with sporadic repeated epidemics. Epidemics in 2006–2007 in the Horn of Africa (Nguku et al., 2007; WHO, 2007; Adam et al., 2010; Andriamandimby et al., 2010; Hightower et al., 2012) and southern Africa were associated with heavy rainfall (Chevalier et al., 2011), strengthening earlier analyses by Anyamba et al. (2009) showing that RVF epizootics and epidemics are closely linked to the occurrence of the warm phase of ENSO and La Niña events (Linthicum et al., 1999; Anyamba et al., 2012) and elevated Indian Ocean temperatures. These conditions lead to heavy rainfall and flooding of habitats suitable for the production of the immature *Aedes* and *Culex* mosquitoes that serve as the primary RVF virus vectors in East Africa. Flooding of mosquito habitats also may introduce the virus into domestic animal populations.

22.3.5.4.4. Ticks and tick-borne diseases

Changing weather patterns could expand the distribution of ticks causing animal disease, particularly in East and South Africa. Ticks carry theileriosis (East Coast fever), which causes anemia and skin damage that expose cattle to secondary infections. Habitat destruction, land use and cover change, and host density also affect tick distribution (Rogers and Randolph, 2006). Using a climate envelope and a species prediction model, Olwoch et al. (2007) projected that by the 2020s, under the A2 scenario, East Africa and South Africa would be particularly vulnerable to climate-related changes in tick distributions and tick-borne diseases: more than 50% of the 30 *Rhipicephalus* species examined showed significant range expansion and shifts. More than 70% of this range expansion was found in tick species of economic importance.

22.3.5.4.5. Schistosomiasis

Worldwide, approximately 243 million people required treatment for schistosomiasis in 2011, of which 90% lived in underdeveloped areas of Africa (WHO, 2013b). Water resource development, such as irrigation dams recommended for adaptation in agriculture, can amplify the risk of schistosomiasis (Huang and Manderson, 1992; Hunter et al., 1993;

Jobin, 1999). Migration and sanitation play a significant role in the spread of schistosomiasis from rural areas to urban environments (Babiker et al., 1985; WHO, 2013b). Temperature and precipitation patterns may play a role in transmission (Odongo-Aginya et al., 2008; Huang et al., 2011; Mutuku et al., 2011). Projections for the period 2070–2099, under A2 and B2 emission scenarios, suggest that although the geographic areas suitable for transmission will increase with climate change, snail regions are expected to contract and/or move to cooler areas; these results highlight the importance of understanding how climate change could alter snail habitats when projecting future human schistosomiasis prevalence under different scenarios (Stensgaard et al., 2011).

22.3.5.4.6. Meningococcal meningitis

There is a strong environmental relationship between the seasonal cycle of meningococcal meningitis and climate, including a relationship between the seasonal pattern of the Harmattan dusty winds and onset of disease. Transmission of meningitis occurs throughout Africa in the dry season and coincides with periods of very low humidity and wind-driven dusty conditions, ending with the onset of the rains (Molesworth et al., 2003). Research corroborates earlier hypothesized relationships between weather and meningitis (Yaka et al., 2008; Palmgren, 2009; Roberts, 2010; Dukić et al., 2012; Agier et al., 2013). In the northern region of Ghana, exposure to smoke from cooking fires increased the risk of contracting meningococcal meningitis (Hodgson et al., 2001). This increased risk suggests that exposure to elevated concentrations of air pollutants, such as carbon monoxide (CO) and particulate matter, may be linked to illness. More research is needed to clarify the possible impact of climate change on atmospheric concentrations of aerosols and particulates that can impact human health and any associations between meningitis and these aerosols and particles. The relationship between the environment and the location of the epidemics suggest connections between epidemics and regional climate variability (Molesworth et al., 2003; Sultan et al., 2005; Thomson et al., 2006), which may allow for early warning systems for predicting the location and onset of epidemics.

22.3.5.4.7. Hantavirus

Novel hantaviruses with unknown pathogenic potential have been identified in some insectivores (shrews and a mole) in Africa (Klempa, 2009), with suggestions that weather and climate, among other drivers, could affect natural reservoirs and their geographic range, and thus alter species composition in ways that could be epidemiologically important (Klempa, 2009).

22.3.5.4.8. Other health issues

Research into other health issues has begun. It has been noted that any increase in food insecurity due to climate change would be expected to further compromise the poor nutrition of people living with HIV/AIDs (Drimie and Gillespie, 2010). Laboratory studies suggest that the geographic range of the tsetse fly (*Glossina* species), the vector of human and animal trypanosomiasis in Africa, may be reduced with climate change (Terblanche et al., 2008). More studies are needed to clarify the role of climate change on HIV and other disease vectors.

22.3.5.4.9. Heat waves and high ambient temperatures

Heat waves and heat-related health effects are only beginning to attract attention in Africa. High ambient temperatures are associated with increased mortality in Ghana, Burkina Faso, and Nairobi with associations varying by age, gender, and cause of death (Azongo et al., 2012; Diboulo et al., 2012; Egondi et al., 2012). Children are particularly at risk. Heat-related health effects also may be of concern in West and southern Africa (Dapi et al., 2010; Mathee et al., 2010). Section 11.4.1 assesses the literature on the health impacts of heat waves and high ambient temperatures. Low ambient temperatures are associated with mortality in Nairobi and Tanzania (Egondi et al., 2012; Mrema et al., 2012). Chapter 11 discusses the relationship between heat and work capacity loss. This is an important issue for Africa because of the number of workers engaged in agriculture.

22.3.5.4.10. Air quality

Climate change is anticipated to affect the sources of air pollutants as well as the ability of pollutants to be dispersed in the atmosphere (Denman et al., 2007). Assessments of the impacts of projected climate change on atmospheric concentrations of aerosols and particules that can adversely affect human health indicate that changes in surface temperature, land cover, and lightning may alter natural sources of ozone precursor gases and consequently ozone levels over Africa (Stevenson et al., 2005; Brasseur et al., 2006; Zeng et al., 2008). However, insufficient climate and emissions data for Africa prevent a more comprehensive assessment and further research is needed to better understand the implications of climate change on air quality in Africa.

22.3.6. Urbanization

The urban population in Africa is projected to triple by 2050, increasing by 0.8 billion (UN DESA Population Division, 2010). African countries are experiencing some of the world's highest urbanization rates (UN-HABITAT, 2008). Many of Africa's evolving cities are unplanned and have been associated with growth of informal settlements, inadequate housing and basic services, and urban poverty (Yuen and Kumssa, 2011).[7]

Climate change could affect the size and characteristics of rural and urban human settlements in Africa because the scale and type of rural-urban migration are partially driven by climate change (UN-HABITAT and UNEP, 2010; Yuen and Kumssa, 2011). The majority of migration flows observed in response to environmental change are within country boundaries (Jäger et al., 2009; Tacoli, 2009). For large urban centers located on mega-deltas (e.g., Alexandria in Egypt in the Nile delta, and Benin City, Port Harcourt, and Aba in Nigeria in the Niger delta),

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[7] However, community-driven upgrading may contribute to reducing the vulnerability of such informal areas (for more detail, see Chapter 8).

urbanization through migration may also lead to increasing numbers of people vulnerable to coastal climate change impacts (Seto, 2011). Floods are exerting considerable impacts on cities and smaller urban centers in many African nations; for example, heavy rains in East Africa in 2002 caused floods and mudslides, which forced tens of thousands to leave their homes in Rwanda, Kenya, Burundi, Tanzania, and Uganda, and the very serious floods in Port Harcourt and Addis Ababa in 2006 (Douglas et al., 2008).

In addition, SLR along coastal zones including coastal settlements could disrupt economic activities such as tourism and fisheries (Naidu et al., 2006; Kebede and Nicholls, 2012; Kebede et al., 2012). More than a quarter of Africa's population lives within 100 km of the coast and more than half of Africa's total population living in low-elevation coastal zones is urban, accounting for 11.5% of the total urban population of the continent (UN-HABITAT, 2008).

In eastern Africa, an assessment of the impact of coastal flooding due to SLR in Kenya found that, by 2030, 10,000 to 86,000 people would be affected, with associated economic costs ranging between US$7 million and US$58 million (SEI, 2009). Detailed assessments of damages arising from extreme events have also been made for some coastal cities, including Mombasa and Dar-es-Salaam. In Mombasa, by 2030 the population and assets at risk of 1-in-100-year return period extreme water levels is estimated to be between 170,700 and 266,300 inhabitants, while economic assets at risk are between US$0.68 billion and US$1.06 billion (Kebede et al., 2012). In Dar-es-Salaam, the population and economic assets at risk of 1-in-100-year return period extreme water levels by 2030 range between 30,300 and 110,000 inhabitants and US$35.6 million to US$404.1 million (Kebede and Nicholls, 2012). For both city assessments, the breadth of these ranges encompasses three different population growth scenarios and four different SLR scenarios (low (B1), medium (A1B), high (A1FI), and Rahmstorf (based on Rahmstorf, 2007)); these four SLR scenarios were also the basis for the broader assessment of the coast of Kenya (SEI, 2009). The scale of the damages projected in the city-specific studies highlights the risks of extremes in the context of projected SLR.

In southern Africa, urban climate change risk assessments have been made at the regional scale (Theron and Rossouw, 2008) as well as at the city level for Durban, Cape Town, and the uMhlathuze local municipality. For these cities, risk assessments have focused on a broad range of sectors, including business and tourism; air quality, heath, and food security; infrastructure and services; biodiversity; and water resources (Naidu et al., 2006; Cartwright, 2008; Zitholele Consulting, 2009).

Assessments for western Africa (Appeaning Addo et al., 2008; Niang et al., 2010) and northern Africa (Snoussi et al., 2009; World Bank, 2011) share similarities with those for eastern and southern Africa. For instance, it was suggested that by the end of the 21st century, about 23%, 42%, and 49% of the total area of coastal governorates of the Nile Delta would be susceptible to inundation under the A1FI, Rahmstorf, and Pfeffer scenarios of SLR. It was also suggested that a considerable proportion of these areas (ranging between 32 and 54%) are currently either wetland or undeveloped areas (Hassaan and Abdrabo, 2013). Another study, assessing the economic impacts of SLR on the Nile Delta, suggested that losses in terms of housing and road would range between 1 and 2 billion EGP in 2030 and between 2 and 16 billion EGP in 2060 under the A1FI and B1 emissions scenarios as well as current SLR trends (Smith et al., 2013).

African cities and towns represent highly vulnerable locations to the impacts of climate change and climate variability (Boko et al., 2007; Diagne, 2007; Dossou and Gléhouenou-Dossou, 2007; Douglas et al., 2008; Adelekan, 2010; Kithiia, 2011). Rapid rates of urbanization represent a burden on the economies of African urban areas, due to the massive investments needed to create job opportunities and provide infrastructure and services. Basic infrastructure services are not keeping up with urban growth, which has resulted in a decline in the coverage of many services, compared to 1990 levels (Banerjee et al., 2007). Squatter and poor areas typically lack provisions to reduce flood risks or to manage floods when they happen (Douglas et al., 2008).

African small- and medium-sized cities have limited adaptive capacity to deal not only with future climate impacts but also with the current range of climate variability (Satterthwaite et al., 2009; UN-HABITAT, 2011; for more detail, see Chapters 5 and 8). African cities, despite frequently having more services compared to rural areas (e.g., piped water, sanitation, schools, and health care) that lead to human life spans above their respective national averages, show a shortfall in infrastructure due to low quality and short lifespan which may be of particular concern, when climate change impacts are taken into consideration (Satterthwaite et al., 2009). It is not possible, however, "to climate-proof infrastructure that is not there" (Satterthwaite et al., 2009). At the same time, hard infrastructural responses such as seawalls and channelized drainage lines are costly and can be maladaptive (Dossou and Gléhouenou-Dossou, 2007; Douglas et al., 2008; Kithiia and Lyth, 2011).

High levels of vulnerability and low adaptive capacity result from structural factors, particularly local governments with poor capacities and resources (Kithiia, 2011). Weak local government creates and exacerbates problems including the lack of appropriate regulatory structures and mandates; poor or no planning; lack of or poor data; lack of disaster risk reduction strategies; poor servicing and infrastructure (particularly waste management and drainage); uncontrolled settlement of high-risk areas such as floodplains, wetlands, and coastlines; ecosystem degradation; competing development priorities and timelines; and a lack of coordination among government agencies (AMCEN and UNEP, 2006; Diagne, 2007; Dossou and Gléhouenou-Dossou, 2007; Mukheibir and Ziervogel, 2007; Douglas et al., 2008; Roberts, 2008; Adelekan, 2010; Kithiia and Dowling, 2010; Kithiia, 2011).

22.4. Adaptation

22.4.1. Introduction

Since 2007, Africa has gained experience in conceptualizing, planning, and beginning to implement and support adaptation activities, from local to national levels and across a growing range of sectors (Sections 22.4.4-5). However, across the continent, most of the adaptation to climate variability and change is reactive in response to short-term motivations, is occurring autonomously at the individual/household level, and lacks support from government stakeholders and policies (Vermeulen et al., 2008; Ziervogel et al., 2008; Berrang-Ford et al., 2011). A complex web of interacting barriers to local-level adaptation, manifesting from national to local scales, both constrains and highlights potential limits to adaptation (Section 22.4.6).

22.4.2. Adaptation Needs, Gaps, and Adaptive Capacity

Africa's urgent adaptation needs stem from the continent's foremost sensitivity and vulnerability to climate change, together with its low levels of adaptive capacity (Ludi et al., 2012; see also Section 22.3). While overall adaptive capacity is considered low in Africa because of economic, demographic, health, education, infrastructure, governance, and natural factors, levels vary within countries and across sub-regions, with some indication of higher adaptive capacity in North Africa and some other countries; individual or household level adaptive capacity depends, in addition to functional institutions and access to assets, on the ability of people to make informed decisions to respond to climatic and other changes (Vincent, 2007; Ludi et al., 2012).

Inherent adaptation-related strengths in Africa include the continent's wealth in natural resources, well-developed social networks, and longstanding traditional mechanisms of managing variability through, for example, crop and livelihood diversification, migration, and small-scale enterprises, all of which are underpinned by local or indigenous knowledge systems for sustainable resource management (Eyong, 2007; Nyong et al., 2007; UNFCCC, 2007; Cooper et al., 2008; Macchi et al., 2008; Nielsen, 2010; Castro et al., 2012). However, it is uncertain to what extent these strategies will be capable of dealing with future changes, among them climate change and its interaction with other development processes (Leary et al., 2008b; Paavola, 2008; van Aalst et al., 2008; Conway, 2009; Jones, 2012; see also Section 22.4.6). Since Africa is extensively exposed to a range of multiple stressors (Section 22.3) that interact in complex ways with longer term climate change, adaptation needs are broad, encompassing institutional, social, physical, and infrastructure needs, ecosystem services and environmental needs, and financial and capacity needs.

Making climate change information more reliable and accessible is one of the most pressing and cross-cutting adaptation needs, but providing information is insufficient to guarantee adaptation, which requires behavioural change (Sections 22.4.5.5, 22.4.6). As noted in the AR4 and emphasized in subsequent literature, monitoring networks in Africa are insufficient and characterized by sparse coverage and short and fragmented digitized records, which makes modeling difficult (Boko et al., 2007; Goulden et al., 2009b; Ziervogel and Zermoglio, 2009; Jalloh et al., 2011a). Adding to this is the shortage of relevant information and skills, in particular for downscaling climate models and using scenario outputs for development and adaptation planning, which is exacerbated by under-resourcing of meteorological agencies and a lack of in-country expertise on climate science; and the capacity of civil society and government organizations to access, interpret, and use climate information for planning and decisionmaking (Ziervogel and Zermoglio, 2009; Brown et al., 2010; Ndegwa et al., 2010; Dinku et al., 2011; Jalloh et al., 2011a).

Given its economic dependence on natural resources, most research on strengthening adaptive capacity in Africa is focused on agriculture-, forestry-, or fisheries-based livelihoods (Collier et al., 2008; Berrang-Ford et al., 2011). The rural emphasis is now being expanded through a growing focus on requirements for enhancing peri-urban and urban adaptive capacity (Lwasa, 2010; Ricci, 2012). Many African countries have prioritized the following knowledge needs: vulnerability and impact assessments with greater continuity in countries; country-specific socioeconomic scenarios and greater knowledge on costs and benefits of different adaptation measures; comprehensive programs that promote adaptation through a more holistic development approach, including integrated programs on desertification, water management, and irrigation; promoting sustainable agricultural practices and the use of appropriate technologies and innovations to address shorter growing seasons, extreme temperatures, droughts, and floods; developing alternative sources of energy; and approaches to deal with water shortages, food security, and loss of livelihoods (UNFCCC, 2007; Bryan et al., 2009; Eriksen and Silva, 2009; Chikozho, 2010; Gbetibouo et al., 2010b; Jalloh et al., 2011b; Sissoko et al., 2011; AAP, 2012). The literature, however, stresses the vast variety of contexts that shape adaptation and adaptive capacity—even when people are faced with the same climatic changes and livelihood stressors, responses vary greatly (Cooper et al., 2008; Vermuelen et al., 2008; Ziervogel et al., 2008; Gbetibouo, 2009; Westerhoff and Smit, 2009).

Despite significant data and vulnerability assessment gaps, the literature highlights that delayed action on adaptation due to this would not be in the best interests of building resilience commensurate with the urgent needs (UNFCCC, 2007; Jobbins, 2011). See Section 22.6.4 for a discussion of adaptation costs and climate finance.

22.4.3. Adaptation, Equity, and Sustainable Development

Multiple uncertainties in the African context mean that successful adaptation will depend upon developing resilience in the face of uncertainty (*high confidence*) (Adger et al., 2011; Conway, 2011; Ludi et al., 2012). The limited ability of developmental strategies to counter current climate risks, in some cases due to significant implementation challenges related to complex cultural, political, and institutional factors, has led to an adaptation deficit, which reinforces the desirability for strong interlinkages between adaptation and development, and for low-regrets adaptation strategies (see Glossary) that produce developmental co-benefits (*high confidence*) (Bauer and Scholz, 2010; Smith et al., 2011).

Research has highlighted that no single adaptation strategy exists to meet the needs of all communities and contexts in Africa (*high confidence*; see Sections 22.4.4-5). In recognition of the socioeconomic dimensions of vulnerability (Bauer and Scholz, 2010), the previous focus on technological solutions to directly address specific impacts is now evolving toward a broader view that highlights the importance of building resilience, through social, institutional, policy, knowledge, and informational approaches (ADF, 2010; Chambwera and Anderson, 2011), as well as on linking the diverse range of adaptation options to the multiple livelihood-vulnerability risks faced by many people in Africa (Tschakert and Dietrich, 2010), and on taking into account local norms and practices in adaptation strategies (Nyong et al., 2007; Ifejika Speranza et al., 2010; see also Section 22.4.5.4).

Table 22-5 | Cross-cutting approaches for equity and social justice in adaptation.

Equitable adaptation approach	Key issues to address for adaptation	Factors that could cause maladaptation	Opportunities	Lessons learned
Gender-mainstreamed adaptation in Africa	Lack of empowerment and participation in decision making (Patt et al., 2009) Climate impacts increase women's household roles, with risk of girls missing school to assist (Raworth, 2008; Romero González et al., 2011; UNDP, 2011b). Male adaptation strategies, e.g., migration, risk increasing women's vulnerability (Djoudi and Brockhaus, 2011).	Employment opportunities not sufficiently extended to women in adaptation initiatives (Madzwamuse, 2010) Failure to incorporate power relations in adaptation responses (Djoudi and Brockhaus, 2011; Romero González et al., 2011)	Women's aptitude for long-term thinking, trusting and integrating scientific knowledge, and taking decisions under uncertainty (Patt et al., 2009) Potential long-term increase in women's empowerment and social and economic status (Djoudi and Brockhaus, 2011) Women opportunistically using development projects for adaptation (Nielsen, 2010)	Security of tenure over land and resource access is critical for enabling enhanced adaptive capacity of women (ADF, 2010). Research on understanding different adaptive strategies of benefit for women and men is needed.
Child-centered approaches to adaptation	50% of Africa's population is under the age of 20 years (UN DESA Population Division, 2011), yet their issues are largely absent from adaptation policy (ADF, 2010). Children's differential vulnerability to projected climate impacts is high, particularly to hunger, malnutrition, and disasters (UNICEF, 2007).	Limits to children's agency related to power imbalances between children and adults, and different cultural contexts (Seballos et al., 2011)	Using approaches that stress agency and empowerment, and "innovative energies" of youth; build on targeted adaptation initiatives, such as child-centered disaster risk reduction and adaptation (ADF, 2010; Seballos et al., 2011)	Positive role of children and youth as change agents for climate adaptation, within appropriate enabling environment Child-sensitive programs and policies can reduce risks children face from disasters (Seballos et al, 2011). Funding for climate resilience programs will protect children's basic rights (UNICEF, 2010, 2011).
Human rights–based approaches (HRBA)	Common critical rights issues for local communities are land/resource rights, gender equality, and political voice and fair adjudication of grievances for the poor and excluded (Castro et al., 2012).	Lack of recognition and promotion of their human rights blocks indigenous peoples' coping and adaptation capacities (UNPFII, 2008).	Using the HRBA lens to understand climate risk necessitates risk analysis to probe the root causes of differential disaster risk vulnerabilities, to enable structural, sustainable responses (Urquhart, 2013).	Applying HRBA presents a framework for addressing conflicting rights and interests, necessary for building resilience and equitable adaptation responses (SIDA, 2010).

Moreover, effective adaptation responses necessitate differentiated and targeted actions from the local to national levels, given the differentiated social impacts based on gender, age, disability, ethnicity, geographical location, livelihood, and migrant status (Tanner and Mitchell, 2008; IPCC, 2012). Additional attention to equity and social justice aspects in adaptation efforts in Africa, including the differential distribution of adaptation benefits and costs, would serve to enhance adaptive capacity (Burton et al., 2002; Brooks et al., 2005; Thomas and Twyman, 2005; Madzwamuse, 2010); nevertheless, some valuable experience has been gained recently on gender-equitable adaptation, human rights-based approaches, and involvement of vulnerable or marginalized groups such as indigenous peoples and children, aged and disabled people, and internally displaced persons and refugees (see Table 22-5; ADF, 2010; UNICEF, 2010, 2011; Levine et al., 2011; Romero González et al., 2011; IDS, 2012; Tanner and Seballos, 2012). See also Box CC-GC on Gender and Climate Change.

22.4.4. Experiences in Building the Governance System for Adaptation, and Lessons Learned

22.4.4.1. Introduction

Section 22.4.4 assesses progress made in developing policy, planning, and institutional systems for climate adaptation at regional, national, and subnational levels in Africa, with some assessment of implementation. This includes an assessment of community-based adaptation, as an important local level response, and a consideration of adaptation decision making and monitoring.

22.4.4.2. Regional and National Adaptation Planning and Implementation

Regional policies and strategies for adaptation, as well as transboundary adaptation, are still in their infancy. Early examples include the Climate Change Strategies and Action Plans being developed by the Southern African Development Community and the Lake Victoria Basin Committee, as well as efforts being made by six highly forested Congo basin countries to coordinate conservation and sustainable forest management of the central African forest ecosystem, and obtain payments for ecosystem services (Harmeling et al., 2011; AfDB, 2012).

At the national level, African countries have initiated comprehensive planning processes for adaptation by developing National Adaptation Programmes of Action (NAPAs), in the case of the Least Developed Countries, or National Climate Change Response Strategies (NCCRS); implementation is, however, lagging and integration with economic and development planning is limited but growing (*high confidence*). Prioritized adaptation measures in the NAPAs tend to focus narrowly on agriculture, food security, water resources, forestry, and disaster management; and on projects, technical solutions, education and capacity development, with little integration with economic planning and poverty reduction processes (Madzwamuse, 2010; Mamouda, 2011; Pramova et al., 2012). Only a small percentage of the NAPA activities have been funded to date, although additional funding is in the pipeline (Prowse et al., 2009; Madzwamuse, 2010; Mamouda, 2011; Romero González et al., 2011).

Subsequent to the NAPAs and early experience with the NCCRS, there is some evidence of evolution to a more integrated, multilevel, and multisector approach to adaptation planning (*medium confidence*). Examples include Ethiopia's Programme of Adaptation to Climate Change, which includes sectoral, regional, national, and local community levels (Hunde, 2012); Lesotho's coordinated policy framework involving all ministries and stakeholders (Corsi et al., 2012); and Mali's experience with a methodology for integrating adaptation into multiple sectors (Fröde et al., 2013). Cross-sectoral adaptation planning and risk management is occurring through mainstreaming initiatives like the 20-country Africa Adaptation Program (AAP), initiated in 2008 (UNDP, 2009; Siegel, 2011). Examples of the more programmatic approach of national climate resilient development strategies include Rwanda's National Strategy on Climate Change and Low Carbon Development, under development in 2012, and the Pilot Programs for Climate Resilience in Niger, Zambia, and Mozambique (Climate Investment Funds, 2009). Intersectoral climate risk management approaches can be detected in integrated water resources management, integrated coastal zone management, disaster risk reduction, and land use planning initiatives (Boateng, 2006; Koch et al., 2007; Awuor et al., 2008; Cartwright et al., 2008; Kebede and Nicholls, 2011; Kebede et al., 2012), while in South Africa climate change design principles have been incorporated into existing systematic biodiversity planning to guide land use planning (Petersen and Holness, 2011).

The move to a more integrated approach to adaptation planning is occurring within efforts to construct enabling national policy environments for adaptation in many countries. Examples include Namibia's National Policy on Climate Change; Zambia's National Climate Change Response Strategy and Policy, and South Africa's National Climate Change Response Policy White Paper. Ten countries were developing new climate change laws or formal policies at the end of 2012, including the proposed National Coastal Adaptation Law in Gabon (Corsi et al., 2012).

Despite this progress in mainstreaming climate risk in policy and planning, significant disconnects still exist at the national level, and implementation of a more integrated adaptation response remains tentative (*high confidence*) (Koch et al., 2007; Fankhauser and Schmidt-Traub, 2010; Madzwamuse, 2010; Oates et al., 2011; UNDP-UNEP Poverty-Environment Initiative, 2011a). Legislative and policy frameworks for adaptation remain fragmented, adaptation policy approaches seldom take into account realities in the political and institutional spheres, and national policies are often at odds with autonomous local adaptation strategies, which can act as a barrier to adaptation, especially where cultural, traditional, and context-specific factors are ignored (Dube and Sekhwela, 2008; Patt and Schröter, 2008; Stringer et al., 2009; Bele et al., 2010; Hisali et al., 2011; Kalame et al., 2011; Naess et al., 2011; Lockwood, 2012; Sonwa et al., 2012; see also Section 22.4.6).

While climate resilience is starting to be mainstreamed into economic planning documents—for example, Zambia's Sixth National Development Plan 2011–2015, and the new Economic and Social Investment Plan in Niger (Corsi et al., 2012)—measures to promote foreign direct investment and industrial competitiveness can undercut adaptive capacity of poor people (Madzwamuse, 2010), while poor business environments impede both foreign direct investment and adaptation (Collier et al., 2008). Stakeholders in climate-sensitive sectors—for example, Botswana's tourism industry—have yet to develop and implement adaptation strategies (Saarinen et al., 2012).

22.4.4.3. Institutional Frameworks for Adaptation

Global adaptation institutions, both within and outside of the United Nations Framework Convention on Climate Change (UNFCCC), are critically important for Africa's ability to move forward on adaptation (Section 14.2.3). Regional institutions focused on specific ecosystems rather than on political groupings, such as the Commission of Central African Forests (COMIFAC), present an opportunity to strengthen the institutional framework for adaptation. National frameworks include a number of institutions that cover all aspects of climate change: most countries have interministerial coordinating bodies and intersectoral technical working groups, while an increasing number now have multi-stakeholder coordinating bodies (Harmeling et al., 2011) and are establishing national institutions to serve as conduits for climate finance (Gomez-Echeverri, 2010; Smith et al., 2011).

Many studies in Africa show that under uncertain climatic futures, replacing hierarchical governance systems that operate within siloes with more adaptive, integrated, multilevel, and flexible governance approaches, and with inclusive decision making that can operate successfully across multiple scales—or adaptive governance and co-management—will enhance adaptive capacity and the effectives of the adaptation response (Folke et al., 2005; Olsson et al., 2006; Koch et al., 2007; Berkes, 2009; Pahl-Wostl, 2009; Armitage and Plummer, 2010; Bunce et al., 2010a; Plummer, 2012). Despite some progress with developing the institutional framework for governing adaptation, there are significant problems with both transversal and vertical coordination, including institutional duplication with other intersectoral platforms, such as disaster risk reduction; while in fragile states, institutions for reducing climate risk and promoting adaptation may be extremely weak or almost nonexistent (Hartmann and Sugulle, 2009; Sietz et al., 2011; Simane et al., 2012). Facilitating institutional linkages and coordinating responses across all boundaries of government, private sector, and civil society would enhance adaptive capacity (Brown et al., 2010). Resolving well-documented institutional challenges of natural resource management, including lack of coordination, monitoring, and enforcement, is a fundamental step toward more effective climate governance. For example, concerning groundwater, developing organizational frameworks and strengthening institutional capacities for more effectively assessing and managing groundwater resources over the long term are critically important (Nyenje and Batelaan, 2009; Braune and Xu, 2010).

22.4.4.4. Subnational Adaptation Governance

Since AR4, there has been additional effort on subnational adaptation planning in African countries, but adaptation strategies at provincial and municipal levels are mostly still under development, with many local governments lacking the capacity and resources for the necessary decentralized adaptation response (*high confidence*). Provinces in some countries have developed policies and strategies on climate change: for example, Lagos State's 2012 Adaptation Strategy in Nigeria (BNRCC, 2012); mainstreaming adaptation into district development plans in Ghana; and communal climate resilience plans in Morocco (Corsi et al., 2012). Promising approaches include subnational strategies that integrate adaptation and mitigation for low-carbon climate-resilient development, as is being done in Delta State in Nigeria, and in other countries (UNDP, 2011a). In response to the identified institutional weaknesses, capacity development has been implemented in many cities and towns, including initiatives in Lagos, Nigeria, and Durban and Cape Town in South Africa: notable examples include Maputo's specialized local government unit to implement climate change response, ecosystem-based adaptation and improved city wetlands; and participatory skills development in integrating community-based disaster risk reduction and climate adaptation into local development planning in Ethiopia (Madzwamuse, 2010; ACCRA, 2012; Castán Broto et al., 2013).

22.4.4.5. Community-Based Adaptation and Local Institutions

Since AR4, there has been progress in Africa in implementing and researching community-based adaptation (*high confidence*), with broad agreement that support to local-level adaptation is best achieved by starting with existing local adaptive capacity, and incorporating and building upon present coping strategies and norms, including indigenous practices (Dube and Sekhwela, 2007; Archer et al., 2008; Huq, 2011). Community-based adaptation is community initiated, and/or draws upon community knowledge or resources (see Glossary). Some relevant initiatives include the Community-Based Adaptation in Africa (CBAA) project, which implemented community-level pilot projects in eight African countries (Sudan, Tanzania, Uganda, Zambia, Malawi, Kenya, Zimbabwe, South Africa) through a learning-by-doing approach; the Adaptation Learning Program, implemented in Ghana, Niger, Kenya, and Mozambique (CARE International, 2012b); and UNESCO Biosphere Reserves, where good practices were developed in Ethiopia, Kenya, South Africa, and Senegal (German Commission for UNESCO, 2011). See Section 22.4.5.6 on institutions for community-based adaptation. The literature includes a wide range of case studies detailing involvement of local communities in adaptation initiatives and projects facilitated by non-governmental organizations (NGOs) and researchers (e.g., Leary et al., 2008a; CCAA, 2011; CARE International, 2012b; Chishakwe et al., 2012); these and other initiatives have generated process-related lessons (Section 22.4.5), with positive assessments of effectiveness in improving adaptive capacity of African communities, local organizations, and researchers (Lafontaine et al., 2012).

The key role for local institutions in enabling community resilience to climate change has been recognized, particularly with respect to natural resource dependent communities—for example, the role of NGOs and community-based organizations in catalyzing agricultural adaptation or in building resilience through enhanced forest governance and sustainable management of non-timber forest products; institutions for managing access to and tenure of land and other natural resources, which are vital assets for the rural and peri-urban poor, are particularly crucial for enabling community-based adaptation and enhancing adaptive capacity in Africa (Bryan et al., 2009; Brown et al., 2010; Mogoi et al., 2010). Local studies and adaptation planning have revealed the following priorities for pro-poor adaptation: social protection, social services, and safety nets; better water and land governance; action research to improve resilience of under-researched food crops of poor people; enhanced water storage and harvesting; better post-harvest services; strengthened civil society and greater involvement in planning; and more attention to urban and peri-urban areas heavily affected by migration of poor people (Moser and Satterthwaite, 2008; Urquhart, 2009; Bizikova et al., 2010).

22.4.4.6. Adaptation Decision Making and Monitoring

Emerging patterns in Africa regarding adaptation decision making, a critical component of adaptive capacity, include limited inclusive governance at the national level, with greater involvement in local initiatives of vulnerable and exposed people in assessing and choosing adaptation responses (*high confidence*). Civil society institutions and communities have to date played a limited role in formulation of national adaptation policies and strategies, highlighting the need for governments to widen the political space for citizens and institutions to participate in decision making, for both effectiveness and to ensure rights are met (Madzwamuse, 2010; Castro et al., 2012). Building African leadership for climate change may assist with this (CCAA, 2011; Chandani, 2011; Corsi et al., 2012). A critical issue is how planning and decision making for adaptation uses scientific evidence and projections, while also managing the uncertainties within the projections (Conway, 2011; Dodman and Carmin, 2011).

A range of tools has been used in adaptation planning in Africa, including vulnerability assessment (Section 22.4.5), risk assessment, cost-benefit analysis, cost-effectiveness, multi-criteria analysis, and participatory scenario planning (see, e.g., Cartwright et al., 2008; Kemp-Benedict and Agyemang-Bonsu, 2008; Njie et al., 2008; Mather and Stretch, 2012), but further development and uptake of decision tools would facilitate enhanced decision making. A related point is that monitoring and assessing adaptation is still relatively undeveloped in Africa, with national coordinating systems for collating data and synthesizing lessons not in place. Approaches for assessing adaptation action at local and regional levels have been developed (see, e.g., Hahn et al., 2009; Gbetibouo et al., 2010a; Below et al., 2012), while there are positive examples of local monitoring of adaptation at the project level (see, e.g., Archer et al., 2008; Below et al., 2012). Chapter 2 contains additional discussion of the foundations for decision making on climate change matters.

22.4.5. Experiences with Adaptation Measures in Africa and Lessons Learned

22.4.5.1. Overview

Section 22.4.5 provides a cross-cutting assessment of experience gained with a range of adaptation approaches, encompassing climate risk reduction measures; processes for participatory learning and knowledge development and sharing; communication, education, and training; ecosystem-based measures; and technological and infrastructural approaches; and concludes with a discussion of maladaptation.

Common priority sectors across countries for implementing adaptation measures since 2008 include agriculture, food security, forestry, energy, water, and education (Corsi et al., 2012), which reflects a broadening of focus since the AR4. While there has been little planning focus on regional adaptation (Sections 22.4.4.2-3), the potential for this has been recognized (UNFCCC, 2007; Sonwa et al., 2009; Niang, 2012).

Attention is increasing on identifying opportunities inherent in the continent's adaptation needs, as well as delineating key success factors for adaptation. A number of studies identify the opportunity inherent in implementing relatively low-cost and simple low-regrets adaptation measures that reduce people's vulnerability to current climate variability, have multiple developmental benefits, and are well-positioned to reduce vulnerability to longer-term climate change as well (UNFCCC, 2007; Conway and Schipper, 2011; see also Section 22.4.3). Responding to climate change provides an opportunity to enhance awareness that maintaining ecosystem functioning underpins human survival and development in a most fundamental way (Shackleton and Shackleton, 2012), and to motivate for new development trajectories (Section 22.4.6). While it is difficult to assess adaptation success, given temporal and spatial scale issues, and local specificities, Osbahr et al. (2010) highlight the role of social networks and institutions, social resilience, and innovation as possible key success factors for adaptation in small-scale farming livelihoods in southern Africa. Kalame et al. (2008) note opportunities for enhancing adaptation through forest governance reforms to improve community access to forest resources, while Martens et al. (2009) emphasize the importance of "soft path" measures for adaptation strategies (see also Section 22.4.5.6).

The following discussion of adaptation approaches under discrete headings does not imply that these are mutually exclusive—adaptation initiatives usually employ a range of approaches simultaneously and, indeed, the literature increasingly recognizes the importance of this for building resilience.

22.4.5.2. Climate Risk Reduction, Risk Transfer, and Livelihood Diversification

Risk reduction strategies used in African countries to offset the impacts of natural hazards on individual households, communities, and the wider economy include early warning systems, emerging risk transfer schemes, social safety nets, disaster risk contingency funds and budgeting, livelihood diversification, and migration (World Bank, 2010; UNISDR, 2011).

Disaster risk reduction (DRR) platforms are being built at national and local levels, with the synergies between DRR and adaptation to climate change being increasingly recognized in Africa (Westgate, 2010; UNISDR, 2011; Hunde, 2012); however, Conway and Schipper (2011) find that additional effort is needed for a longer-term vulnerability reduction perspective in disaster management institutions.

Early warning systems (EWS) are gaining prominence as multiple stakeholders strengthen capabilities to assess and monitor risks and warn communities of a potential crisis, through regional systems such as the Permanent Inter-States Committee for Drought Control in the Sahel (CILSS) and the Famine Early Warning System Network (FEWS NET), as well as national, local, and community-based EWS on for example food and agriculture (Pantuliano and Wekesa, 2008; FAO, 2011; Sissoko et al., 2011). Some of the recent EWSs emphasize a gendered approach, and may incorporate local knowledge systems used for making short-, medium-, and long-term decisions about farming and livestock-keeping, as in Kenya (UNDP, 2011b). The health sector has employed EWS used to predict disease for adaptation planning and implementation, such as the prediction of conditions expected to lead to an outbreak of Rift Valley fever in the Horn of Africa in 2006/2007 (Anyamba et al., 2010). Progress has been made in prediction of meningitis and in linking climate/weather variability and extremes to the disease (Thomson et al., 2006; Cuevas et al., 2007).

Local projects often use participatory vulnerability assessment or screening to design adaptation strategies (van Vliet, 2010; GEF Evaluation Office, 2011; Hambira, 2011), but vulnerability assessment at the local government level is often lacking, and assessments to develop national adaptation plans and strategies have not always been conducted in a participatory fashion (Madzwamuse, 2010). Kienberger (2012) details spatial modeling of social and economic vulnerability to floods at the district level in Búzi, Mozambique. Lessons from vulnerability analysis highlight that the highest exposure and risk do not always correlate with vulnerable ecosystems, socially marginalized groups, and areas with at-risk infrastructure, but may also lie in unexpected segments of the population (Moench, 2011).

Community-level DRR initiatives include activities that link food security, household resilience, environmental conservation, asset creation, and infrastructure development objectives and co-benefits (Parry et al., 2009a; UNISDR, 2011; Frankenberger et al., 2012). Food security and nutrition-related safety nets and social protection mechanisms can mutually reinforce each other for DRR that promotes adaptation, as in Uganda's Karamoja Productive Assets Program (Government of Uganda and WFP, 2010; WFP, 2011). Initiatives in Kenya, South Africa, Swaziland, and Tanzania have also sought to deploy local and traditional knowledge for the purposes of disaster preparedness and risk management (Mwaura, 2008; Galloway McLean, 2010). Haan et al. (2012) highlight the need for increased donor commitment to the resilience-building agenda within the framework of DRR, based on lessons from the 2011 famine in Somalia.

Social protection,[8] a key element of the African Union social policy framework, is being increasingly used in Ethiopia, Rwanda, Malawi, Mozambique, South Africa, and other countries to buffer against shocks by building assets and increasing resilience of chronically and transiently poor households; in some cases this surpasses repeated relief interventions to address slower onset climate shocks, as in Ethiopia's Productive Safety Net Program (Brown et al., 2007; Heltberg et al., 2009). While social protection is helping with *ex post* and *ex ante* DRR and will be increasingly important for securing livelihoods should climate variability increase, less evidence exists for its effectiveness against the most extreme climatic shocks associated with higher emissions scenarios, which would require reducing dependence on climate-sensitive livelihood activities (Davies et al., 2009; Wiseman et al., 2009; Pelham et al., 2011; Béné et al., 2012). Social protection could further build adaptive capacity if based on improved understanding of the structural causes of poverty, including political and institutional dimensions (Brown et al., 2007; Davies et al., 2009; Levine et al., 2011).

Risk spreading mechanisms used in the African context include kinship networks; community funds; and disaster relief and insurance, which

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[8] Social protection can include social transfers (cash or food), minimum standards such as for child labor, and social insurance.

Box 22-1 | Experience with Index-Based Weather Insurance in Africa

Malawi's initial experience of dealing with drought risk through index-based weather insurance directly to smallholders appears positive: 892 farmers purchased the insurance in the first trial period, which was bundled with a loan for groundnut production inputs (Hellmuth et al., 2009). In the next year, the pilot expanded, with the addition of maize, taking numbers up to 1710 farmers and stimulating interest among banks, financiers, and supply chain participants such as processing and trading companies and input suppliers. A pilot insurance project in Ethiopia was designed to pay claims to the government based on a drought index that uses a time window between observed lack of rain and actual materialization of losses. This allows stakeholders to address threats to food security in ways that prevent the depletion of farmers' productive assets, which reduces the future demand for humanitarian aid by enabling households to produce more food during subsequent seasons (Krishnamurty, 2011). Another key innovation in Ethiopia is the insurance for work program that allows cash-poor farmers to work for their insurance premiums by engaging in community-identified disaster risk reduction products, such as soil management and improved irrigation (WFP, 2011), which makes insurance affordable to the most marginalized and resource-poor sectors of society.

can provide financial security against extreme events such as droughts, floods, and tropical cyclones, and concurrently reduce poverty and enhance adaptive capacity[9] (Leary et al., 2008a; Linnerooth-Bayer et al., 2009; Coe and Stern, 2011). Recent developments include the emergence of index-based insurance contracts (Box 22-1), which pay out not with the actual loss, but with a measurable event that could cause loss.

The challenges associated with current risk reduction strategies include political and institutional challenges in translating early warning into early action (Bailey, 2013); communication challenges related to EWS; conveying useful information in local languages and communicating EWS in remote areas; national-level mistrust of locally collected data, which are perceived to be inflated to leverage more relief resources (Hellmuth et al., 2007; Cartwright et al., 2008; Pantuliano and Wekesa, 2008; FAO, 2011); the call for improved user-friendliness of early warning information, including at smaller spatial scales; the need for increased capacity in national meteorological centers (Section 22.4.2); and the need for better linkages between early warning, response, and prevention (Haan et al., 2012).

Evidence is increasing that livelihood diversification, long used by African households to cope with climate shocks, can also assist with building resilience for longer term climate change by spreading risk. Over the past 20 years, households in the Sahel have reduced their vulnerability and increased their wealth through livelihood diversification, particularly when diversifying out of agriculture (Mertz et al., 2011). Households may employ a range of strategies, including on-farm diversification or specialization (Sissoko et al., 2011; Tacoli, 2011). Motsholapheko et al. (2011) show how livelihood diversification is used as an adaptation to flooding in the Okavango Delta, Botswana, and Badjeck et al. (2010) recommend private and public insurance schemes to help fishing communities rebuild after extreme events, and education and skills upgrading to enable broader choices when fishery activities can no longer be sustained. See Chapter 9 for a fuller discussion of the role of livelihood diversification in adaptation, particularly Sections 9.3.3.1 and 9.3.5.2. Remittances are a longstanding and important means of reducing risk to climate variability and other household stressors, and of contributing to recovery from climatic shocks, as further discussed in Chapter 9 (Sections 9.3.3.3, 9.3.5.2).

While livelihood diversification is an important adaptation strategy, it may replace formerly sustainable practices with livelihood activities that have negative environmental impacts (Section 22.4.5.8).

Rural finance and micro-credit can be enabling activities for adaptive response, which are also used by women for resilience-building activities (e.g., as documented in Sudan by Osman-Elasha et al., 2008). Credit and storage systems are instrumental in supporting families during the lean period, to prevent the sale of assets to buy food when market prices are higher (Romero González et al., 2011). Long seen as a fundamental process for most African families to incorporate choice into their risk profile and adapt to climate variability (Goldstone, 2002; Urdal, 2005; Reuveny, 2007; Fox and Hoelscher, 2010), there is evidence in some areas of the increased importance of migration (discussed in Sections 8.2, 9.3.3.3, 12.4, 22.6.1) and trade for livelihood strategies, as opposed to subsistence agriculture, as shown by Mertz et al. (2011) for the Sudano-Sahelian region of West Africa.

22.4.5.3. Adaptation as a Participatory Learning Process

Since AR4, there has been more focus on the importance of flexible and iterative learning approaches for effective adaptation (*medium evidence*, *high agreement*). Owing to the variety of intersecting social, environmental, and economic factors that affect societal adaptation, governments, communities, and individuals (Jones et al., 2010; Jones,

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[9] Climate (or disaster) risk financing instruments include contingency funds, agricultural and property (private) insurance, sovereign insurance, reallocation of program expenditures, weather derivatives, and bonds.

2012), adaptation is increasingly recognized as a complex process involving multiple linked steps at several scales, rather than a series of simple planned technical interventions (Moser and Ekstrom, 2010). Implementing adaptation as a participatory learning process enables people to adopt a proactive or anticipatory stance to avoid "learning by shock" (Tschakert and Dietrich, 2010).

Iterative and experiential learning allows for flexible adaptation planning, appropriate considering the uncertainty inherent in climate projections that is compounded by other sources of flux affecting populations in Africa (Suarez et al., 2008; Dodman and Carmin, 2011; Huq, 2011; Koelle and Annecke, 2011). Many studies have highlighted the utility of participatory action research, social and experiential learning, and creating enabling spaces for multi-stakeholder dialog for managing uncertainty and unlocking the social and behavioral change required for adaptation (e.g., Tompkins and Adger, 2003; Bizikova et al., 2010; Tschakert and Dietrich, 2010; Ziervogel and Opere, 2010; CCAA, 2011; Ebi et al., 2011; Thorn, 2011; UNDP-UNEP Poverty-Environment Initiative, 2011b; Faysse et al., 2013). Transdisciplinary approaches, which hold promise for enhancing linkages between sectors and thus reducing maladaptation are also starting to be adopted, as for example in the urban context (Evans, 2011). Learning approaches for adaptation may involve co-production of knowledge—such as combining local and traditional knowledge with scientific knowledge (Section 22.4.5.4).

Adaptive co-management[10] holds potential to develop capacity to deal with change (Watkiss et al., 2010; Plummer, 2012); the implications of strategic adaptive management for adaptation in aquatic protected areas in South Africa are being explored (Kingsford et al., 2011).

Caveats and constraints to viewing adaptation as a participatory learning process include the time and resources required from both local actors and external facilitators, the challenges of multidisciplinary research, the politics of stakeholder participation and the effects of power imbalances, and the need to consider not only the consensus approach but also the role of conflicts (Aylett, 2010; Tschakert and Dietrich, 2010; Beardon and Newman, 2011; Jobbins, 2011; Shankland and Chambote, 2011). Learning throughout the adaptation process necessitates additional emphasis on ways of sharing experiences between communities and other stakeholders, both horizontally and vertically (Section 22.4.5.4). Information and communication technologies, including mobile phones, radio, and the internet, can play a role in facilitating participatory learning processes and helping to overcome some of the challenges (Harvey et al., 2012).

The increased emphasis on the importance of innovation for successful adaptation, in both rural and urban contexts, relates to interventions that employ innovative methods, as well as the innovation role of institutions (Tschakert and Dietrich, 2010; Dodman and Carmin, 2011; Rodima-Taylor, 2012; Scheffran et al., 2012). Scheffran et al. (2012) demonstrate how migrant social organizations in the western Sahel initiate innovations across regions by transferring technology and knowledge, as well as remittances and resources. While relevant high-quality data is important as a basis for adaptation planning, innovative methods are being used to overcome data gaps, particularly local climatic data and analysis capability (Tschakert and Dietrich, 2010; GEF Evaluation Office, 2011).

22.4.5.4. Knowledge Development and Sharing

Recent literature has confirmed the positive role of local and traditional knowledge in building resilience and adaptive capacity, and shaping responses to climatic variability and change in Africa (Nyong et al., 2007; Osbahr et al., 2007; Goulden et al., 2009b; Ifejika Speranza et al., 2010; Jalloh et al., 2011b; Newsham and Thomas, 2011). This is particularly so at the community scale, where there may be limited access to, quality of, or ability to use scientific information. The recent report on extreme events and disasters (IPCC, 2012) supports this view, finding *robust evidence* and *high agreement* of the positive impacts of integrating indigenous and scientific knowledge for adaptation. Concerns about the future adequacy of local knowledge to respond to climate impacts within the multi-stressor context include the decline in intergenerational transmission; a perceived decline in the reliability of local indicators for variability and change, as a result of sociocultural, environmental, and climate changes (Hitchcock 2009; Jennings and Magrath 2009); and challenges of the emerging and anticipated climatic changes seeming to overrun indigenous knowledge and coping mechanisms of farmers (Berkes, 2009; Ifejika Speranza et al., 2010; Jalloh et al., 2011b; see also Section 22.4.6). Based on analysis of the responses to the Sahel droughts during the 1970s and 1980s, Mortimore (2010) argues that local knowledge systems are more dynamic and robust than is often acknowledged. Linking indigenous and conventional climate observations can add value to climate change adaptation within different local communities in Africa (Roncoli et al., 2002; Nyong et al., 2007; Chang'a et al., 2010; Guthiga and Newsham, 2011).

Choosing specific adaptation actions that are informed by users' perceptions and supported by accurate climate information, relevant to the scale where decisions are made, would be supportive of the largely autonomous adaptation taking place in Africa (Vogel and O'Brien, 2006; Ziervogel et al., 2008; Bryan et al., 2009; Godfrey et al., 2010). Key problems regarding how science can inform decision making and policy are how best to match scientific information, for example about uncertainty of change, with decision needs; how to tailor information to different constituencies; and what criteria to use to assess whether or not information is legitimate to influence policy and decision making (Vogel et al., 2007; Hirsch Hadorn et al., 2008). Institutional innovation is one solution; for example, Nigeria established the Science Committee on Climate Change to develop strategies to bridge the gap between increasing scientific knowledge and policy (Corsi et al., 2012).

There is agreement that culture—or the shaping social norms, values, and rules including those related to ethnicity, class, gender, health, age, social status, cast, and hierarchy—is of crucial importance for adaptive capacity as a positive attribute but also as a barrier to successful local adaptation (Section 22.4.6); further research is required in this field, not

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[9] Adaptive co-management is understood as "a process by which institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of learning-by-doing" (Folke et al., 2002).

least because culture is highly heterogeneous within a society or locality (Adger et al., 2007, 2009; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Jones, 2012). Studies show that, while it is important to develop further the evidence base for the effectiveness of traditional knowledge, integrating cultural components such as stories, myths, and oral history into initiatives to document local and traditional knowledge on adaptive or coping mechanisms is a key to better understanding how climate vulnerability and adaptation are framed and experienced (Urquhart, 2009; Beardon and Newman, 2011; Ford et al., 2012). Appropriate and equitable processes of participation and communication between scientists and local people have been found to prevent misuse or misappropriation of local and scientific knowledge (Nyong et al., 2007; Crane, 2010; Orlove et al., 2010).

While multi-stakeholder platforms promote collaborative adaptation responses (CARE International, 2012a), adaptation initiatives in Africa lack comprehensive, institutionalized, and proactive systems for knowledge sharing (GEF Evaluation Office, 2011; AAP, 2012).

22.4.5.5. Communication, Education, and Capacity Development

Capacity development and awareness raising to enhance understanding of climate impacts and adaptation competencies and engender behavioral change have been undertaken through civil society-driven approaches or by institutions, such as regional and national research institutes, international and national programs and non-governmental organizations (UNFCCC, 2007; Reid et al., 2010; CCAA, 2011; START International, 2011; Figueiredo and Perkins, 2012). Promising examples include youth ambassadors in Lesotho and civil society organizations in Tanzania (Corsi et al., 2012), and children as effective communicators and advocates for adaptation-related behavioral and policy change (Section 22.4.3). Progress on inclusion of climate change into formal education is mixed, occurring within the relatively low priority given to environmental education in most countries (UNFCCC, 2007; Corsi et al., 2012; Mukute et al., 2012).

Innovative methods used to communicate climate change include participatory video, photo stories, oral history videos, vernacular drama, radio, television, and festivals, with an emphasis on the important role of the media (Suarez et al., 2008; Harvey, 2011; Chikapa, 2012; Corsi et al., 2012). Better evidence-based communication processes will enhance awareness raising of the diverse range of stakeholders at all levels on the different aspects of climate change (Niang, 2007; Simane et al., 2012). A better understanding of the dimensions of the problem could be achieved by bringing together multiple users and producers of scientific and local knowledge in a transdisciplinary process (Vogel et al., 2007; Hirsch Hadorn et al., 2008; Ziervogel et al., 2008; Koné et al., 2011).

22.4.5.6. Ecosystem Services, Biodiversity, and Natural Resource Management

Africa's longstanding experiences with natural resource management, biodiversity use, and ecosystem-based responses such as afforestation, rangeland regeneration, catchment rehabilitation, and community-based natural resource management (CBNRM) can be harnessed to develop effective and ecologically sustainable local adaptation strategies (*high confidence*). Relevant specific experiences include using mobile grazing to deal with both spatial and temporal rainfall variability in the Sahel (Djoudi et al., 2013); reducing the negative impacts of drought and floods on agricultural and livestock-based livelihoods through forest goods and services in Mali, Tanzania, and Zambia (Robledo et al., 2012); and ensuring food security and improved livelihoods for indigenous and local communities in West and Central Africa through the rich diversity of plant and animal genetic resources (Jalloh et al., 2011b).

Box 22-2 | African Success Story: Integrating Trees into Annual Cropping Systems

Recent success stories from smallholder systems in Africa illustrate the potential for transforming degraded agricultural landscapes into more productive, sustainable, and resilient systems by integrating trees into annual cropping systems. For example, in Zambia and Malawi, an integrated strategy for replenishing soil fertility on degraded lands, which combines planting of nitrogen-fixing *Faidherbia* trees with small doses of mineral fertilizers, has consistently more than doubled yields of maize leading to increased food security and greater income generation (Garrity et al., 2010). In the Sahel, natural regeneration, or the traditional selection and protection of small trees to maturity by farmers and herders has, perhaps for centuries, produced extensive parks of *Acacia albida* (winter thorn) in Senegal (Lericollais, 1989), *Adansonia digitata* (baobab) in West and southern Africa (Sanchez et al., 2011), and *Butyrospermum parkii* (shea butter) in Burkina Faso (Gijsbers et al., 1994). Recent natural regeneration efforts have increased tree density and species richness at locations in Burkina Faso (Ræbild et al., 2012) and Niger (Larwanou and Saadou, 2011), though adoption and success is somewhat dependent on soil type (Haglund et al., 2011; Larwanou and Saadou, 2011). In southern Niger, farmer-managed natural regeneration of *Faidherbia albida* and other field trees, which began in earnest in the late 1980s, has led to large-scale increase in tree cover across 4.8 million ha, and to decreased sensitivity to drought of the production systems, compared to other regions in Niger (Reij et al., 2009; Tougiani et al., 2009; Sendzimir et al., 2011).

Natural resource management (NRM) practices that improve ecosystem resilience can serve as proactive, low-regrets adaptation strategies for vulnerable livelihoods (*high confidence*). Two relevant widespread dual-benefit practices, developed to address desertification, are natural regeneration of local trees (see Box 22-2) and water harvesting. Water harvesting practices[11] have increased soil organic matter, improved soil structure, and increased agricultural yields at sites in Burkina Faso, Mali, Niger, and elsewhere, and are used by 60% of farmers in one area of Burkina Faso (Barbier et al., 2009; Fatondji et al., 2009; Vohland and Barry, 2009; Larwanou and Saadou, 2011). Although these and other practices serve as adaptations to climate change, revenue generation and other concerns may outweigh climate change as a motivating factor in their adoption (Mertz et al., 2009; Nielsen and Reenberg, 2010). While destocking of livestock during drought periods may also address desertification and adaptation, the lack of individual incentives and marketing mechanisms to destock and other cultural barriers inhibit their widespread adoption in the Sahel (Hein et al., 2009; Nielsen and Reenberg, 2010). Despite these provisos and other constraints (see, e.g., Nelson and Agrawal, 2008; Section 22.4.6 further highlights local-level institutional constraints), local stakeholder institutions for CBNRM do enable a more flexible response to changing climatic conditions; CBNRM is also a vehicle for improving links between ecosystem services and poverty reduction, to enable sustainable adaptation approaches (Shackleton et al., 2010; Chishakwe et al., 2012; Girot et al., 2012). Based on lessons learned in Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe, Chishakwe et al. (2012) point out the synergies between CBNRM and adaptation at the community level, notwithstanding institutional and other constraints experienced with CBNRM.

Differentiation in the literature is growing between "hard path" and "soft path" approaches to adaptation (Kundzewicz, 2011; Sovacool, 2011)—with "soft path," low-regrets approaches, such as using intact wetlands for flood risk management, often the first line of defense for poor people in Africa, as contrasted with "hard path" approaches such as dams and embankments for flood control (McCully, 2007; Kundzewicz, 2011). Intact ecosystem services and biodiversity are recognized as critical components of successful human adaptation to climate change that may be more effective and incur lower costs than "hard" or engineered solutions (Abramovitz et al., 2002; Petersen and Holness, 2011; UNDP-UNEP Poverty-Environment Initiative, 2011a; Girot et al., 2012; Pramova et al., 2012; Roberts et al., 2012; Box 22-2). This provides a compelling reason for linking biodiversity, developmental, and social goals, as taken up, for example, in Djibouti's NAPA project on mangrove restoration to reduce saltwater intrusion and coastal production losses due to climate hazards (Pramova et al., 2012).

The emerging global concept of ecosystem-based adaptation (EbA) provides a system-oriented approach for Africa's longstanding local NRM practices. Despite the evidence from studies cited in this section, scaling-up to prioritize ecosystem responses and EbA in plans and policy has been slow; a broad understanding that EbA is an integral component of the developmental agenda, rather than a competing "green" agenda, would promote this process. Adaptive environmental governance represents one of the future challenges for the implementation of EbA strategies in Africa, together with sustainable use of resources, secure access to meet needs under climate change, and strong local institutions to enable this (Robledo et al., 2012). Ecosystem-based adaptation could be an important approach to consider for the globally significant Congo Basin forests, particularly given the predominance of REDD+ approaches for this region that risk neglecting adaptation responses, or may result in maladaptation (Somorin et al., 2012; Sonwa et al., 2012; see also Sections 22.4.5.8, 22.6.2). Ecosystem-based approaches are further discussed in Chapter 4 and Box CC-EA.

22.4.5.7. Technological and Infrastructural Adaptation Responses

Since AR4, experience has been gained on technological and infrastructural adaptation in agricultural and water management responses, for climate-proofing infrastructure, and for improved food storage and management to reduce post-harvest losses; this has been increasingly in conjunction with "soft" measures.

There is increased evidence that farmers are changing their production practices in response to increased food security risks linked to climate change and variability, through both technical and behavioral means. Examples include planting cereal crop varieties that are better suited to shorter and more variable growing seasons (Akullo et al., 2007; Thomas et al., 2007; Yesuf et al., 2008; Yaro, 2010; Laube et al., 2012), constructing bunds to more effectively capture rainwater and reduce soil erosion (Nyssen et al., 2007; Thomas et al., 2007; Reij et al., 2009), reduced tillage practices and crop residue management to more effectively bridge dry spells (Ngigi et al., 2006; Marongwe et al., 2011), and adjusting planting dates to match shifts in the timing of rainfall (Abou-Hadid, 2006; Vincent et al., 2011b).

Conservation agriculture has good potential to both bolster food production and enable better management of climate risks (*high confidence*) (Verchot et al., 2007; Thomas, 2008; Syampungani et al., 2010; Thierfelder and Wall, 2010; Kassam et al., 2012). Such practices—which include conservation/zero tillage, soil incorporation of crop residues and green manures, building of stone bunds, agroforestry, and afforestation/reforestation of croplands—reduce runoff and protect soils from erosion, increase rainwater capture and soil water-holding capacity, replenish soil fertility, and increase carbon storage in agricultural landscapes. Conservation agriculture systems have potential to lower the costs of tillage and weed control with subsequent increase in net returns, as found in Malawi by Ngwira et al. (2012).

Expansion of irrigation in sub-Saharan Africa holds significant potential for spurring agricultural growth while also better managing water deficiency risks associated with climate change (Dillon, 2011; You et al., 2011). Embedding irrigation expansion within systems-level planning that considers the multi-stressor context in which irrigation expansion is occurring can help to ensure that efforts to promote irrigation can be

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[10] Water harvesting refers to a collection of traditional practices in which farmers use small planting pits, half-moon berms, rock bunds along contours, and other structures to capture runoff from episodic rain events (Kandji et al., 2006).

sustained and do not instead generate a new set of hurdles for producers or engender conflict (van de Giesen et al., 2010; Burney and Naylor, 2012; Laube et al., 2012). Suitable approaches to expand irrigation in Africa include using low-pressure drip irrigation technologies and construction of small reservoirs, both of which can help to foster diversification toward irrigated high-value horticultural crops (Karlberg et al., 2007; Woltering et al., 2011; Biazin et al., 2012). If drought risk increases and rainfall patterns change, adaptation in agricultural water management would be enhanced through a strategic approach that encompasses overall water use efficiency for both rainfed and irrigated production (Weiß et al., 2009), embeds irrigation expansion efforts within a larger rural development context that includes increased access to agricultural inputs and markets (You et al., 2011; Burney and Naylor, 2012), and that involves an integrated suite of options (e.g., plant breeding and improved pest and disease and soil fertility management, and *in situ* rainwater harvesting) to increase water productivity (Passioura, 2006; Biazin et al., 2012).

Experience has been gained since the AR4 on adaptation of infrastructure (transportation, buildings, food storage, coastal), with evidence that this can sometimes be achieved at low cost, and additional implementation of soft measures such as building codes and zone planning (UNFCCC, 2007; Halsnæs and and Trarup, 2009; Urquhart, 2009; UN-HABITAT and UNEP, 2010; AfDB, 2011; Mosha, 2011; Siegel, 2011; Corsi et al., 2012). Examples of adaptation actions for road and transportation infrastructure include submersible roads in Madagascar and building dikes to avoid flooding in Djibouti (UNFCCC, 2007; Urquhart, 2009). Infrastructural climate change impact assessments and enhanced construction and infrastructural standards—such as raising foundations of buildings, strengthening roads, and increasing stormwater drainage capacity—are steps to safeguard buildings in vulnerable locations or with inadequate construction (UN-HABITAT and UNEP, 2010; Mosha, 2011; Corsi et al., 2012). Mainstreaming adaptation into infrastructure development can be achieved at low cost, as has been shown for flood-prone roads in Mozambique (Halsnæs and and Trarup, 2009). Integrating climate change considerations into infrastructure at the design stage is preferable from a cost and feasibility perspective than trying to retrofit infrastructure (Chigwada, 2005; Siegel, 2011). Softer measures, such as building codes and zone planning are being implemented and are needed to complement and/or provide strategic guidance for hard infrastructural climate proofing, for example, the adoption of cyclone-resistant standards for public buildings in Madagascar (AfDB, 2011). Research in South Africa has recognized that the best option for adaptation in the coastal zone is not to combat coastal erosion in the long term, but rather to allow progression of the natural processes (Naidu et al., 2006; Zitholele Consulting, 2009).

Reducing post-harvest losses through improved food storage, food preservation, greater access to processing facilities, and improved systems of transportation to markets are important means to enhance food security (Brown et al., 2009; Godfray et al., 2010; Codjoe and Owusu, 2011). Low cost farm-level storage options, such as metal silos (Tefera et al., 2011) and triple-sealed plastic bags (Baoua et al., 2012), are effective for reducing post-harvest losses from pests and pathogens. Better storage allows farmers greater flexibility in when they sell their grain, with related income benefits (Brown et al., 2009), and reduces post-harvest infection of grain by aflatoxins, which is widespread in Africa and increases with drought stress and high humidity during storage (Cotty and Jaime-Garcia, 2007; Shephard, 2008).

22.4.5.8. Maladaptation Risks

The literature increasingly highlights the need, when designing development or adaptation research, policies, and initiatives, to adopt a longer-term view and to consider the multi-stressor context in which people live, in order to avoid maladaptation, or outcomes that may serve short-term goals but come with future costs to society (see Glossary). The short-term nature of policy and other interventions, especially if they favor economic growth and modernization over resilience and human security, may themselves act as stressors or allow people to react only to short-term climate variability (Brooks et al., 2009; Bryan et al., 2009; Bunce et al., 2010a; Levine et al., 2011). The political context can also undermine autonomous adaptation and lead to maladaptation; for instance, Smucker and Wisner (2008) found that political and economic changes in Kenya meant that farmers could no longer use traditional strategies for coping with climatic shocks and stressors, with the poorest increasingly having to resort to coping strategies that undermined their long-term livelihood security, also known as erosive coping, such as more intensive grazing of livestock and shorter crop rotations (van der Geest and Dietz, 2004). In a case from the Simiyu wetlands in Tanzania, Hamisi et al. (2012) find that coping and reactive adaptation strategies may lead to maladaptation—for instance, through negative impacts on natural vegetation because of increased intensity of farming in wetter parts of the floodplain, where farmers have moved to exploit the higher soil water content.

Some diversification strategies, such as charcoal production and artisanal mining, may increase risk through promoting ecological change and the loss of ecosystem services to fall back on (Paavola, 2008; Adger et al., 2011; Shackleton and Shackleton, 2012). Studies also highlight risks that traditional adaptive pastoralism systems may be replaced by maladaptive activities. For example, charcoal production has become a major source of income for 70% of poor and middle-income pastoralists in some areas of Somaliland, with resultant deforestation (Hartmann and Sugulle, 2009).

Another example of maladaptation provided in the literature is the potential long-term hydro-dependency risks and threats to ecosystem health and community resilience as a result of increased dam building in Africa, which may be underpinned by policies of multilateral donors (Avery, 2012; Beilfuss, 2012; Jones et al., 2012). While increased rainwater storage will assist with buffering dry periods, and hydropower can play a key role in ending energy poverty, it is important that this is designed to promote environmental and social sustainability; that costs and benefits are equitably shared; and that water storage and energy generation infrastructure is itself climate-proofed. Additional substantive review of such international development projects would assist in assuring that these do not result in maladaptation.

See Chapter 4 for a discussion of the unwanted consequences of building more and larger impoundments and increased water abstraction on terrestrial and freshwater ecosystems; health aspects of this are noted in Sections 22.3.5.1 and 22.3.5.4. See Section 22.6.2 on avoiding undesirable trade-offs between REDD+ approaches and adaptation that have the potential to result in significant maladaptation.

22.4.6. Barriers and Limits to Adaptation in Africa

A complex web of interacting barriers to local-level adaptation exists that manifests from national to local scales to constrain adaptation, which includes institutional, political, social, cultural, biophysical, cognitive, behavioral, and gender-related aspects (*high confidence*). While relatively few studies from Africa have focused specifically on barriers and limits to adaptation, perceived and experienced constraints distilled from the literature encompass the resources needed for adaptation, the factors influencing adaptive capacity, the reasons for not employing particular adaptive strategies or not responding to climate change signals, and the reasons why some groups or individuals adapt but not others (Roncoli et al., 2010; Bryan et al., 2011; Nyanga et al., 2011; Ludi et al., 2012).

At the local level, institutional barriers hamper adaptation through elite capture and corruption; poor survival of institutions without social roots; and lack of attention to the institutional requirements of new technological interventions (Ludi et al., 2012). Tenure security over land and vital assets is widely accepted as being crucial for enabling people to make longer-term and forward-looking decisions in the face of uncertainty, such as changing farming practices, farming systems, or even transforming livelihoods altogether (Bryan et al., 2009; Brown et al., 2010; Romero González et al., 2011). In addition to unclear land tenure, legislation forbidding ecosystem use is one of the issues strengthening underlying conflicts over resources in Africa; resolving this would enable ecosystems to contribute to adaptation beyond short-term coping (Robledo et al., 2012). There is also evidence that innovation may be suppressed if the dominant culture disapproves of departure from the "normal way of doing things" (Jones, 2012; Ludi et al., 2012).

Characteristics such as wealth, gender, ethnicity, religion, class, caste, or profession can act as social barriers for some to adapt successfully or acquire the required adaptive capacities (Ziervogel et al., 2008; Godfrey et al., 2010; Jones and Boyd, 2011). Based on field research conducted in the Borana area of southern Ethiopia, Debsu (2012) highlights the complex way in which external interventions may affect local and indigenous institutions by strengthening some coping and adaptive mechanisms and weakening others. Restrictive institutions can block attempts to enhance local adaptive capacity by maintaining structural inequities related to gender and ethnic minorities (Jones, 2012). Constraints faced by women, often through customs and legal barriers, include limited access to land and natural resources, lack of credit and input in decision making, limited ability to take financial risk, lack of confidence, limited access to information and new ideas, and under-valuation of women's opinions (McFerson, 2010; Djoudi and Brockhaus, 2011; Peach Brown, 2011; Codjoe et al., 2012; Goh, 2012; Jones, 2012; Ludi et al., 2012).

Few small-scale farmers across Africa are able to adapt to climatic changes, while others are restricted by a suite of overlapping barriers (*robust evidence*, *high agreement*). Constraints identified in Kenya, South Africa, Ethiopia, Malawi, Mozambique, Zimbabwe, Zambia, and Ghana included poverty and a lack of cash or credit (financial barriers); limited access to water and land, poor soil quality, land fragmentation, poor roads, and pests and diseases (biophysical and infrastructural barriers); lack of access to inputs, shortage of labor, poor quality of seed and inputs attributed to a lack of quality controls by government and corrupt business practices by traders, insecure tenure, and poor market access (institutional, technological, and political barriers); and finally a lack of information on agroforestry/afforestation, different crop varieties, climate change predictions and weather, and adaptation strategies (informational barriers) (Barbier et al., 2009; Bryan et al., 2009, 2011; Clover and Eriksen, 2009; Deressa et al., 2009; Roncoli et al., 2010; Mandleni and Anim, 2011; Nhemachena and Hassan, 2011; Nyanga et al., 2011; Vincent et al., 2011a).

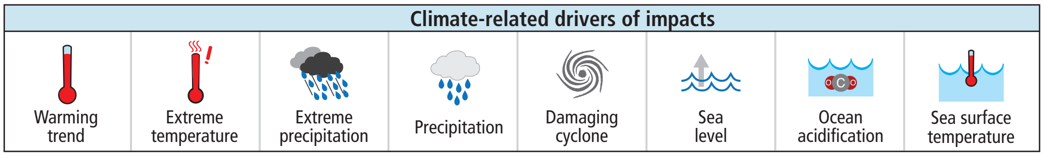
Recognition is increasing that understanding psychological factors such as mindsets and risk perceptions is crucial for supporting adaptation (Grothmann and Patt, 2005; Patt and Schröter, 2008; Jones, 2012). Cognitive barriers to adaptation include alternative explanations of extreme events and weather such as religion (God's will), the ancestors, and witchcraft, or seeing these changes as out of people's own control (Byran et al., 2009; Roncoli et al., 2010; Mandleni and Anim, 2011; Artur and Hilhorst, 2012; Jones, 2012; Mubaya et al., 2012).

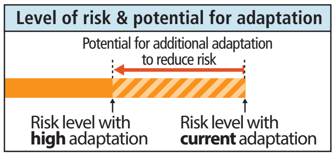
Climate uncertainty, high levels of variability, lack of access to appropriate real-time and future climate information, and poor predictive capacity at a local scale are commonly cited barriers to adaptation from the individual to national level (Repetto, 2008; Dinku et al., 2011; Jones, 2012; Mather and Stretch, 2012). Despite the cultural and psychological barriers noted earlier, several studies have shown that farmers with access to climate information are more predisposed to adjust their behavior in response to perceived climate changes (Mubaya et al., 2012).

At a policy level, studies have detected political, institutional, and discursive barriers to adaptation. Adaptation options in southern Africa have been blocked by political and institutional inefficiencies, lack of prioritization of climate change, and the dominance of other discourses, such as the mitigation discourse in South Africa and short-term disaster-focused views of climate variability (Madzwamuse, 2010; Bele et al., 2011; Berrang-Ford et al., 2011; Conway and Schipper, 2011; Kalame et al., 2011; Chevallier, 2012; Leck et al., 2012; Toteng, 2012). Lack of local participation in policy formulation, the neglect of social and cultural context, and the inadvertent undermining of local coping and adaptive strategies have also been identified by several commentators as barriers to appropriate national policies and frameworks that would support local-level adaptation (e.g., Brockhaus and Djoudi, 2008; Bele et al., 2011; Chevallier, 2012).

Many of these constraints to adaptation are well-entrenched and will be far from easy to overcome; some may act as limits to adaptation for particular social groups (*high confidence*). Biophysical barriers to adaptation in the arid areas could present as limits for more vulnerable groups if current climate change trends continue (Leary et al., 2008b; Roncoli et al., 2010; Sallu et al., 2010). Traditional and autonomous adaptation strategies, particularly in the drylands, have been constrained by social-ecological change and drivers such as population growth, land privatization, land degradation, widespread poverty, HIV/AIDS, poorly conceived policies and modernization, obstacles to mobility and use of

Table 22-6 | Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Africa. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as *very low*, *low*, *medium*, *high*, or *very high*. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.





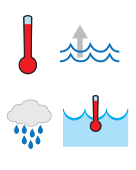
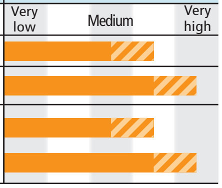
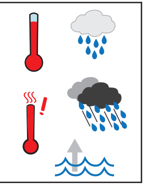
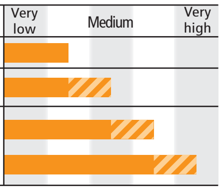
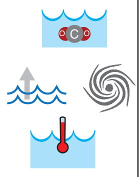
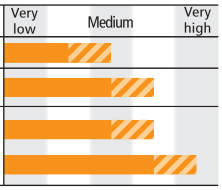
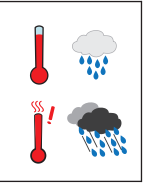
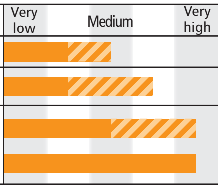
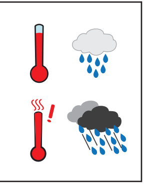
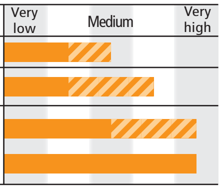
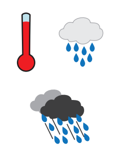
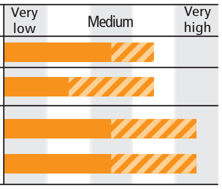
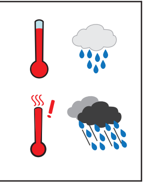
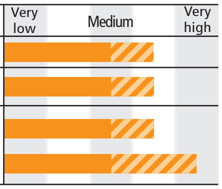
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Shifts in biome distribution, and severe impacts on wildlife due to diseases and species extinction (*high confidence*) [22.3.2.1, 22.3.2.3]	Very few adaptation options; migration corridors; protected areas; better management of natural resources		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future, with drought stress exacerbated in drought-prone regions of Africa (*high confidence*) [22.3-4]	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance • Sustainable urban development		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Degradation of coral reefs results in loss of protective ecosystems and fishery stocks (*medium confidence*). [22.3.2.3]	Few adaptation options; marine protected areas; conservation and protection; better management of natural resources		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Reduced crop productivity associated with heat and drought stress, with strong adverse effects on regional, national, and household livelihood and food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*) [22.3-4]	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation, enhanced observation systems) • Enhancing smallholder access to credit and other critical production resources; Diversifying livelihoods • Strengthening institutions at local, national, and regional levels to support agriculture (including early warning systems) and gender-oriented policy • Agronomic adaptation responses (e.g., agroforestry, conservation agriculture)		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Adverse effects on livestock linked to temperature rise and precipitation changes that lead to increased heat and water stress, and shifts in the range of pests and diseases, with adverse impacts on pastoral livelihoods and rural poverty (*medium confidence*) [22.3.4.2, 22.4.5.2, 22.4.5.6, 22.4.5.8]	Addressing non-climate stressors facing pastoralists, including policy and governance features that perpetuate their marginalization, is critical for reducing vulnerability. Natural resource-based strategies such as reducing drought risk to pastoral livelihoods through use of forest goods and services hold potential, provided sufficient attention is paid to forest conservation and sustainable management.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*) [22.3]	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors • Sustainable urban development		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Undernutrition, with its potential for life-long impacts on health and development and its associated increase in vulnerability to malaria and diarrheal diseases, can result from changing crop yields, migration due to weather and climate extremes, and other factors (*medium confidence*). [22.3.5.2]	Early warning systems and vulnerability mapping (for targeted interventions); diet diversification; coordination with food and Agriculture sectors; improved public health functions to address underlying diseases		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

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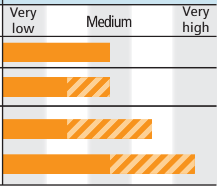
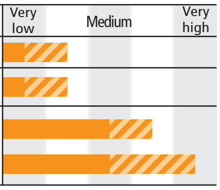
Table 22-6 (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased migration leading to human suffering, human rights violations, political instability and conflict (*medium confidence*) [22.3.6, 22.4.5, 22.5.1.3]	Adaptation deficit to current flood and drought risk; effective adaptation includes sustainable land management and modification of land use, dought relief, flood control and effective regional and national policy and legislative environment that allows for flexible adaptation responses.	🌡 🌧 🌊 ⛈	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	
Sea level rise and extreme weather events disrupt transport systems, production systems, infrastructure, public services (water, education, health, sanitation), especially in informal areas (flooding) (*medium confidence*) [22.3.7, 22.4.4.4, 22.4.4.6, 22.4.5.6, 22.4.5.7]	Limited options for migration away from flood prone localities Enhanced urban management and land use control would reduce both vulnerability and exposure to risks; would require policy review, significant capacity development and enforcement. Low-cost soft protective coastal infrastructure options could reduce risk significantly in some areas; while hard infrastructural options are expensive, need technical knowledge and not always environmentally sustainable.	🌀 🌊	Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	

indigenous knowledge, as well as erosion of traditional knowledge, to the extent that it is difficult or no longer possible to respond to climate variability and risk in ways that people did in the past (Dabi et al., 2008; Leary et al., 2008b; Paavola, 2008; Smucker and Wisner, 2008; Clover and Eriksen, 2009; Conway, 2009; UNCCD et al., 2009; Bunce et al., 2010b; Quinn et al., 2011; Jones, 2012; see also Section 22.4.5.4). As a result of these multiple stressors working together, the number of response options has decreased and traditional coping strategies are no longer sufficient (Dube and Sekhwela, 2008). Studies have shown that most autonomous adaptation usually involves minor adjustments to current practices (e.g., changes in planting decisions); there are simply too many barriers to implementing substantial changes that require investment (e.g., agroforestry and irrigation) (Bryan et al., 2011). Such adaptation strategies would be enhanced through government and private sector/NGO support, without which many poor groups in Africa may face real limits to adaptation (Vincent et al., 2011a; Jones, 2012).

These findings highlight the benefits of transformational change in situations where high levels of vulnerability and low adaptive capacity detract from the possibility for systems to adapt sustainably. This is in agreement with the *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, which additionally found *robust evidence* and *high agreement* for the importance of a spectrum of actions ranging from incremental steps to transformational changes in order to reduce climate risks (IPCC, 2012). In support of such solutions, Moench (2011) has called for distilling common principles for building adaptive capacity at different stages, and adaptive management and learning are seen as critical approaches for facilitating transformation (IPCC, 2012; see also Section 22.4.5.3). Chapter 16 provides further discussion on how encountering limits to adaptation may trigger transformational change, which can be a means of adapting to hard limits.

22.5. Key Risks for Africa

Table 22-6 highlights key risks for Africa (see also Table 19-4 and Box CC-KR), as identified through assessment of the literature and expert judgment of the author team, with supporting evaluation of evidence and agreement in the sections of this chapter bracketed.

As indicated in Table 22-6, seven of the nine key regional risks are assessed for the present as being either medium or high under current adaptation levels, reflecting both the severity of multiple relevant stressors and Africa's existing adaptation deficit. This is the case for risks relating to shifts in biome distribution (Section 22.3.2.1), degradation of coral reefs (Section 22.3.2.3), reduced crop productivity (Section 22.3.4.1), adverse effects on livestock (Section 22.3.4.2), vector- and water-borne diseases (Sections 22.3.5.2, 22.3.5.4), undernutrition (Section 22.3.5.3), and migration (Section 22.6.1.2). This assessment indicates that allowing current emissions levels to result in a +4°C world (above preindustrial levels) by the 2080–2100 period would have negative impacts on Africa's food security, as even under high adaptation levels, risks of reduced crop productivity and adverse effects on livestock are assessed as remaining very high. Moreover, our assessment is that even if high levels of adaptation were achieved, risks of stress on water resources (Section 22.3.3), degradation of coral reefs (Section 22.3.2.3), and the destructive effects of SLR and extreme weather events (Section 22.3.6) would remain high. However, even under a lower emissions scenario leading to a long-term 2°C warming, all nine key regional risks are assessed as remaining high or very high under current levels of adaptation. The assessment indicates that even under high adaptation, residual impacts in a 2°C world would be significant, with only risk associated with migration rated as being capable of reduction to low under high levels of adaptation. High adaptation would be enabled by concerted effort and substantial funding; even if this is realized, no risk is assessed as being capable of reduction to below medium status.

22.6. Emerging Issues

22.6.1. Human Security

Although the significance of human security cannot be overestimated, the evidence of the impact of climate change on human security in Africa is disputable (see Chapters 12 and 19). Adverse climate events potentially impact all aspects of human security, either directly or indirectly (on mapping climate security vulnerability in Africa see Busby et al., 2013). Food security, water stress, land use, health security, violent conflict, changing migration patterns, and human settlements are all interrelated issues with overlapping climate change and human security dimensions.

Violent conflict and migration are discussed below (for further detail, see Chapter 12).

22.6.1.1. Violent Conflict

While there seems to be consensus that the environment is only one of several interconnected causes of conflict and is rarely considered to be the most decisive factor (Kolmannskog, 2010), it remains disputed whether, and if so, how, the changing climate directly increases the risk of violent conflict in Africa (for more detail, see Chapters 12 and 19, in particular Sections 12.5.1, 19.4; Gleditsch, 2012). However, views are emerging that there is a positive relationship between increases in temperature and increases in human conflict (Hsiang et al., 2013). Some of the factors which may increase the risk of violent conflict, such as low per capita incomes, economic contraction, and inconsistent state institutions are sensitive to climate change (Section 12.5.1). For the African Sahel States it has been argued that the propensity for communal conflict across ethnic groups within Africa is influenced by political and economic vulnerability to climate change (Raleigh, 2010). Evidence on the question of whether, and if so, to what extent, climate change and variability increases the risk of civil war in Africa is contested (Burke et al., 2009b; Buhaug, 2010; Devitt and Tol, 2012). It has been suggested that due to the depletion of natural resources in Africa as a result of overexploitation and the impact of climate change on environmental degradation, competition for scarce resources could increase and lead to violent conflict (Kumssa and Jones, 2010). For East Africa it has been suggested that increased levels of malnutrition are related to armed conflicts (Rowhani et al., 2011). There is some agreement that rainfall variation has an inconsistent relationship to conflict: both higher and lower anomalous rainfall is associated with increased communal conflict levels; although dry conditions have a lesser effect (Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012).

Frequently Asked Questions

FAQ 22.2 | What role does climate change play with regard to violent conflict in Africa?

Wide consensus exists that violent conflicts are based on a variety of interconnected causes, of which the environment is considered to be one, but rarely the most decisive factor. Whether the changing climate increases the risk of civil war in Africa remains disputed and little robust research is available to resolve this question. Climate change impacts that intensify competition for increasingly scarce resources such as freshwater and arable land, especially in the context of population growth, are areas of concern. The degradation of natural resources as a result of both overexploitation and climate change will contribute to increased conflicts over the distribution of these resources. In addition to these stressors, however, the outbreak of armed conflict depends on many country-specific socio-political, economic, and cultural factors.

22.6.1.2. Migration

Human migration has social, political, demographic, economic, and environmental drivers, which may operate independently or in combination (for more in-depth discussions, see Sections 12.4 and 19.4.2.1; Perch-Nielsen et al., 2008; Piguet, 2010; Black et al., 2011a; Foresight, 2011; Piguet et al., 2011; Van der Geest, 2011). Many of these drivers are climate sensitive (Black et al., 2011c; see also Section 12.4.1). People migrate either temporarily or permanently, within their country or across borders (Section 12.4.1.2; Figure 12-1; Table 12-3; Warner et al., 2010; Kälin and Schrepfer, 2012). The evidence base in the field of migration in Africa is both varied and patchy. Evidence suggests that migration is a strategy to adapt to climate change (Section 12.4.2). Mobility is indeed a strategy (not a reaction) to high levels of climatic variation that is characteristic of Africa (Tacoli, 2011) and the specifics of the response are determined by the economic context of the specific communities.

Besides low-lying islands and coastal and deltaic regions in general, sub-Saharan Africa is one of the regions that would particularly be affected by environmentally induced migration (Gemenne, 2011a). Case studies from Somalia and Burundi emphasize the interaction of climate change, disaster, conflict, displacement, and migration (Kolmannskog, 2010). In Ghana, for example, an African country with few conflicts caused by political, ethnic, or religious tensions, and thus with migration drivers more likely related to economic and environmental motivators (Tschakert and Tutu, 2010), some different types of migration flows are considered to have different sensitivity to climate change (Black et al., 2011a). The floods of the Zambezi River in Mozambique in 2008 have displaced 90,000 people, and it has been observed that along the Zambezi River Valley, with approximately 1 million people living in the flood-affected areas, temporary mass displacement is taking on permanent characteristics (Jäger et al., 2009; Warner et al., 2010).

Different assessments of future trends have recently produced contradictory conclusions (e.g., UN-OCHA and IDMC, 2009; Naude, 2010; ADB, 2011; IDMC, 2011; Tacoli, 2011). One approach in assessing future migration potentials, with considerable relevance to the African context, focused on capturing the net effect of environmental change on aggregate migration through analysis of both its interactions with other migration drivers and the role of migration within adaptation strategies, rather than identifying specific groups as potential 'environmental migrants' (Foresight, 2011). Even if Africa's population doubles by 2050 to 2 billion (Lutz and K.C., 2010) and the potential for displacement rises as a consequence of the impact of extreme weather events, recent analyses (Black et al., 2011b; Foresight, 2011) show that the picture for future migration is much more complex than previous assessments of a rise in climate-induced migration suggest, and relates to the intersection of multiple drivers with rates of global growth, levels of governance, and climate change.

The empirical base for major migration consequences is weak (Black et al., 2011a; Gemenne, 2011b; Lilleør and Van den Broeck, 2011) and nonexistent for international migration patterns (Marchiori et al., 2011). Even across the same type of extreme weather event, the responses can vary (Findlay, 2011; Gray, 2011 for Kenya and Uganda; Raleigh, 2011 for the African Sahel States).

22.6.2. Integrated Adaptation/Mitigation Approaches

Relevant experience gained in Africa since AR4 in implementing integrated adaptation-mitigation responses within a pro-poor orientation that leverages developmental benefits encompasses some participation of farmers and local communities in carbon offset systems, increasing the use of relevant technologies such as agroforestry and farmer-assisted tree regeneration (Section 22.4.5.6), and emerging Green Economy policy responses. The recognition that adaptation and mitigation are complementary elements of the global response to climate change, and not trade-offs, is gaining traction in Africa (Goklany, 2007; Nyong et al., 2007; UNCCD et al., 2009; Woodfine, 2009; Jalloh et al., 2011b; Milder et al., 2011).

While the suitability of on- and off-farm techniques for an integrated adaptation-mitigation response depends on local physical conditions as well as political and institutional factors, sustainable land management techniques are particularly beneficial for an integrated response in Africa; these include agroforestry, including through farmer-managed natural regeneration; and conservation agriculture (Woodfine, 2009; Milder et al., 2011; Mutonyi and Fungo, 2011; see also Section 22.4.5.6; Box 22-2). An emerging area is multiple-benefit initiatives that aim to reduce poverty, promote adaptation through restoring local ecosystems, and deliver benefits from carbon markets. Brown et al. (2011) note the example of a community-based project in Humbo, Ethiopia, which is facilitating adaptation and generating temporary certified emissions reductions under the Clean Development Mechanism, by restoration of degraded native forests (2728 ha) through farmer-managed natural regeneration.

The key role of local communities in carbon offset systems through community forestry entails land use flexibility (Purdon, 2010), but can be constrained by the lack of supportive policy environments—for example, for conservation agriculture (Milder et al., 2011).

The literature highlights the desirability of responding to climate change through integrated adaptation-mitigation approaches, including through spatial planning, in the implementation of REDD+ in Africa, especially given the significant contribution to food security and livelihoods of forest systems (Bwango et al., 2000; Nkem et al., 2007; Guariguata et al., 2008; Nasi et al., 2008; Biesbroek et al., 2009; Somorin et al., 2012). However, forests are mainly used for reactive coping and not anticipatory adaptation; studies show that governments favor mitigation while local communities prioritize adaptation (Fisher et al., 2010; Somorin et al., 2012). Flexible REDD+ models that include agriculture and adaptation hold promise for generating co-benefits for poverty reduction, given food security and adaptation priorities, and help to avoid trade-offs between REDD+ implementation and adaptive capacities of communities, ecosystems, and nations (Nkem et al., 2008; Thomson et al., 2010; CIFOR, 2011; Richard et al., 2011; Wertz-Kanounnikoff et al., 2011).

Integrated adaptation-mitigation responses are being considered within the context of the emerging Green Economy discussions. African leaders agreed in 2011 to develop an African Green Growth Strategy, to build a shared vision for promoting sustainable low-carbon growth through a linked adaptation-mitigation approach, with adaptation seen as an urgent priority (TICAD, 2011). A national example is the launch of Ethiopia's Climate Resilient Green Economy Facility in 2012 (Corsi et al., 2012).

22.6.3. Biofuels and Land Use

The potential for first-generation biofuel production in Africa, derived from bioethanol from starch sources and biodiesel production from oilseeds, is significant given the continent's extensive arable lands, labor availability, and favorable climate for biofuel crop production (Amigun et al., 2011; Arndt et al., 2011; Hanff et al., 2011). While biofuel production has positive energy security and economic growth implications, the prospect of wide-scale biofuel production in Africa carries with it significant risks related to environmental and social sustainability. Among the concerns are competition for land and water between fuel and food crops, adverse impacts of biofuels on biodiversity and the environment, contractual and regulatory obligations that expose farmers to legal risks, changes in land tenure security, and reduced livelihood opportunities for women, pastoralists, and migrant farmers who depend on access to the land resource base (Unruh, 2008; Amigun et al., 2011; German et al., 2011; Schoneveld et al., 2011).

More research is needed to understand fully the socioeconomic and environmental trade-offs associated with biofuel production in Africa. One critical knowledge gap concerns the effect of biofuel production, particularly large-scale schemes, on land use change and subsequent food and livelihood security. For example, the conversion of marginal lands to biofuel crop production would impact the ability of users of these lands (pastoralists and in some cases women who are allocated marginal land for food and medicinal production) to participate in land use and food production decisions (Amigun et al., 2011; Schoneveld et al., 2011). In addition, biofuel production could potentially lead to the extension of agriculture into forested areas, either directly through conversion of fallow vegetation or the opening of mature woodland, or indirectly through use of these lands to offset food crop displacement (German et al., 2011). Such land use conversion would result in biofuel production reducing terrestrial carbon storage potential (Vang Rasmussen et al., 2012a,b).

Better agronomic characterization of biofuel crops is another key knowledge gap. For example, little information exists with respect to the agronomic characteristics of the oilseed crop Jatropha (*Jatropha curcas*) under conditions of intensive cultivation across differing growing environments, despite the fact that Jatropha has been widely touted as an appropriate feedstock for biofuel production in Africa because of its ability to grow in a wide range of climates and soils. Oilseed yields of Jatropha can be highly variable, and even basic information about yield potential and water and fertilizer requirements for producing economically significant oilseed yields is scanty (Achten et al., 2008; Peters and Thielmann, 2008; Hanff et al., 2011). Such knowledge would not only provide a basis for better crop management but would also help to gain better estimates of the extent of water consumption for biofuel production in the context of non-biofuel water-use needs across landscapes. Assessments of Jatropha's potential as an invasive species and its potential allelopathic effects on native vegetation are also needed, in light of the fact that some countries have designated Jatropha as an invasive species (Achten et al., 2008).

22.6.4. Climate Finance and Management

Recent analyses emphasize the significant financial resources and technological support needed to both address Africa's current adaptation deficit and to protect rural and urban livelihoods, societies, and economies from climate change impacts at different local scales, with estimates of adaptation costs between US$20 and US$30 billion per annum over the next couple of decades, up to US$60 billion per annum by 2030 (Parry et al, 2009b; Fankhauser and Schmidt-Traub, 2010; Watkiss et al, 2010; AfDB, 2011; Dodman and Carmin, 2011; LDC Expert Group, 2011; Smith et al., 2011; e.g., see Figure 22-6). However, these figures are likely to be underestimates, as studies upon which these estimates are based do not always include the costs of overcoming Africa's current adaptation deficit, may be run for one scenario at a time, and do not factor in a range of uncertainties in the planning environment.

Damages related to climate change may affect economic growth and the ability to trade (Lecocq and Shalizi, 2007; Ruppel and Ruppel-Schlichting, 2012). Costs of adaptation and negative economic impacts of climate change have been referred to in Sections 22.3.4.4 and 22.3.6; Warner et al. (2012) have highlighted the residual impacts of climate change that would occur after adaptation, for case studies in Kenya and The Gambia. The following examples are illustrative of the move to discuss financial implications in the literature.

Scenarios for Tanzania, where agriculture accounts for about half of gross production and employs about 80% of the labor force (Thurlow and Wobst, 2003), project that changes in the mean and extremes of climate variables could increase poverty vulnerability (Ahmed et al., 2011). Scenarios for Namibia based on a computable general equilibrium model project that annual losses to the economy ascribed to the impacts of climate change on the country's natural resources could range between 1.0 and 4.8% of GDP (Reid et al., 2008). Ghana's agricultural and economic sector with cocoa being the single most important export product is particularly vulnerable, since cocoa is prone to the effects of a changing climate (Black et al., 2011c), which has been central to the country's debates on development and poverty alleviation strategies (WTO, 2008).

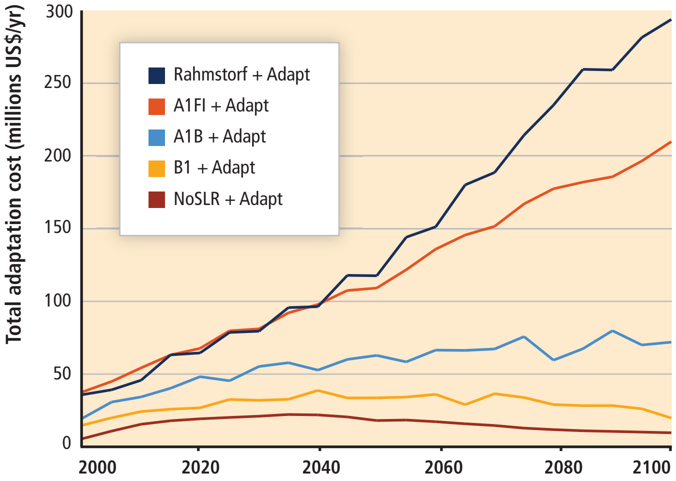


Figure 22-6 | Total additional costs of adaptation per year from 2000 to 2100 for Tanzania (including beach nourishment and sea and river dikes). The values do not consider the existing adaptation deficit (values in US$ 2005, without discounting). Source: Kebede et al., 2010.

Table 22-7 | Land inundated and economic impacts in Cape Town (CT) based on a risk assessment (Cartwright, 2008).

Sea level rise scenarios	Land inundated	Economic impacts (for 25 years)
Scenario 1 (+2.5 to 6.5 m depending on the exposure): 95%	25.1 km^2 (1% of the total CT area)	5.2 billion rands (US$794 million)
Scenario 2 (+4.5 m): 85%	60.9 km^2 (2% of the total CT area)	23.7 billion rands (US$30.3 billion)
Scenario 3 (+6.5 m): 20%	95 km^2 (4% of the total CT area)	54.8 billion rands

Note: The economic impacts are determined based on the value of properties, losses of touristic revenues, and the cost of infrastructure replacement. The total geographical gross product for Cape Town in 2008 was 165 billion rands.

The potential for adaptation to reduce the risks associated with SLR is substantial for cumulative land loss and for numbers of people flooded or forced to migrate, with adaptation costs lower than the economic and social damages expected if nothing is done (Kebede et al., 2010). See Figure 22-6.

The Dynamic Interactive Vulnerability Assessment (DIVA) model was used to assess the monetary and non-monetary impacts of SLR on the entire coast (3461 km) of Tanzania. Under the B1 low-range SLR scenario it was estimated that, by 2030, a total area of 3579 to 7624 km^2 would be lost, mainly through inundation, with around 234,000 to 1.6 million people per year who could potentially experience flooding. Without adaptation, residual damages have been estimated at between US$26 and US$55 million per year (Kebede et al., 2010). Table 22-7 shows the economic impacts of land inundated in Cape Town based on different SLR scenarios.

In line with increasing international impetus for adaptation (Persson et al., 2009), the Parties to the UNFCCC agreed on providing "adequate, predictable and sustainable financial resources" for adaptation in developing countries, and, within this context, paid special attention to Africa which is "particularly vulnerable" to the adverse effects of climate change (UNFCCC, 2009, 2011; Berenter, 2012). Doubts remain about how private sector financing can be effectively mobilized and channeled toward adaptation in developing countries (Atteridge, 2011; Naidoo et al., 2012). The 2012 Landscape of Climate Finance Report (Buchner et al., 2012) stated that mitigation activities attracted US$350 billion, mostly related to renewable energy and energy efficiency, while adaptation activities attracted US$14 billion. Approximately 30% of the global distributed adaptation finance went to Africa (Nakhoda et al., 2011) and seems to prioritize the continent (Naidoo et al., 2012).

Table 22-8 | Research gaps in different sectors.

Key sectors	Gaps observed
Climate science	• Research in climate and climate impacts would be greatly enhanced if data custodians and researchers worked together to use observed station data in scientific studies. Research into regional climate change and climate impacts relies on observed climate and hydrological data as an evaluative base. These data are most often recorded by meteorological institutions in each country and sold to support data collection efforts. However, African researchers are generally excluded from access to these critical data because of the high costs involved, which hinders both climate and climate impacts research. • Downscaling General Circulation Model (GCM) data to the regional scale captures the influence of topography on the regional climate. Regional climate information is essential for understanding regional climate processes, regional impacts, and potential future changes in these. In addition, impacts models such as hydrology and crop models generally require input data at a resolution higher than what GCMs can provide. Regional downscaling, either statistically or through use of regional climate models, can provide information at these scales and can also change the sign of GCM-projected rainfall change over topographically complex areas (Section 22.2.2.2).
Ecosystems	• Monitoring networks for assessing long-term changes to critical ecosystems such as coastal ecosystems, lakes, mountains, grasslands, forests, wetlands, deserts, and savannas to enhance understanding of long-term ecological dynamics, feedbacks between climate and ecosystems, the effects of natural climate variability on ecosystems, the limits of natural climate variability, and the marginal additional effects of global climate forcing • Develop the status of protected areas to include climate change effects
Food systems	• Socioeconomic and environmental trade-offs of biofuel production, especially the effect on land use change and food and livelihood security; better agronomic characterization of biofuel crops to avoid maladaptive decisions with respect to biofuel production • Vulnerability to and impacts of climate change on food systems (production, transport, processing, storage, marketing, and consumption) • Impacts of climate change on urban food security, and dynamic of rural–urban linkages in vulnerability and adaptive capacity • Impacts of climate change on food safety and quality
Water resources	• Characterization of Africa's groundwater resource potential; understanding interactions between non-climate and climate drivers as related to future groundwater resources • Impacts of climate change on water quality, and how this links to food and health security • Decision making under uncertainty with respect to water resources given limitations of climate models for adequately capturing future rainfall projections
Human security and urban areas	• Research to explore and monitor the links between climate change and migration and its potential negative effects on environmental degradation; the potential positive role of migration in climate change adaptation • Improved methods and research to analyze the relation between climate change and violent conflict.
Livelihoods and poverty	• Methodologies for cyclical learning and decision support to enable anticipatory adaptation in contexts of high poverty and vulnerability (Tschakert and Dietrich, 2010) • Frameworks to integrate differentiated views of poverty into adaptation and disaster risk reduction, and to better link these with social protection in different contexts • Ethical and political dimensions of engaging with local and traditional knowledge on climate change
Health	• Research and improved methodologies (including longitudinal studies) to assess and quantify the impact of climate change on vector-borne, food-borne, water-borne, nutrition, heat stress, and indirect impacts on HIV • Research to quantify the direct and indirect health impacts of extreme weather events in Africa; injuries, mental illness; health infrastructure • Frameworks and research platforms to be developed with other sectors to determine how underlying risks (e.g., food security) will be addressed to improve health outcomes
Adaptation	• Research to develop home-grown and to localize global adaptation technologies to build resilience • Equitable adaptation frameworks to deal with high uncertainty levels and integrate marginalized groups; and that identify and eliminate multi-level constraints to women's adaptive ability • Multi-tiered approach to building institutional and community capacity to respond to climate risk • Potential changes in economic and social systems under different climate scenarios, to understand the implications of adaptation and planning choices (Clements et al., 2011) • Principles/determining factors for effective adaptation, including community-based adaptation • Understanding synergies and trade-offs between different adaptation and mitigation approaches (Chambwera and Anderson, 2011) • Additional national and sub-national modeling and analysis of the economic costs of impacts and adaptation, including of the "soft" costs of impacts and adaptation • Monitoring adaptation
Other	• Methods in vulnerability analysis for capturing the complex interactions in systems across scales • Understanding compound impacts from concomitant temperature and precipitation stress, e.g., effect on a particular threshold of a heat wave occurring during a period of below normal precipitation

However, it is being questioned, whether the adaptation funding that is currently delivered does fulfill demonstrated needs (Flåm and Skjærseth, 2009; Denton, 2010; for sub-Saharan Africa Nakhooda et al., 2011).

Effective adaptation requires more than sufficient levels of funding. It requires developing country "readiness," which includes abilities to plan and access finances; the capacity to deliver adaptation projects and programs, and to monitor, report, and evaluate their effectiveness (Vandeweerd et al., 2012); and also a regulatory framework, which guarantees, for example, property rights (WGIII AR5 Chapter 16). Particularly serious challenges are associated with directing finance to the sectors and people most vulnerable to climate change (Denton, 2010; Nakhooda et al., 2011; Pauw et al., 2012). The risk of fund mismanagement with regard to climate finance and adaptation funds needs to be borne in mind. Suggestions to address adequately the level of complexity, uncertainty, and novelty that surrounds many climate finance issues *inter alia* include longer term and integrated programs rather than isolated projects; building capacity and institutions in African countries (Nakhooda et al., 2011; Pauw et al., 2012); identifying priorities, processes, and knowledge needs at the local level (Haites, 2011; Pauw, 2013); and, accordingly, developing grassroots projects (Fankhauser and Burton, 2011).

22.7. Research Gaps

Research has a key role to play in providing information for informed decision making at local to national levels (Fankhauser, 1997; Ziervogel et al., 2008; Arendse and Crane, 2010). While there is significant activity in African research institutions, much African research capacity is spent on foreign-led research that may necessarily prioritize addressing national knowledge gaps about climate change (Madzwamuse, 2010), and African research may lack merited policy uptake or global recognition as it is often not published in peer-reviewed literature (Denton et al., 2011).

The following overarching data and research gaps have been identified (see also Table 22-8):

- Data management and monitoring of climate and hydroclimate parameters and development of climate change scenarios as well as monitoring systems to address climate change impacts in the different sectors (e.g., the impacts of pests and diseases on crops and livestock) and systems
- Research and improved methodologies to assess and quantify the impact of climate change on different sectors and systems
- Socioeconomic consequences of the loss of ecosystems and also of economic activities as well as of certain choices in terms of mitigation (e.g., biofuels and their links with food and livelihood security) and adaptation to climate change
- The links' influence of climate change in emerging issues such as migration and urban food security
- Developing decision-making tools to enable policy and other decisions based on the complexity of the world under climate change, taking into consideration gender, age, and the potential contribution of local communities.

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23

Europe

Coordinating Lead Authors:
R. Sari Kovats (UK), Riccardo Valentini (Italy)

Lead Authors:
Laurens M. Bouwer (Netherlands), Elena Georgopoulou (Greece), Daniela Jacob (Germany), Eric Martin (France), Mark Rounsevell (UK), Jean-Francois Soussana (France)

Contributing Authors:
Martin Beniston (Switzerland), Maria Vincenza Chiriacò (Italy), Philippe Cury (France), Michael Davies (UK), Paula Harrison (UK), Olaf Jonkeren (Netherlands), Mark Koetse (Netherlands), Markus Lindner (Finland), Andreas Matzarakis (Greece/Germany), Reinhard Mechler (Germany), Annette Menzel (Germany), Marc Metzger (UK), Luca Montanarella (Italy), Antonio Navarra (Italy), Juliane Petersen (Germany), Martin Price (UK), Boris Revich (Russian Federation), Piet Rietveld (Netherlands), Cristina Sabbioni (Italy), Yannis Sarafidis (Greece), Vegard Skirbekk (Austria), Donatella Spano (Italy), Jan E. Vermaat (Netherlands), Paul Watkiss (UK), Meriwether Wilson (UK), Thomasz Zylicz (Poland)

Review Editors:
Lucka Kajfez Bogataj (Slovenia), Roman Corobov (Moldova), Ramón Vallejo (Spain)

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Executive Summary

Observed climate trends and future climate projections show regionally varying changes in temperature and rainfall in Europe (*high confidence*), {23.2.2} in agreement with Fourth Assessment Report (AR4) findings, with projected increases in temperature throughout Europe and increasing precipitation in Northern Europe and decreasing precipitation in Southern Europe. {23.2.2.2} Climate projections show a marked increase in high temperature extremes (*high confidence*), meteorological droughts (*medium confidence*), {23.2.3} and heavy precipitation events (*high confidence*), {23.2.2.3} with variations across Europe, and small or no changes in wind speed extremes (*low confidence*) except increases in winter wind speed extremes over Central and Northern Europe (*medium confidence*). {23.2.2.3}

Observed climate change in Europe has had wide ranging effects throughout the European region including the distribution, phenology, and abundance of animal, fish, and plant species (*high confidence*) {23.6.4-5; Table 23-6}; stagnating wheat yields in some sub-regions (*medium confidence*, limited evidence) {23.4.1}; and forest decline in some sub-regions (*medium confidence*). {23.4.4} Climate change has affected both human health (from increased heat waves) (*medium confidence*) {23.5.1} and animal health (changes in infectious diseases) (*high confidence*). {23.4.2} There is less evidence of impacts on social systems attributable to observed climate change, except in pastoralist populations (*low confidence*). {23.5.3}

Climate change will increase the likelihood of systemic failures across European countries caused by extreme climate events affecting multiple sectors (*medium confidence*). {23.2.2.3, 23.2.3, 23.3-6, 23.9.1} Extreme weather events currently have significant impacts in Europe in multiple economic sectors as well as adverse social and health effects (*high confidence*). {Table 23-1} There is limited evidence that resilience to heat waves and fires has improved in Europe (*medium confidence*), {23.9.1, 23.5} while some countries have improved their flood protection following major flood events. {23.9.1, 23.7.3} Climate change is *very likely* to increase the frequency and intensity of heat waves, particularly in Southern Europe (*high confidence*), {23.2.2} with mostly adverse implications for health, agriculture, forestry, energy production and use, transport, tourism, labor productivity, and the built environment. {23.3.2-4, 23.3.6, 23.4.1-4, 23.5.1; Table 23-1}

The provision of ecosystem services is projected to decline across all service categories in response to climate change in Southern Europe (*high confidence*). {23.9.1; Box 23-1} Both gains and losses in the provision of ecosystem services are projected for the other European sub-regions (*high confidence*), but the provision of cultural services is projected to decline in the Continental, Northern, and Southern sub-regions (*low confidence*). {Box 23-1}

Climate change is expected to impede economic activity in Southern Europe more than in other sub-regions (*medium confidence*) {23.9.1; Table 23-4}, and may increase future intra-regional disparity (*low confidence*). {23.9.1} There are also important differences in vulnerability within sub-regions; for example, plant species and some economic sectors are most vulnerable in high mountain areas due to lack of adaptation options (*medium confidence*). {23.9.1} Southern Europe is particularly vulnerable to climate change (*high confidence*), as multiple sectors will be adversely affected (tourism, agriculture, forestry, infrastructure, energy, population health) (*high confidence*). {23.9; Table 23-4}

The impacts of sea level rise on populations and infrastructure in coastal regions can be reduced by adaptation (*medium confidence*). {23.3.1, 23.5.3} Populations in urban areas are particularly vulnerable to climate change impacts because of the high density of people and built infrastructure (*medium confidence*). {23.3, 23.5.1}

Synthesis of evidence across sectors and sub-regions confirm that there are limits to adaptation from physical, social, economic, and technological factors (*high confidence*). {23.7; Table 23-3} Adaptation is further impeded because climate change affects multiple sectors. {23.7} The majority of published assessments are based on climate projections in the range 1°C to 4°C global mean temperature per century. Limited evidence exists regarding the potential impacts in Europe under high rates of warming (>4°C global mean temperature per century). {23.9.1}

Impacts by Sector

Sea level rise and increases in extreme rainfall are projected to further increase coastal and river flood risk in Europe and, without adaptive measures, will substantially increase flood damages (people affected and economic losses) (*high confidence*). {23.3.1, 23.5.1} Adaptation can prevent most of the projected damages (*high confidence*, based on *medium evidence*, *high agreement*) but there may be constraints to building flood defenses in some areas. {23.3.1, 23.7.1} Direct economic river flood damages in Europe have increased over recent decades (*high confidence*) but this increase is due to development in flood zones and not due to observed climate change. {23.3.1.2; SREX 4.5} Some areas in Europe show changes in river flood occurrence related to observed changes in extreme river discharge (*medium confidence*). {23.2.3}

Climate change is projected to affect the impacts of hot and cold weather extremes on transport leading to economic damage and/or adaptation costs, as well as some benefits (e.g., reduction of maintenance costs) during winter (*medium confidence*). {23.3.3} Climate change is projected to reduce severe accidents in road transport (*medium confidence*) and adversely affect inland water transport in summer in some rivers (e.g., the Rhine) after 2050 (*medium confidence*). Damages to rail infrastructure from high temperatures may also increase (*medium confidence*). Adaptation through maintenance and operational measures can reduce adverse impacts to some extent.

Climate change is expected to affect future energy production and transmission. {23.3.4} Hydropower production is *likely* to decrease in all sub-regions except Scandinavia (*high confidence*). {23.3.4} Climate change is *unlikely* to affect wind energy production before 2050 (*medium confidence*) but will have a negative impact in summer and a varied impact in winter after 2050 (*medium confidence*). Climate change is *likely* to decrease thermal power production during summer (*high confidence*). {23.3.4} Climate change will increase the problems associated with overheating in buildings (*medium confidence*). {23.3.2} Although climate change is *very likely* to decrease space heating demand (*high confidence*), cooling demand will increase (*very high confidence*) although income growth mostly drives projected cooling demand up to 2050 (*medium confidence*). {23.3.4} More energy-efficient buildings and cooling systems as well as demand-side management will reduce future energy demands. {23.3.4}

After 2050, tourism activity is projected to decrease in Southern Europe (*low confidence*) and increase in Northern and Continental Europe (*medium confidence*). No significant impacts on the tourism sector are projected before 2050 in winter or summer tourism except for ski tourism in low-altitude sites and under limited adaptation (*medium confidence*). {23.3.6} Artificial snowmaking may prolong the activity of some ski resorts (*medium confidence*). {23.3.6}

Climate change is *likely* to increase cereal yields in Northern Europe (*medium confidence*, disagreement) but decrease yields in Southern Europe (*high confidence*). {23.4.1} In Northern Europe, climate change is *very likely* to extend the seasonal activity of pests and plant diseases (*high confidence*). {23.4.1} Yields of some arable crop species like wheat have been negatively affected by observed warming in some European countries since the 1980s (*medium confidence*, limited evidence). {23.4.1} Compared to AR4, new evidence regarding future yields in Northern Europe is less consistent regarding the magnitude and sign of change. Climate change may adversely affect dairy production in Southern Europe because of heat stress in lactating cows (*medium confidence*). {23.4.2} Climate change has contributed to vector-borne disease in ruminants in Europe (*high confidence*) {23.4.2} and northward expansion of tick disease vectors (*medium confidence*). {23.4.2, 23.5.1}

Climate change will increase irrigation needs (*high confidence*) but future irrigation will be constrained by reduced runoff, demand from other sectors, and by economic costs. {23.4.1, 23.4.3} By the 2050s, irrigation will not be sufficient to prevent damage from heat waves to crops in some sub-regions (*medium confidence*). System costs will increase under all climate scenarios (*high confidence*). {23.4.3} Integrated management of water, also across countries' boundaries, is needed to address future competing demands among agriculture, energy, conservation, and human settlements. {23.7.2}

As a result of increased evaporative demand, climate change is *likely* to significantly reduce water availability from river abstraction and from groundwater resources (*medium confidence*), in the context of increased demand (from agriculture, energy and industry, and domestic use) and cross-sectoral implications that are not fully understood. {23.4.3, 23.9.1} Some adaptation is possible through uptake of more water-efficient technologies and water-saving strategies. {23.4.3, 23.7.2}

Climate change will change the geographic distribution of wine grape varieties (*high confidence*) and this will reduce the value of wine products and the livelihoods of local wine communities in Southern and Continental Europe (*medium confidence*) and increase production in Northern Europe (*low confidence*). {23.4.1, 23.3.5, 23.5.4; Box 23-2} Some adaptation is possible through technologies and good practice. {Box 23-2}

Climate warming will increase forest productivity in Northern Europe (*medium confidence*), {23.4.4} although damage from pests and diseases in all sub-regions will increase due to climate change (*high confidence*). {23.4.4} Wildfire risk in Southern Europe (*high confidence*) and damages from storms in Central Europe (*low confidence*) may also increase due to climate change. {23.4.4} Climate change is *likely* to cause ecological and socioeconomic damages from shifts in forest tree species range (from southwest to northeast) (*medium confidence*), and in pest species distributions (*low confidence*). {23.4.4} Forest management measures can enhance ecosystem resilience (*medium confidence*). {23.4.4}

Observed warming has shifted marine fish species ranges to higher latitudes (*high confidence*) and reduced body size in species (*medium confidence*). {23.4.6} There is limited and diverging evidence on climate change impacts on net fisheries economic turnover. Local economic impacts attributable to climate change will depend on the market value of (high temperature tolerant) invasive species. {23.4.6} Climate change is *unlikely* to entail relocation of fishing fleets (*high confidence*). {23.4.6} Observed higher water temperatures have adversely affected both wild and farmed freshwater salmon production in the southern part of their distribution (*high confidence*). {23.4.6} High temperatures may increase the frequency of harmful algal blooms (*low confidence*). {23.4.6}

Climate change will affect bioenergy cultivation patterns in Europe by shifting northward their potential area of production (*medium confidence*). {23.4.5} Elevated atmospheric carbon dioxide (CO_2) can improve drought tolerance of bioenergy crop species due to improved plant water use, maintaining high yields in future climate scenarios in temperate regions (*low confidence*). {23.4.5}

Climate change is *likely* to affect human health in Europe. Heat-related deaths and injuries are *likely* to increase, particularly in Southern Europe (*medium confidence*). {23.5.1} Climate change may change the distribution and seasonal pattern of some human infections, including those transmitted by arthropods (*medium confidence*), and increase the risk of introduction of new infectious diseases (*low confidence*). {23.5.1}

Climate change and sea level rise may damage European cultural heritage, including buildings, local industries, landscapes, archaeological sites, and iconic places (*medium confidence*), and some cultural landscapes may be lost forever (*low confidence*). {23.5.4; Table 23-3}

Climate change may adversely affect background levels of tropospheric ozone (*low confidence*; *limited evidence*, *low agreement*), assuming no change in emissions, but the implications for future particulate pollution (which is more health-damaging) are very uncertain. {23.6.1} Higher temperatures may have affected trends in ground level tropospheric ozone (*low confidence*). {23.6.1} Climate change is *likely* to decrease surface water quality due to higher temperatures and changes in precipitation patterns (*medium confidence*), {23.6.3} and is *likely* to increase soil salinity in coastal regions (*low confidence*). {23.6.2} Climate change may also increase soil erosion (from increased extreme events) and reduce soil fertility (*low confidence*, limited evidence). {23.6.2}

Observed climate change is affecting a wide range of flora and fauna, including plant pests and diseases (*high confidence*) {23.4.1, 23.4.4, 23.6.4} and the disease vectors and hosts (*medium confidence*). {23.4.2} Climate change is *very likely* to cause changes in habitats and species, with local extinctions (*high confidence*) and continental-scale shifts in species distributions (*medium confidence*). {23.6.4} The habitat of alpine plants is *very likely* to be significantly reduced (*high confidence*). {23.6.4} Phenological mismatch will constrain both terrestrial and marine ecosystem functioning under climate change (*high confidence*), {23.6.4-5} with a reduction in some ecosystem services (*low confidence*). {23.6.4; Box 23-1} The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe is *likely* to increase with climate change (*medium confidence*). {23.6.4} Climate change is *likely* to entail the loss or displacement of coastal wetlands (*high confidence*). {23.6.5} Climate change threatens the effectiveness of European conservation areas (*low confidence*), {23.6.4} and stresses the need for habitat connectivity through specific conservation policies. {23.6.4}

Adaptation

The capacity to adapt in Europe is high compared to other world regions, but there are important differences in impacts and in the capacity to respond between and within the European sub-regions. In Europe, adaptation policy has been developed at international (European Union), national, and local government levels, {23.7} including the prioritization of adaptation options. There is limited systematic information on current implementation or effectiveness of adaptation measures or policies. {Box 23-3} Some adaptation planning has been integrated into coastal and water management, as well as disaster risk management. {23.7.1-3} There is limited evidence of adaptation planning in rural development or land use planning. {23.7.4-5}

Adaptation will incur a cost, estimated from detailed bottom-up sector-specific studies for coastal defenses, energy production, energy use, and agriculture. {23.7.6} The costs of adapting buildings (houses, schools, hospitals) and upgrading flood defenses increase under all scenarios relative to no climate change (*high confidence*). {23.3.2} Some impacts will be unavoidable owing to limits (physical, technological, social, economic, or political). {23.7.7; Table 23-3}

There is also emerging evidence regarding opportunities and unintended consequences of policies, strategies, and measures that address adaptation and/or mitigation goals. {23.8} Some agricultural practices can reduce greenhouse gas (GHG) emissions and also increase resilience of crops to temperature and rainfall variability. {23.8.2} There is evidence for unintended consequences of mitigation policies in the built environment (especially dwellings) and energy sector (*medium confidence*). {23.8.1} Low-carbon policies in the transport and energy sectors to reduce emissions are associated with large benefits to human health (*high confidence*). {23.8.3}

23.1. Introduction

This chapter reviews the scientific evidence published since the IPCC Fourth Assessment Report (AR4) on observed and projected impacts of anthropogenic climate change in Europe and adaptation responses. The geographical scope of this chapter is the same as in AR4 with the inclusion of Turkey. Thus, the European region includes all countries from Iceland in the west to the Russian Federation (west of the Urals) and the Caspian Sea in the east, and from the northern shores of the Mediterranean and Black Seas and the Caucasus in the south to the Arctic Ocean in the north. Impacts above the Arctic Circle are addressed in Chapter 28 and impacts in the Baltic and Mediterranean Seas in Chapter 30. Impacts in Malta, Cyprus, and other island states in Europe are discussed in Chapter 29. The European region has been divided into five sub-regions (see Figure 23-1): Atlantic, Alpine, Southern, Northern, and Continental. The sub-regions are derived by aggregating the climate zones developed by Metzger et al. (2005) and therefore represent geographical and ecological zones rather than political boundaries. The scientific evidence has been evaluated to compare impacts across (rather than within) sub-regions, although this was not always possible depending on the scientific information available.

23.1.1. Scope and Route Map of Chapter

The chapter is structured around key policy areas. Sections 23.3 to 23.6 summarize the latest scientific evidence on sensitivity climate, observed impacts and attribution, projected impacts, and adaptation options, with respect to four main categories of impacts:

- Production systems and physical infrastructure
- Agriculture, fisheries, forestry, and bioenergy production
- Health protection and social welfare
- Protection of environmental quality and biological conservation.

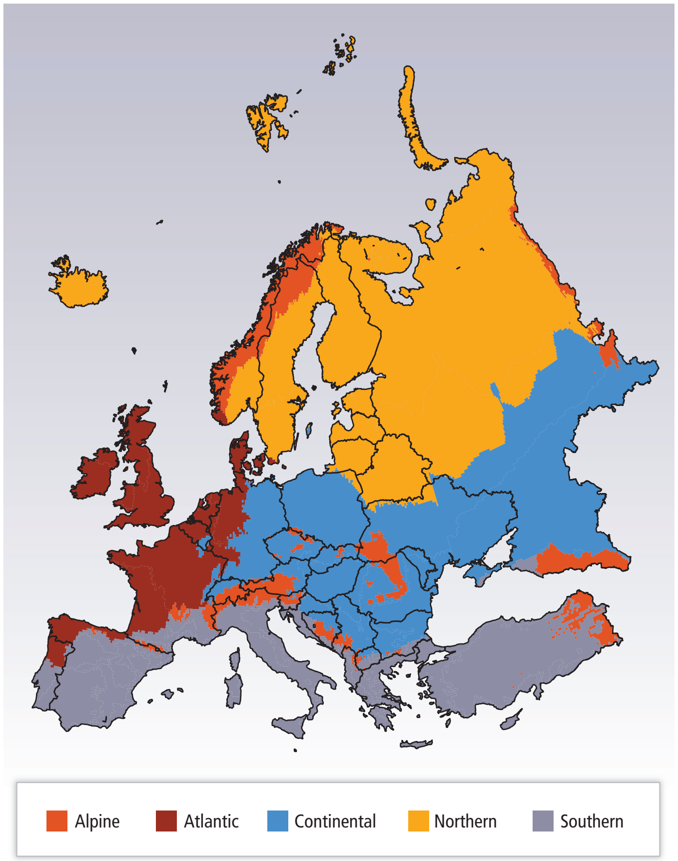


Figure 23-1 | Sub-regional classification of the IPCC Europe region. Based on Metzger et al., 2005.

The benefit of assessing evidence in a regional chapter is that impacts across sectors can be described, and interactions between impacts can be identified. Further, the cross-sectoral decision making required to address climate change can be reviewed. The chapter also includes sections that were not in AR4. As adaptation and mitigation policy develops, the evidence for potential co-benefits and unintended consequences of such strategies is reviewed (Section 23.8). The final section synthesizes the key findings with respect to: observed impacts of climate change, key vulnerabilities, and research and knowledge gaps.

The chapter evaluates the scientific evidence in relation to the five sub-regions highlighted above. The majority of the research in the Europe region is for impacts in countries in the European Union due to targeted research funding through the European Commission and national governments, which means that countries in Eastern Europe and the Russian Federation are less well represented in this chapter. Further, regional assessments may be reported for the EU15, EU27, or EEA (32) group of countries (Table SM23-1).

23.1.2. Policy Frameworks

Since AR4, there have been significant changes in Europe in responses to climate change. More countries now have adaptation and mitigation policies in place. An important force for climate policy development in the region is the European Union (EU). EU member states have mitigation targets, as well as the overall EU target, with both sectoral and regional aspects to the commitments.

Adaptation policies and practices have been developed at international, national, and local levels although research on implementation of such policies is limited. Owing to the vast range of policies, strategies, and measures it is not possible to describe them extensively here. However, adaptation in relation to cross-sectoral decision making is discussed in Section 23.7 (see also Box 23-3 on national adaptation policies). The European Climate Adaptation Platform (Climate-ADAPT) catalogs adaptation actions reported by EU Member States (EC, 2013a). The EU Adaptation Strategy was adopted in 2013 (EC, 2013b). See Chapter 15 for a more extensive discussion of institutions and governance in relation to adaptation planning and implementation.

23.1.3. Conclusions from Previous Assessments

AR4 documented a wide range of impacts of observed climate change in Europe (WGII AR4 Chapter 12). The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) confirmed increases in warm days and warm nights and decreases in cold days and cold nights since 1950 (*high confidence*; SREX Section 3.3.1). Extreme precipitation increased in part of the continent, mainly in winter over Western-Central Europe and European Russia (*medium confidence*; SREX Section 3.3.2). Dryness has increased mainly in Southern Europe (*medium confidence*; SREX Section 3.3.2). Climate change is expected to magnify regional differences within Europe for agriculture and forestry because water stress was projected to increase over Central and Southern Europe (WGII AR4 Section 12.4.1; SREX Sections 3.3.2, 3.5.1). Many climate-related hazards were projected to increase in frequency and intensity, but with significant variations within the region (WGII AR4 Section12.4).

The AR4 identified that climate changes would pose challenges to many economic sectors and was expected to alter the distribution of economic activity within Europe (*high confidence*). Adaptation measures were evolving from reactive disaster response to more proactive risk management. A prominent example was the implementation of heat health warning systems following the 2003 heat wave event (WGII AR4 Section 12.6.1; SREX Section 9.2.1). National adaptation plans were developed and specific plans were incorporated in European and national policies (WGII AR4 Sections 12.2.3, 12.5), but these were not yet evaluated (WGII AR4 Section 12.8).

23.2. Current and Future Trends

23.2.1. Non-Climate Trends

European countries are diverse in both demographic and economic trends. Population health and social welfare have improved everywhere in Europe, with reductions in adult and child mortality rates, but social inequalities both within and between countries persist (Marmot et al., 2012). Population has increased in most EU27 countries, primarily as a result of net immigration (Eurostat, 2011a), although population growth is slow (total and working age population; Rees et al., 2012). Aging of the population is a significant trend in Europe. This will have both economic and social implications, with many regions experiencing a decline in the labor force (Rees et al., 2012). Since AR4, economic growth has slowed or become negative in many countries, leading to a reduction in social protection measures and increased unemployment (Eurostat, 2011b). The longer term implications of the financial crisis in Europe are unclear, although it may lead to a modification of the economic outlook and affect future social protection policies with implications for adaptation.

Europe is one of the world's largest and most productive suppliers of food and fiber (Easterling et al., 2007). Agriculture is an important land use across the European region; for example, it covers about 35% of the total land area of western Europe (Rounsevell et al., 2006). After 1945, an unprecedented increase in agricultural productivity occurred, but also declines in agricultural land use areas. This intensification had several negative impacts on the ecological properties of agricultural systems, such as carbon sequestration, nutrient cycling, soil structure and functioning, water purification, and pollination. Pollution from agriculture has led to eutrophication and declines in water quality in some areas (Langmead et al., 2007). Most scenario studies suggest that agricultural land areas will continue to decrease in the future (see also Busch, 2006, for a discussion). Agriculture accounts for 24% of total national freshwater abstraction in Europe and more than 80% in some Southern European countries (EEA, 2009). Economic restructuring in some Eastern European countries has led to a decrease in water abstraction for irrigation, suggesting the potential for future increases in irrigated agriculture and water use efficiency (EEA, 2009).

Forest in Europe covers approximately 34% of the land area (Eurostat, 2009). The majority of forests now grow faster than in the early 20th century as a result of advances in forest management practices, genetic improvement, and, in Central Europe, the cessation of site-degrading practices such as litter collection for fuel. Increasing temperatures and carbon dioxide (CO_2) concentrations, nitrogen deposition, and the reduction of air pollution (sulfur dioxide (SO_2)) have also had a positive effect on forest growth. Scenario studies suggest that forested areas will increase in Europe in the future on land formerly used for agriculture (Rounsevell et al., 2006). Soil degradation is already intense in parts of the Mediterranean and Central-Eastern Europe and, together with prolonged drought periods and fires, is already contributing to an increased risk of desertification. Projected risks for future desertification are the highest in these areas (EEA, 2012).

Urban development is projected to increase all over Europe (Reginster and Rounsevell, 2006), but especially rapidly in Eastern Europe, with the magnitude of these increases depending on population growth, economic growth, and land use planning policy. Although changes in urban land use will be relatively small in area terms, urban development has major impacts locally on environmental quality. Outdoor air quality has, however, been improving (Langmead et al., 2007). Peri-urbanization is an increasing trend in which residents move out of cities to locations with a rural character, but retain a functional link to cities by commuting to work (Reginster and Rounsevell, 2006; Rounsevell and Reay, 2009). Several European scenario studies have been undertaken to describe European future trends with respect to socioeconomic development (de Mooij and Tang, 2003), land use change (Verburg et al., 2010; Haines-Young et al., 2012; Letourneau et al., 2012), land use and biodiversity (Spangenberg et al., 2011), crop production (Hermans et al., 2010), demographic change (Davoudi et al., 2010), economic development (Dammers, 2010), and European policy (Lennert and Robert, 2010; Helming et al., 2011). Many of these scenarios also account for the effects of future climate change (see Rounsevell and Metzger, 2010, for a review). Long-term projections (to the end of the century) are described under the new Shared Socioeconomic Pathway scenarios (SSPs) (Kriegler et al., 2010). Detailed country and regional scale socioeconomic scenarios have also been produced for the Netherlands (WLO, 2006), the UK (UK National Ecosystem Assessment, 2011), and Scotland (Harrison et al., 2013). The probabilistic representation of socioeconomic futures has also been developed for agricultural land use change (Hardacre et al., 2013). There is little evidence to suggest, however, that probabilistic futures or scenarios more generally are being used in policy making (Bryson et al., 2010).

23.2.2. Observed and Projected Climate Change

23.2.2.1. Observed Climate Change

The average temperature in Europe has continued to increase, with regionally and seasonally different rates of warming being greatest in high latitudes in Northern Europe (Chapter 28). Since the 1980s, warming has been strongest over Scandinavia, especially in winter, whereas the Iberian Peninsula warmed mostly in summer (EEA, 2012). The decadal average temperature over land area for 2002–2011 is 1.3° ± 0.11°C above the 1850–1899 average, based on Hadley Centre/Climatic Research Unit gridded surface temperature data set 3 (HadCRUT3; Brohan et al., 2006), Merged Land-Ocean Surface Temperature (MLOST; Smith et al., 2008), and Goddard Institute of Space Studies (GISS) Temp (Hansen et al., 2010). See WGI AR5 Section 2.4 for a discussion of data and uncertainties and Chapter 21 for observed regional climate change.

Since 1950, high-temperature extremes (hot days, tropical nights, and heat waves) have become more frequent, while low-temperature extremes (cold spells, frost days) have become less frequent (WGI AR5 Section 2.6; SREX Chapter 3; EEA, 2012). The recent cold winters in Northern and Atlantic Europe reflect the high natural variability in the region (Peterson et al., 2012; see also WGI AR5 Section 2.7), and do not contradict the general warming trend. In Eastern Europe, including the European part of Russia, summer 2010 was exceptionally hot, with an amplitude and spatial extent that exceeded the previous 2003 heat wave (Barriopedro et al., 2011). Table 23-1 describes the impacts of major extreme events in Europe in the last decade.

Since 1950, annual precipitation has increased in Northern Europe (up to +70 mm per decade), and decreased in parts of Southern Europe (EEA, 2012, based on Haylock et al., 2008). Winter snow cover extent has a high interannual variability and a nonsignificant negative trend over the period 1967–2007 (Henderson and Leathers, 2010). Regional observed changes in temperature and precipitation extremes are also described in Table 3-2 of SREX and in Berg et al. (2013). Mean wind speeds have declined over Europe over recent decades (Vautard et al., 2010) with *low confidence* because of problematic anemometer data and climate variability (SREX Section 3.3). Bett et al. (2013) did not find any trend in windspeed using the Twentieth Century Reanalysis.

Europe is marked by increasing mean sea level with regional variations, except in the northern Baltic Sea, where the relative sea level decreased due to vertical crustal motion (Haigh et al., 2010; Menendez and Wood-Worth, 2010; Albrecht et al., 2011; EEA, 2012). Extreme sea levels have increased due to mean sea level rise (*medium confidence*; SREX Section 3.5; Haigh et al., 2010; Menendez and WoodWorth, 2010). Variability in waves is related to internal climate variability rather than climate trends (SREX Section 3.5; Charles et al., 2012).

23.2.2.2. Projected Climate Changes

Sub-regional information from global (see Chapter 21 supplementary material; see also WGI AR5 Section 14.8.6, Annex I) and regional high-resolution climate model output (Chapters 21, 23; see also WGI AR5 Section 14.8.6) provide more knowledge about the range of possible future climates under the *Special Report on Emissions Scenarios* (SRES) and Representative Concentration Pathway (RCP) emission scenarios. Within the recognized limitations of climate projections (Chapter 21; WGI AR5 Chapter 9), new research on inter-model comparisons has provided a more robust range of future climates to assess future impacts. Since AR4, climate impact assessments are more likely to use a range for the projected changes in temperature and rainfall. Access to comprehensive and detailed sets of climate projections for decision making exist in Europe (SREX Section 3.2.1; Mitchell et al., 2004; Fronzek et al., 2012; Jacob et al., 2013).

Climate models show significant agreement for all emission scenarios in warming (magnitude and rate) all over Europe, with strongest warming projected in Southern Europe in summer, and in Northern Europe in winter (Goodess et al., 2009; Kjellström et al., 2011). Even under an average global temperature increase limited to 2°C compared to preindustrial times, the climate of Europe is simulated to depart significantly in the next decades from today's climate (Van der Linden and Mitchell, 2009; Jacob and Podzun, 2010).

Precipitation signals vary regionally and seasonally. Trends are less clear in Continental Europe, with agreement in increase in Northern Europe and decrease in Southern Europe (*medium confidence*; Kjellström et al., 2011). Precipitation is projected to decrease in the summer months up to southern Sweden and increase in winter (Schmidli et al., 2007), with more rain than snow in mountainous regions (Steger et al., 2013). In Northern Europe, a decrease of long-term mean snowpack (although snow-rich winters will remain) toward the end of the 21st century (Räisänen and Eklund, 2012) is projected. There is lack of information about past and future changes in hail occurrence in Europe. Changes in future circulation patterns (Ulbrich et al., 2009; Kreienkamp et al., 2010) and mean wind speed trends are uncertain in sign (Kjellström et al., 2011; McInnes et al., 2011).

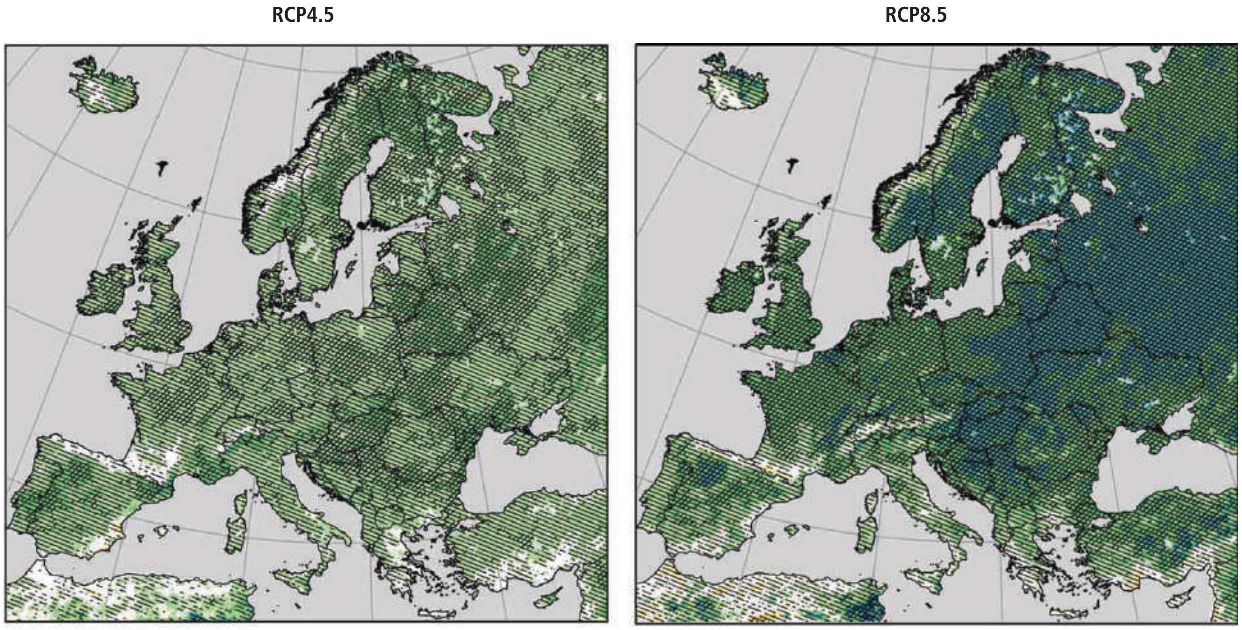
Regional coupled simulations over the Mediterranean region provide a more realistic characterization of impact parameters (e.g., snow cover, aridity index, river discharge), which were not revealed by Coupled Model Intercomparison Project Phase 3 (CMIP3) global simulations (Dell'Aquila et al., 2012).

For 2081–2100 compared to 1986–2005, projected global mean sea level rises (meters) are in the range 0.29 to 0.55 for RCP2.6, 0.36 to 0.63 for RCP4.5, 0.37 to 0.64 for RCP6.0, and 0.48 to 0.82 for RCP8.5 (*medium confidence*; WGIII AR5 Chapter 5). There is a *low confidence* on projected regional changes (Slangen et al., 2012; WGI AR5 Section 13.6). Low-probability/high-impact estimates of extreme mean sea level rise projections derived from the SRES A1FI scenario for the Netherlands (Katsman et al., 2011) indicate that the mean sea level could rise globally between 0.55 and 1.15 m, and locally (Netherlands) by 0.40 to 1.05 m, by 2100. Extreme (*very unlikely*) scenarios for the UK vary from 0.9 to 1.9 m by 2100 (Lowe et al., 2009).

23.2.2.3. Projected Changes in Climate Extremes

There will be a marked increase in extremes in Europe, in particular, in heat waves, droughts, and heavy precipitation events (Beniston et al., 2007; Lenderink and Van Meijgaard, 2008; see also Chapter 21 supplementary material). There is a general *high confidence* concerning changes in temperature extremes (toward increased number of warm days, warm nights, and heat waves; SREX Table 3-3). Figure 23-2c shows projected changes in the mean number of heat waves in May to September for 2071–2100 compared to 1971–2000 for RCP4.5 and

(a) DJF seasonal changes in heavy precipitation (%), 2071–2100 compared to 1971–2000



(b) JJA seasonal changes in heavy precipitation (%), 2071–2100 compared to 1971–2000

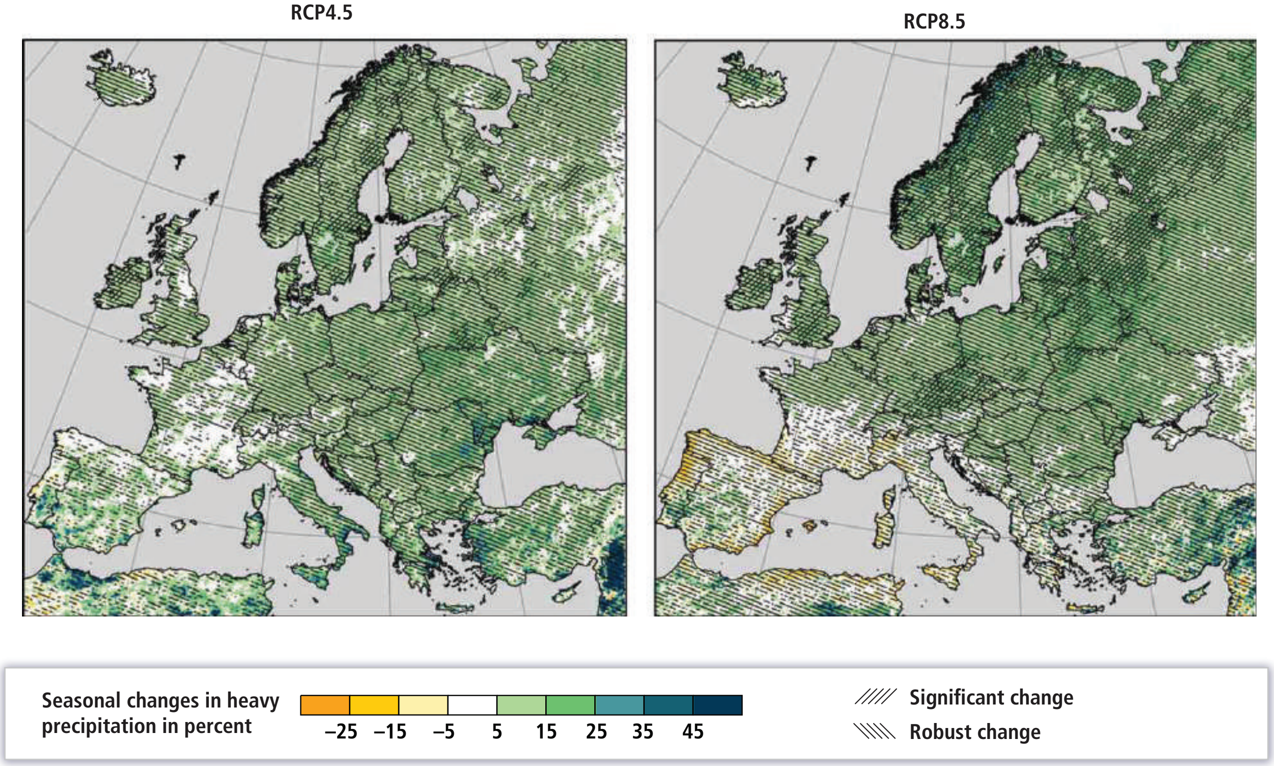
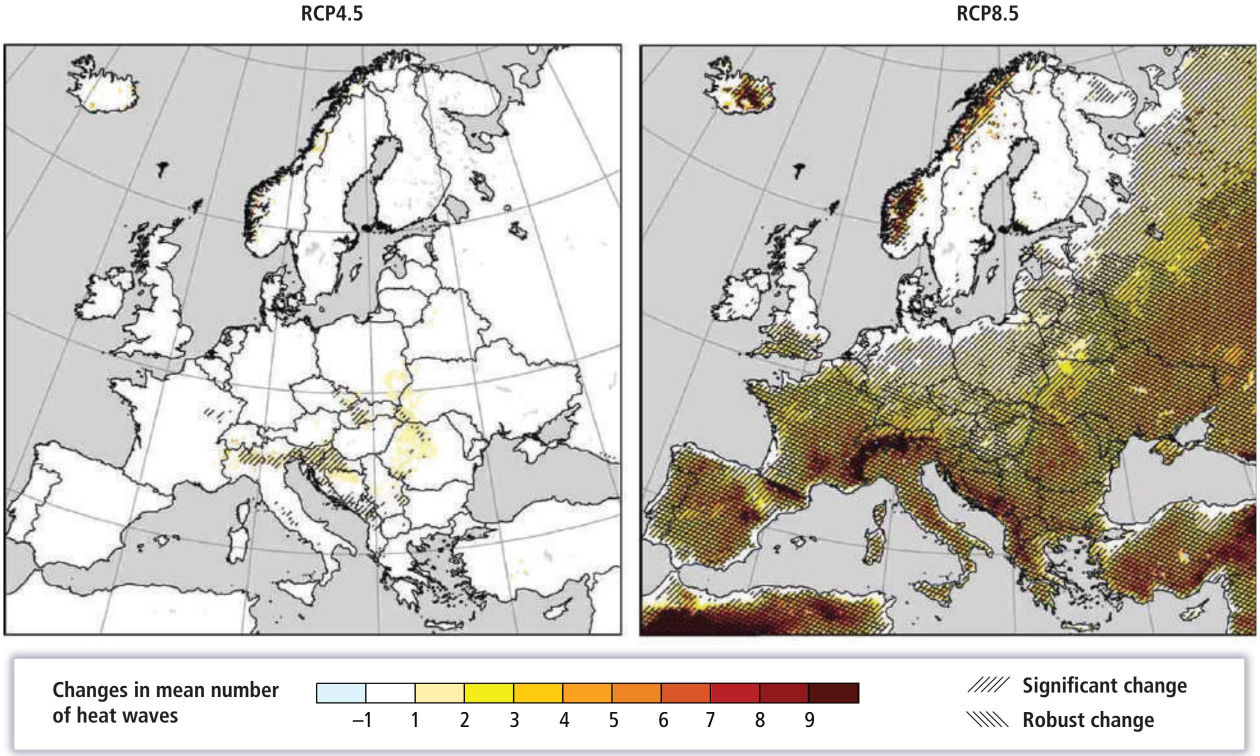


Figure 23-2 | (a) and (b): Projected seasonal changes in heavy precipitation defined as the 95th percentile of daily precipitation (only days with precipitation >1 mm day^{-1} are considered) for the period 2071–2100 compared to 1971–2000 (in %) in the months December to February (DJF) and June to August (JJA). (c) Projected changes in the mean number of heat waves occurring in the months May to September for the period 2071–2100 compared to 1971–2000 (number per 30 years). Heat waves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season of the control period (1971–2000) by at least 5°C. (d) Projected changes in the 95th percentile of the length of dry spells for the period 2071–2100 compared to 1971–2000 (in days). Dry spells are defined as periods of at least 5 consecutive days with daily precipitation below 1 mm. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistically significant change (significant on a 95% confidence level using Mann–Whitney U test). For the eastern parts of Black Sea, eastern Anatolia, and southeast Anatolia (Turkey), no regional climate model projections are available. Changes represent the mean over 8 (RCP4.5, left side) and 9 (RCP8.5, right side) regional model simulations compiled within the Coordinated Downscaling Experiment – European Domain (EURO-CORDEX) initiative. Adapted from Jacob et al., 2013.

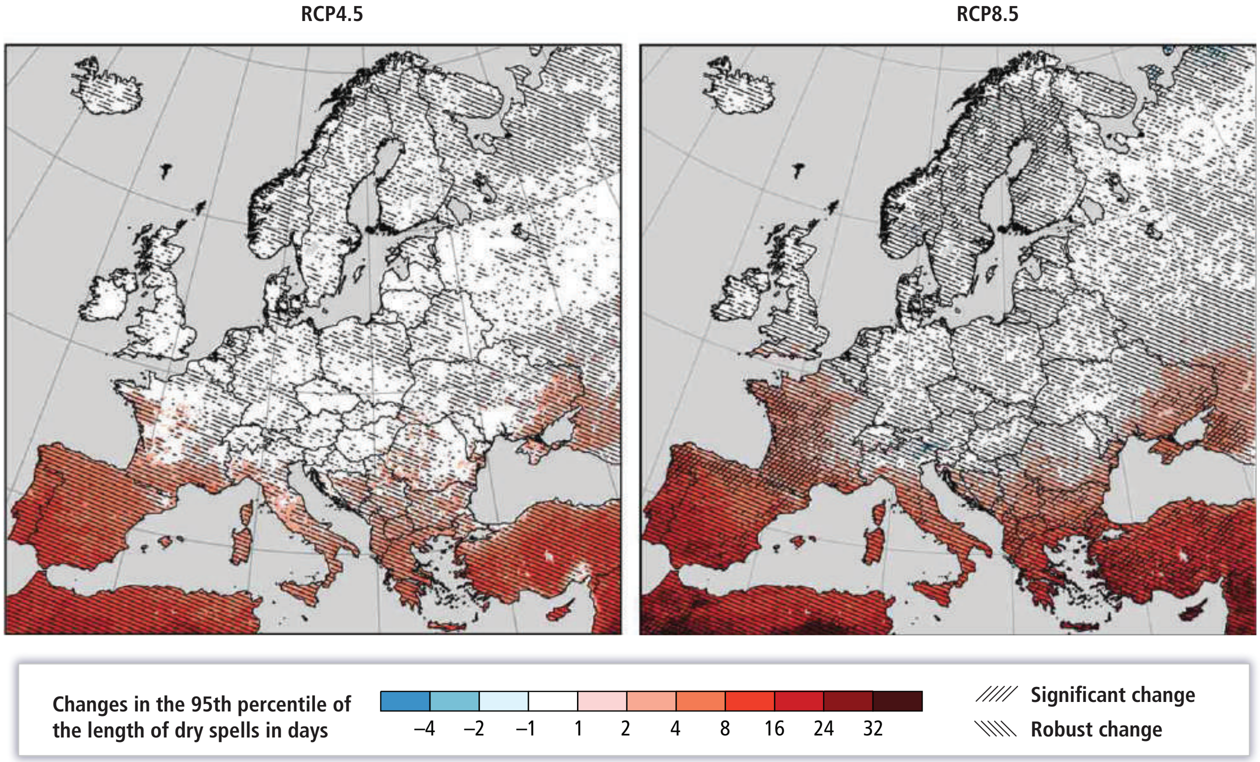
Continued next page →

Figure 23-2 (continued)

(c) Changes in mean number of heat waves for MJJAS, 2071–2100 compared to 1971–2000



(d) Changes in the 95th percentile of the length of dry spells (days) 2071–2100 compared to 1971–2000



RCP8.5 with large differences depending on the emission scenario. The increase in likelihood of some individual events due to anthropogenic change has been quantified for the 2003 heat wave (Schär and Jendritzky, 2004), the warm winter of 2006/2007, and warm spring of 2007 (Beniston, 2007).

Changes in extreme precipitation depend on the region, with a *high confidence* of increased extreme precipitation in Northern Europe (all seasons) and Continental Europe (except summer). Future projections are regionally and seasonally different in Southern Europe (SREX Table 3-3). Figure 23-2a,b shows projected seasonal changes of heavy precipitation events for 2071–2100 compared to 1971–2000 for RCP4.5 and RCP8.5.

Projected changes of spatially averaged indices over the European sub-regions are described in the supplemental information (Tables SM23-2 and SM23-3 for sub-regions, and Table SM23-4 for three Alpine areas).

In winter, small increases in extreme wind speed are projected for Central and Northern Europe (*medium confidence*; Section 21.3.3.1.6; SREX Figure 3-8; Beniston et al., 2007; Rockel and Woth, 2007; Haugen and Iversen, 2008; Rauthe et al., 2010; Schwierz et al., 2010), connected to changes in storm tracks (*medium confidence*; Pinto et al., 2007a,b, 2010; Donat et al., 2010). Other parts of Europe and seasons are less clear in sign with a small decreasing trend in Southern Europe (*low confidence*; Donat et al., 2011; McInnes et al., 2011).

Extreme sea level events will increase (*high confidence*; WGI AR5 Section 13.7; SREX Section 3.5.3), mainly dominated by the global mean sea level increase. Storm surges are expected to vary along the European coasts. Significant increases are projected in the eastern North Sea (increase of 6 to 8% of the 99th percentile of the storm surge residual, 2071–2100 compared to 1961–1990, based on the B2, A1B, and A2 SRES scenarios; Debernard and Rÿed, 2008) and west of UK and Ireland (Debernard and Rÿed, 2008; Wang et al., 2008), except south of Ireland (Wang et al., 2008). There is a *medium agreement* for the south of North Sea and Dutch coast where trends vary from increasing (Debernard and Rÿed, 2008) to stable (Sterl et al., 2009). There is a *low agreement* on the trends in storm surge in the Adriatic Sea (Planton et al., 2006; Jordà et al., 2012; Lionello et al., 2012; Troccoli et al., 2012b).

23.2.3. Observed and Projected Trends in Riverflow and Drought

Streamflows have decreased in the south and east of Europe and increased in Northern Europe (Stahl et al., 2010; Wilson et al., 2010; see also Section 3.2.3). In general, few changes in flood trends can be attributed to climate change, partly owing to the lack of sufficiently long records (Kundzewicz et al., 2013). European mean and peak discharges are highly variable (Bouwer et al., 2008); for instance, in France, upward trends in low flows were observed over 1948–1988 and downward trends over 1968–2008 (Giuntoli et al., 2013). Alpine glacier retreat during the last 2 decades caused a 13% increase in glacier contribution to August runoff of the four main rivers originating in the Alps, compared to the long-term average (Huss, 2011). Increases in extreme river discharge (peak flows) over the past 30 to 50 years have been observed in parts of Germany (Petrow et al., 2007, 2009), the Meuse River basin (Tu et al., 2005), parts of Central Europe (Villarini et al., 2011), Russia (Semenov, 2011), and northeastern France (Renard et al., 2008). Decreases in extreme river discharge have been observed in the Czech Republic (Yiou et al., 2006), and no change observed in Switzerland (Schmocker-Fackel and Naef, 2010), Germany (Bormann et al., 2011), and the Nordic countries (Wilson et al., 2010). River regulation possibly partly masks increasing peak flows in the Rhine (Vorogushyn et al., 2012). One study (Pall et al., 2011) suggested that the UK 2000 flood was partly due to anthropogenic forcing, although another showed a weaker effect (Kay et al., 2011).

Climate change is projected to affect the hydrology of river basins (Chapter 4; SREX Chapter 3). The occurrence of current 100-year return period discharges is projected to increase in Continental Europe, but decrease in some parts of Northern and Southern Europe by 2100 (Dankers and Feyen, 2008; Rojas et al., 2012). In contrast, studies for individual catchments indicate increases in extreme discharges, to varying degrees, in Finland (Veijalainen et al., 2010), Denmark (Thodsen, 2007), Ireland (Wang et al., 2006; Steele-Dunne et al., 2008; Bastola et al., 2011), the Rhine basin (Görgen et al., 2010; te Linde et al., 2010a), Meuse basin (Leander et al., 2008; Ward et al., 2011), the Danube basin (Dankers et al., 2007), and France (Quintana-Segui et al., 2011; Chauveau et al., 2013). Although snowmelt floods may decrease, increased autumn and winter rainfall could lead to higher peak discharges in Northern Europe (Lawrence and Hisdal, 2011). Declines in low flows are projected for the UK (Christierson et al., 2012), Turkey (Fujihara et al., 2008), France (Chauveau et al., 2013), and rivers fed by Alpine glaciers (Huss, 2011).

The analysis of trends in droughts is made complex by the different categories or definitions of drought (meteorological, agricultural, and hydrological) and the lack of long-term observational data (SREX Box 3-3). Southern Europe shows trends toward more intense and longer meteorological droughts, but they are still inconsistent (Sousa et al., 2011). Drought trends in all other sub-regions are not statistically significant (SREX Section 3.5.1). Regional and global climate simulations project (*medium confidence*) an increase in duration and intensity of droughts in Central and Southern Europe and the Mediterranean up until the UK for different definitions of drought (Gao and Giorgi, 2008; Feyen and Dankers, 2009; Vidal and Wade, 2009; Koutroulis et al., 2010; Tsanis et al., 2011; Chapter 21). Even in regions where summer precipitation is expected to increase, soil moisture and hydrological droughts may become more severe as a result of increasing evapotranspiration (Wong et al., 2011). Projected changes in the length of meteorological dry spells show that the increase is large in Southern Europe (Figure 23-2d).

23.3. Implications of Climate Change for Production Systems and Physical Infrastructure

23.3.1. Settlements

23.3.1.1. Coastal Flooding

As the risk of extreme sea level events increases with climate change (Section 23.2.3; Chapter 5), coastal flood risk will remain a key challenge for several European cities, port facilities, and other infrastructure (Hallegatte et al., 2008, 2011; Nicholls et al., 2008). With no adaptation, coastal flooding in the 2080s is projected to affect an additional 775,000 and 5.5 million people per year in the EU27 (B2 and A2 scenarios, respectively; Ciscar et al., 2011). The Atlantic, Northern, and Southern European regions are projected to be most affected. Direct costs from sea level rise in the EU27 without adaptation could reach €17 billion per year by 2100 (Hinkel et al., 2010), with indirect costs also estimated for land-locked countries (Bosello et al., 2012). Countries with high absolute damage costs include Netherlands, Germany, France, Belgium, Denmark, Spain, and Italy (Hinkel et al., 2010). Upgrading coastal defenses would substantially reduce impacts and damage costs (Hinkel et al., 2010). However, the amount of assets and populations that need to be protected by coastal defenses is increasing; thus, the magnitude of losses when floods do occur will also increase in the future (Hallegatte et al., 2013).

An increase in future flood losses due to climate change have been estimated for Copenhagen (Hallegatte et al., 2011), UK coast (Mokrech et al., 2008; Purvis et al., 2008; Dawson et al., 2011), the North Sea coast (Gaslikova et al., 2011), cities including Amsterdam and Rotterdam (Hanson et al., 2011), and the Netherlands (Aerts et al., 2008). A 1 m sea level rise in Turkey could affect 3 million additional people and put US$12 billion capital value at risk, with around US$20 billion adaptation costs (10% of GNP; Karaca and Nicholls, 2008). In Poland, up to 240,000 people would be affected by increasing flood risk on the Baltic coast (Pruszak and Zawadzka, 2008). The increasing cost of insurance and unwillingness of investors to place assets in affected areas is a potential growth impediment to coastal and island economies (Day et al., 2008).

23.3.1.2. River and Pluvial Flooding

Recent major flood events in Europe include the 2007 floods in the UK (Table 23-1; Chatterton et al., 2010) and the 2013 floods in Germany. The observed increase in river flood events and damages in Europe is well documented (see Section 18.4.2.1); however, the main cause is increased exposure of persons and property in flood risk areas (Barredo, 2009). Since AR4, new studies provide a wider range of estimates of future economic losses from river flooding attributable to climate change, depending on the modeling approach and climate scenario (Bubeck et al., 2011). Studies now also quantify risk under changes in population and economic growth, generally indicating this contribution to be about equal or larger than climate change per se (Feyen et al., 2009; Maaskant et al., 2009; Bouwer et al., 2010; Rojas et al., 2013; te Linde et al., 2011). Some regions may see increasing risks, but others may see decreases or little to no change (ABI, 2009; Feyen et al., 2009, 2012; Lugeri et al., 2010; Mechler et al., 2010; Bubeck et al., 2011; Lung et al., 2012). In the EU15, river flooding could affect 250,000 to 400,000

Table 23-1 | Impacts of climate extremes in the last decade in Europe.[a]

Year	Region	Meteorological characteristics	Production systems and physical infrastructure, settlements	Agriculture, fisheries, forestry, bioenergy	Health and social welfare	Environmental quality and biological conservation	Mega-fire
2003	Western and central Europe	Hottest summer in at least 500 years (Luterbacher et al., 2004)	Damage to road and rail transport systems Reduced/interrupted operation of nuclear power plants (mostly in France) High transport prices on the Rhine due to low water levels	Grain harvest losses of 20% (Ciais et al., 2005)	35,000 deaths in August in central and western Europe (Robine et al., 2008)	Decline in water quality (Daufresne et al., 2007) High outdoor pollution levels (EEA, 2012)	Yes
2004/ 2005	Iberian Peninsula	Hydrological drought		Grain harvest losses of 40% (EEA, 2010c)			
2007	Southern Europe	Hottest summer on record in Greece since 1891 (Founda and Giannakopoulos, 2009)	1710 buildings burned down or rendered uninhabitable in Greece (JRC, 2008)	~575,500 hectares burnt area (JRC, 2008)	6 deaths in Portugal, 80 deaths in Greece (JRC, 2008)	Several protected conservation sites (Natura, 2000) were destroyed (JRC, 2008).	Yes, Greece
2007	England and Wales	May–July wettest since records began in 1766	Estimated total losses £4 billion (£3 billion insured losses) (Chatterton et al., 2010) Failure of pumping station led to 20,000 people without water for 2 weeks.	78 farms flooded. Impacts on agriculture £50 million (Chatterton et al., 2010)	13 deaths and 48,000 flooded homes (Pitt, 2008). Damage costs for health effects, including loss of access to education, £287 million (Chatterton et al., 2010)		
2010	Western Russia	Hottest summer since 1500 (Barriopedro et al., 2011)		Fire damage to forests (Shvidenko et al., 2011) Reduction in crop yields (Barriopedro et al., 2011; Coumou and Rahmstorf, 2012)	Estimated 10,000 excess deaths due to heat wave in Moscow in July and August (Revich and Shaposhnikov, 2012)	High outdoor pollution levels in Moscow (Bondur, 2011; Revich and Shaposhnikov, 2012)	Yes
2011	France	Hottest and driest spring in France since 1880	Reduction in snow cover for skiing	8% decline in wheat yield (AGRESTE, 2011)			

[a] Extreme events derived from Coumou and Rahmstorf (2012).

additional people by the 2080s (SRES A2 and B2 scenarios, respectively) more than doubling annual average damages, with Central and Northern Europe and the UK most affected (Ciscar, 2009; Ciscar et al., 2011). When economic growth is included, economic flood losses in Europe could increase 17-fold under the A1B climate scenario (Rojas et al., 2013).

Few studies have estimated future damages from inundation in response to an increase in intense rainfall (Hoes, 2006; Willems et al., 2012). Processes that influence flash flood risk include increasing exposure from urban expansion, and forest fires that lead to erosion and increased surface runoff (Lasda et al., 2010). Some studies have costed adaptation measures but these may only partly offset anticipated impacts (Zhou et al., 2012).

23.3.1.3. Windstorms

Several studies project an overall increase in storm hazard in northwest Europe (Section 23.2.2.3) and in economic and insured losses (Section 17.7), but natural variations in frequencies are large. There is no evidence that the observed increase in European storm losses is due to anthropogenic climate change (Barredo, 2010). There is a lack of information for other storm types, such as tornadoes and thunderstorms.

23.3.1.4. Mass Movements and Avalanches

In the European Alps, the frequency of rock avalanches and large rock slides has apparently increased over the period 1900–2007 (Fischer et al., 2012). The frequency of landslides may also have increased in some locations (Lopez Saez et al., 2013). Mass movements are projected to become more frequent with climate change (Huggel et al., 2010; Stoffel and Huggel, 2012), although several studies indicate a more complex or stabilizing response of mass movements to climate change (Dixon and Brook, 2007; Jomelli et al., 2007, 2009; Huggel et al., 2012; Melchiorre and Frattini, 2012). Some land use practices have led to conditions favorable to increased landslide risk, despite climate trends that would result in a decrease of landslide frequency, as reported in Calabria (Polemio and Petrucci, 2010) and in the Apennines (Wasowski et al., 2010). Snow avalanche frequency changes in Europe are dominated by climate variability; studies based on avalanche observations (Eckert et al., 2010) or favorable meteorological conditions (Castebrunet et al., 2012; Teich et al., 2012) show contrasting variations, depending on the region, elevation, season, and orientation.

23.3.2. Built Environment

Built infrastructure in Europe is vulnerable to extreme weather events, including overheating of buildings (houses, hospitals, schools) during hot weather (Crump et al., 2009; DCLG, 2012). Buildings that were originally designed for certain thermal conditions will need to function in warmer climates in the future (WHO, 2008). Climate change in Europe is expected to increase cooling energy demand (Dolinar et al., 2010; see also Section 23.3.4), with implications for mitigation and adaptation policies (Section 23.8.1). A range of adaptive strategies for buildings are available, including effective thermal mass and solar shading (Three Regions Climate Change Group, 2008). Climate change may also increase the frequency and intensity of drought-induced soil subsidence and associated damage to dwellings (Corti et al., 2009).

With respect to the outdoor built environment, there is limited evidence regarding the potential for differential rates of radiatively forced climate change in urban compared to rural areas (McCarthy et al., 2010). Climate change may exacerbate London's nocturnal urban heat island (UHI) (Wilby, 2008); however, the response of different cities may vary. For example, a study of Paris (Lemonsu et al., 2013) indicated a future reduction in strong urban heat island events when increased soil dryness was taken into effect. Modification of the built environment, via enhanced urban greening, for example, can reduce temperatures in urban areas, with co-benefits for health and well-being (Sections 23.7.4, 23.8.1).

23.3.3. Transport

Systematic and detailed knowledge on climate change impacts on transport in Europe remains limited (Koetse and Rietveld, 2009).

On road transport, in line with AR4, more frequent but less severe collisions due to reduced speed are expected in case of increased precipitation (Kilpeläinen and Summala, 2007; Brijs et al., 2008). However, lower traffic speed may cause welfare losses due to additional time spent driving (Sabir et al., 2010). Severe snow and ice-related accidents will also decrease, but the effect of fewer frost days on total accidents is unclear (Andersson and Chapman, 2011a,b). Severe accidents caused by extreme weather are projected to decrease by 63 to 70% in 2040–2070 compared to 2007 as a result of modified climate and expected developments in vehicle technology and emergency systems (Nokkala et al., 2012).

For rail, consistent with AR4, increased buckling in summer, as occurred in 2003 in the UK, is expected to increase the average annual cost of heat-related delays in some regions, while the opposite is expected for ice and snow-related delays (Lindgren et al., 2009; Dobney et al., 2010; Palin et al., 2013). Effects from extreme precipitation, as well as the net overall regional impact of climate change remain unclear. Efficient adaptation comprises proper maintenance of track and track bed.

Regarding inland waterways, the case of Rhine shows that, for 1°C to 2°C increases by 2050, more frequent high water levels are expected in winter, while after 2050 days with low water levels in summer will also increase (te Linde, 2007; Hurkmans et al., 2010; Jonkeren et al., 2011; te Linde et al., 2011). Low water levels will reduce the load factor of inland ships and consequently increase transport prices, as in the Rhine and Moselle in 2003 (Jonkeren et al., 2007; Jonkeren, 2009). Adaptation includes modal shifts, increased navigational hours per day under low water levels, and infrastructure modifications (e.g., canalization of river parts) (Jonkeren et al., 2011; Krekt et al., 2011).

For long range ocean routes, the economic attractiveness of the Northwest Passage and the Northern Sea Route depends also on passage fees, bunker prices, and cost of alternative sea routes (Verny and Grigentin, 2009; Liu and Kronbak, 2010; Lasserre and Pelletier, 2011).

Regarding air transport, for Heathrow airport (UK), future temperature and wind changes were estimated to cause a small net annual increase but much larger seasonal changes on the occurrence of delays (Pejovic et al., 2009).

23.3.4. Energy Production, Transmission, and Use

On wind energy, no significant changes are expected before 2050, at least in Northern Europe (Pryor and Barthelmie, 2010; Pryor and Schoof, 2010; Seljom et al., 2011; Barstad et al., 2012; Hueging et al., 2013). After 2050, in line with AR4, the wind energy potential in Northern, Continental, and most of Atlantic Europe may increase during winter and decrease in summer (Rockel and Woth, 2007; Harrison et al., 2008; Nolan et al., 2012; Hueging et al., 2013). For Southern Europe, a decrease in both seasons is expected, except for the Aegean Sea and Adriatic coast, where a significant increase during summer is possible (Bloom et al., 2008; Najac et al., 2011; Pašičko et al., 2012; Hueging et al., 2013).

For hydropower, electricity production in Scandinavia is expected to increase by 5 to 14% during 2071–2100 compared to historic or present levels (Haddeland et al., 2011; Golombek et al., 2012); for 2021–2050, increases by 1 to 20% were estimated (Haddeland et al., 2011; Seljom et al., 2011; Hamududu and Killingtveit, 2012). In Continental and part of Alpine Europe, reductions in electricity production by 6 to 36% were estimated (Schaefli et al., 2007; Stanzel and Nachtnebel, 2010; Paiva et al., 2011; Pašičko et al., 2012; Hendrickx and Sauquet, 2013). For Southern Europe, production is expected to decrease by 5 to 15% in 2050 compared to 2005 (Hamududu and Killingtveit, 2012; Bangash et al., 2013). Adaptation consists of improved water management, including pump storage if appropriate (Schaefli et al., 2007; García-Ruiz et al., 2011).

Biofuel production is discussed in Section 23.4.5. There are few studies of impacts on solar energy production. Crook et al. (2011) estimated an increase of the energy output from photovoltaic panels and especially from concentrated solar power plants in most of Europe under the A1B scenario.

On thermal power, in line with AR4, van Vliet et al. (2012) estimated a 6 to 19% decrease of the summer average usable capacity of power plants by 2031–2060 compared to 1971–2000, while smaller decreases have been also estimated (Förster and Lilliestam, 2010; Linnerud et al., 2011). Closed-cooling circuits are efficient adaptation choices for new plants (Koch and Vögele, 2009). In power transmission, increasing lightning and decreasing snow-sleet and blizzard faults for 2050–2080 were estimated for the UK (McColl et al., 2012).

By considering both heating and cooling, under a +3.7°C scenario by 2100 a decrease of total annual energy demand in Europe as a whole during 2000–2100 was estimated (Isaac and van Vuuren, 2009). Seasonal changes will be prominent, especially for electricity (see Figure 23-3), with summer peaks arising also in countries with moderate summer temperatures (Hekkenberg et al., 2009). Heating degree days are expected to decrease by 11 to 20% between 2000 and 2050 due solely to climate change (Isaac and van Vuuren, 2009). For cooling, very large percentage increases up to 2050 are estimated by the same authors for most of Europe as the current penetration of cooling devices is low; then, increases by 74 to 118% in 2100 (depending on the region) from 2050 are expected under the combined effect of climatic and non-climatic drivers. In Southern Europe, cooling degree days by 2060 will increase, while heating degree days will decrease but with substantial spatial variations (Giannakopoulos et al., 2009). Consequently, net annual electricity generation cost will increase in most of the Mediterranean and decrease in the rest of Europe (Mirasgedis

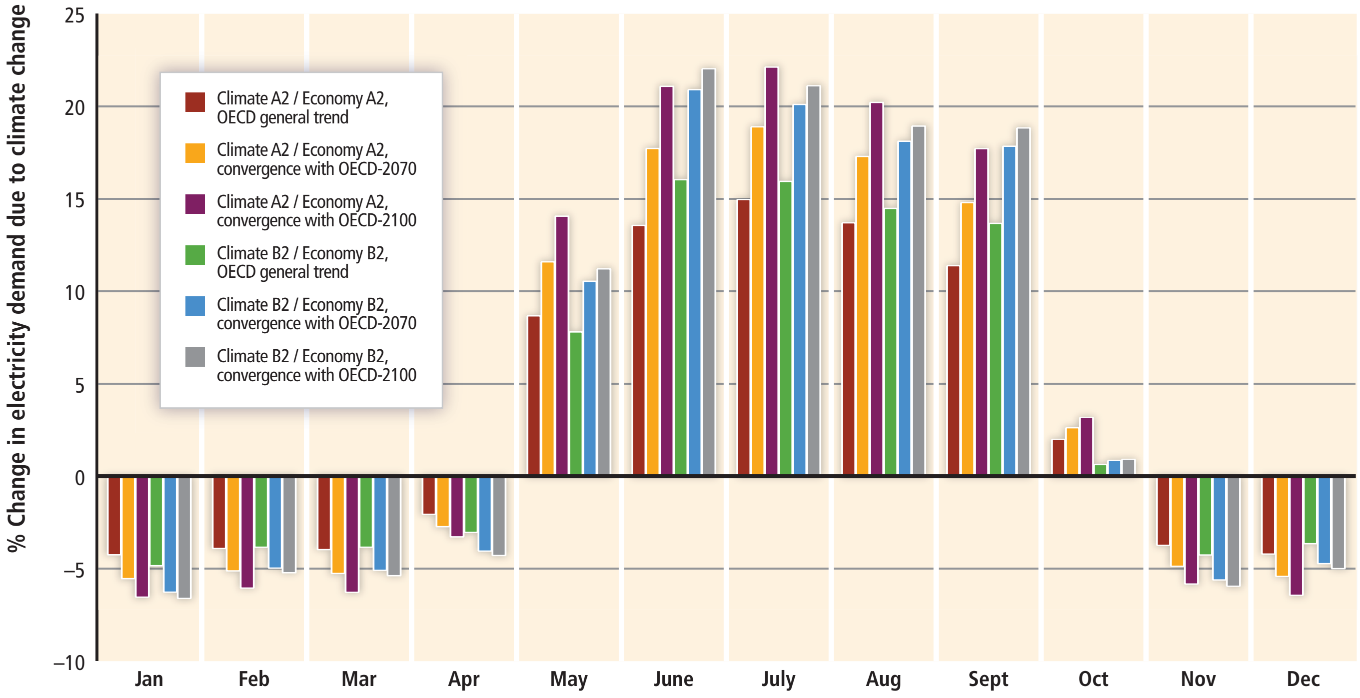


Figure 23-3 | Percentage change in electricity demand in Greece attributable to climate change, under a range of climate scenarios and economic assumptions. Source: Mirasgedis et al., 2007.

et al., 2007; Eskeland and Mideksa, 2010; Pilli-Sihlova et al., 2010; Zachariadis, 2010).

Future building stock changes and retrofit rates are critical for impact assessment and adaptation (Olonscheck et al., 2011). Energy-efficient buildings and cooling systems, and demand-side management, are effective adaptation options (Artmann et al., 2008; Jenkins et al., 2008; Day et al., 2009; Breesch and Janssens, 2010; Chow and Levermore, 2010).

23.3.5. Industry and Manufacturing

Research on the potential effects of climate change in industry is limited. Modifications in future consumption of food and beverage products have been estimated on the basis of current sensitivity to seasonal temperature (Mirasgedis et al., 2013). Higher temperatures may favor the growth of food-borne pathogens or contaminants (Jacxsens et al., 2010; Popov Janevska et al., 2010; see also Section 23.5.1). The quality of some products, such as wine (Section 23.4.1; Box 23-2), is also likely to be affected. In other sectors, the cumulative cost of direct climate change impacts in the Greek mining sector for 2021–2050 has been estimated at €0.245 billion, in 2010 prices (Damigos, 2012). Adaptation to buildings or work practices are likely to be needed to maintain labor productivity during hot weather (Kjellstrom et al., 2009; see also Section 11.6.2.2).

23.3.6. Tourism

In line with AR4, the climate for general tourist activities especially after 2070 is expected to improve significantly during summer and less during autumn and spring in northern Continental Europe, Finland, southern Scandinavia, and southern England (Amelung et al., 2007; Nicholls and Amelung, 2008; Amelung and Moreno, 2012). For the Mediterranean, climatic conditions for light outdoor tourist activities are expected to deteriorate in summer mainly after 2050, but improve during spring and autumn (Amelung et al., 2007; Amelung and Moreno, 2009; Hein et al., 2009; Perch-Nielsen et al., 2010; Giannakopoulos et al., 2011). Others concluded that before 2030 (or even 2060) this region as a whole will not become too hot for beach or urban tourism (Moreno and Amelung, 2009; Rutty and Scott, 2010), while surveys showed that beach tourists are deterred mostly by rain (De Freitas et al., 2008; Moreno, 2010).

Thus, from 2050, domestic tourism and tourist arrivals at locations in Northern and parts of Continental Europe may be enhanced at the expense of southern locations (Hamilton and Tol, 2007; Hein et al., 2009; Amelung and Moreno, 2012; Bujosa and Roselló, 2012). The age of tourists, the climate in their home country, and local economic and environmental conditions (e.g., water stress, tourist development) are also critical (Hamilton and Tol, 2007; Lyons et al., 2009; Moreno and Amelung, 2009; Rico-Amoros et al., 2009; Eugenio-Martin and Campos-Soria, 2010; Perch-Nielsen et al., 2010).

Tourism in mountainous areas may benefit from improved climatic conditions in summer (Endler et al., 2010; Perch-Nielsen et al., 2010; Endler and Matzarakis, 2011; Serquet and Rebetez, 2011). However, in agreement with AR4, natural snow reliability and thus ski season length will be adversely affected, especially where artificial snowmaking is limited (Moen and Fredman, 2007; OECD, 2007; Steiger, 2011). Low-lying areas will be the most vulnerable (Uhlmann et al., 2009; Endler et al., 2010; Endler and Matzarakis, 2011; Serquet and Rebetez, 2011; Steiger, 2011). Tourist response to marginal snow conditions remains largely unknown, while changes in weather extremes may also be critical (Tervo, 2008). Up to 2050, demographic changes (e.g., population declines in source countries, aging populations) may have a higher impact than climate change (Steiger, 2012). Artificial snowmaking has physical and economic limitations, especially in small sized and low-altitude ski stations (Steiger and Mayer, 2008; Sauter et al., 2010; Steiger, 2010, 2011), and increases water and energy consumption. Shifts to higher altitudes, operational/ technical measures, and year-round tourist activities may not fully compensate for adverse impacts.

23.3.7. Insurance and Banking

Insurance and banking face problems related to accurate pricing of risks, shortage of capital after large loss events, and by an increasing burden of losses that can affect markets and insurability, within but also outside the European region (CEA, 2007; Botzen et al., 2010a,b; see also Section 10.7). However, risk transfer, including insurance, also holds potential for adaptation by providing incentives to reduce losses (Botzen and van den Bergh, 2008; CEA, 2009; Herweijer et al., 2009).

Banking is potentially affected through physical impacts on assets and investments, as well as through regulation and/or mitigation actions by changing demands regarding sustainability of investments and lending portfolios. Few banks have adopted climate strategies that also address adaptation (Cogan, 2008; Furrer et al., 2009).

Windstorm losses are well covered in Europe by building and motor policies, and thus create a large exposure to the insurance sector. Flood losses in the UK in 2000, 2007, and 2009 have put the insurance market under further pressure, with increasing need for the government to reduce risk (Ward et al., 2008; Lamond et al., 2009). Other risks of concern to the European insurance industry is building subsidence related to drought (Corti et al., 2009), and hail damage to buildings and agriculture (Kunz et al., 2009; Botzen et al., 2010b; GDV, 2011).

The financial sector can adapt by adjusting premiums, restricting or reducing coverage, spreading risk further, and importantly incentivizing risk reduction (Crichton, 2006, 2007; Clemo, 2008; Botzen et al., 2010a; Surminski and Philp, 2010; Wamsler and Lawson, 2011). Public attitudes in Scotland and the Netherlands would support insurance of private property and public infrastructure damages in the case of increasing flood risk (Botzen et al., 2009; Glenk and Fisher, 2010). Government intervention is, however, often needed to provide compensation and back-stopping in the event of major losses (Aakre and Rübbelke, 2010; Aakre et al., 2010). Hochrainer et al. (2010) analyzed the performance of the European Union Solidarity Fund that supports European governments in large events, and argue there is a need to increase its focus on risk reduction. Current insurance approaches present in Europe are likely to remain, as they are tailored to local situations and preferences (Schwarze et al., 2011).

23.4. Implications of Climate Change for Agriculture, Fisheries, Forestry, and Bioenergy Production

23.4.1. Plant (Food) Production

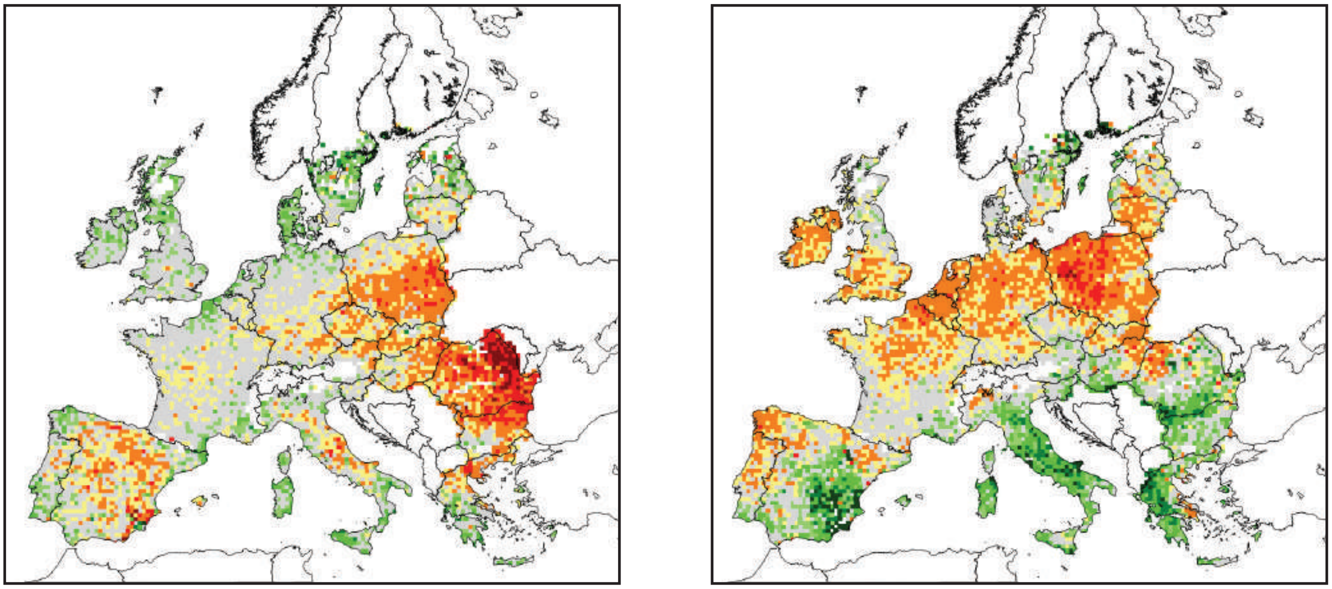
In AR4, Alcamo et al. (2007) reported that crop suitability is likely to change throughout Europe. During the 2003 and 2010 summer heat waves, grain-harvest losses reached 20 and 25-30% in affected regions of Europe and Russia, respectively (Ciais et al., 2005; Barriopedro et al., 2011; see also Table 23-1). Cereals production fell on average by 40% in the Iberian Peninsula during the intense 2004/2005 drought (EEA, 2010a). Climate-induced variability in wheat production has increased in recent decades in Southern and Central Europe (Ladanyi, 2008; Brisson et al., 2010; Hawkins et al., 2013), but no consistent reduction has been recorded in the northernmost areas of Europe (Peltonen-Sainio et al., 2010). Country-scale rainfed cereals yields are below agro-climatic potentials (Supit et al., 2010), and wheat yield increases have leveled off in several countries over 1961–2009 (Olesen et al., 2011). High temperatures and droughts during grain filling have contributed to the lack of yield increase of winter wheat in France despite improvements in crop breeding (Brisson et al., 2010; Kristensen et al., 2011). In contrast, in eastern Scotland, warming has favored an increase in potato yields since 1960 (Gregory and Marshall, 2012). In northeast Spain, grape yield was reduced by an increased water deficit in the reproductive stage since the 1960s (Camps and Ramos, 2012).

Insight into the potential effect of climate change on crops requires the combination of a wide range of emission scenarios, Global Climate Models (GCMs), and impact studies (Trnka et al., 2007; Soussana et al., 2010). In the EU27, a 2.5°C regional temperature increase in the 2080s under the B2 scenario could lead to small changes (on average +3%) in crop yields, whereas a 5.4°C regional warming under the A2 scenario could reduce mean yields by 10% according to a study based on regional climate models (Ciscar et al., 2011). An initial benefit from the increasing CO_2 concentration for rainfed crop yields would contrast by the end of the century with yield declines in most European sub-regions, although wheat yield could increase under the A2 scenario (three GCMs, B1, A2 scenarios; Supit et al., 2012). Disease-limited yields of rainfed wheat and maize in the 2030s does not show consistent trends across two GCMs (Donatelli et al., 2012). For a global temperature increase of 5°C, agroclimatic indices show an increasing frequency of extremely unfavorable years in European cropping areas (Trnka et al., 2011). Under the A2 and B2 scenarios, crop production shortfalls, defined as years with production below 50% of its average climate normal production would double by 2020 and triple by 2070 as compared to a current frequency of 1 to 3 years per decade in the currently most productive southern European regions of Russia (Alcamo et al., 2007).

The regional distribution of climate change impacts on agricultural production is likely to vary widely (Donatelli et al., 2012; Iglesias et al., 2012; see also Figure 23-4). Southern Europe would experience the largest yield losses (–25% by 2080 under a 5.4°C warming; Ciscar et al., 2011), with increased risks of rainfed summer crop failure (Ferrara et al., 2010; Bindi and Olesen, 2011; Ruiz-Ramos et al., 2011). Warmer and drier conditions by 2050 (Trnka et al., 2010, 2011) would cause moderate declines in crop yields in Central Europe regions (Ciscar et al., 2011). In Western Europe, increased heat stress around flowering could cause considerable yield losses in wheat (Semenov, 2009). For Northern Europe, there is diverging evidence concerning future impacts. Positive yield changes combined with the expansion of climatically suitable areas could lead to crop production increases (between 2.5°C and 5.4°C regional warming) (Bindi and Olesen, 2011). However, increased climatic variability would limit winter crops expansion (Peltonen-Sainio et al., 2010) and cause at high latitudes high risk of marked cereal yield loss (Rötter et al., 2011). Spring crops from tropical origin like maize for silage could become cultivated in Finland by the end of the century (Peltonen-Sainio et al., 2009). Cereal yield reduction from ozone (Fuhrer, 2009) could reach 6 and 10 % in 2030 for the European Union with the B1 and A2 scenarios, respectively (Avnery et al., 2011a,b). Because of limited land availability and soil fertility outside of Chernozem (black earth) areas, the shift of agriculture to the boreal forest zone would not compensate for crop losses owing to increasing aridity in South European regions of Russia with the best soils (Dronin and Kirilenko, 2011).

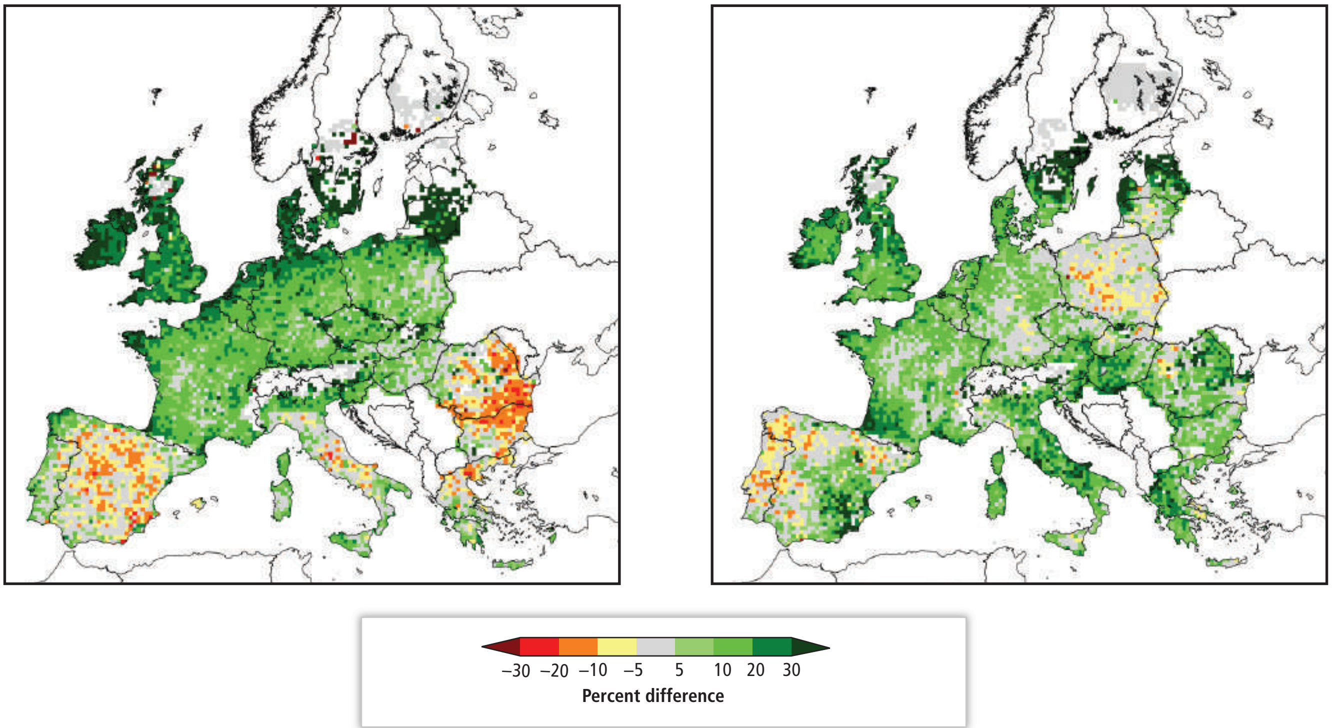
With generally warmer and drier conditions, deep rooted weeds (Gilgen et al., 2010) and weeds with contrasting physiology, such as C_4 species, could pose a more serious threat (Bradley et al., 2010) to crops than shallow rooted C_3 weeds (Stratonovitch, 2012). Arthropod-borne diseases (viruses and phytoplasmas), winter infection root and stem diseases (phoma stem canker of oilseed rape and eyespot of wheat; Butterworth et al., 2010; West et al., 2012), *Fusarium* blight (Madgwick et al., 2011), grapevine moth (Caffarra et al., 2012), and a black rot fungus in fruit trees (Weber, 2009) could create increasing damages in Europe under climate change. However, other pathogens such as cereal stem rots (e.g., *Puccinia striiformis*; Luck et al., 2011) and grapevine powdery mildew (Caffarra et al., 2012) could be limited by increasing temperatures. Increased damages from plant pathogens and insect pests are projected by 2050 in Nordic countries, which have hitherto been protected by cold winters and geographic isolation (Hakala et al., 2011; Roos et al., 2011). Some pests, such as the European corn borer (Trnka et al., 2007), could also extend their climate niche in Central Europe. Pests and disease management will be affected with regard to timing, preference, and efficacy of chemical and biological measures of control (Kersebaum et al., 2008).

Autonomous adaptation by farmers, through the advancement of sowing and harvesting dates and the use of longer cycle varieties (Howden et al., 2007; Moriondo et al., 2010a, 2011; Olesen et al., 2011) could result in a general improvement of European wheat yields in the 2030s compared to the 2000s (Donatelli et al., 2012; see also Figure 23-4). However, farmer sowing dates seem to advance slower than crop phenology (Menzel et al., 2006; Siebert and Ewert, 2012), possibly because earlier sowing is often prevented by lack of soil workability and frost-induced soil crumbling (Oort et al., 2012). Simulation studies that anticipate on earlier sowing in Europe may thus be overly optimistic. Further adaptation options include changes in crop species, fertilization, irrigation, drainage, land allocation, and farming system (Bindi and Olesen, 2011). At the high range of the projected temperature changes, only plant breeding aimed at increasing yield potential jointly with drought resistance and adjusted agronomic practices may reduce risks of yield shortfall (Olesen et al., 2011; Rötter et al., 2011; Ventrella et al., 2012). Crop breeding is, however, challenged by temperature and rainfall variability, since (1) breeding has not yet succeeded in altering crop plant development responses to short-term changes in temperature (Parent and Tardieu, 2012), and (2) distinct crop drought tolerance traits are required for mild and severe water deficit scenarios (Tardieu, 2012). Adaptation to increased climatic variability may require an increased use of between and within species genetic diversity in farming systems (Smith and Olesen, 2010) and the development of insurance products against weather-related yield variations (Musshoff et al., 2011). Adaptive capacity and long-term economic viability of farming systems may vary given farm structural change induced by climate change (Moriondo et al., 2010b; Mandryk et al., 2012). In Southern Europe, the regional welfare



Percent difference of water-limited yield for wheat
A1B scenario, ECHAM5, 2030–2000 (baseline)

Percent difference of water-limited yield for wheat
A1B scenario, HadCM3, 2030–2000 (baseline)



Percent difference of water-limited yield for wheat with adaptation
A1B scenario, ECHAM5, 2030–2000 (baseline)

Percent difference of water-limited yield for wheat with adaptation
A1B scenario, HadCM3, 2030–2000 (baseline)

Figure 23-4 | Percentage change in simulated water-limited yield for winter wheat in 2030 with respect to the 2000 baseline for the A1B scenario using European Centre for Medium Range Weather Forecasts and Hamburg 5 (ECHAM5; left column) and Hadley Centre Coupled Model version 3 (HadCM3; right) General Circulation Models (GCMs). Upper maps do not take adaptation into account. Bottom maps include adaptation. Analysis developed at the Joint Research Centre of the European Commission. Source: Donatelli et al., 2012.

loss caused by changes in the agriculture sector under a high warming scenario (+5.4°C) was estimated at 1% of gross domestic product (GDP). Northern Europe was the single sub-region with welfare gains (+0.7%) from agriculture in this scenario (Ciscar et al., 2011).

23.4.2. Livestock Production

Livestock production is adversely affected by heat (Tubiello et al., 2007; see also Section 7.2.1.3). With intensive systems, heat stress reduced dairy production and growth performance of large finishing pigs at daily mean air temperatures above 18°C and 21°C, respectively (André et al., 2011; Renaudeau et al., 2011). High temperature and air humidity during breeding increased cattle mortality risk by 60% in Italy (Crescio et al., 2010). Adaptation requires changes in diets and in farm buildings (Renaudeau et al., 2012) as well as targeted genetic improvement programs (Hoffmann, 2010).

With grass-based livestock systems, model simulations (A1B scenario, ensemble of downscaled GCMs) show by the end of the 21st century increases in potential dairy production in Ireland and France, with, however, higher risks of summer-autumn production failures in Central Europe and at French sites (Trnka et al., 2009; Graux et al., 2012). Climate conditions projected for the 2070s in central France (A2 scenario) reduced significantly grassland production in a 4-year experiment under elevated CO_2 (Cantarel et al., 2013). At the same site, a single experimental summer drought altered production during the next 2 years (Zwicke et al., 2013).

Resilience of grassland vegetation structure was observed to prolonged experimental heating and water manipulation (Grime et al., 2008). However, weed pressure from tap-rooted forbs was increased after severe experimental summer droughts (Gilgen et al., 2010). Mediterranean populations could be used to breed more resilient and better adapted forage plant material for livestock production (Poirier et al., 2012).

Climate change has affected animal health in Europe (*high confidence*). The spread of bluetongue virus in sheep across Europe has been partly attributed to climate change (Arzt et al., 2010; Guis et al., 2012) through increased seasonal activity of the *Culicoides* vector (Wilson and Mellor, 2009). The distribution of this vector is unlikely to expand but its abundance could increase in Southern Europe (Acevedo et al., 2010). Ticks, the primary arthropod vectors of zoonotic diseases in Europe (e.g., Lyme disease and tick-borne encephalitis), have changed distributions towards higher altitudes and latitudes with climate change (Randolph and Rogers, 2010; van Dijk et al., 2010; Petney et al., 2012; see also Section 23.5). Exposure to fly strike could increase in a warmer climate but adaptation in husbandry practices would limit impacts on livestock (Wall and Ellse, 2011). The overall risk of incursion of Crimean-Congo hemorrhagic fever virus in livestock through infected ticks introduced by migratory bird species would not be increased by climate change (Gale et al., 2012). The probability of introduction and large-scale spread of Rift Valley fever in Europe is also very low (Chevalier et al., 2010). Epidemiological surveillance and increased coordinated regional monitoring and control programs have the potential to reduce the incidence of vector-borne animal diseases (Wilson and Mellor, 2009; Chevalier et al., 2010).

23.4.3. Water Resources and Agriculture

Future projected trends confirm the widening of water resource differences between Northern and Southern Europe reported in AR4 (Alcamo et al., 2007). In Southern Europe, soil water content will decline, saturation conditions and drainage will be increasingly rare and restricted to periods in winter and spring, and snow accumulation and melting will change, especially in the mid-mountain areas (García-Ruiz et al., 2011). Across most of Northern and Continental Europe, an increase in flood hazards (Falloon and Betts, 2010; see also Section 23.3.1) could increase damages to crops and plant growth, complicate soil workability, and increase yield variability (Olesen et al., 2011). Groundwater recharge and/or water table level would be significantly reduced by the end of the 21st century under A2 scenario for river basins located in southern Italy, Spain, northern France, and Belgium (Ducharne et al., 2010; Goderniaux et al., 2011; Guardiola-Albert and Jackson, 2011; Senatore et al., 2011). However, nonsignificant impacts were found for aquifers in Switzerland and in England (Jackson et al., 2011; Stoll et al., 2011). Less precipitation in summer and higher rainfall during winter could increase nitrate leaching (Kersebaum et al., 2008) with negative impacts on water quality (Bindi and Olesen, 2011). Even with reduced nitrogen fertilizer application, groundwater nitrate concentrations would increase by the end of the century in the Seine river basin (Ducharne et al., 2007). More robust water management, pricing, and recycling policies to secure adequate future water supply and prevent tensions among users could be required in Southern Europe (García-Ruiz et al., 2011).

Reduced suitability for rainfed agricultural production (Henriques et al., 2008; Daccache and Lamaddalena, 2010; Trnka et al., 2011; Daccache et al., 2012) will increase water demand for crop irrigation (Savé et al., 2012). However, increased irrigation may not be a viable option, especially in the Mediterranean area, because of projected declines in total runoff and groundwater resources (Olesen et al., 2011). In a number of catchments water resources are already over-licensed and/or over-abstracted (Daccache et al., 2012) and their reliability is threatened by climate change-induced decline in groundwater recharge and to a lesser extent by the increase in potential demand for irrigation (Ducharne et al., 2010; Majone et al., 2012). To match this demand, irrigation system costs could increase by 20 to 27% in southern Italy (Daccache and Lamaddalena, 2010) and new irrigation infrastructures would be required in some regions (van der Velde et al., 2010). However, since the economic benefits are expected to be small, the adoption of irrigation would require changes in institutional and market conditions (Finger et al., 2011). Moreover, since aquatic and terrestrial ecosystems are affected by agricultural water use (Kløve et al., 2011), irrigation demand restrictions are projected in environmentally focussed future regional scenarios (Henriques et al., 2008). Earlier sowing dates, increased soil organic matter content, low-energy systems, deficit irrigation, and improved water use efficiency of irrigation systems and crops can be used as adaptation pathways (Gonzalez-Camacho et al., 2008; Lee et al., 2008; Daccache and Lamaddalena, 2010; Schutze and Schmitz, 2010), especially in Southern and southeastern regions of Europe (Trnka et al., 2009; Falloon and Betts, 2010). Improved water management in upstream agricultural areas could mitigate adverse impacts downstream (Kløve et al., 2011), and groundwater recharge could be targeted in areas with poor water-holding soils (Wessolek and Asseng, 2006).

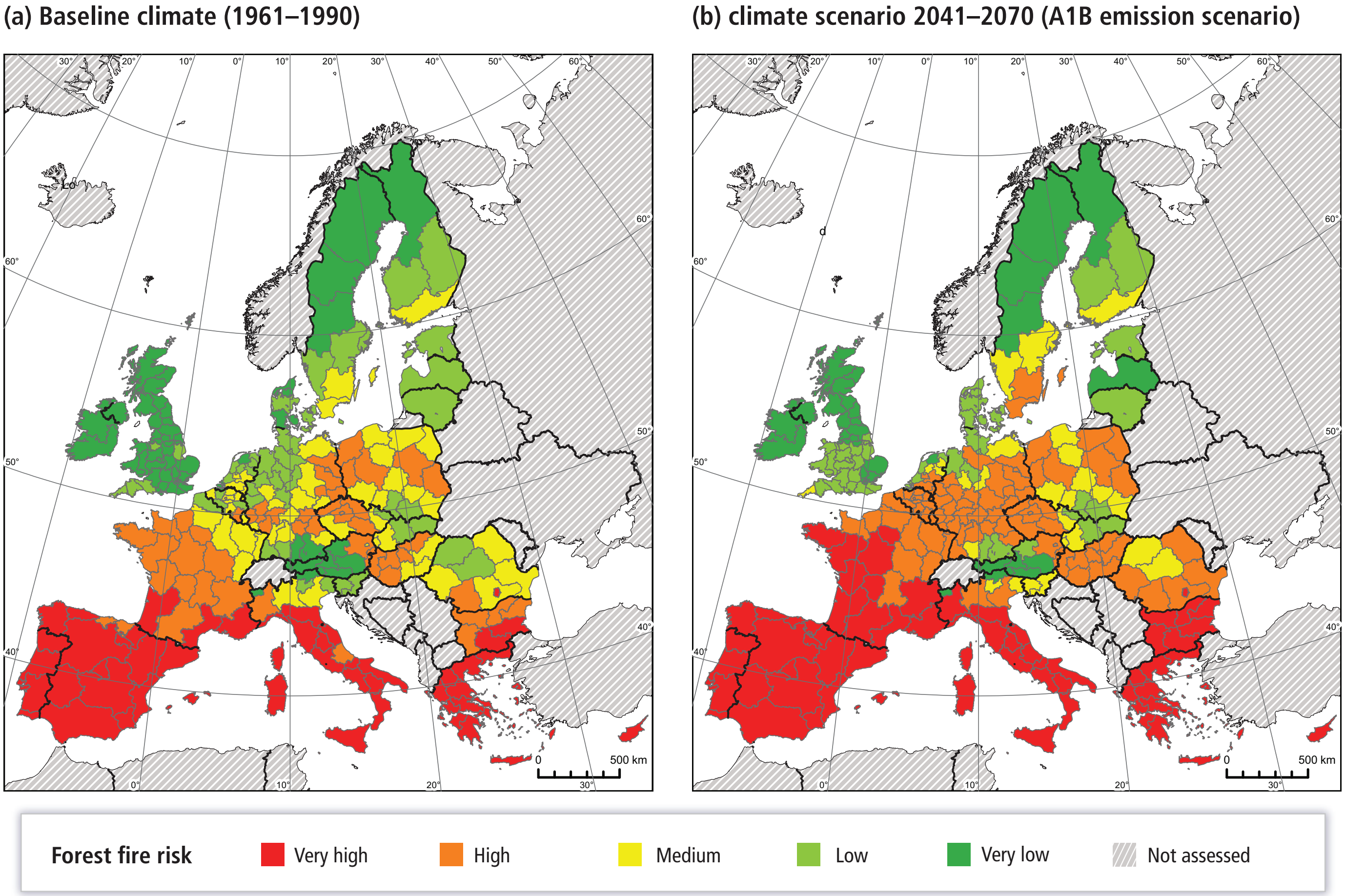
23.4.4. Forestry

Observed and future responses of forests to climate change include changes in growth rates, phenology, composition of animal and plant communities, increased fire and storm damage, and increased insect and pathogen damage. Tree mortality and forest decline due to severe drought events were observed in forest populations in Southern Europe (Bigler et al., 2006; Raftoyannis et al., 2008; Affolter et al., 2010), including Italy (Giuggiola et al., 2010; Bertini et al., 2011), Cyprus (ECHOES Country Report: Cyprus, 2009), and Greece (Raftoyannis et al., 2008), as well as in Belgium (Kint et al., 2012), Switzerland (Rigling et al., 2013), and the pre-Alps in France (Rouault et al., 2006; Allen et al., 2010; Charru et al., 2010). Declines have also been observed in wet forests not normally considered at risk of drought (Choat et al., 2012). An increase in forest productivity has been observed in the Russian Federation (Sirotenko and Abashina, 2008).

Future projections show that, in Northern and Atlantic Europe, increasing atmospheric CO_2 and higher temperatures are expected to increase forest growth and wood production, at least in the short to medium term (Lindner et al., 2010). On the other hand, in Southern and Eastern Europe, increasing drought and disturbance risks will cause adverse effects and productivity is expected to decline (Sirotenko and Abashina, 2008; Lavalle et al., 2009; Lindner et al., 2010; Hlásny et al., 2011; Keenan et al., 2011; Silva et al., 2012). By 2100, climate change is expected to reduce the economic value of European forest land depending on interest rate and climate scenario, which equates to potential damages of several hundred billion euros (Hanewinkel et al., 2013).

In Southern Europe, fire frequency and wildfire extent significantly increased after the 1970s compared with previous decades (Pausas and Fernández-Muñoz, 2012) as a result of fuel accumulation (Koutsias et al., 2012), climate change (Lavalle et al., 2009), and extreme weather events (Camia and Amatulli, 2009; Hoinka et al., 2009; Carvalho et al., 2011; Koutsias et al., 2012; Salis et al., 2013), especially in the Mediterranean basin (Fernandes et al., 2010; Marques et al., 2011; Koutsias et al., 2012; Pausas and Fernández-Muñoz, 2012). The most severe events in France, Greece, Italy, Portugal, Spain, and Turkey in 2010 were associated with strong winds during a hot dry period (EEA, 2010c). However, for the Mediterranean region as a whole, the total burned area has decreased since 1985 and the number of wildfires has decreased from 2000 to 2009, with large interannual variability (Marques et al., 2011; San-Miguel-Ayanz et al., 2012; Turco et al., 2013). Megafires, triggered by extreme climate events, had caused record maxima of burnt areas in some Mediterranean countries during the last decades (San-Miguel-Ayanz et al., 2013).

Future wildfire risk is projected to increase in Southern Europe (Lindner et al., 2010; Carvalho et al., 2011; Dury et al., 2011; Vilén and Fernandes,


(a) Baseline climate (1961–1990)

(b) climate scenario 2041–2070 (A1B emission scenario)

Figure 23-5 | Forest fire risk in Europe for two time periods: baseline (left) and 2041–2070 (right), based on high-resolution regional climate models and the Special Report on Emission Scenarios (SRES) A1B emission scenario. Forest fire risk indicator is based on climate and non-climate factors (e.g., fuel availability, fire ignition potential). Source: Lung et al., 2013.

2011), with an increase in the occurrence of high fire danger days (Arca et al., 2012; Lung et al., 2012) and in fire season length (Pellizzaro et al., 2010). The annual burned area is projected to increase by a factor of 3 to 5 in Southern Europe compared to the present under the A2 scenario by 2100 (Dury et al., 2011). In Northern Europe, fires are projected to become less frequent due to increased humidity (Rosan and Hammarlund, 2007). Overall, the projected increase in wildfires is likely to lead to a significant increase in greenhouse gas (GHG) emissions due to biomass burning (Pausas et al., 2008; Vilén and Fernandes, 2011; Chiriacò et al., 2013), even if often difficult to quantify (Chiriacò et al., 2013).

Wind storm damage to forests in Europe has recently increased (Usbeck et al., 2010). Boreal forests will become more vulnerable to autumn/early spring storm damage due to expected decrease in period of frozen soil (Gardiner et al., 2010). Increased storm losses by 8 to 19% under A1B and B2 scenarios, respectively, is projected in western Germany for 2060–2100 compared to 1960–2000, with the highest impacts in the mountainous regions (Pinto et al., 2010; Klaus et al., 2011).

An increase in the incidence of diseases has been observed in many European forests (Marcais and Desprez-Loustau, 2007; FAO, 2008b). In Continental Europe, some species of fungi benefit from milder winters and others spread during drought periods from south to north (Drenkhan et al., 2006; Hanso and Drenkhan, 2007). Projected increased late summer warming events will favor diffusion of bark beetle in Scandinavia, in lowland parts of Central Europe, and Austria (Jönsson et al., 2009, 2011; Seidl et al., 2009).

Possible response approaches to the impacts of climate change on forestry include short- and long-term strategies that focus on enhancing ecosystem resistance and resilience and responding to potential limits to carbon accumulation (Millar et al., 2007; Nabuurs et al., 2013). Fragmented small-scale forest ownership can constrain adaptive capacity (Lindner et al., 2010). Landscape planning and fuel load management may reduce the risk of wildfires but may be constrained by the higher flammability owing to warmer and drier conditions (Moreira et al., 2011). Strategies to reduce forest mortality include preference of species better adapted to relatively warm environmental conditions (Resco de Dios et al., 2007). The selection of tolerant or resistant families and clones may also reduce the risk of damage by pests and diseases in pure stands (Jactel et al., 2009).

23.4.5. Bioenergy Production

The potential distribution of temperate oilseeds (e.g., oilseed rape, sunflower), starch crops (e.g., potatoes), cereals (e.g., barley), and solid biofuel crops (e.g., sorghum, *Miscanthus*) is projected to increase in Northern Europe by the 2080s, as a result of increasing temperatures, and to decrease in Southern Europe due to increased drought frequency

Box 23-1 | Assessment of Climate Change Impacts on Ecosystem Services by Sub-region

Ecosystems provide a number of vital provisioning, regulating, and cultural services for people and society that flow from the stock of natural capital (Stoate et al., 2009; Harrison et al., 2010). Provisioning services such as food from agro-ecosystems or timber from forests derive from intensively managed ecosystems; regulating services underpin the functioning of the climate and hydrological systems; and cultural services such as tourism, recreation, and aesthetic value are vital for societal well-being (see Section 23.5.4). The table summarizes the potential impacts of climate change on ecosystem services in Europe by sub-region based on an assessment of the published literature (2004–2013). The direction of change (increasing, decreasing, or neutral) is provided, as well as the number of studies/papers on which the assessment was based (in parentheses). Empty cells indicate the absence of appropriate literature. Unless otherwise stated, impacts assume no adaptation and are assessed for the mid-century (2050s). A decrease in natural hazard regulation (e.g., for wildfires) implies an increased risk of the hazard occurring. Biodiversity is included here as a service (for completeness), although it is debated whether biodiversity should be considered as a service or as part of the natural capital from which services flow. What is agreed, however, is that biodiversity losses within an ecosystem will have deleterious effects on service provision (Mouillot et al., 2013).

The provision of ecosystem services in Southern Europe is projected to decline across all service categories in response to climate change (*high confidence*). Other European sub-regions are projected to have both losses and gains in the provision of ecosystem services (*high confidence*). The Northern sub-region will have increases in provisioning services arising from climate change (*high confidence*). Except for the Southern sub-region, the effects of climate change on regulating services are balanced with respect to gains and losses (*high confidence*). There are fewer studies for cultural services, although these indicate a balance in service provision for the Alpine and Atlantic regions, with decreases in service provision for the Continental, Northern, and Southern sub-regions (*low confidence*).

Continued next page →

Box 23-1 (continued)

			Southern	Atlantic	Continental	Alpine	Northern
Provisioning services	Food production		↓ (1)	↓ (1)	↓ (1)	No (1) ↓ (4)	↑ (1) ↓ (1)
	Livestock production					No (1) ↓ (1)	
	Fiber production					↓ (1)	
	Bioenergy production		↓ (1)			↑ (1)	↑ (1)
	Fish production		No (1) ↓ (2)	No (1) ↓ (1)	↓ (1)		No (1) ↓ (1)
	Timber production		↓ (2)	↑ (2) No (3)	↑ (1) No (2) ↓ (1)	↑ (5) No (2) ↓ (5)	↑ (6) No (1)
	Non-wood forest products		↓ (1)				↑ (1) No (1)
	Sum of effects on provisioning services		No (1) ↓ (7)	↑ (2) No (4) ↓ (2)	↑ (1) No (2) ↓ (3)	↑ (6) No (4) ↓ (11)	↑ (9) No (3) ↓ (2)
Regulating services	Climate regulation (carbon sequestration)	General/forests	↑ (3) ↓ (1)	↑ (4) No (1)	↑ (3) No (1)	↑ (4) No (1) ↓ (3)	↑ (4) No (1) ↓ (1)
		Wetland	No (1) ↓ (1)	No (1) ↓ (1)	↓ (1)		No (1) ↓ (1)
		Soil carbon stocks	No (1) ↓ (1)	No (1) ↓ (2)	No (1) ↓ (1)	No (1) ↓ (2)	↓ (3)
	Pest control		↓ (1)		↑ (1)	↑ (1)	↑ (1)
	Natural hazard regulation[a]	Forest fires/wildfires	↓ (1)	↓ (1)	↓ (2)		
		Erosion, avalanche, landslide				↑ (2) ↓ (1)	
		Flooding				↓ (1)	
		Drought	No (1) ↓ (1)		↓ (1)		
	Water quality regulation			↓ (1)			↓ (1)
	Biodiversity		↑ (1) ↓ (8)	↑ (2) No (1) ↓ (4)	↑ (2) ↓ (4)	↑ (2) ↓ (4)	↑ (3) ↓ (2)
	Sum of effects on regulating services		↑ (4) No (3) ↓ (14)	↑ (6) No (4) ↓ (9)	↑ (6) No (2) ↓ (9)	↑ (9) No (2) ↓ (11)	↑ (8) No (2) ↓ (8)
Cultural services	Recreation (fishing, nature enjoyment)		↑ (1)	↓ (1)			↑ (1) ↓ (2)
	Tourism (skiing)					↑ (1)	↑ (1)
	Aesthetic/heritage (landscape character, cultural landscapes)		↓ (1)	↓ (1)	No (1) ↓ (1)	↑ (1)	
	Sum of effects on cultural services		↓ (2)	↑ (1) ↓ (1)	No (1) ↓ (1)	↑ (1) ↓ (1)	↑ (1) ↓ (3)

↓ = Climate change impacts are decreasing ecosystem service

↑ = Climate change impacts are increasing ecosystem service

No = Neutral effect

(1) = Numbers in brackets refer to the number of studies supporting the change (increasing, decreasing, neutral) in ecosystem service.

[a] A decline in ecosystem services implies an increased risk of the specified natural hazard.

Entries for biodiversity are those that were found during the literature search for climate change impacts on ecosystem services. A wider discussion of the impacts of climate change on biodiversity can be found in Sections 4.3.4 and 23.6.

References: Wessel et al. (2004); Schroter et al. (2005); Fuhrer et al. (2006); Koca et al. (2006); Gret-Regamy et al. (2008); Hemery (2008); Metzger et al. (2008); Palahi et al. (2008); Bolte et al. (2009); Garcia-Fayos and Bochet (2009); Johnson et al. (2009); Albertson et al. (2010); Canu et al. (2010); Clark et al. (2010a); Lindner et al. (2010); Lorz et al. (2010); Milad et al. (2011); Okruszko et al. (2011); Seidl et al. (2011); Briner et al. (2012); Civantos et al. (2012); Rusch (2012); Bastian (2013); Forsius et al. (2013); Gret-Regamy et al. (2013); Seidl and Lexer (2013).

(Tuck et al., 2006). Mediterranean oil and solid biofuel crops, currently restricted to Southern Europe, are likely to extend further north (Tuck et al., 2006). The physiological responses of bioenergy crops, in particular C_3 Salicaceae trees, to rising atmospheric CO_2 concentration may increase drought tolerance because of improved plant water use; consequently yields in temperate environments may remain high in future climate scenarios (Oliver et al., 2009).

A future increase in the northward extension of the area for short rotation coppice (SRC) cultivation leading to GHG neutrality is expected (Liberloo et al., 2010). However, the northward expansion of SRC would erode the European terrestrial carbon sink due to intensive management and high turnover of SRC compared to conventional forest where usually harvesting is less than annual growth (Liberloo et al., 2010).

23.4.6. Fisheries and Aquaculture

In AR4, Easterling et al. (2007) reported that the recruitment and production of marine fisheries in the North Atlantic are *likely* to increase. In European seas, warming causes a displacement to the north and/or in depth of fish populations (Daufresne et al., 2009; see also Chapter 6; Section 23.6.4), which has a direct impact on fisheries (Tasker, 2008; Cheung et al., 2010, 2013). For instance, in British waters, the lesser sandeel (*Ammodytes marinus*), which is a key link in the food web, shows declining recruitments since 2002 and is projected to further decline in the future with a warming climate (Heath et al., 2012). In the Baltic Sea, although some new species would be expected to immigrate because of an expected increase in sea temperature, only a few of these would be able to successfully colonize the Baltic because of its low salinity (Mackenzie et al., 2007). In response to climate change and intensive fishing, widespread reductions in fish body size (Daufresne et al., 2009) and in the mean size of zooplankton (Beaugrand and Reid, 2012) have been observed over time and these trends further affect the sustainability of fisheries (Pitois and Fox, 2006; Beaugrand and Kirby, 2010; see also Chapter 6). Aquaculture can be affected as the areal extent of some habitats that are suitable for aquaculture can be reduced by sea level rise. Observed higher water temperatures have adversely affected both wild and farmed freshwater salmon production in the southern part of the distribution areas (Jonsson and Jonsson, 2009). In addition, ocean acidification may disrupt the early developmental stages of shellfish (Callaway et al., 2012).

Numerous studies confirm the amplification through fishing of the effects of climate change on population dynamics and consequently on fisheries (Planque et al., 2010). The decline of the North Sea cod during the 1980–2000 period resulted from the combined effects of overfishing and of an ecosystem regime shift due to climate change (Beaugrand and Kirby, 2010). Over the next decade, this stock was not restored from its previous collapse (Mieszkowska et al., 2009; ICES, 2010). In the North and Celtic Seas, the steep decline in boreal species (Henderson, 2007) was compensated for by the arrival of southern (Lusitanian) species (ter Hofstede et al., 2010; Engelhard et al., 2011; Lenoir et al., 2011).

Climate change may reinforce parasitic diseases and impose severe risks for aquatic animal health (see Chapter 6). As water temperatures increase, a number of endemic diseases of both wild and farmed salmonid populations are *likely* to become more prevalent and threats associated with exotic pathogens may rise (Marcos-Lopez et al., 2010). In the Iberian Atlantic, the permitted harvesting period for the mussel aquaculture industry was reduced because of harmful algal blooms resulting from changes in phytoplankton communities linked to a weakening of the Iberian upwelling (Perez et al., 2010). With freshwater systems, summer heat waves boost the development of harmful cyanobacterial blooms (Johnk et al., 2008). For oysters in France, toxic algae may be linked to both climate warming and direct anthropogenic stressors (Buestel et al., 2009).

Fishery management thresholds will have to be reassessed as the ecological basis on which existing thresholds have been established changes, and new thresholds will have to be developed for immigrant species (Mackenzie et al., 2007; Beaugrand and Reid, 2012). These changes may lead to loss of productivity, but also the opening of new fishing opportunities, depending on the interactions between climate impacts, fishing grounds, and fleet types. They will also affect fishing regulations, the price of fish products, and operating costs, which in turn will affect the economic performance of the fleets (Cheung et al., 2012). Climate change impacts on fisheries profits range from negative for sardine fishery in the Iberian Atlantic fishing grounds (Garza-Gil et al., 2010; Perez et al., 2010) to nonsignificant for the Bay of Biscay (Le Floc'h et al., 2008) and positive on the Portuguese coast, since most of the immigrant fish species are marketable (Vinagre et al., 2011). Human social fishing systems dealing with high variability upwelling systems with rapidly reproducing fish species may have greater capacities to adjust to the additional stress of climate change than human social fishing systems focused on longer-lived and generally less variable species (Perry et al., 2010, 2011). Climate change adaptation is being considered for integration in European maritime and fisheries operational programs (EC, 2013c).

23.5. Implications of Climate Change for Health and Social Welfare

23.5.1. Human Population Health

Climate change is likely to have a range of health effects in Europe. Studies since AR4 have confirmed the effects of heat on mortality and morbidity in European populations and particularly in older people and those with chronic disease (Kovats and Hajat, 2008; Åström et al., 2011; Corobov et al., 2012, 2013). With respect to sub-regional vulnerability, populations in Southern Europe appear to be most sensitive to hot weather (Michelozzi et al., 2009; D'Ippoliti et al., 2010; Baccini et al., 2011), and also will experience the highest heat wave exposures (Figure 23-2). However, populations in Continental (Hertel et al., 2009) and Northern Europe (Rocklöv and Forsberg, 2010; Armstrong et al., 2011; Varakina et al., 2011) are also vulnerable to heat wave events. Adaptation measures to reduce heat health effects include heat wave plans (Bittner et al., 2013) which have been shown to reduce heat-related mortality in Italy (Schifano et al., 2012), but evidence of effectiveness is still very limited (Hajat et al., 2010; Lowe et al., 2011). There is little information about how future changes in housing and infrastructure (Section 23.3.2) would reduce the regional or local future burden of heat-related mortality or morbidity. Climate change is likely to increase future heat-related mortality (Baccini et al., 2011; Ballester et al., 2011; Huang et al., 2011) and morbidity (Åström et al., 2013), although most published risk assessments do not include consideration of adaptation (Huang et al., 2011). For most countries in Europe, the current burden of cold-related mortality (Analitis et al., 2008) is greater than the burden of heat mortality. Climate change is likely to reduce future cold-related mortality (Ballester et al., 2011; HPA, 2012; see also Section 11.4.1).

Mortality and morbidity associated with flooding is becoming better understood, although the surveillance of health effects of disasters remains inadequate (WHO, 2013). Additional flood mortality due to sea level rise has been estimated in the Netherlands (Maaskant et al., 2009) and in the UK for river flooding (Hames and Vardoulakis, 2012), but estimates of future mortality due to flooding are highly uncertain. There remains limited evidence regarding the long-term mental health impacts of flood events (Paranjothy et al., 2011; WHO, 2013).

Evidence about future risks from climate change with respect to infectious diseases is still limited (Semenza and Menne, 2009; Randolph and Rogers, 2010; Semenza et al., 2012). There have been developments in mapping the current and potential future distribution of important disease vector species in Europe. The Asian tiger mosquito *Aedes albopictus* (a vector of dengue and Chikungunya; Queyriaux et al., 2008) is currently present in Southern Europe (ECDC, 2009) and may extend eastward and northward under climate change (Fisher et al., 2011; Roiz et al., 2011; Caminade et al., 2012). The risk of introduction of dengue remains very low because it would depend on the introduction and expansion of the *Aedes aegypti* together with the absence of effective vector control measures (ECDC, 2012).

Climate change is unlikely to affect the distribution of visceral and cutaneous leishmaniasis (currently present in the Mediterranean region) in the near term (Ready, 2010). However, in the long term (15 to 20 years), there is potential for climate change to facilitate the expansion of either vectors or current parasites northwards (Ready, 2010). The risk of introduction of exotic *Leishmania* species was considered very low due to the low competence of current vectors (Fischer, D. et al., 2010). The effect of climate change on the risk of imported or locally transmitted (autochthonous) malaria in Europe has been assessed in Spain (Sainz-Elipe et al., 2010), France (Linard et al., 2009), and the UK (Lindsay et al., 2010). Disease re-emergence would depend on many factors, including the introduction of a large population of infectious people or mosquitoes, high levels of people-vector contact, resulting from significant changes in land use, as well as climate change (see Chapter 11).

Since AR4, there has been more evidence on implications of climate change on food safety at all stages from production to consumption (FAO, 2008a; Jacxsens et al., 2010; Popov Janevska et al., 2010). The sensitivity of salmonellosis to ambient temperature has declined in recent years (Lake et al., 2009) and the overall incidence of salmonellosis is declining in most European countries (Semenza et al., 2012). Climate change may also have effects on food consumption patterns. Weather affects pre- and post-harvest mycotoxin production but the implications of climate change are unclear. Cold regions may become liable to temperate-zone problems concerning contamination with ochratoxin A, patulin, and *Fusarium* toxins (Paterson and Lima, 2010). Control of the environment of storage facilities may avoid post-harvest problems but at additional cost (Paterson and Lima, 2010).

Other potential consequences concern marine biotoxins in seafood following production of phycotoxins by harmful algal blooms and the presence of pathogenic bacteria in foods following more frequent extreme weather conditions (Miraglia et al., 2009). There is little evidence that climate change will affect human exposures to contaminants in the soil or water (e.g., persistent organic pollutants). Risk modeling is often developed for single-exposure agents (e.g., a pesticide) with known routes of exposure. These are difficult to scale up to the population level. The multiple mechanisms by which climate may affect transmission or contamination routes also make this very complex (Boxall et al., 2009).

Adaptation in the health sector has so far been largely limited to the development of heat health warning systems, with many research gaps regarding effective adaptation options (HPA, 2012). A survey of national infectious disease experts in Europe identified several institutional changes that needed to be addressed to improve future responses to climate change risks: ongoing surveillance programs, collaboration with veterinary sector and management of animal disease outbreaks, national monitoring and control of climate-sensitive infectious diseases, health services during an infectious disease outbreak, and diagnostic support during an epidemic (Semenza et al., 2012).

23.5.2. Critical Infrastructure

Critical national infrastructure is defined as assets (physical or electronic) that are vital to the continued delivery and integrity of essential services on which a country relies, the loss or compromise of which would lead to severe economic or social consequences or to loss of life. Extreme weather events, such as floods, heat waves, and wild fires are known to damage critical infrastructure. The UK floods in 2007 led to significant damage to power and water utilities, and to communications and transport infrastructure (Chatterton et al., 2010; see also Table 23-1). Forest fires can affect transport infrastructure, as well as the destruction of buildings. Major storms in Sweden and Finland have led to loss of trees, with damage to the power distribution network, leading to electricity blackouts lasting weeks, as well as the paralysis of services such as rail transport and other public services that depend on grid electricity.

Health system infrastructure (hospitals, clinics) is vulnerable to extreme events, particularly flooding (Radovic et al., 2012). The heat waves of 2003 and 2006 had adverse effects on patients and staff in hospitals from overheating of buildings. Evidence from France and Italy indicate that death rates among in-patients increased significantly during heat wave events (Ferron et al., 2006; Stafoggia et al., 2008). Further, higher temperatures have had serious implications for the delivery of health care, as well drug storage and transport (Carmichael et al., 2013).

23.5.3. Social Impacts

There is little evidence regarding the implications of climate change for employment and/or livelihoods in Europe. However, the evidence so far (as reviewed in this chapter) indicates that there are likely to be changes to some industries (e.g., tourism, agriculture) that may lead to changes in employment opportunities by sub-region and by sector.

Current damages from weather-related disasters (floods and storms) are significant (Section 23.3.1). Disasters have long lasting effects on the affected populations (Schnitzler et al., 2007). Households are often displaced while their homes are repaired (Whittle et al., 2010). Little research has been carried out on the impact of extreme weather events such as heat waves and flooding on temporary or permanent displacement in Europe. Coastal erosion associated with sea level rise, storm surges, and coastal flooding will require coastal retreat in some of Europe's low-lying areas (Philippart et al., 2011). Managed retreat is also an adaptation option in some coastal areas. Concerns have been raised about equality of access to adaptation within coastal populations at risk from climate change. For example, a study in the UK found that vulnerability to climate change in coastal communities is likely to be increased by social deprivation (Zsamboky et al., 2011).

In the European region, the indigenous populations present in the Arctic are considered vulnerable to climate change impacts on livelihoods and food sources (ACIA, 2005; see also Sections 12.3, 28.2.4). Research has focused on indigenous knowledge, impacts on traditional food sources, and community responses/adaptation (Mustonen and Mustonen, 2011a,b). However, these communities are also experiencing rapid social, economic, and other non-climate-related environmental changes (such as oil and gas exploration; see Section 28.2.4). There is evidence that climate change has altered the seasonal behavior of pastoralist populations, such as the Nenets reindeer herders in northern Russia (Amstislavski et al., 2013). However, socioeconomic factors may be more important than climate change for the future sustainability of reindeer husbandry (Rees et al., 2008; see also Section 28.2.3.5).

23.5.4. Cultural Heritage and Landscapes

Climate change will affect culturally valued buildings (Storm et al., 2008) through extreme events and chronic damage to materials (Brimblecombe et al., 2006; Brimblecombe and Grossi, 2010; Brimblecombe, 2010a, 2010b; Grossi et al., 2011; Sabbioni et al., 2012). Cultural heritage is a non-renewable resource and impacts from environmental changes are assessed over long time scales (Brimblecombe and Grossi, 2008, 2009, 2010; Grossi et al., 2008; Bonazza et al., 2009a,b). Climate change may also affect indoor environments where cultural heritage is preserved (Lankester and Brimblecombe, 2010) as well as visitor behavior at heritage sites (Grossi et al., 2010). There is also evidence to suggest that climate change and sea level rise will affect maritime heritage in the form of shipwrecks and other submerged archaeology (Björdal, 2012).

Surface recession on marble and compact limestone will be affected by climate change (Bonazza et al., 2009a). Marble monuments in Southern Europe will continue to experience high levels of thermal stress (Bonazza et al., 2009b) but warming is likely to reduce frost damage across Europe, except in Northern and Alpine Europe and permafrost areas (Iceland) (Grossi et al., 2007; Sabbioni et al., 2008). Damage to porous materials due to salt crystallization may increase all over Europe (Benavente et al., 2008; Grossi et al., 2011). In Northern and Eastern Europe, wood

Box 23-2 | Implications of Climate Change for European Wine and Vineyards

Wine production in Europe accounts for more than 60% of the global total (Goode, 2012) and makes an important contribution to cultural identity. Apart from impacts on grapevine yield, higher temperatures are also expected to affect wine quality in some regions and grape varieties by changing the ratio between sugar and acids (Duchêne et al., 2010; Bock et al., 2011; Santos et al., 2011). In Western and Central Europe, projected future changes could benefit wine quality, but might also demarcate new potential areas for viticulture (Malheiro et al., 2010). Adaptation measures are already occurring in some vineyards (e.g., vine management, technological measures, production control, and to a smaller extent relocation; Battaglini et al., 2009; Holland and Smit, 2010; Malheiro et al., 2010; Duarte Alonso and O'Neill, 2011; Moriondo et al., 2011; Santos et al., 2011).Vineyards may be displaced geographically beyond their traditional boundaries ("terroir" linked to soil, climate, and traditions; Metzger and Rounsevell, 2011) and, in principle, wine producers could adapt to this problem by growing grape varieties that are more suited to warmer climates. Such technical solutions, however, do not account for the unique characteristics of wine production cultures and consumer perceptions of wine quality that strongly affect the prices paid for the best wines (White et al., 2009; Metzger and Rounsevell, 2011). It would become very difficult, for example, to produce fine wines from the cool-climate Pinot Noir grape within its traditional "terroir" of Burgundy under many future climate scenarios, but consumers may not be willing to pay current day prices for red wines produced from other grape varieties (Metzger and Rounsevell, 2011). An additional barrier to adaptation is that wine is usually produced within rigid, regionally specific, regulatory frameworks that often prescribe, among other things, what grapes can be grown where, for example, the French AOC (Appellation d'Origine Controlee) or the Italian DOC (Denominazione di Origine Controllata) and DOCG (Denominazione di Origine Controllata e Garantita) designations. Suggestions have been made to replace these rigid concepts of regional identity with a geographically flexible "terroir" that ties a historical or constructed sense of culture to the wine maker and not to the region (White et al., 2009).

structures will need additional protection against rainwater and high winds (Sabbioni et al., 2012). AR4 concluded that current flood defenses would not protect Venice from climate change. Venice now has a flood forecasting system, and is introducing the MOSE (MOdulo Sperimentale Elettromeccanico) system of flood barriers (Keskitalo, 2010). Recent evidence suggests, however, that climate change may lead to a decrease in the frequency of extreme storm surges in this area (Troccoli et al., 2012a).

Europe has many unique rural landscapes, which reflect the cultural heritage that has evolved from centuries of human intervention, for example, the cork oak based Montado in Portugal, the Garrigue of southern France, Alpine meadows, grouse moors in the UK, machair in Scotland, peatlands in Ireland, the polders of Belgium and the Netherlands, and vineyards. Many, if not all, of these cultural landscapes are sensitive to climate change and even small changes in the climate could have significant impacts (Gifford et al., 2011). Alpine meadows, for example, are culturally important within Europe, but although there is analysis of the economics (tourism, farming) and functionality (water runoff, flooding, and carbon sequestration) of these landscapes there is very little understanding of how climate change will affect the cultural aspects on which local communities depend. Because of their societal value, cultural landscapes are often protected and managed through rural development and environmental policies. The peat-rich uplands of Northern Europe, for example, have begun to consider landscape management as a means of adapting to the effects of climate change (e.g., the moors for the future partnership in the Peak District National Park, UK). For a discussion of the cultural implications of climate change for vineyards, see Box 23-2.

23.6. Implications of Climate Change for the Protection of Environmental Quality and Biological Conservation

Terrestrial and freshwater ecosystems provide a number of vital services for people and society, such as biodiversity, food, fiber, water resources, carbon sequestration, and recreation (Box 23-1).

23.6.1. Air Quality

Climate change will have complex and local effects on pollution chemistry, transport, emissions, and deposition. Outdoor air pollutants have adverse effects on human health, biodiversity, crop yields, and cultural heritage. The main outcomes of concern are both the average (background) levels and peak events for tropospheric ozone, particulates, sulfur oxides (SO_x), and nitrogen oxides (NO_x). Future pollutant concentrations in Europe have been assessed using atmospheric chemistry models, principally for ozone (Forkel and Knoche, 2006, 2007). Reviews have concluded that GCM/Chemical Transport Model (CTM) studies find that climate change per se (assuming no change in future emissions or other factors) is likely to increase summer tropospheric ozone levels (range 1 to 10 ppb) by 2050s in polluted areas (i.e., where concentrations of precursor nitrogen oxides are higher) (AQEG, 2007; Jacob and Winner, 2009; see also Section 21.3.3.6). The effect of future climate change alone on future concentrations of particulates, nitrogen oxides, and volatile organic compounds (VOCs) is much more uncertain. Higher temperatures also affect natural VOC emissions, which are ozone precursors (Hartikainen et al., 2012). One study has projected an increase in fire-related air pollution (ozone and particulate matter with aerodynamic diameter <10 µm (PM_{10})) in Southern Europe (Carvalho et al., 2011).

Overall, the model studies are inconsistent regarding future projections of background level and exceedances. Recent evidence has shown adverse impacts on agriculture from even low concentrations of ozone; however, there is more consistent evidence now regarding the threshold for health (mortality) impacts of ozone. Therefore, it is unclear whether increases in background levels below health-related thresholds would be associated with an increased burden of ill health.

Some studies have attributed an observed increase in European ozone levels to observed warming (Meleux et al., 2007), which appears to be driven by the increase in extreme heat events (Solberg et al., 2008). High ozone levels were observed during the major heat waves in Europe in multiple countries (Table 23-1). Wildfire events have had an impact on local and regional air quality (Hodzic et al., 2007; Liu et al., 2009; Miranda et al., 2009), with implications for human health (Analitis et al., 2012; Table 23-1).

23.6.2. Soil Quality and Land Degradation

The current cost of soil erosion, organic matter decline, salinization, landslides, and contamination is estimated to be €38 billion annually for the EU (JRC and EEA, 2010), in the form of damage to infrastructures, treatment of water contaminated through the soil, disposal of sediments, depreciation of land, and costs related to the ecosystem functions of soil (JRC and EEA, 2010). Projections show significant reductions in summer soil moisture in the Mediterranean region, and increases in the northeastern part of Europe (Calanca et al., 2006). Climate change impacts on erosion shows diverging evidence under the A2 scenario. In Tuscany, even with a decline in precipitation volume until 2070, in some months higher erosion rates would occur because of higher rainfall erosivity (Marker et al., 2008). For two Danish river catchments, assuming a steady-state land use, suspended sediment transport would increase by 17 to 27% by 2071–2100 (Thodsen, 2007; Thodsen et al., 2008). In Upper Austria, with the regional climate model HadRM3H, a small reduction in average soil losses is projected for croplands in all tillage systems, however, with high uncertainty (Scholz et al., 2008). In Northern Ireland, erosion decreases are generally projected with downscaled GCMs for a case study hillslope (Mullan et al., 2012).

Adaptive land use management can reduce the impact of climate change through soil conservation methods such as zero tillage and conversion of arable land to grasslands (Klik and Eitzinger, 2010). In central Europe, compared to conventional tillage, conservation tillage systems reduced modeled soil erosion rates under future climate scenarios by between 49 and 87% (Scholz et al., 2008). Preserving upland vegetation reduced both erosion and loss of soil carbon and favored the delivery of a high-quality water resource (McHugh, 2007; House et al., 2011). Maintaining soil water retention capacity, for example, through adaptation measures (Post et al., 2008), contributes to reduce risks of flooding as soil organic matter absorbs up to 20 times its weight in water.

23.6.3. Water Quality

Climate change may affect water quality in several ways, with implications for food production and forestry (Section 23.4), ecosystem functioning (Box 23-1), human and animal health, and compliance with environmental quality standards, including those of the Water Framework Directive. Shallower waters will witness a more rapid temperature increase than deeper waters, since heat is absorbed mainly in the upper water layers and turbulent mixing is truncated by shallow depth. In parallel, a decrease in saturating oxygen concentrations occurs. Since AR4, there is further evidence of adverse effects caused by extreme weather events: reductions in dissolved oxygen, algal blooms (Mooij et al., 2007; Ulén and Weyhenmeyer, 2007) during hot weather, and contamination of surface and coastal waters with sewage and/or chemicals (pesticides) after rainfall (Boxall et al., 2009). A reduction in rainfall may lead to low flows that increase concentrations of biological and chemical contaminants. Reduced drainage can also enhance sedimentation in drainage systems and hence enhance particle-bound phosphorous retention and reduce phosphorous load to downstream higher order streams (Hellmann and Vermaat, 2012).

Variability in changes in rainfall and runoff, as well as water temperature increases, will lead to differences in water quality impacts by sub-region. Climate change is projected to increase nutrient loadings: In Northern Europe this is caused by increased surface runoff, and in Southern Europe by increased evapotranspiration and increased concentrations due to reduced volumes of receiving lakes (Jeppesen et al., 2011). Local studies generally confirm this pattern. Increased nutrient loads are foreseen in Danish watersheds (Andersen et al., 2006), and in France (Delpla et al., 2011) and the UK (Whitehead et al., 2009; Howden et al., 2010; Macleod et al., 2012; see also Section 4.3.3.3). In larger rivers, such as the Meuse, increased summer temperature and drought can lead to more favorable conditions for algal blooms and reduced dilution capacity of effluent from industry and sewage works (van Vliet and Zwolsman, 2008).

23.6.4. Terrestrial and Freshwater Ecosystems

Current and projected future climate changes, including CO_2 increase, are determining negative effects of habitat loss on species density and diversity (Rickebusch et al., 2008; Mantyka-pringle et al., 2012). Projected habitat loss is greater for species at higher elevations (Castellari, 2009; Engler et al., 2011; Dullinger et al., 2012) and suitable habitats for Europe's breeding birds are projected to shift nearly 550 km northeast by the end of the 21st century (Huntley et al., 2007). Aquatic habitats and habitat connectivity in river networks may become increasingly fragmented (Fronzek et al., 2006, 2010, 2011; Elzinga et al., 2007; Della Bella et al., 2008; Harrison et al., 2008; Blaustein et al., 2010; Gallego-Sala et al., 2010; Gómez-Rodríguez et al., 2010; Hartel et al., 2011; Morán-López et al., 2012). Despite some local successes and increasing responses, the rate of biodiversity loss does not appear to be slowing (Butchart et al., 2010). The effectiveness of Natura 2000 areas to respond to climate change has been questioned (Araújo et al., 2011). However, when considering connectivity related to the spatial properties of the network, the Natura 2000 network appears rather robust (Mazaris et al., 2013). Several studies now highlight the importance of taking into account climate change projections in the selection of conservation areas (Araújo et al., 2011; Ellwanger et al., 2011; Filz et al., 2013; Virkkala et al., 2013).

Observed changes in plant communities in European mountainous regions show a shift of species ranges to higher altitudes resulting in species richness increase in boreal-temperate mountain regions and decrease in Mediterranean mountain regions (Gottfried et al., 2012; Pauli et al., 2012). In Southern Europe, a great reduction in phylogenetic diversity of plant, bird, and mammal assemblages will occur, and gains are expected in regions of high latitude or altitude for 2020, 2050, and 2080. However, losses will not be offset by gains and a trend toward homogenization across the continent will be observed (Alkemade et al., 2011; Thuiller et al., 2011). Large range contractions due to climate change are projected for several populations of *Pinus cembra* and *Pinus Sylvestris* (Casalegno et al., 2010; Giuggiola et al., 2010) while for the dominant Mediterranean tree species, holm oak, a substantial range expansion is projected under the A1B emissions scenario (Cheaib et al., 2012). The human impacts on distribution of tree species landscape may make them more vulnerable to climate change (del Barrio et al., 2006; Hemery et al., 2010).

Observed climate changes are altering breeding seasons, timing of spring migration, breeding habitats, latitudinal distribution, and migratory behavior of birds (Jonzén et al., 2006; Lemoine et al., 2007a,b; Rubolini et al., 2007a,b; Feehan et al., 2009). A northward shift in bird community composition has been observed (Devictor et al., 2008). Common species of European birds with the lowest thermal maxima have showed the sharpest declines between 1980 and 2005 (Jiguet et al., 2010).

Projections for 120 native terrestrial non-volant European mammals suggest that 5 to 9% are at risk of extinction, assuming no migration, during the 21st century due to climate change, while 70 to 78% may be severely threatened under A1 and B2 climatic scenarios (Levinsky et al., 2007). Those populations not showing a phenological response to climate change may decline (Moller et al., 2008), such as amphibian and reptile species (Araújo et al., 2006), or experience ecological mismatches (Saino et al., 2011). Climate change can affect trophic interactions, as co-occurring species may not react in a similar manner. Novel emergent ecosystems composed of new species assemblages arising from differential rates of range shifts of species can occur (Keith et al., 2009; Montoya and Raffaelli, 2010; Schweiger et al., 2012).

Since invasive alien species rarely change their original climatic niches (Petitpierre et al., 2012), climate change can exacerbate the threat posed by invasive species to biodiversity in Europe (West et al., 2012), amplifying the effects of introduction of the exotic material such as alien bioenergy crops (EEA, 2012), pest and diseases (Aragòn and Lobo, 2012), tropical planktonic species (Cellamare et al., 2010), and tropical vascular plants (Skeffington and Hall, 2011; Taylor et al., 2012).

23.6.5. Coastal and Marine Ecosystems

Climate change will affect Europe's coastal and marine ecosystems by altering the biodiversity, functional dynamics, and ecosystem services of coastal wetlands, dunes, inter-tidal and subtidal habitats, offshore shelves, seamounts, and currents (Halpern et al., 2008) through changes in eutrophication, invasive species, species range shifts, changes in fish stocks, and habitat loss (EEA, 2010d; Doney et al., 2011). The relative magnitude of these changes will vary temporally and spatially, requiring a range of adaptation strategies that target different policy measures, audiences, and instruments (Airoldi and Bec, 2007; Philippart et al., 2011).

Europe's northern seas are experiencing greater increases in sea surface temperatures (SSTs) than the southern seas, with the Baltic, North, and Black Seas warming at two to four times the mean global rate (Belkin, 2009; Philippart et al., 2011). In the Baltic, decreased sea ice will expose coastal areas to more storms, changing the coastal geomorphology (HELCOM, 2007; BACC Author Team, 2008). Warming SSTs will influence biodiversity and drive changes in depth and latitudinal range for intertidal and subtidal marine communities, particularly in the North and Celtic Seas (Sorte et al., 2010; Hawkins et al., 2011; Wethey et al., 2011).

Warming is affecting food chains and changing phenological rates (Durant et al., 2007). For example, changes in the timing and location of phytoplankton and zooplankton are affecting North Sea cod larvae (Beaugrand et al., 2010; Beaugrand and Kirby, 2010). Temperature changes have affected the distribution of fisheries in all seas over the past 30 years (Beaugrand and Kirby, 2010; Hermant et al., 2010). Warmer waters also increase the rate of the establishment and spread of invasive species, further altering trophic dynamics and the productivity of coastal marine ecosystems (Molnar et al., 2008; Rahel and Olden, 2008). Changes in the semi-enclosed seas could be indicative of future conditions in other coastal-marine ecosystems (Lejeusne et al., 2009). In the Mediterranean, invasive species have arrived in recent years at the rate of one introduction every 4 weeks (Streftaris et al., 2005). While in this case the distribution of endemic species remained stable, most non-native species have spread northward by an average of 300 km since the 1980s, resulting in an area of spatial overlap with invasive species replacing natives by nearly 25% in 20 years.

Dune systems will be lost in some places due to coastal erosion from combined storm surge and sea level rise, requiring restoration (Day et al., 2008; Magnan et al., 2009; Ciscar et al., 2011). In the North Sea, the Iberian coast, and Bay of Biscay, a combination of coastal erosion, infrastructure development, and sea defenses may lead to narrower coastal zones ("coastal squeeze") (EEA, 2010d; OSPAR, 2010; Jackson and McIlvenny, 2011).

23.7. Cross-Sectoral Adaptation Decision Making and Risk Management

Studies on impacts and adaptation in Europe generally consider single sectors or outcomes, as described in the previous sections of this chapter. For adaptation decision making, more comprehensive approaches are required. Considerable progress has been made to advance planning and development of adaptation measures, including economic analyses (Section 23.7.6; see Box 23-3), and the development of climate services (WMO, 2011; Medri et al., 2012). At the international level, the European

Box 23-3 | National and Local Adaptation Strategies

The increasing number of national (EEA, 2013) and local (Heidrich et al., 2013) adaptation strategies in Europe has led to research on their evaluation and implementation (Biesbroek et al., 2010). Many adaptation strategies were found to be agendas for further research, awareness raising, and/or coordination and communication for implementation (e.g., Pfenniger et al., 2010; Dumollard and Leseur, 2011). Actual implementation often was limited to disaster risk reduction, environmental protection, spatial planning (Section 23.7.4), and coastal zone and water resources management. The implementation of planned adaptation at the national level was attributed to political will and good financial and information capacity (Westerhoff et al., 2011). Analysis of seven national adaptation strategies (Denmark, Finland, France, Germany, Netherlands, Spain, UK) found that although there is a high political commitment to adaptation planning and implementation, evaluation of the strategies and actual implementation is yet to be defined (Swart et al., 2009b; Biesbroek et al., 2010; Westerhoff et al., 2011). One of the earliest national adaptation strategies (Finland) has been evaluated, in order to compare identified adaptation measures with those launched in different sectors. It has found that although good progress has been made on research and identification of options, few measures have been implemented except in the water resources sector (Ministry of Agriculture and Forestry, 2009).

At the local government level, adaptation plans are being developed in several cities (EEA, 2013), including London (GLA, 2010), Madrid, Manchester, Copenhagen, Helsinki, and Rotterdam. Adaptation in general is a low priority for many European cities, and many plans do not have adaptation priority as the main focus (Carter, 2011). Many studies are covering sectors sensitive to climate variability, as well as sectors that are currently under pressure from socioeconomic development. A recent assessment found a lack of cross-sector impact and adaptation linkages as an important weakness in the city plans (Hunt and Watkiss, 2011). Flexibility in adaptation decision making needs to be maintained (Hallegatte et al., 2008; Biesbroek et al., 2010).

Union has started adaptation planning, through information sharing (Climate-ADAPT platform) and legislation (EC, 2013b). National and local governments are also beginning to monitor progress on adaptation, including the development of a range of indicators (UK-ASC, 2011).

23.7.1. Coastal Zone Management

Coastal zone management and coastal protection plans that integrate adaptation concerns are now being implemented. Underlying scientific studies increasingly assess effectiveness and costs of specific options (Hilpert et al., 2007; Kabat et al., 2009; Dawson et al., 2011; see also Section 23.7.6). Early response measures are needed for floods and coastal erosion, to ensure that climate change considerations are incorporated into marine strategies, with mechanisms for regular update (OSPAR, 2010; UNEP, 2010).

In the Dutch plan for flood protection, adaptation to increasing river runoff and sea level rise plays a prominent role (Delta Committee, 2008). It also includes synergies with nature conservation and freshwater storage (Kabat et al., 2009), and links to urban renovation (cost estimates are included in Section 23.7.6). Though that plan mostly relies on large-scale measures, new approaches such as small-scale containment of flood risks through compartmentalization are also studied (Klijn et al., 2009). The UK government has developed extensive adaptation plans (TE2100) to adjust and improve flood defenses for the protection of London from future storm surges and flooding (EA, 2009). An elaborate analysis has provided insight in the pathways for different adaptation options and decision-points that will depend on the eventual sea level rise (Box 5-1).

23.7.2. Integrated Water Resource Management

Water resources management in Europe has experienced a general shift from "hard" to "soft" measures that allow more flexible responses to environmental change (Pahl-Wostl, 2007). Integrated water resource management explicitly includes the consideration of environmental and social impacts (Wiering and Arts, 2006). Climate change has been incorporated into water resources planning in England and Wales (Arnell, 2011; Charlton and Arnell, 2011; Wade et al., 2013) and in the Netherlands (de Graaff et al., 2009). The robustness of adaptation strategies for water management in Europe has been tested in England (Dessai and Hulme, 2007) and Denmark (Haasnoot et al., 2012; Refsgaard et al., 2013). Other studies have emphasized the search for robust pathways, for instance, in the Netherlands (Kwadijk et al., 2010; Haasnoot et al., 2012).

Public participation has also increased in decision making, for example, river basin management planning (Huntjens et al., 2010), flood defense plans (e.g., TE2100), and drought contingency plans (Iglesias et al., 2007). Guidance has been developed on the inclusion of adaptation in water management (UNECE, 2009) and river basin management plans (EC, 2009b). Adaptation in the water sector could also be achieved through the EU Water Framework and Flood Directives (Quevauviller, 2011), but a study of decision makers, including local basin managers, identified several important barriers to this (Brouwer et al., 2013). Water allocation between upstream and downstream countries is challenging in regions exposed to prolonged droughts such as the Euphrates-Tigris river basin, where Turkey plans to more than double water abstraction by 2023 (EEA, 2010a).

23.7.3. Disaster Risk Reduction and Risk Management

A series of approaches to disaster risk management are employed in Europe, in response to national and European policy developments to assess and reduce natural hazard risks. New developments since the AR4 include assessment and protection efforts in accordance with the EU Floods Directive (European Parliament and EU Council, 2007), the mapping of flood risks, and improvement of civil protection response and early warning systems (Ciavola et al., 2011). Most national policies address hazard assessment and do not include analyses of possible impacts (de Moel et al., 2009). The effectiveness of flood protection (Bouwer et al., 2010) and also non-structural or household level measures to reduce losses from river flooding has been assessed (Botzen et al., 2010a; Dawson et al., 2011). Some studies show that current plans may be insufficient to cope with increasing risks from climate change, as shown, for instance, for the Rhine River basin (te Linde et al., 2010a,b).

Other options that are being explored are the reduction of consequences, response measures, and increasing social capital (Kuhlicke et al., 2011), as well as options for insuring and transferring losses (Section 23.3.7). The Netherlands carried out a large-scale analysis and simulation exercise to study the possible emergency and evacuation response for a worst-case flood event (ten Brinke et al., 2010). Increasing attention is also being paid in Europe to non-government actions that can reduce possible impacts from extreme events. Terpstra and Gutteling (2008) found through a survey that individual citizens are willing to assume some responsibility for managing flood risk, and they are willing to contribute to preparations in order to reduce impacts. Survey evidence is available for Germany and the Netherlands that, under certain conditions, individuals can be encouraged to adopt loss prevention measures (Thieken et al., 2006; Botzen et al., 2009). Small businesses can reduce risks when informed about possibilities immediately after an event (Wedawatta and Ingirige, 2012).

23.7.4. Land Use Planning

Spatial planning policies can build resilience to the impacts of climate change (Bulkeley, 2010). However, the integration of adaptation into spatial planning is often limited to a general level of policy formulation that can sometimes lack concrete instruments and measures for implementation in practice (Mickwitz et al., 2009; Swart et al., 2009a). There is evidence to suggest the widespread failure of planning policy to account for future climate change (Branquart et al., 2008). Furthermore, a lack of institutional frameworks to support adaptation is, potentially, a major barrier to the governance of adaptation through spatial planning (ESPACE, 2007; Chapter 16). Climate change adaptation is often treated as a water management or flooding issue, which omits other important aspects of the contribution of land use planning to adaptation (Wilson, 2006; Mickwitz et al., 2009; Van Nieuwaal et al., 2009). For example, in the UK, houses were still being built in flood risk areas (2001–2011) because of competing needs to increase the housing stock (ARUP, 2011).

City governance is also dominated by the issues of climate mitigation and energy consumption rather than adapting to climate change (Bulkeley, 2010; Heidrich et al., 2013). Some cities, for example, Rotterdam, have started to create climate adaptation plans and this process tends to be driven by the strong political leadership of mayors (Sanchez-Rodriguez, 2009). The Helsinki Metropolitan Area's Climate Change Adaptation Strategy (HSY, 2010) is a regional approach focusing on the built environment in the cities of Helsinki, Espoo, Vantaa, and Kauniainen, and their surroundings. It includes approaches for dealing with increasing heat waves, more droughts, milder winters, increasing (winter) precipitation, heavy rainfall events, river floods, storm surges, drainage water floods, and sea level rise.

Green infrastructure provides both climate adaptation and mitigation benefits as well as offering a range of other benefits to urban areas, including health improvements, amenity value, inward investment, and the reduction of noise and outdoor air pollution. Green infrastructure is an attractive climate adaptation option since it also contributes to the sustainable development of urban areas (Gill et al., 2007; James et al., 2009). Urban green space and green roofs can moderate temperature and decrease surface rainwater runoff (Gill et al., 2007). Despite the benefits of urban green space, conflict can occur between the use of land for green space and building developments (Hamin and Gurran, 2009).

European policies for biodiversity (e.g., the European Biodiversity Strategy (EC, 2011)) look to spatial planning to help protect and safeguard internationally and nationally designated sites, networks, and species, as well as locally valued sites in urban and non-urban areas, and to create new opportunities for biodiversity through the development process (Wilson, 2008). Conservation planning in response to climate change impacts on species aims to involve several strategies to better manage isolated habitats, increase colonization capacity of new climate zones, and optimize conservation networks to establish climate refugia (Vos et al., 2008).

23.7.5. Rural Development

Rural development is one of the key policy areas for Europe, yet there is little or no discussion about the role of climate change in affecting future rural development. The EU White Paper on adapting to climate change (EC, 2009a) encourages member states to embed climate change adaptation into the three strands of rural development aimed at improving competitiveness, the environment, and the quality of life in rural areas. It appears however that little progress has been made in achieving these objectives.

For example, the EUs Leader program was designed to help rural actors improve the long-term potential of their local areas by encouraging the implementation of sustainable development strategies. Many Leader projects address climate change adaptation, but only as a secondary or in many cases a non-intentional by-product of the primary rural development goals. The World Bank's community adaptation project has seen a preponderance of proposals from rural areas in Eastern Europe and Central Asia (Heltberg et al., 2012), suggesting that adaptation-based development needs in Eastern Europe are currently not being met by policy.

23.7.6. Economic Assessments of Adaptation

Compared to studies assessed in AR4 (WGII AR4 Section 17.2.3), cost estimates for Europe are increasingly derived from bottom-up and sector-specific studies, aimed at costing response measures (Watkiss and Hunt, 2010), in addition to the economy-wide assessments (Aaheim et al., 2012). The evidence base, however, is still fragmented and incomplete. The coverage of adaptation costs and benefit estimates is dominated by structural (physical) protection measures, where effectiveness and cost components can be more easily identified. For energy, agriculture, and infrastructure, there is medium coverage of cost and benefit categories. There is a lack of information regarding adaptation costs in the health and social care sector. Table 23-2 summarizes some of the more comprehensive cost estimates for Europe for sectors at regional and

Table 23-2 | Selected published cost estimates for planned adaptation in European countries.

Region	Cost estimate	Time period	Sectors/outcomes	Reference
Europe	€2.6–3.5 billion yr^{-1}	In 2100	Coastal adaptation costs	Hinkel et al. (2010)
	€1.7 billion yr^{-1}	By 2020s	Protection from river flood risk for EU27	Rojas et al. (2013)
	€3.4 billion yr^{-1}	By 2050s		
	€7.9 billion yr^{-1}	By 2080s		
Netherlands	€1.2–1.6 billion yr^{-1}	Up to 2050	Protection from coastal and river flooding	Delta Committee (2008)
	€0.9–1.5 billion yr^{-1}	2050–2100		
Sweden	Total of up to €2.4 billion	2010–2100	Investments in structural adaptation, information campaigns, and research	Swedish Commission on Climate and Vulnerability (2007)
Italy	€0.4–2 billion	By 2080s	Coastal protection	Bosello et al. (2012)
	Up to €44 billion	By 2080s	Hydrogeological protection	Medri et al. (2013)
Greece	€0.4–3.3 billion	Up to 2100	Coastal protection	Bank of Greece (2011)
United Kingdom	€1.8 billion	Until 2035	Maintain and improve Thames flood protection	EA (2011)
	€2.2 billion	2035–2050	Renew and improve Thames flood protection	
	€7–8 billion	At 2100	New Thames barrier for London	

national levels. It is stressed that the costing studies use a range of methods and metrics and relate to different time periods and sectors, which renders robust comparison difficult. As an example, there are large differences between the cost estimates for coastal and river protection in the Netherlands and other parts of Europe (Table 23-2), which is due to the objectives for adaptation and the large differences in the level of acceptable risk. For example, Rojas et al. (2013) assess a 1-in-100 year level of protection for Europe, while the Netherlands has set standards up to 1-in-4000 and 10,000-year level return periods. More detailed treatment of the economics of adaptation is provided in Chapter 17.

23.7.7. Barriers and Limits to Adaptation

Implementation of adaptation options presents a range of opportunities, constraints, and limits. Constrains (barriers) to implementation are financial, technical, and political (see discussion in Chapter 16). Some impacts will be unavoidable due to physical, technological, social, economic, or political limits. Examples of limits in the European context are described by sector in Table 23-3. For example, the contraints on building or extending flood defenses would include pressure for land, conservation needs, and amenity value of coastal areas (Section 5.5.6).

Toward the end of the century, it is likely that adaptation limits will be reached earlier under higher rates of warming. Opportunities and co-benefits of adaptation are also discussed in Section 23.8.

23.8. Co-Benefits and Unintended Consequences of Adaptation and Mitigation

Scientific evidence for decision making is more useful if impacts are considered in the context of impacts on other sectors and in relation to adaptation, mitigation, and other important policy goals. The benefits of adaptation and mitigation policies can be felt in the near term and in the local population, although benefits relating to GHG emissions reduction may not be apparent until the longer term. The benefits of adaptation measures are often assessed using conventional economic analyses, some of which include non-market costs and benefits (externalities) (Watkiss and Hunt, 2010). This section describes policies, strategies, and measures where there is good evidence regarding mitigation/adaptation costs and benefits. Few studies have quantified directly the trade-offs/synergies for a given policy.

23.8.1. Production and Infrastructure

Mitigation policies (decarbonization strategies) are likely to have important implications for dwellings across Europe. The unintended consequences of mitigation in the housing sector include changes to household energy prices and adverse effects from decreased ventilation in dwellings (Jenkins et al., 2008; Jenkins, 2009; Davies and Oreszczyn, 2012; Mavrogianni et al., 2012). The location, type, and dominant energy use of the building will determine its overall energy gain or loss to maintain comfort levels. Adaptation measures such as the use of cooling devices will probably increase a building's energy consumption if no other mitigation measures are applied. The potential for cooling dwellings without increased energy consumption, and with health benefits is large (Wilkinson et al., 2009).

When looking at the broader context of urban infrastructures, despite existing efforts to include both adaptation and mitigation into sustainable development strategies at the city level (e.g., Hague, Rotterdam, Hamburg, Madrid, London, Manchester), priority on adaptation still remains low (Carter, 2011). There is potential to develop strategies that can address both mitigation and adaptation solutions, as well as have health and environmental benefits (Milner et al., 2012). In energy supply, the adverse effect of climate change on water resources in some coastal regions in Southern Europe may further enhance the development of

Table 23-3 | Limits to adaptation to climate change.

Area/location	System	Adaptation measures	Limits to adaptation measure(s)	References
Low-altitude/small-size ski resorts	Ski tourism	Artificial snowmaking	Climatic, technological, and environmental constraints; economic viability; social acceptability of charging for previously free skiing; social acceptability of alternatives for winter sport/leisure	Steiger and Mayer (2008); Unbehaun et al. (2008); Steiger (2010, 2011); Landauer et al. (2012)
Thermal power plants/cooling through river intake and discharge	Once-through cooling systems	Closed-circuit cooling	High investment cost for retrofitting existing plants	Koch and Vögele (2009); van Vliet et al. (2012); Hoffman et al. (2013)
Rivers used for freight transport	Inland transport	Reduced load factor of inland ships	Increased transport prices (Rhine and Moselle market)	Jonkeren et al. (2007); Jonkeren (2009)
		Use of smaller ships	Existing barges below optimal size (Rhine)	Demirel (2011)
Agriculture, northern and continental Europe	Arable crops	Changing sowing date as agricultural adaptation	Other constraints (e.g., frost) limit farmer behavior.	Oort (2012)
		Irrigation	Groundwater availability; competition with other users	Olesen et al. (2011)
Agriculture, viticulture	High-value crops	Change distribution	Legislation on cultivar and geographical region	Box 23-1
Conservation; cultural landscapes	Alpine meadow	Extend habitat	No technological adaptation option	Engler et al. (2011); Dullinger et al. (2012)
Conservation of species richness	Movement of species	Extend habitat	Landscape barriers and absence of climate projections in selection of conservation areas	Butchart et al. (2010); Araújo et al. (2011); Filz et al. (2012); Virkkala et al. (2013)
Forests	Movement of species and productivity reduction	Introduce new species	Not socially acceptable; legal barriers to non-native species	Casalegno et al. (2007); Giuggiola et al. (2010); Hemery et al. (2010); García-López and Alluéa (2011)

desalination plants as an adaptation measure, possibly increasing energy consumption and thus GHG emissions. Coastal flood defense measures may alter vector habits and have implications for local vector-borne disease transmission (Medlock and Vaux, 2013).

In tourism, adaptation and mitigation may be antagonistic, as in the case of artificial snowmaking in European ski resorts, which requires significant amounts of energy and water (OECD, 2007; Rixen et al., 2011), and the case of desalination for potable water production, which also requires energy. However, depending on the location and size of the resort, implications are expected to differ and thus need to be investigated on a case-by-case basis. A similar relationship between adaptation and mitigation may hold for tourist settlements in Southern Europe, where expected temperature increases during the summer may require increased cooling to maintain tourist comfort and thus increase GHG emissions and operating costs. Furthermore, a change of tourist flows as a result of tourists adapting to climate change may affect transport emissions, while mitigation in transport could also lead to a change in transport prices and thus possibly affect tourist flows.

23.8.2. Agriculture, Forestry, and Bioenergy

Agriculture and forestry face two challenges under climate change, both to reduce emissions and to adapt to a changing and more variable climate (Lavalle et al., 2009; Smith and Olesen, 2010). The agriculture sector contributes about 10% of the total anthropogenic GHG emissions in the EU27 (EEA, 2010b). Estimates of European CO_2, methane, and NO_x fluxes between 2000 and 2005 suggest that methane emissions from livestock and NO_x emissions from agriculture are fully compensated for by the CO_2 sink provided by forests and by grassland soils (Schulze et al., 2010). However, projections following a baseline scenario suggest a significant decline (–25 to –40%) of the forest carbon sink of the EU until 2030 compared to 2010. Using wood for bioenergy results initially in a carbon debt due to reduced storage in forests, which affects the net GHG balance depending on the energy type that is replaced and the time span considered (McKechnie et al., 2011). Including additional bioenergy targets of EU member states has an effect on the development of the European forest carbon sink (and on the carbon stock), which is not accounted for in the EU emission reduction target (Bottcher et al., 2012).

In arable production systems, adapting to climate change by increasing the resilience of crop yields to heat and to rainfall variability would have positive impacts on mitigation by reducing soil erosion, as well as soil organic carbon and nitrogen losses. Improving soil water holding capacity through the addition of crop residues and manure to arable soils, or by adding diversity to the crop rotations, may contribute both to adaptation and to mitigation (Smith and Olesen, 2010). There are also synergies and trade-offs between mitigation and adaptation options for soil tillage, irrigation, and livestock breeding (Smith and Olesen, 2010). Reduced tillage (and no-till) may contribute to both adaptation and mitigation as it tends to reduce soil erosion and runoff (Soane et al., 2012) and fossil-fuel use (Khaledian et al., 2010), while increasing in some situations soil organic carbon stock (Powlson et al., 2011). However, increased N_2O emission may negate the mitigation effect of reduced tillage (Powlson et al., 2011). Irrigation may enhance soil carbon sequestration in arable systems (Rosenzweig and Tubiello, 2007; Rosenzweig et al., 2008), but increased irrigation under climate change would increase energy use and may reduce water availability for hydropower (reduced mitigation potential) (Wreford et al., 2010). In intensive livestock systems, warmer conditions in the coming decades might trigger the implementation of enhanced cooling and ventilation in farm buildings (Rosenzweig and Tubiello, 2007), thereby increasing energy use and associated GHG emissions. In grass-based livestock systems, adaptation by adjusting the mean annual animal stocking density to the herbage growth potential (Graux et al., 2012) is *likely* to create a positive feedback on GHG emissions per unit area (Soussana and Luscher, 2007; Soussana et al., 2010).

Land management options may also create synergies and trade-offs between mitigation and adaptation. Careful adaptation of forestry and soil management practices will be required to preserve a continental ecosystem carbon sink in Europe (Schulze et al., 2010) despite the vulnerability of this sink to climatic extremes (Ciais et al., 2005) and first signs of carbon sink saturation in European forest biomass (Nabuurs et al., 2013). In areas that are vulnerable to extreme events (e.g., fires, storms, droughts) or with high water demand, the development of bioenergy production from energy crops and from agricultural residues (Fischer, G. et al., 2010; De Wit et al., 2011) could further increase demands on adaptation (Wreford et al., 2010). Conversely, increased demands on mitigation could be induced by the potential expansion of agriculture at high latitudes, which may release large amounts of carbon and nitrogen from organic soils (Rosenzweig and Tubiello, 2007).

23.8.3. Social and Health Impacts

Significant research has been undertaken since AR4 on the health co-benefits of mitigation policies (see Chapter 11 and WGIII AR5 Chapters 7, 8, 9). Several assessments have quantified benefits in terms of lives saved by reducing particulate air pollution. Policies that improve health from changes in transport and energy can be said to have a general benefit to population health and resilience (Haines et al., 2009a,b).

Changes to housing and energy policies also have indirect implications for human health. Research on the benefits of various housing options (including retrofitting) has been intensively addressed in the context of low-energy, healthy, and sustainable housing (see WGIII AR5 Chapters 9, 12).

23.8.4. Environmental Quality and Biological Conservation

There are several conservation management approaches that can address mitigation, adaptation, and biodiversity objectives (Lal et al., 2011). Some infrastructure adaptation strategies—such as desalinization, sea defenses, and flood control infrastructure—may have negative effects on both mitigation and biodiversity. However, approaches, such as forest conservation and urban green space (Section 23.7.4) have multiple benefits and potentially significant effects. There has been relatively little research about the impacts of future land use demand for bioenergy production, food production, and urbanization on nature conservation.

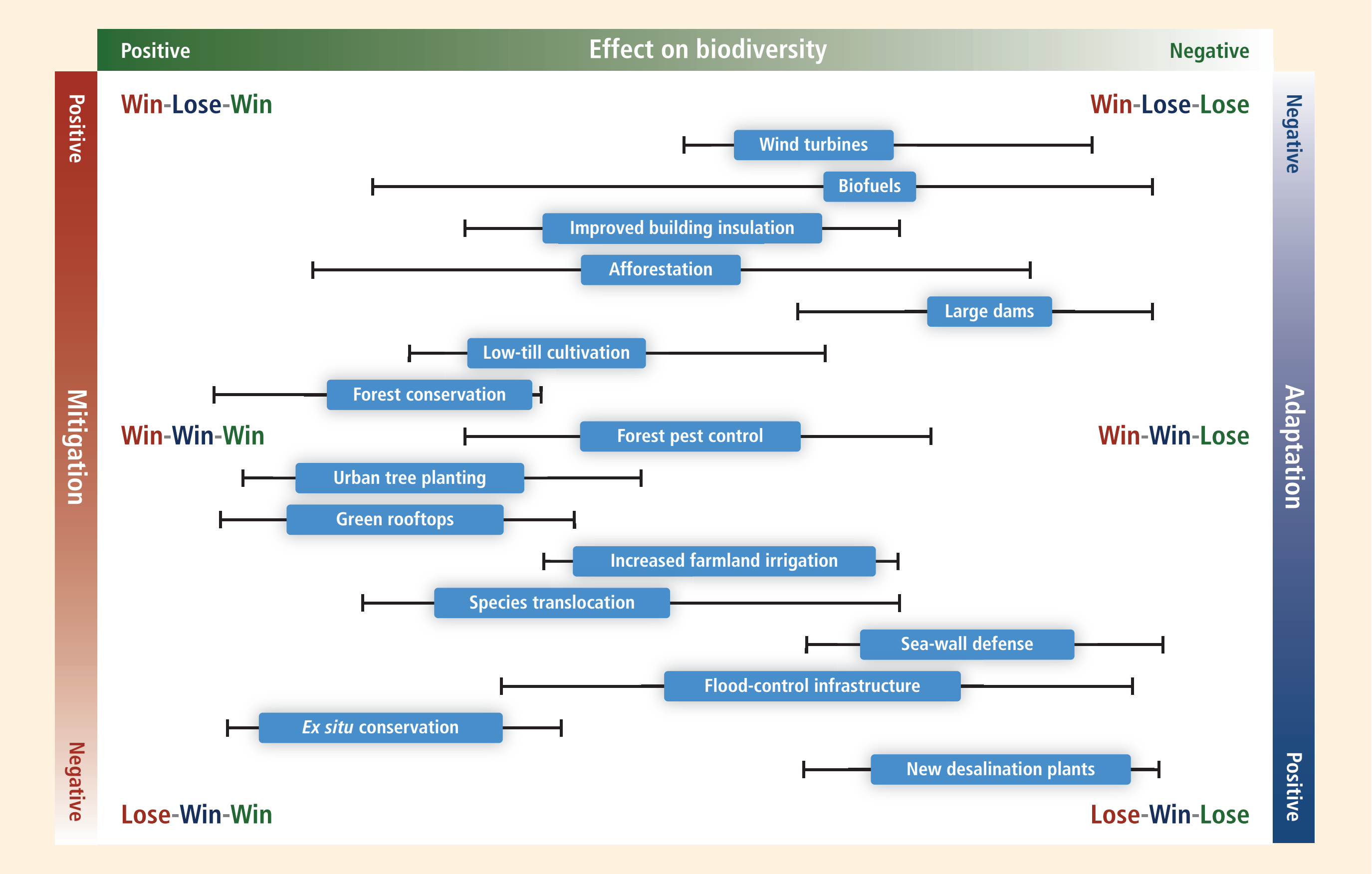


Figure 23-6 | Adaptation and mitigation options and their effects on biodiversity. The horizontal axis ranges from positive effects on biodiversity (lefthand side) to negative effects (righthand side). Each mitigation/adaptation option is located on the biodiversity effect axis (solid bars), including an estimate of the uncertainties associated with the assessment (error bars). The various options are given vertically with mitigation at the top and adaptation at the bottom. Options located toward the center of the vertical axis have benefits for both mitigation and adaptation. Thus, options located at the center left of the figure have benefits for mitigation, adaptation, and biodiversity and hence are labeled as win-win-win. Other combinations of benefits and dis-benefits are labeled accordingly, for example, win-lose-win, lose-win-lose, etc. Based on Paterson et al., 2008.

Figure 23-6 (Paterson et al., 2008) summarizes the evidence regarding mitigation and adaptation options on biodiversity assessed from the literature. The figure shows that the options that come closest to being win-win-win are green rooftops, urban tree planting, forest conservation, and low-till cultivation. Other options with clear benefits are afforestation, forest pest control, increased farmland irrigation, and species translocation.

23.9. Synthesis of Key Findings

23.9.1. Key Vulnerabilities

Climate change will have adverse impacts in nearly all sectors and across all sub-regions. Table 23-4 describes the range of impacts projected in 2050 on infrastructure, settlements, environmental quality, and the health and welfare of the European population. The projected impacts of climate change on ecosystem services (including food production) are described in Box 23-1. A key finding is that all sub-regions are vulnerable to some impacts from climate change but these impacts differ significantly in type between the sub-regions. Impacts in neighboring regions (inter-regional) may also redistribute economic activities across the European landscape. The sectors most likely to be affected by climate change, and therefore with implications for economic activity and population movement (changes in employment opportunities), include tourism (Section 23.3.6), agriculture (Section 23.4.1), and forestry (Section 23.4.4).

The majority of published assessments are based on climate projections in the range of 1°C to 4°C global mean temperature per century. Under these scenarios, regions in Europe may experience higher rates of warming (in the range 1°C to 4°C per century), due to climate variability (Jacob et al., 2013). Limited evidence exists on the potential impacts in Europe under very high rates of warming (>4°C above preindustrial levels) but these would lead to a large increase in coastal flood risk as well as impacts on global cereal yields and other effects on the global economy (Section 19.5.1).

Many key vulnerabilities are already well known since the AR4, but some new vulnerabilities are emerging based on the evidence reviewed in this report. The policy/governance context in Europe is extremely important in determining (reducing or exacerbating) key vulnerabilities since Europe is a highly regulated region. Further, vulnerability will be strongly affected by changes in the non-climate drivers of change (e.g., economic, social protection measures, governance, technological drivers).

Table 23-4 | Assessment of climate change impacts by sub-region by 2050, assuming a medium emissions scenario and no planned adaptation. Impacts assume economic development, including land use change. Impacts are assessed for the whole sub-region, although differences in impact within sub-regions are estimated for some impacts.

		Southern	Atlantic	Continental	Alpine	Northern	Sections
Energy	Wind energy production	🟩↗ → 🟥↘ [a]	🟩↗ → 🟥↘	→	→	🟩↗ →	23.3.4
	Hydropower generation	🟥↘	🟥↘	🟥↘	🟩↗ [b] 🟥↘	🟩↗ →	
	Thermal power production	→ 🟥↘	→ 🟥↘	→ 🟥↘	→ 🟥↘	→	23.3.4, 8.2.3.2
	Energy consumption (net annual change)	🟥↗	🟩↘	🟩↘	🟩↘	🟩↘	23.3.4, 23.8.1
Transport	Road accidents[c]	🟩↘	→ 🟩↘	→ 🟩↘	→ 🟩↘	→ 🟩↘	23.3.3
	Rail delays (weather-related)	?	🟥↗ 🟩↘ [d]	?	?	🟥↗	23.3.3, 8.3.3.6
	Load factor of inland ships	?	→ 🟥↘	→ 🟥↘	?	?	23.3.3
	Transport time and cost in ocean routes	?	?	🟩↘	?	🟩↘	23.3.3, 18.3.3.3.5
Settlements	River flood damages	→	🟥↗ 🟩↘	🟥↗ 🟩↘	→	→	23.3.1
	Coastal flood damages	🟥↗ →	🟥↗ →	🟥↗ →	N/A	🟥↗ →	
Tourism	Length of ski season	?	?	🟥↘	→ 🟥↘	🟥↘	23.3.6, 3.5.7
Human health	Heat wave mortality and morbidity[e]	🟥↗	🟥↗	🟥↗	→	🟥↗	23.5.1
	Food-borne disease[e]	🟥↗	🟥↗	🟥↗	→	🟥↗	
Social and cultural impacts	Social costs of floods	🟥↗ →	🟥↗ 🟩↘	🟥↗ 🟩↘	→	🟥↗ →	23.5.3
	Damage to cultural buildings	🟥↗ 🟩↘	🟥↗	🟥↗	🟥↗	🟥↗	23.5.4
	Loss of cultural landscapes	?	🟥↗	🟥↗	🟥↗	🟥↗	
Environmental quality	Air quality (ozone background levels)	🟥↗ 🟩↘	🟥↗ 🟩↘	🟥↗ 🟩↘	?	🟥↗ 🟩↘	23.6.1
	Air quality (particulates)	🟥↗ 🟩↘	🟥↗ 🟩↘	🟥↗ 🟩↘	?	🟥↗ 🟩↘	
	Water quality	🟥↘	🟥↘	→	→	→	23.6.3

Increasing	↗	A range from no change to increasing	↗ →	🟩 Green arrows mean a "beneficial change"
No change	→	A range from no change to decreasing	→ ↘	🟥 Red arrows means a "harmful change"
Decreasing	↘	A range from increasing to decreasing	↗ ↘	? means no relevant literature found

[a] Simulations have been performed, but mostly for the period after 2070.
[b] The increasing trend is for Norway.
[c] The decreasing trends refers mainly to the number of severe accidents.
[d] Impacts have been studied and quantified for UK only. The increasing trend stands for summer delays and the decreasing trends for winter delays.
[e] Impacts shown with respect to future world without climate change.

Extreme events affect multiple sectors and have the potential to cause systemic impacts from secondary effects (Chapter 19). Past events indicate the vulnerability of transport, energy, agriculture, water resources, and health systems. Resilience to very extreme events varies by sector, and by country (Pitt, 2008; Ludwig et al., 2011; Ulbrich et al., 2012). Extreme events (heat waves and droughts) have had significant impacts on populations as well as multiple economic sectors (Table 23-1), and resilience to future heat waves has been addressed only within some sectors. However, there is surprisingly little evidence regarding the impacts of major extreme events (e.g., Russian heat wave of 2010) and on responses implemented post-event to increase resilience. Future vulnerability will also be strongly affected by cross-sectoral (indirect) interactions, for example, flooding-ecosystems, agriculture-species, agriculture-cultural landscapes, and so on.

Climate change is likely to have significant impacts on future water availability, and the increased risks of water restrictions in Southern, Central, and Atlantic sub-regions. Studies indicate a significant reduction in water availability from river abstraction and from groundwater resources, combined to increased demands from a range of sectors (irrigation, energy and industry, domestic use) and to reduced water drainage and runoff (as a result of increased evaporative demand) (Ludwig et al., 2011).

Climate change will affect rural landscapes by modifying relative land values, and hence competition, between different land uses (Smith et al., 2010). This will occur directly, for example, through changes in the productivity of crops and trees (Section 23.4), and indirectly through climate change impacts on the global supply of land-based commodities and their movement through international trade (Section 23.9.2).

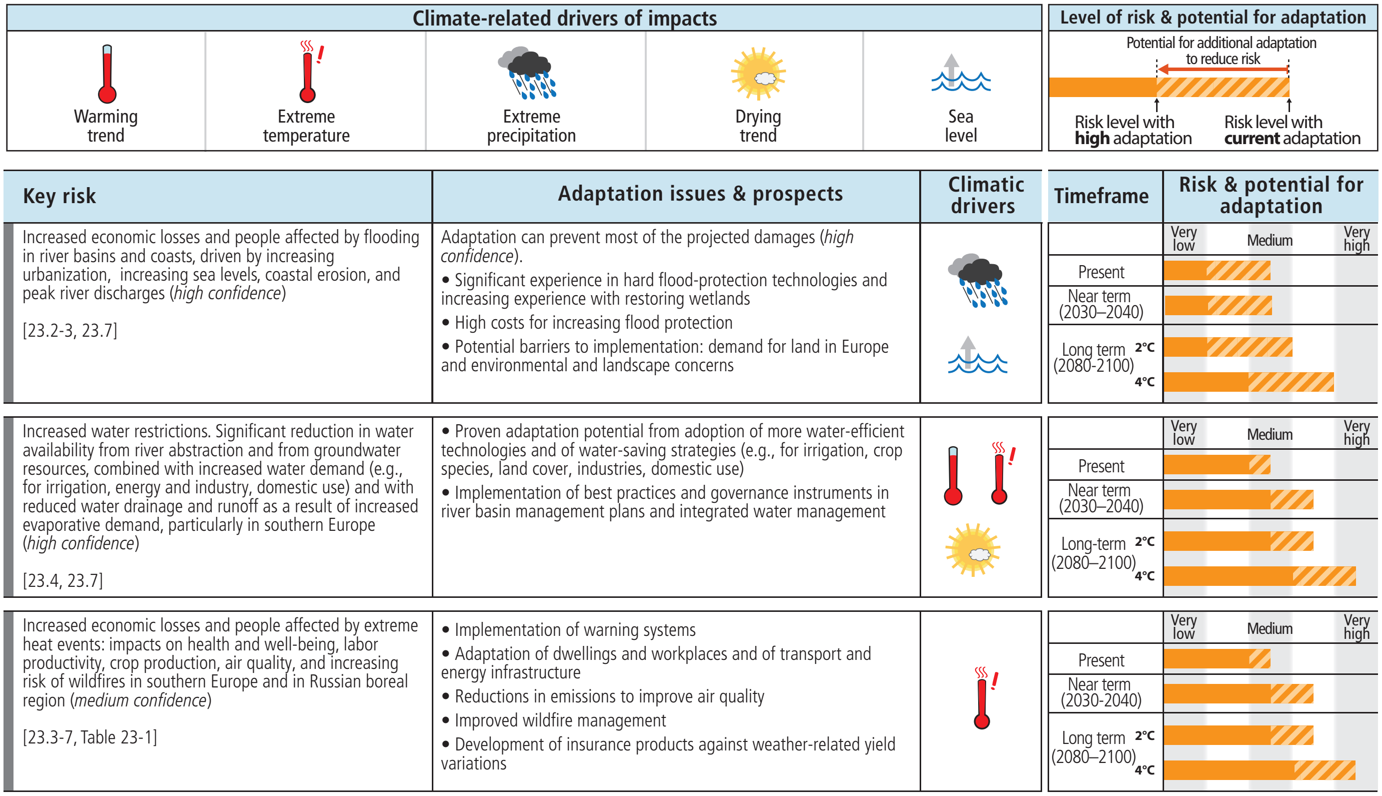
Climate change will have a range of impacts in different European sub-regions. The adaptive capacity of populations is likely to vary significantly within Europe. Adaptive capacity indicators have been developed based on future changes in socioeconomic indicators and projections (Metzger et al., 2008; Lung et al., 2012; Acosta et al., 2013). These studies concluded that the Nordic countries have higher adaptive capacity than most of the Southern European countries, with countries around the Mediterranean having a lower capacity than the countries around the Baltic Sea region. Some regions or areas are particularly vulnerable to climate change:

- Populations and infrastructure in coastal regions are likely to be adversely affected by sea level rise, particularly after mid-century (Sections 23.3.1, 23.5.3).
- Urban areas are also vulnerable to weather extremes owing to high density of people and built infrastructure (Sections 23.3, 23.5.1).
- Owing to high impact of climate change on natural hazard, and water and snow resources, and the lack of migration possibilities for plant species, mountain regions concentrate vulnerabilities in infrastructure for transport and energy sectors, as well as for tourism, agriculture, and biodiversity.
- The Mediterranean region will suffer multiple stresses and systemic failures due to climate changes. Changes in species composition, increase of alien species, habitat losses, and degradation both in land and sea together with agricultural and forests production losses due to increasing heat waves and droughts exacerbated also by the competition for water will increase vulnerability (Ulbrich et al., 2012).

The following risks have emerged from observations of climate sensitivity and observed adaptation:

- There is new evidence to suggest that arable crop yields and production may be more vulnerable as a result of increasing climate

Table 23-5 | Key risks from climate change in Europe and the potential for reducing risk through mitigation and adaptation. Risk levels are presented in three timeframes: the present, near-term (2030–2040), and longer term (2080–2100). For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions. Key risks were identified based on assessment of the literature and expert judgment.



Climate-related drivers of impacts					Level of risk & potential for adaptation
Warming trend	Extreme temperature	Extreme precipitation	Drying trend	Sea level	Potential for additional adaptation to reduce risk Risk level with **high** adaptation Risk level with **current** adaptation

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization, increasing sea levels, coastal erosion, and peak river discharges (*high confidence*) [23.2-3, 23.7]	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies and increasing experience with restoring wetlands • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns	Extreme precipitation Sea level	Present Near term (2030–2040) Long term (2080-2100) 2°C 4°C	Very low Medium Very high
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand, particularly in southern Europe (*high confidence*) [23.4, 23.7]	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Implementation of best practices and governance instruments in river basin management plans and integrated water management	Warming trend Extreme temperature Drying trend	Present Near term (2030–2040) Long-term (2080–2100) 2°C 4°C	Very low Medium Very high
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, air quality, and increasing risk of wildfires in southern Europe and in Russian boreal region (*medium confidence*) [23.3-7, Table 23-1]	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infrastructure • Reductions in emissions to improve air quality • Improved wildfire management • Development of insurance products against weather-related yield variations	Extreme temperature	Present Near term (2030-2040) Long term (2080–2100) 2°C 4°C	Very low Medium Very high

variability. This will limit the potential poleward expansion of agricultural production. Limits to genetic progress to adapt are increasingly reported.

- New evidence has emerged regarding implications during summer on inland waterways (decreased access) and long-range ocean transport (increased access).
- Terrestrial and freshwater species are vulnerable from climate change shifts in habitats. There is new evidence that species cannot populate new habitat due to habitat fragmentation (urbanization). Observed migration rates are less than that assumed in modeling studies. There are legal barriers to introducing new species (e.g., forest species in France). New evidence reveals that phenological mismatch will cause additional adverse effects on some species.
- A positive (and emerging) effect that may reduce vulnerability is that many European governments (and individual cities) have become aware of the need to adapt to climate change and so are developing and/or implementing adaptation strategies and measures.

Additional risks have emerged from the assessed literature:

- Increased summer energy demand, especially in Southern Europe, requires additional power generation capacity (underutilized during the rest of the year), entailing higher supply costs.
- Housing will be affected, with increased overheating under no adaptation and damage from subsidence and flooding. Passive cooling measures alone are unlikely to be sufficient to address adaptation in all regions and types of buildings. Retrofitting current housing stock will be expensive.
- The vulnerability of cultural heritage, including monuments/buildings and cultural landscapes, is an emerging concern. Some cultural landscapes will disappear. Grape production is highly sensitive to climate, but production (of grape varieties) is strongly culturally dependent and adaptation is potentially limited by the regulatory context.
- There is strong evidence that climate change will increase the distribution and seasonal activity of pests and diseases, and limited evidence that such effects are already occurring. Increased threats to plant and animal health are noted. Public policies are in place to reduce pesticide use in agriculture use and antibiotics in livestock, and this will increase vulnerability to the impact of climate change on agriculture and livestock production.
- Lack of institutional frameworks is a major barrier to adaptation governance, in particular, the systematic failure in land use planning policy to account for climate change.

23.9.2. Climate Change Impacts Outside Europe and Inter-regional Implications

With increasing globalization, the impacts of climate change outside the European region are likely to have implications for countries within the region. For example, the Mediterranean region (Southern Europe and non-European Mediterranean countries) has been considered highly vulnerable to climate change (Navarra, 2013).

Eastern European countries have, in general, lower adaptive capacity than Western or Northern European countries. The high volume of international travel increases Europe's vulnerability to invasive species, including the vectors of human and animal infectious diseases. The transport of animals and animal products has facilitated the spread of animal diseases (Conraths and Mettenleiter, 2011). Important "exotic" vectors that have become established in Europe include the vector *Aedes albopictus* (Becker, 2009; see also Section 23.5.1).

Another inter-regional implication concerns the changes in the location of commercial fish stocks shared between countries. Such changes may render existing international agreements regarding the sharing of yield from these stocks obsolete, giving rise to international disputes (Arnason, 2012). For instance, the North Sea mackerel stock has recently been extending westwards beyond the EU jurisdiction into the Exclusive Economic Zones of Iceland and the Faroe Islands, which unilaterally claimed quota for mackerel. Territorial disagreements of this type could increase in the future with climate change.

Although several studies have proposed a role for climate change in increasing migration pressures in low- and middle-income countries in the future, there is little robust information regarding the respective roles of climate change, environmental resource depletion, and weather disasters in future inter-continental population movements. The effect of climate change on external migration flows into Europe is highly uncertain (see Section 12.4.1 for a more complete discussion). Modeling future migration patterns is complex, and so far no robust approaches have been developed.

23.9.3. Effects of Observed Climate Change in Europe

Table 23-6 summarizes the evidence with respect to key indicators in Europe for the detection of a trend and the attribution of that trend to observed changes in climate factors. The attribution of local warming to anthropogenic climate change is less certain (see Chapter 18 for a full discussion).

Further and better quality evidence since 2007 supports the conclusion of AR4 (Alcamo et al., 2007) that climate change is affecting land, freshwater, and marine ecosystems in Europe. Observed warming has caused advancement in the life cycles of many animal groups, including frogs spawning, birds nesting, and the arrival of migrant birds and butterflies (see Chapter 4 and review by Feehan et al., 2009). There is further evidence that observed climate change is already affecting agricultural, forest, and fisheries productivity (see Section 23.4).

The frequency of river flood events, and annual flood and windstorm damages, in Europe have increased over recent decades, but this increase is attributable mainly to increased exposure and the contribution of observed climate change is unclear (*high confidence*, based on *robust evidence*, *high agreement*; SREX Section 4.5.3; Barredo, 2010).

The observed increase in the frequency of hot days and hot nights (*high confidence*) is likely to have increased heat-related health effects in Europe (*medium confidence*), as well as a decrease in cold-related health effects (*medium confidence*; Christidis et al., 2010). Multiple impacts on health, welfare, and economic sectors were observed due to the major heat wave events of 2003 and 2010 in Europe (Table 23-1; see Chapter 18 for discussion on attribution of events).

Table 23-6 | Observed changes in key indicators in ecological and human systems attributable to climate factors.

	Indicator	Change in indicator	Confidence in detection	Confidence in attribution to change in climate factors*	Key references	Section
Bio-physical systems	Glacier retreat	Fast mass loss of 30 Swiss glaciers since the 1980s	*High confidence*	*Medium confidence*	Huss (2010)	18.3.1, WGI 10.5
Infrastructure	Storm losses	Increase since 1970s	*High confidence*	No causal role for climate	Barredo (2010)	23.3.7
	Hail losses	Increase in parts of Germany	*Low confidence*	*Low confidence*	Kunz et al. (2009)	23.3.7
	Flood losses	Increasing general trend in economic losses in Europe since 1970s; none in Spain	*Medium confidence*	No causal role for climate	Barredo (2009); Barredo et al. (2012)	23.3.1
Agriculture, fisheries, forestry, and bioenergy production	C$_3$ crop yield	CO$_2$-induced positive contribution to yield since pre-industrial for C$_3$ crops	*High confidence* (*high agreement, robust evidence*)	*High confidence* (*high agreement, robust evidence*)	Amthor (2001); Long et al. (2006); McGrath and Lobell (2011)	7.2.1
	Wheat yield	Stagnation of wheat yields in some countries in recent decades	*High confidence*	*Medium confidence*	Brisson et al. (2010); Kristensen et al. (2011); Lobell et al. (2011)	23.4.1
	Phenology—leaf greening	Earlier greening, earlier leaf emergence and fruit set in temperate and boreal climate	*High confidence* (*high agreement, robust evidence*)	*High confidence* (*high agreement, robust evidence*)	Menzel et al. (2006)	4.4.1.1
	Phytoplankton productivity	Increased phytoplankton productivity in northeast Atlantic, decrease in warmer regions, due to warming trend and hydroclimatic variations	*High confidence*	*Medium confidence*	Beaugrand et al. (2002); Edwards and Richardson (2004)	6.3
	Ocean systems	Northward movement of species and increased species richness due to warming trend	*High confidence*	*Medium confidence*	Philippart et al. (2011)	6.3
Environmental quality and biodiversity	Biodiversity	Increased number of colonization events by alien plant species in Europe	*Medium confidence* (*high agreement, medium evidence*)	*Medium confidence*	Walther et al. (2009)	4.2.4.6
	Migratory birds	Decline over the period 1990–2000 of species that did not advance their spring migration	*Medium confidence* (*medium agreement, medium evidence*)	*Medium confidence*	Moller et al. (2008)	4.4.1.1
	Tree species	Upward shift in tree line in Europe	*Medium evidence* (*medium agreement, high evidence*)	*Medium confidence*	Gehrig-Fasel et al. (2007); Lenoir et al. (2008)	18.3.2
	Forest fires	Increase in burnt area	*High confidence*	*High confidence* (*high agreement, robust evidence*)	Pereira et al. (2005); Camia and Amatulli (2009); Hoinka et al. (2009); Carvalho et al. (2010); Koutsias et al. (2012); Salis et al. (2013)	23.4.4

*The studies included in this table are those with good evidence of a detection of a long-term trend in the outcome of interest, and where there has been an assessment of the attribution of the trend to an observed change in climate factor. It is not possible to make an attribution to anthropogenic climate change at this scale; see Chapter 18 for a more complete discussion.

23.9.4. Key Knowledge Gaps and Research Needs

There is a clear mismatch between the volume of scientific work on climate change since the AR4 and the insights and understanding required for policy needs, as many categories of impacts are still under-studied. Some specific research needs have been identified:

- Little information is available on integrated and cross-sectoral climate change impacts in Europe, as the impact studies typically describe a single sector (see Sections 23.3-6). This also includes a lack of information on cross-sector vulnerabilities, and the indirect effects of climate change impacts and adaptation responses. This is a major barrier in developing successful evidence-based adaptation strategies that are cost-effective.
- Climate change impact models are difficult to validate (Sections 23.3-6); proper testing of the characteristics of baseline impact estimates against baseline information and data would improve their reliability, or the development of alternative methods where baseline data are not available.
- There is little knowledge on co-benefits and unintended consequences of adaptation options across a range of sectors (Sections 23.3-6).
- There is a need to better monitor and evaluate local and national adaptation and mitigation responses to climate change, in both public and private sectors (Section 23.7; Box 23-3). This includes policies and strategies—as well as the effectiveness of individual adaptation measures. Evaluation of adaptation strategies, over a range of time scales, would better support decision making. Although some means for reporting of national actions exist in Europe (e.g., EU Climate-ADAPT), there is no consistent method of monitoring or a mechanism for information exchange (Section 23.7).
- There are now more economic methods and tools available for the costing and valuation of specific adaptation options, in particular for flood defenses, water, energy, and agriculture sectors (Section 23.7.6). However, for other sectors—such as biodiversity, business and industry, and population health costs—cost estimates are still lacking or incomplete. The usefulness of this costing information in decision making needs to be evaluated and research can be undertaken to make economic evaluation more relevant to decision making.
- The need for local climate information to inform decision making also needs to be evaluated.

- Further research is needed on the effects of climate change on critical infrastructure, including transport, water and energy supplies, and health services (Section 23.5.2).
- Further research is needed on the role of governance in adaptation (local and national institutions) with respect to implementation of measures in the urban environment, including flood defenses, overheating, and urban planning.
- The impacts from high end scenarios of climate change (>4°C global average warming, with higher temperature change in Europe) are not yet known. Such scenarios have only recently become available, and related impact studies still need to be undertaken for Europe.
- More study of the implications for rural development would inform policy in this area (Section 23.7.5). There is also a lack of information on the resilience of cultural landscapes and communities, and how to manage adaptation, particularly in low-technology (productively marginal) landscapes.
- More research is needed for the medium- and long-term monitoring of forest responses and adaptation to climate change and on the

Frequently Asked Questions

FAQ 23.1 | Will I still be able to live on the coast in Europe?

Coastal areas affected by storm surges will face increased risk both because of the increasing frequency of storms and because of higher sea level. Most of this increase in risk will occur after the middle of this century. Models of the coast line suggest that populations in the northwestern region of Europe are most affected and many countries, including the Netherlands, Germany, France, Belgium, Denmark, Spain, and Italy, will need to strengthen their coastal defenses. Some countries have already raised their coastal defense standards. The combination of raised sea defenses and coastal erosion may lead to narrower coastal zones in the North Sea, the Iberian coast, and the Bay of Biscay. Adapting dwellings and commercial buildings to occasional flooding is another response to climate change. But though adapting buildings in coastal communities and upgrading coastal defenses can significantly reduce adverse impacts of sea level rise and storm surges, they cannot eliminate these risks, especially as sea levels will continue to rise over time. In some locations, "managed retreat" is likely to become a necessary response.

Frequently Asked Questions

FAQ 23.2 | Will climate change introduce new infectious diseases into Europe?

Many factors play a role in the introduction of infectious diseases into new areas. Factors that determine whether a disease changes distribution include: importation from international travel of people, vectors or hosts (insects, agricultural products), changes in vector or host susceptibility, drug resistance, and environmental changes, such as land use change or climate change. One area of concern that has gained attention is the potential for climate change to facilitate the spread of tropical diseases, such as malaria, into Europe. Malaria was once endemic in Europe. Even though its mosquito vectors are still present and international travel introduces fresh cases, malaria has not become established in Europe because infected people are quickly detected and treated. Maintaining good health surveillance and good health systems are therefore essential to prevent diseases from spreading. When an outbreak has occurred (i.e., the introduction of a new disease) determining the causes is often difficult. It is likely that a combination of factors will be important. A suitable climate is a necessary but not a sufficient factor for the introduction of new infectious diseases.

Frequently Asked Questions

FAQ 23.3 | Will Europe need to import more food because of climate change?

Europe is one of the world's largest and most productive suppliers of food, but also imports large amounts of some agricultural commodities. A reduction in crop yields, particularly wheat in Southern Europe, is expected under future climate scenarios. A shift in cultivation areas of high-value crops, such as grapes for wine, may also occur. Loss of food production may be compensated by increases in other European sub-regions. However, if the capacity of the European food production system to sustain climate shock events is exceeded, the region would require exceptional food importation.

predictive modeling of wildfire distribution to better address adaptation and planning policies. There is also a lack of information on the impact of climate changes and climate extremes on carbon sequestration potential of agricultural and forestry systems (Section 23.4.4).

- More research is needed on impacts of climate change on transport, especially on the vulnerability of road and rail infrastructure, and on the contribution of climatic and non-climatic parameters in the vulnerability of air transport (e.g., changes in air traffic volumes, airport capacities, air traffic demand, weather at the airports of origin, intermediate and final destination; Section 23.3.3).
- Improved monitoring of droughts is needed to support the management of crop production (Section 23.4). Remote sensing could be complemented by field experiments that assess the combined effects of elevated CO$_2$ and extreme heat and drought on crops and pastures.
- Research is needed on resilience of human populations to extreme events (factors that increase resilience), including responses to flood and heat wave risks. Research is also needed on how adaptation policies may increase or reduce social inequalities (Section 23.5).
- Improved risk models need to be developed for vector-borne disease (human and animal diseases) to support health planning and surveillance (Sections 23.4.2, 23.5.1).

A major barrier to research is lack of access to data, which is variable across regions and countries (especially with respect to socioeconomic data, climate data, forestry, and routine health data). There is a need for long-term monitoring of environmental and social indicators and to ensure open access to data for long-term and sustainable research programs. Cross-regional cooperation could also ensure compatibility and consistency of parameters across the European region.

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Asia

Coordinating Lead Authors:
Yasuaki Hijioka (Japan), Erda Lin (China), Joy Jacqueline Pereira (Malaysia)

Lead Authors:
Richard T. Corlett (China), Xuefeng Cui (China), Gregory Insarov (Russian Federation), Rodel Lasco (Philippines), Elisabet Lindgren (Sweden), Akhilesh Surjan (India)

Contributing Authors:
Elena M. Aizen (USA), Vladimir B. Aizen (USA), Rawshan Ara Begum (Bangladesh), Kenshi Baba (Japan), Monalisa Chatterjee (USA/India), J. Graham Cogley (Canada), Noah Diffenbaugh (USA), Li Ding (Singapore), Qingxian Gao (China), Matthias Garschagen (Germany), Masahiro Hashizume (Japan), Manmohan Kapshe (India), Andrey G. Kostianoy (Russia), Kathleen McInnes (Australia), Sreeja Nair (India), S.V.R.K. Prabhakar (India), Yoshiki Saito (Japan), Andreas Schaffer (Singapore), Rajib Shaw (Japan), Dáithí Stone (Canada/South Africa /USA), Reiner Wassman (Philippines), Thomas J. Wilbanks (USA), Shaohong Wu (China)

Review Editors:
Rosa Perez (Philippines), Kazuhiko Takeuchi (Japan)

Volunteer Chapter Scientists:
Yuko Onishi (Japan), Wen Wang (China)

This chapter should be cited as:

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Executive Summary

Warming trends and increasing temperature extremes have been observed across most of the Asian region over the past century (*high confidence*). {24.3} Increasing numbers of warm days and decreasing numbers of cold days have been observed, with the warming trend continuing into the new millennium. Precipitation trends including extremes are characterized by strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia.

Water scarcity is expected to be a major challenge for most of the region as a result of increased water demand and lack of good management (*medium confidence*). {24.4.3} Water resources are important in Asia because of the massive population and vary among regions and seasons. However, there is *low confidence* in future precipitation projections at a sub-regional scale and thus in future freshwater availability in most parts of Asia. Population growth and increasing demand arising from higher standards of living could worsen water security in many parts in Asia and affect many people in the future. Integrated water management strategies could help adapt to climate change, including developing water-saving technologies, increasing water productivity, and water reuse.

The impacts of climate change on food production and food security in Asia will vary by region, with many regions to experience a decline in productivity (*medium confidence*). {24.4.4} This is evident in the case of rice production. Most models, using a range of General Circulation Models (GCMs) and *Special Report on Emission Scenarios* (SRES) scenarios, show that higher temperatures will lead to lower rice yields as a result of shorter growing periods. There are a number of regions that are already near the heat stress limits for rice. However, carbon dioxide (CO_2) fertilization may at least in part offset yield losses in rice and other crops. In Central Asia, some areas could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters, and slight increase in winter precipitation), while others could be losers (western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase water demand for irrigation, and exacerbate desertification). In the Indo-Gangetic Plains of South Asia there could be a decrease of about 50% in the most favorable and high-yielding wheat area as a result of heat stress at 2 times CO_2. Sea level rise will inundate low-lying areas and will especially affect rice growing regions. Many potential adaptation strategies are being practiced and proposed but research studies on their effectiveness are still few.

Terrestrial systems in many parts of Asia have responded to recent climate change with shifts in the phenologies, growth rates, and the distributions of plant species, and with permafrost degradation, and the projected changes in climate during the 21st century will increase these impacts (*high confidence*). {24.4.2} Boreal trees will *likely* invade treeless arctic vegetation, while evergreen conifers will *likely* invade deciduous larch forest. Large changes may also occur in arid and semiarid areas, but uncertainties in precipitation projections make these more difficult to predict. The rates of vegetation change in the more densely populated parts of Asia may be reduced by the impact of habitat fragmentation on seed dispersal, while the impacts of projected climate changes on the vegetation of the lowland tropics are currently poorly understood. Changes in animal distributions have also been projected, in response to both direct impacts of climate change and indirect impacts through changes in the availability of suitable habitats.

Coastal and marine systems in Asia are under increasing stress from both climatic and non-climatic drivers (*high confidence*). {24.4.3} It is *likely* that mean sea level rise will contribute to upward trends in extreme coastal high water levels. {WGI AR5 3.7.6} In the Asian Arctic, rising sea levels are expected to interact with projected changes in permafrost and the length of the ice-free season to cause increased rates of coastal erosion (*medium evidence*, *high agreement*). Mangroves, salt marshes, and seagrass beds may decline unless they can move inland, while coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea levels. Widespread damage to coral reefs correlated with episodes of high sea surface temperature has been reported in recent decades and there is *high confidence* that damage to reefs will increase during the 21st century as a result of both warming and ocean acidification. Marine biodiversity is expected to increase at temperate latitudes as warmwater species expand their ranges northward (*high confidence*), but may decrease in the tropics if thermal tolerance limits are exceeded (*medium confidence*).

Multiple stresses caused by rapid urbanization, industrialization, and economic development will be compounded by climate change (*high confidence*). {24.4-7} Climate change is expected to adversely affect the sustainable development capabilities of most Asian developing countries by aggravating pressures on natural resources and the environment. Development of sustainable cities in Asia with fewer fossil fuel-driven vehicles and with more trees and greenery would have a number of co-benefits, including improved public health.

Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia (*high confidence*). {24.4.6} More frequent and intense heat waves in Asia will increase mortality and morbidity in vulnerable groups. Increases in heavy rain and temperature will increase the risk of diarrheal diseases, dengue fever, and malaria. Increases in floods and droughts will exacerbate rural poverty in parts of Asia as a result of negative impacts on the rice crop and resulting increases in food prices and the cost of living.

Studies of observed climate changes and their impacts are still inadequate for many areas, particularly in North, Central, and West Asia (*high confidence*). {24.8} Improved projections for precipitation, and thus water supply, are most urgently needed. Understanding of climate change impacts on ecosystems in Asia is currently limited by the incompleteness and inaccessibility of biodiversity information. Major research gaps in the tropics include the temperature dependence of carbon fixation by tropical trees and the thermal tolerances and acclimation capacities of both plants and animals. Interactions between climate change and the direct impacts of rising CO_2 on crops and natural ecosystems are also currently poorly understood. More research is needed on impacts, vulnerability, and adaptation in urban settlements, especially cities with populations of less than 500,000. More generally, there is a need to develop low-cost adaptation measures appropriate to the least developed parts of the region.

24.1. Introduction

Asia is defined here as the land and territories of 51 countries/regions (see Figure 24-1). It can be broadly divided into six subregions based on geographical position and coastal peripheries. These are, in alphabetical order, Central Asia (5 countries), East Asia (7 countries/regions), North Asia (2 countries), South Asia (8 countries), Southeast Asia (12 countries), and West Asia (17 countries). The population of Asia was reported to be about 4299 million in 2013, which is about 60% of the world population (UN DESA Population Division, 2013). Population density was reportedly about 134 per square kilometer in 2012 (PRB, 2012). The highest life expectancy at birth is 84 (Japan) and the lowest is 50 (Afghanistan) (CIA, 2013). The gross domestic product (GDP) per capita ranged from US$620 (Afghanistan for 2011) to US$51,709 (Singapore for 2012) (World Bank, 2013).

24.2. Major Conclusions from Previous Assessments

Major highlights from previous assessments for Asia include:

- Warming trends, including higher extremes, are strongest over the continental interiors of Asia, and warming in the period 1979 onward was strongest over China in winter, and northern and eastern Asia in spring and autumn (WGI AR4 Section 3.2.2.7; SREX Section 3.3.1).
- From 1900 to 2005, precipitation increased significantly in northern and central Asia but declined in parts of southern Asia (WGI AR4 SPM).
- Future climate change is *likely* to affect water resource scarcity with enhanced climate variability and more rapid melting of glaciers (WGII AR4 Section 10.4.2).
- Increased risk of extinction for many plant and animal species in Asia is *likely* as a result of the synergistic effects of climate change and habitat fragmentation (WGII AR4 Section 10.4.4).
- Projected sea level rise is *very likely* to result in significant losses of coastal ecosystems (WGII AR4 Sections 10.4.3.2, 10.6.1).
- There will be regional differences within Asia in the impacts of climate change on food production (WGII AR4 Section 10.4.1.1).
- Due to projected sea level rise, a million or so people along the coasts of South and Southeast Asia will likely be at risk from flooding (*high confidence*; WGII AR4 Section 10.4.3.1).
- It is *likely* that climate change will impinge on sustainable development of most developing countries of Asia as it compounds the pressures on natural resources and the environment associated with rapid urbanization, industrialization, and economic development (WGII AR4 Section 10.7).
- Vulnerabilities of industry, infrastructure, settlements, and society to climate change are generally greater in certain high-risk locations, particularly coastal and riverine areas (WGII AR4 Sections 7.3-5).

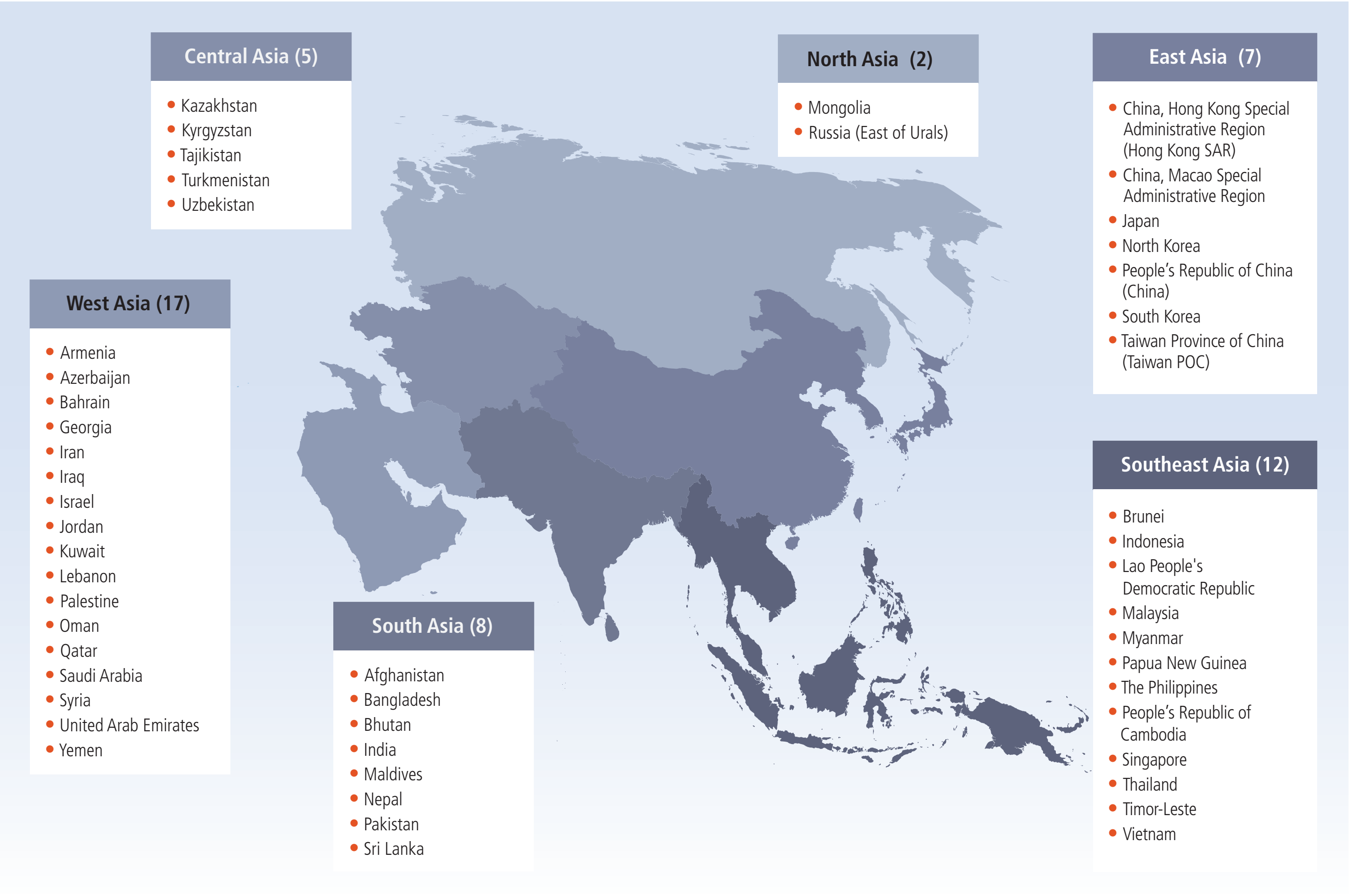


Figure 24-1 | The land and territories of 51 countries/regions in Asia. Maps contained in this report are only for the purpose of geographic information reference.

Box 24-1 | What's New on Asia in AR5?

- There is improved country coverage on observed and future impacts of climate change.
- There is an increase in the number of studies reflecting advances in research tools (e.g., more use of remote sensing and modeling of impacts), with an evaluation of detection and attribution where feasible.
- More conclusions have confidence statements, while confidence levels have changed in both directions since AR4.
- Expanded coverage of issues—for example, discussion of the Himalayas has been expanded to cover observed and projected impacts (Box 3-2), including those on tourism (see Section 10.6.2); livelihood assets such as water and food (Sections 9.3.3.1, 13.3.1.1, 18.5.3, 19.6.3); poverty (Section 13.3.2.3); culture (Section 12.3.2); flood risks (Sections 18.3.1.1, 24.2.1); health risks (Section 24.4.6.2); and ecosystems (Section 24.4.2.2).

24.3. Observed and Projected Climate Change

24.3.1. Observed Climate Change

24.3.1.1. Temperature

It is *very likely* that mean annual temperature has increased over the past century over most of the Asia region, but there are areas of the interior and at high latitudes where the monitoring coverage is insufficient for the assessment of trends (see WGI AR5 Chapter 2; Figure 24-2). New analyses continue to support the Fourth Assessment Report (AR4) and IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX) conclusions that it is *likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased across most of Asia since about 1950, and heat wave frequency has increased since the middle of the 20th century in large parts of Asia (see WGI AR5 Section 2.6.1).

As a part of the polar amplification, large warming trends (>2°C per 50 years) in the second half of the 20th century were observed in the northern Asian sector (see WGI AR5 Section 14.8.8). Over the period 1901–2009, the warming trend was particularly strong in the cold season between November and March, with an increase of 2.4°C in the mid-latitude semiarid area of Asia (see WGI AR5 Section 14.8.8). Increasing annual mean temperature trends at the country scale in East and South Asia have been observed during the 20th century (Table SM24-1). In West Asia, upward temperature trends are notable and robust in recent decades (WGI AR5 Section 14.8.10). Across Southeast Asia, temperature has been increasing at a rate of 0.14°C to 0.20°C per decade since the 1960s, coupled with a rising number of hot days and warm nights, and a decline in cooler weather (see WGI AR5 Section 14.8.12).

24.3.1.2. Precipitation and Monsoons

Most areas of the Asian region lack sufficient observational records to draw conclusions about trends in annual precipitation over the past century (see WGI AR5 Chapter 2; Figure 24-2; Table SM24-2). Precipitation trends, including extremes, are characterized by strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia (see WGI AR5 Chapter 14; Table SM24-2). In northern Asia, the observations indicate some increasing trends of heavy precipitation events, but in central Asia, no spatially coherent trends were found (see WGI AR5 Section 14.8.8). Both the East Asian summer and winter monsoon circulations have experienced an inter-decadal scale weakening after the 1970s, due to natural variability of the coupled climate system, leading to enhanced mean and extreme precipitation along the Yangtze River valley (30°N), but deficient mean precipitation in North China in summer (see WGI AR5 Section 14.8.9). A weakening of the East Asian summer monsoon since the 1920s was also found in sea level pressure gradients (*low confidence*; see WGI AR5 Section 2.7.4). In West Asia, a weak but non-significant downward trend in mean precipitation was observed in recent decades, although with an increase in intense weather events (see WGI AR5 Section 14.8.10). In South Asia, seasonal mean rainfall shows inter-decadal variability, noticeably a declining trend with more frequent deficit monsoons under regional inhomogeneities (see WGI AR5 Section 14.8.11). Over India, the increase in the number of monsoon break days and the decline in the number of monsoon depressions are consistent with the overall decrease in seasonal mean rainfall (see WGI AR5 Section 14.8.11). But an increase in extreme rainfall events occurred at the expense of weaker rainfall events over the central Indian region and in many other areas (see WGI AR5 Section 14.2.2.1). In South Asia, the frequency of heavy precipitation events is increasing, while light rain events are decreasing (see WGI AR5 Section 14.8.11). In Southeast Asia, annual total wet-day rainfall has increased by 22 mm per decade, while rainfall from extreme rain days has increased by 10 mm per decade, but climate variability and trends differ vastly across the region and between seasons (see WGI AR5 Sections 14.4.12, 14.8.12). In Southeast Asia, between 1955 and 2005 the ratio of rainfall in the wet to the dry seasons increased. While an increasing frequency of extreme events has been reported in the northern parts of Southeast Asia, decreasing trends in such events are reported in Myanmar (see WGI AR5 Section 14.4.12). In Peninsular Malaya during the southwest monsoon season, total rainfall and the frequency of wet days decreased, but rainfall intensity increased in much of the region. On the other hand, during the northeast monsoon, total rainfall, the frequency of extreme rainfall events, and rainfall intensity all increased over the peninsula (see WGI AR5 Section 14.4.12).

24.3.1.3. Tropical and Extratropical Cyclones

Significant trends in tropical cyclones making landfall are not found on shorter timescales. Time series of cyclone indices show weak upward trends in the western North Pacific since the late 1970s, but interpretation of longer term trends is constrained by data quality concerns (see WGI AR5 Section 2.6.3). A decrease in extratropical cyclone activity and intensity over the last 50 years has been reported for northern Eurasia (60°N to 40°N), including lower latitudes in East Asia (see WGI AR5 Section 2.6.4).

24.3.1.4. Surface Wind Speeds

Over land in China, including the Tibetan region, a weakening of the seasonal and annual mean winds, as well as the maximums, is reported from around the 1960s or 1970s to the early 2000s (*low confidence*; see WGI AR5 Section 2.7.2).

24.3.1.5. Oceans

A warming maximum is observed at 25°N to 65°N with signals extending to 700 m depth and is consistent with poleward displacement of the mean temperature field (WGI AR5 Section 3.2.2). The pH measurements between 1983 and 2008 in the western North Pacific showed a –0.0018 ± 0.0002 yr^{-1} decline in winter and –0.0013 ± 0.0005 yr^{-1} decline in summer (see WGI AR5 Section 3.8.2). Over the period 1993–2010, large rates of sea level rise in the western tropical Pacific were reported, corresponding to an increase in the strength of the trade winds in the central and eastern tropical Pacific (see WGI AR5 Section 13.6.1). Spatial variation in trends in Asian regional sea level may also be specific to a particular sea or ocean basin. For example, a rise of 5.4 ± 0.3 mm yr^{-1} in the Sea of Japan from 1993 to 2001 is nearly two times the global mean sea level (GMSL) trend, with more than 80% of this rise being thermosteric, and regional changes of sea level in the Indian Ocean that have emerged since the 1960s are driven by changing surface winds associated with a combined enhancement of Hadley and Walker cells (see WGI AR5 Section 13.6.1).

24.3.2. Projected Climate Change

The AR4 assessed that warming is *very likely* in the 21st century (Christensen et al., 2007), and that assessment still holds for all land areas of Asia in the mid- and late-21st century, based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations under all four Representative Concentration Pathway (RCP) scenarios (Figures 24-2, SM24-1; Table SM24-3). Ensemble-mean changes in mean annual temperature exceed 2°C above the late-20th-century baseline over most land areas in the mid-21st century under RCP8.5, and range from greater than 3°C over South and Southeast Asia to greater than 6°C over high latitudes in the late-21st century. The ensemble-mean changes are less than 2°C above the late-20th-century baseline in both the mid- and late-21st century under RCP2.6, with the exception of changes between 2°C and 3°C over the highest latitudes.

Projections of future annual precipitation change are qualitatively similar to those assessed in the AR4 (Christensen et al., 2007; see Figure 24-2). Precipitation increases are *very likely* at higher latitudes by the mid-21st century under the RCP8.5 scenario, and over eastern and southern areas by the late-21st century. Under the RCP2.6 scenario, increases are *likely* at high latitudes by the mid-21st century, while it is *likely* that changes at low latitudes will not substantially exceed natural variability.

24.3.2.1. Tropical and Extratropical Cyclones

The future influence of climate change on tropical cyclones is *likely* to vary by region, but there is *low confidence* in region-specific projections of frequency and intensity. However, better process understanding and model agreement in specific regions indicate that precipitation will *likely* be more extreme near the centers of tropical cyclones making landfall in West, East, South, and Southeast Asia (see WGI AR5 Sections 14.6, 14.8.9-12). There is *medium confidence* that a projected poleward shift in the North Pacific storm track of extratropical cyclones is *more likely than not*. There is *low confidence* in the magnitude of regional storm track changes and the impact of such changes on regional surface climate (see WGI AR5 Section 14.6).

24.3.2.2. Monsoons

Future increases in precipitation extremes related to the monsoon are *very likely* in East, South, and Southeast Asia (see WGI AR5 Sections 14.2.1, 14.8.9, 14.8.11-12). More than 85% of CMIP5 models show an increase in mean precipitation in the East Asian summer monsoons, while more than 95% of models project an increase in heavy precipitation events (see WGI AR5 Section 14.2.2, Figure 14.4). All models and all scenarios project an increase in both the mean and extreme precipitation in the Indian summer monsoon (see WGI AR5 Section 14.2.2 and Southern Asia (SAS) in Figure 14.4). In these two regions, the interannual standard deviation of seasonal mean precipitation also increases (see WGI AR5 Section 14.2.2).

24.3.2.3. Oceans

The ocean in subtropical and tropical regions will warm in all RCP scenarios and will show the strongest warming signal at the surface (WGI AR5 Section 12.4.7, Figure 12.12). Negligible change or a decrease in mean significant wave heights are projected for the trade and monsoon wind regions of the Indian Ocean (see WGI AR5 Section 13.7.3).

24.4. Observed and Projected Impacts, Vulnerabilities, and Adaptation

Key observed and projected climate change impacts are summarized in Tables 24-1, SM24-4, and SM24-5 (based on Sections 24.4.1-6).

24.4.1. Freshwater Resources

24.4.1.1. Sub-regional Diversity

Freshwater resources are very important in Asia because of the massive population and heavy economic dependence on agriculture, but water

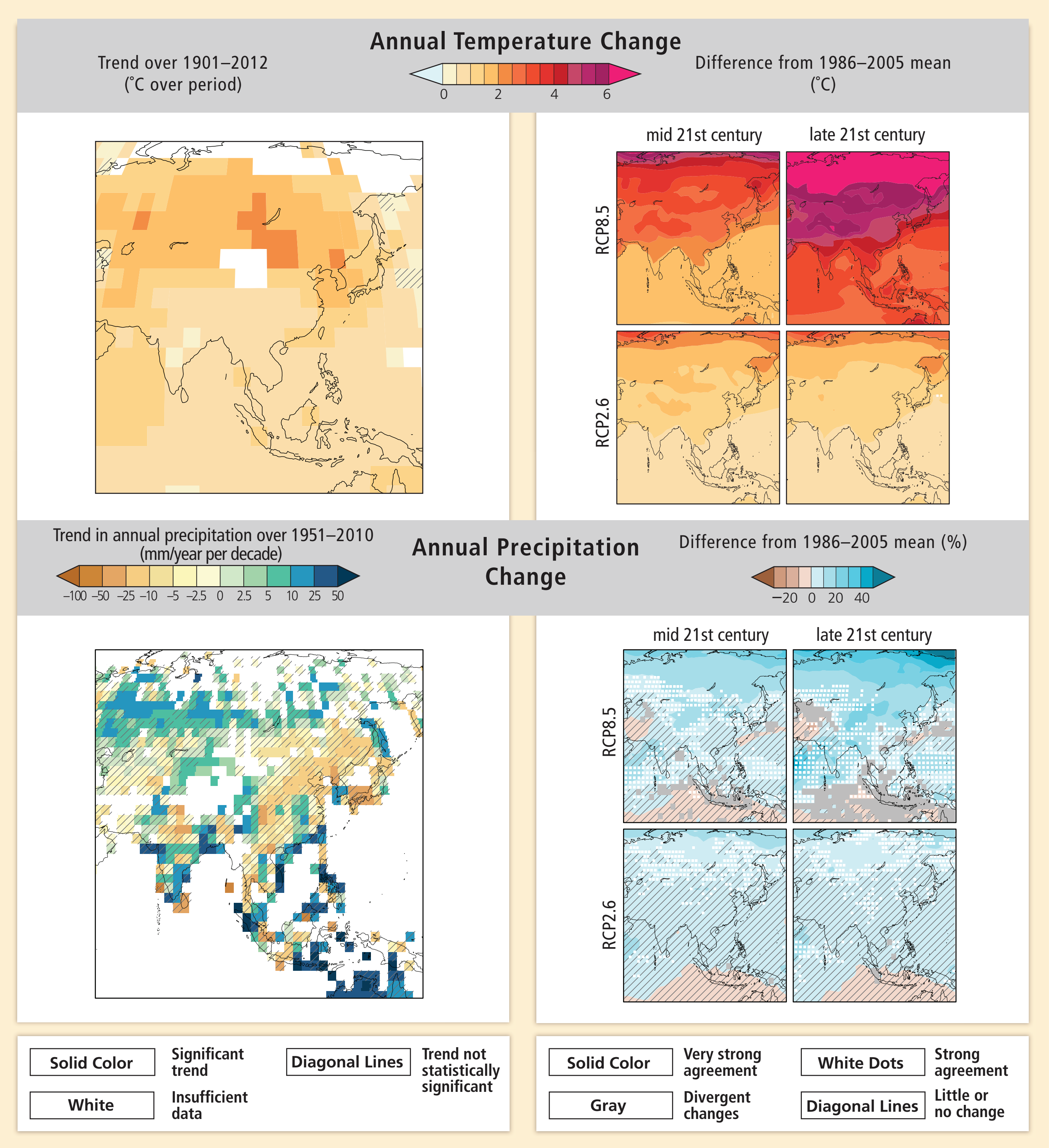
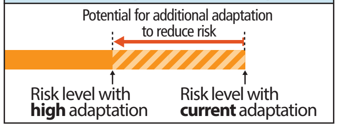


Figure 24-2 | Observed and projected changes in annual average temperature and precipitation in Asia. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5 Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

Table 24-1 | Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Asia. Key risks are identified based on assessment of the literature and expert judgments, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Climate-related drivers of impacts						
🌡	🌡!	🌧	☀	🌀	🌊	🌊
Warming trend	Extreme temperature	Extreme precipitation	Drying trend	Damaging cyclone	Sea level	Ocean acidification

Level of risk & potential for adaptation



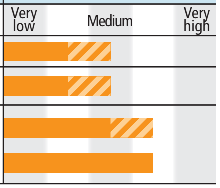
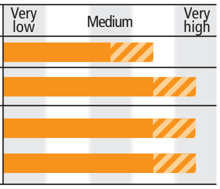
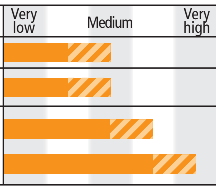
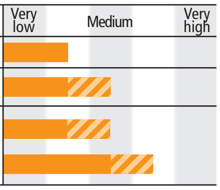
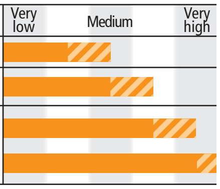
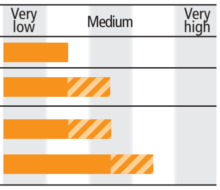
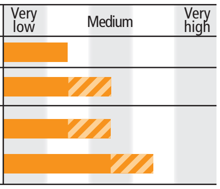
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased risk of crop failure and lower crop production could lead to food insecurity in Asia (*medium confidence*) [24.4.4]	Autonomous adaptation of farmers on-going in many parts of Asia.	🌡 ☀ 🌧 🌡! 🌀 🌊	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Water shortage in arid areas of Asia (*medium confidence*) [24.4.1.3, 24.4.1.4]	Limited capacity for water resource adaptation; options include developing water saving technology, changing drought-resilient crops, building more water reservoirs.	🌡 ☀	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased riverine, coastal, and urban flooding leading to widespread damage to infrastructure, livelihoods, and settlements in Asia (*medium confidence*) [24.4]	• Exposure reduction via structural and non-structural measures, effective land-use planning, and selective relocation • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Construction of monitoring and early warning systems; Measures to identify exposed areas, assist vulnerable areas and households, and diversify livelihoods • Economic diversification	🌧 🌀 🌊	Present Near term (2030–2040) Long-term (2080–2100) 2°C 4°C	
Increased risk of flood-related deaths, injuries, infectious diseases and mental disorders (*medium confidence*) [24.4.6.2, 24.4.6.3, 24.4.6.5]	Disaster preparedness including early-warning systems and local coping strategies.	🌧 🌀	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased risk of heat-related mortality (*high confidence*) [24.4]	• Heat health warning systems • Urban planning to reduce heat islands; Improvement of the built environment; Development of sustainable cities • New work practices to avoid heat stress among outdoor workers	🌡 🌡!	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*) [24.4]	• Disaster preparedness including early-warning systems and local coping strategies • Adaptive/integrated water resource management • Water infrastructure and reservoir development • Diversification of water sources including water re-use • More efficient use of water (e.g., improved agricultural practices, irrigation management, and resilient agriculture)	🌡 ☀ 🌡!	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Increased risk of water and vector-borne diseases (*medium confidence*) [24.4.6.2, 24.4.6.3, 24.4.6.5]	Early-warning systems, vector control programs, water management and sanitation programs.	🌡 ☀ 🌡! 🌧	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

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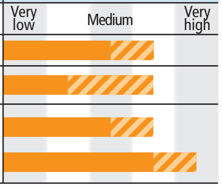
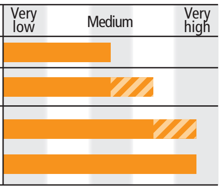
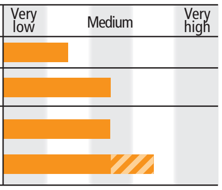
Table 24-1 (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Exacerbated poverty, inequalities and new vulnerabilities (*high confidence*) [24.4.5, 24.4.6]	Insufficient emphasis and limited understanding on urban poverty, interaction between livelihoods, poverty and climate change.	🌡 ☀ 🌡 🌧	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Coral reef decline in Asia (*high confidence*) [24.4.3.3, 24.4.3.5, CC-CR, CC-OA]	The limited adaptation options include minimizing additional stresses in marine protected areas sited where sea surface temperatures are expected to change least and reef resilience is expected to be highest.	🌡 🌊	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Mountain-top extinctions in Asia (*high confidence*) [24.4.2.4, 24.4.2.5]	Adaptation options are limited. Reducing non-climate impacts and maximizing habitat connectivity will reduce risks to some extent, while assisted migration may be practical for some species.	🌡 ☀	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

availability is highly uneven and requires assessment on the sub-regional scale because of Asia's huge range of climates (Pfister et al., 2009).

Adequate water supply is one of the major challenges in many regions (Vörösmarty et al., 2010), particularly Central Asia. Growing demand for water is driven by soaring populations, increasing per capita domestic use due to urbanization and thriving economic growth, and increasing use of irrigation.

24.4.1.2. Observed Impacts

The impact of changes in climate, particularly precipitation, on water resources varies cross Asia (Table SM24-4). There is *medium confidence* that water scarcity in northern China has been exacerbated by decreasing precipitation, doubling population, and expanding water withdrawal (Xu et al., 2010). There is no evidence that suggests significant changes of groundwater in the Kherlen River Basin in Mongolia over the past half century (Brutsaert and Sugita, 2008). Apart from water availability, there is *medium confidence* that climate change also leads to degradation of water quality in most regions of Asia (Delpla et al., 2009; Park et al., 2010), although this is also heavily influenced by human activities (Winkel et al., 2011).

Glaciers are important stores of water and any changes have the potential to influence downstream water supply in the long term (see Section 24.9.2). Glacier mass loss shows a heterogeneous pattern across Asia (Gardner et al., 2013).

Glaciers in the polar section of the Ural Mountains; in the Kodar Mountains of Southeast Siberia; in the Suntar Khayata and Chersky Ranges of Northeast Siberia; in Georgia and Azerbaijan on the southern flank of the Greater Caucasus Range; on the Tibetan Plateau (see Box 3-1) and the surrounding areas; and on Puncak Jaya, Papua, Indonesia lost 9 to 80% of their total area in different periods within the 1895–2010 time interval (Ananicheva et al., 2005, 2006; Anisimov et al., 2008; Prentice and Glidden, 2010; Allison, 2011; Shahgedanova et al., 2012; Yao, T. et al., 2012; Stokes et al., 2013) due to increased temperature (Casassa et al., 2009; Shrestha and Aryal, 2011). Changes in the Kamchatka glaciers are driven by both warming and volcanic activity, with the area of some glaciers decreasing, while others increased because they are covered by ash and clinker (Anisimov et al., 2008).

24.4.1.3. Projected Impacts

Projected impacts of climate change on future water availability in Asia differ substantially among river basins and seasons (A1B scenario with five General Circulation Models (GCMs): Immerzeel et al., 2010; A1B with Meteorological Research Institute of Japan Meteorological Agency (MRI)-Atmospheric General Circulation Models (AGCMs): Nakaegawa et al., 2013). There is *high confidence* that water demand in most Asian countries is increasing because of increases in population, irrigated agriculture (Lal, 2011), and industry.

24.4.1.3.1. Tropical Asia

Future projections (A1B with MRI-AGCMs) suggest a decrease in river runoff in January in the Chao Phraya River basin in Thailand (Champathong et al., 2013). In a study of the Mahanadi River Basin in India, a water availability projection (A2, Coupled General Circulation Model 2 (CGCM2)) indicated increasing possibility of floods in September but increasing water scarcity in April (Asokan and Dutta, 2008).

In the Ganges, an increase in river runoff could offset the large increases in water demand due to population growth in a +4°C world (ensemble

Frequently Asked Questions

FAQ 24.1 | What will the projected impact of future climate change be on freshwater resources in Asia?

Asia is a huge and diverse region, so both climate change and the impact on freshwater resources will vary greatly depending on location. But throughout the region, adequate water resources are particularly important because of the massive population and heavy dependence of the agricultural sector on precipitation, river runoff, and groundwater. Overall, there is *low confidence* in the projections of specifically how climate change will impact future precipitation on a sub-regional scale, and thus in projections of how climate change might impact the availability of water resources. However, water scarcity is expected to be a big challenge in many Asian regions because of increasing water demand from population growth and consumption per capita with higher standards of living. Shrinkage of glaciers in central Asia is expected to increase as a result of climate warming, which will influence downstream river runoff in these regions. Better water management strategies could help ease water scarcity. Examples include developing water saving technologies in irrigation, building reservoirs, increasing water productivity, changing cropping systems, and water reuse.

GCMs), due to a projected large increase in average rainfall, although high uncertainties remain at the seasonal scale (Fung et al., 2011).

24.4.1.3.2. Northern and temperate Asia

Projections (A2 and B2 with the Global Assessment of Security (GLASS) model) suggest an increase in average water availability in Russia in the 2070s (Alcamo et al., 2007). In China, a projection (downscaling Hadley Centre Atmospheric Model version 3H (HadAM3H) A2 and B2 scenarios with the Providing Regional Climates for Impacts Studies (PRECIS) regional model) suggests that there will be insufficient water for agriculture in the 2020s and 2040s due to the increases in water demand for non-agricultural uses, although precipitation may increase in some areas (Xiong et al., 2010). In the late-21st century (MRI-AGCMs, A1B), river discharge in northern Japan is projected to increase in February but decrease in May, due to increased winter precipitation and decreased spring snowmelt (Sato et al., 2013).

24.4.1.3.3. Central and West Asia

Given the already very high level of water stress in many parts of Central Asia, projected temperature increases and precipitation decreases (SRES scenarios from IPCC AR4, 23 models) in the western part of Kazakhstan, Uzbekistan, and Turkmenistan could exacerbate the problems of water shortage and distribution (Lioubimtseva and Henebry, 2009). Considering the dependence of Uzbekistan's economy on its irrigated agriculture, which consumes more than 90% of the available water resources of the Amu Darya basin, climate change impacts on river flows would also strongly affect the economy (Schlüter et al., 2010).

24.4.1.4. Vulnerabilities to Key Drivers

It is suggested that freshwater resources will be influenced by changes in rainfall variability, snowmelt, glacier retreat (Im et al., 2010; Li, Z. et al., 2010; Sato et al., 2012; Yamanaka et al., 2012; Nakaegawa et al., 2013), or evapotranspiration in the river catchment, which are associated with climate change (Jian et al., 2009). Mismanagement of water resources has increased tension because of water scarcity in arid areas (Biswas and Seetharam, 2008; Lioubimtseva and Henebry, 2009; Siegfried et al., 2010; Aarnoudse et al., 2012). Unsustainable consumption of groundwater for irrigation and other uses is considered to be the main cause of groundwater depletion in the Indian states of Rajasthan, Punjab, and Haryana (Rodell et al., 2009).

24.4.1.5. Adaptation Options

Adaptation of freshwater resources to climate change can be identified as developing adaptive/integrated water resource management (Sadoff and Muller, 2009; Schlüter et al., 2010) of the trade-offs balancing water availability against increasing demand, in order to cope with uncertainty and change (Molle and Hoanh, 2009).

Examples of the options include: developing water saving technologies in irrigation (Ngoundo et al., 2007); water infrastructure development in the Ganges river basin (Bharati et al., 2011); increasing water productivity in the Indus and Ganges river basins (Cai et al., 2010), Taiwan, China, and the Philippines (Barker and Levine, 2012), and Uzbekistan (Tischbein et al., 2011); changing cropping systems and patterns in West Asia (Thomas, 2008); and water reuse in China (Yi et al., 2011). During the second half of the 20th century, Asia built many reservoirs and almost tripled its surface water withdrawals for irrigation (Biemans et al., 2011). Reservoirs partly mitigate seasonal differences and increase water availability for irrigation (Biemans et al., 2011). Water management in river basins would benefit from integrated coordination among countries (Kranz et al., 2010). For example, water management in the Syr Darya river basin relates to Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan, and Kazakhstan (Siegfried et al., 2010), while the Indus and Ganges-Brahmaputra-Meghna river basins concern Bangladesh, India, Nepal, and Pakistan (Uprety and Salman, 2011).

24.4.2. Terrestrial and Inland Water Systems

24.4.2.1. Sub-regional Diversity

Boreal forests and grasslands dominate in North Asia, deserts and semi-deserts in Central and West Asia, and alpine ecosystems on the Tibetan Plateau. Human-dominated landscapes predominate in the other sub-regions, but the major natural ecosystems are temperate deciduous and subtropical evergreen forests in East Asia, with boreal forest in the northeast and grasslands and deserts in the west, while Southeast Asia was largely covered in tropical forests. South Asia also has tropical forests, with semi-desert in the northwest and alpine ecosystems in the north. Asia includes several of the world's largest river systems, as well as the world's deepest freshwater lake, Lake Baikal, the semi-saline Caspian Sea, and the saline Aral Sea.

24.4.2.2. Observed Impacts

Biological changes consistent with climate trends have been reported in the north and at high altitudes, where rising temperatures have relaxed constraints on plant growth and the distributions of organisms. Few changes have been reported from tropical lowlands and none linked to climate change with *high confidence*, although data are insufficient to distinguish lack of observations from lack of impacts. Impacts on inland water systems have been difficult to disentangle from natural variability and other human impacts (Bates et al., 2008; Vörösmarty et al., 2010; Zheng, 2011; see Section 4.3.3.3). For example, the shrinking of the Aral Sea over the last 50 years has resulted largely from excessive water extraction from rivers, but was probably exacerbated by decreasing precipitation and increasing temperature (Lioubimtseva and Henebry, 2009; Kostianoy and Kosarev, 2010).

24.4.2.2.1. Phenology and growth rates

In humid temperate East Asia, plant observations and satellite measurements of "greenness" (Normalized Difference Vegetation Index (NDVI); see Section 4.3.2.2) show a trend to earlier leafing in spring since the 1980s, averaging 2 days per decade, although details vary between sites, species, and periods (Table SM24-6; detected with *high confidence* and attributed to warming with *medium confidence*). Earlier spring flowering and delayed autumn senescence have also been recorded (Table SM24-6). Trends in semiarid temperate regions were heterogeneous in space and time (Liu et al., 2013a; Yu, Z. et al., 2013a,b). Earlier greening has been reported from boreal forests (Delbart et al., 2008) and from the Hindu-Kush-Himalayan region (Panday and Ghimire, 2012; Shrestha et al., 2012), but with spatial and temporal heterogeneity. Patterns were also heterogeneous in Central Asia (Kariyeva et al., 2012). On the Tibetan Plateau, spring growth advanced until the mid-1990s, but the trend subsequently differs between areas and NDVI data sets (Yu et al., 2010, 2012; Dong et al., 2013; Jin et al., 2013; Shen et al., 2013; Yu, Z. et al., 2013a; Zhang, G. et al., 2013; Zhang, L. et al., 2013).

Satellite NDVI for Asia for 1988–2010 shows a general greening trend (i.e., increasing NDVI, a rough proxy for increasing plant growth), except where water is limiting (Dorigo et al., 2012). Changes at high latitudes (>60°N) show considerable spatial and temporal variability, despite a consistent warming trend, reflecting water availability and non-climatic factors (Bi et al., 2013; Jeong et al., 2013). Arctic tundra generally showed increased greening since 1982, while boreal forests were variable (Goetz et al., 2011; de Jong et al., 2012; Epstein et al., 2012; Xu et al., 2013). An overall greening trend for 2000–2011 north of the boreal forest correlated with increasing summer warmth and ice retreat (Dutrieux et al., 2012). In China, trends have varied in space and time, reflecting positive impacts of warming and negative impacts of increasing drought stress (Peng et al., 2011; Sun et al., 2012; Xu et al., 2012). The steppe region of northern Kazakhstan showed an overall browning (decreasing NDVI) trend for 1982–2008, linked to declining precipitation (de Jong et al., 2012). In Central Asia, where NDVI is most sensitive to precipitation (Gessner et al., 2013), there was a heterogeneous pattern for 1982–2009, with an initial greening trend stalled or reversed in some areas (Mohammat et al., 2013).

Tree-ring data for 800–1989 for temperate East Asia suggests recent summer temperatures have exceeded those during past warm periods of similar length, although this difference was not statistically significant (Cook et al., 2012). Where temperature limits tree growth, growth rates have increased with warming in recent decades (Duan et al., 2010; Sano et al., 2010; Shishov and Vaganov, 2010; Borgaonkar et al., 2011; Xu et al., 2011; Chen et al., 2012a,b,c,d, 2013; Li et al., 2012), while where drought limits growth, there have been increases (Li et al., 2006; Davi et al., 2009; Shao et al., 2010; Yang et al., 2010) or decreases (Li et al., 2007; Dulamsuren et al., 2010a, 2011; Kang et al., 2012; Wu et al., 2012; Kharuk et al., 2013; Liu et al., 2013b), reflecting decreasing or increasing water stress (*high confidence* in detection, *medium confidence* in attribution to climate change). In boreal forest, trends varied between species and locations, despite consistent warming (Lloyd and Bunn, 2007; Goetz et al., 2011).

24.4.2.2.2. Distributions of species and biomes

Changes in species distributions consistent with a response to warming have been widely reported: upwards in elevation (Soja et al., 2007; Bickford et al., 2010; Kharuk et al., 2010a,b,e; Moiseev et al., 2010; Chen et al., 2011; Jump et al., 2012; Grigor'ev et al., 2013; Telwala et al., 2013) or polewards (Tougou et al., 2009; Ogawa-Onishi and Berry, 2013) (*high confidence* in detection, *medium confidence* in attribution to climate change). Changes in the distributions of major vegetation types (biomes) have been reported from the north and high altitudes, where trees are invading treeless vegetation, and forest understories are being invaded from adjacent biomes (Kharuk et al., 2006; Soja et al., 2007; Bai et al., 2011; Singh et al., 2012; Wang and Liu, 2012). In central Siberia, dark needle conifers (DNCs) and birch have invaded larch-dominated forest over the last 3 decades (Kharuk et al., 2010c,d; Osawa et al., 2010; Lloyd et al., 2011). Meanwhile, warming has driven larch stand crown closure and larch invasion into tundra at a rate of 3 to 10 m yr^{-1} in the northern forest-tundra ecotone (Kharuk et al., 2006). Shrub expansion in arctic tundra has also been observed (Blok et al., 2011; Myers-Smith et al., 2011; see Section 28.2.3.1). Soil moisture and light are the main factors governing the forest-steppe ecotone (Soja et al., 2007; Zeng et al., 2008; Eichler et al., 2011; Kukavskaya et al., 2013), and Mongolian taiga forests have responded heterogeneously to recent climate changes, but declines in larch growth and regeneration are more widespread than increases (Dulamsuren et al., 2010a,b).

24.4.2.2.3. Permafrost

Permafrost degradation, including reduced area and increased active layer thickness, has been reported from parts of Siberia, Central Asia, and the Tibetan Plateau (*high confidence*; Romanovsky et al., 2010; Wu and Zhang, 2010; Zhao et al., 2010; Yang et al., 2013). Most permafrost observatories in Asian Russia show substantial warming of permafrost during the last 20 to 30 years (Romanovsky et al., 2008, 2010). Permafrost formed during the Little Ice Age is thawing at many locations and Late Holocene permafrost has begun to thaw at some undisturbed locations in northwest Siberia. Permafrost thawing is most noticeable within the discontinuous permafrost zone, while continuous permafrost is starting to thaw in a few places, so the boundary between continuous and discontinuous permafrost is moving northward (Romanovsky et al., 2008, 2010).

Thawing permafrost may lead to increasing emissions of greenhouse gases from decomposition of accumulated organic matter (see Sections 4.3.3.4, 19.6.3.5). In Mongolia, mean annual permafrost temperature at 10 to 15 m depth increased over the past 10 to 40 years in the Hovsgol, Hangai, and Hentei Mountain regions. Permafrost warming during the past 15 to 20 years was greater than during the previous 15 to 20 years (Sharkhuu et al., 2008; Zhao et al., 2010). In the Kazakh part of the Tien Shan Mountains, permafrost temperature and active layer thickness have increased since the early 1970s. Significant permafrost warming also occurred in the eastern Tien Shan Mountains, in the headwaters of the Urumqi River (Marchenko et al., 2007; Zhao et al., 2010). Monitoring across the Qinghai-Tibet Plateau over recent decades has also revealed permafrost degradation caused by warming and other impacts. Areas of permafrost are shrinking, the active layer depth is increasing, the lower altitudinal limit is rising, and the seasonal frost depth is thinning (Li et al., 2008; Wu and Zhang, 2010; Zhao et al., 2010). In the alpine headwater regions of the Yangtze and Yellow Rivers, rising temperatures and permafrost degradation have resulted in lower lake levels, drying swamps, and shrinking grasslands (Cheng and Wu, 2007; Wang et al., 2011).

24.4.2.3. Projected Impacts

24.4.2.3.1. Phenology and growth rates

Trends toward an earlier spring greening and longer growing season are expected to continue in humid temperate and boreal forest areas, although photoperiod or chilling requirements may reduce responses to warming in some species (Ge et al., 2013; Hadano et al., 2013; Richardson et al., 2013). Changes in precipitation will be important for semiarid and arid ecosystems, as may the direct impacts of atmospheric carbon dioxide (CO_2) concentrations, making responses harder to predict (Liancourt et al., 2012; Poulter et al., 2013). The "general flowering" at multi-year intervals in lowland rainforests in Southeast Asia is triggered by irregular droughts (Sakai et al., 2006), so changes in drought frequency or intensity could have large impacts.

24.4.2.3.2. Distributions of species and biomes

Climate change is expected to modify the vegetation distribution across the region (Tao and Zhang, 2010; Wang, 2013), but responses will be slowed by limitations on seed dispersal, competition from established plants, rates of soil development, and habitat fragmentation (*high confidence*; Corlett and Westcott, 2013). Rising CO_2 concentrations are expected to favor increased woody vegetation in semiarid areas (*medium confidence*; Higgins and Scheiter, 2012; Donohue et al., 2013; Poulter et al., 2013; Wang, 2013). In North Asia, rising temperatures are expected to lead to large changes in the distribution of potential natural ecosystems (*high confidence*; Ni, 2011; Tchebakova et al., 2011; Insarov et al., 2012; Pearson et al., 2013). It is *likely* that the boreal forest will expand northward and eastward, and that tundra will decrease, although differences in models, time periods, and other assumptions have resulted in widely varying projections for the magnitude of this change (Woodward and Lomas, 2004; Kaplan and New, 2006; Lucht et al., 2006; Golubyatnikov and Denisenko, 2007; Sitch et al., 2008; Korzukhin and Tcelniker, 2010; Tchebakova et al., 2010, 2011; Pearson et al., 2013). Boreal forest expansion and the continued invasion of the existing larch-dominated forest by DNCs could lead to larch reaching the Arctic shore, while the traditional area of larch dominance turns into mixed forest (Kharuk et al., 2006, 2010c). Both the replacement of summer-green larch with evergreen conifers and expansion of trees and shrubs into tundra decrease albedo, causing regional warming and potentially accelerating vegetation change (Kharuk et al., 2006, 2010d; McGuire et al., 2007; Pearson et al., 2013). The future direction and rate of change of steppe vegetation are unclear because of uncertain precipitation trends (Golubyatnikov and Denisenko, 2007; Tchebakova et al., 2010). The role of CO_2 fertilization is also potentially important here (Poulter et al., 2013; see WGI AR5 Box 6.3).

In East Asia, subtropical evergreen forests are projected to expand north into the deciduous forest and tropical forests to expand along China's southern coast (Choi et al., 2011; Wang, 2013), but vegetation change may lag climate change by decades or centuries (Corlett and Westcott, 2013). On the Tibetan Plateau, projections suggest that alpine vegetation will be largely replaced by forest and shrubland, with tundra and steppe retreating to the north (Liang et al., 2012; Wang, 2013). Impacts in Central and West Asia will depend on changes in precipitation. In India, a dynamic vegetation model (A2 and B2 scenarios) projected changes in more than a third of the forest area by 2100, mostly from deciduous to evergreen forest in response to increasing rainfall, although fragmentation and other human pressures are expected to slow these changes (Chaturvedi et al., 2011). By 2100, large areas of tropical and subtropical lowland Asia are projected to experience combinations of temperature and rainfall outside the current global range, under a variety of model projections and emission scenarios (Williams et al., 2007; Beaumont et al., 2010; García-López and Allué, 2013), but the potential impacts of these novel conditions on biodiversity are largely unknown (Corlett, 2011).

In Southeast Asia, projected climate (A2 and B1 scenarios) and vegetation changes are expected to produce widespread declines in bat species richness, northward range shifts for many species, and large reductions in the distributions of most species (Hughes et al., 2012). Projections for various bird species in Asia under a range of scenarios also suggest major impacts on distributions (Menon et al., 2009; Li, R. et al., 2010; Ko et al., 2012). Projections for butterflies in Thailand (A2 and B2 scenarios) suggest that species richness within protected areas will decline approximately 30% by 2070–2099 (Klorvuttimontara et al., 2011). Projections for dominant bamboos in the Qinling Mountains (A2 and B2 scenarios) suggest substantial range reductions by 2100, with potentially adverse consequences for the giant pandas that eat them (Tuanmu et al., 2012). Projections for snow leopard habitat in the Himalayas (B1, A1B, and A2 scenarios) suggest contraction by up to 30% as forests replace open habitats (Forrest et al., 2012).

24.4.2.3.3. Permafrost

In the Northern Hemisphere, a 20 to 90% decrease in permafrost area and a 50 to 300 cm increase in active layer thickness driven by surface warming is projected for 2100 by different models and scenarios (Schaefer et al., 2011). It is *likely* that permafrost degradation in North Asia will spread from the southern and low-altitude margins, advancing northward and upward, but rates of change vary greatly between model projections (Cheng and Wu, 2007; Riseborough et al., 2008; Romanovsky et al., 2008; Anisimov, 2009; Eliseev et al., 2009; Nadyozhina et al., 2010; Schaefer et al., 2011; Wei et al., 2011). Substantial retreat is also expected on the Qinghai-Tibet Plateau (Cheng and Wu, 2007). Near-surface permafrost is expected to remain only in Central and Eastern Siberia and parts of the Qinghai-Tibet Plateau in the late-21st century.

24.4.2.3.4. Inland waters

Climate change impacts on inland waters will interact with dam construction, pollution, and land use changes (Vörösmarty et al., 2010; see also Sections 3.3.2, 24.9.1). Increases in water temperature will impact species- and temperature-dependent processes (Hamilton, 2010; Dudgeon, 2011, 2012). Coldwater fish will be threatened as rising water temperatures make much of their current habitat unsuitable (Yu, D. et al., 2013). Climate change is also expected to change flow regimes in running waters and consequently impact habitats and species that are sensitive to droughts and floods (see Box CC-RF). Habitats that depend on seasonal inundation, including floodplain grasslands and freshwater swamp forests, will be particularly vulnerable (Maxwell, 2009; Bezuijen, 2011; Arias et al., 2012). Reduced dry season flows are expected to combine with sea level rise to increase saltwater intrusion in deltas (Hamilton, 2010; Dudgeon, 2012), although non-climatic impacts will continue to dominate in most estuaries (Syvitski et al., 2009). For most Asian lakes, it is difficult to disentangle the impacts of water pollution, hydro-engineering, and climate change (Battarbee et al., 2012).

24.4.2.4. Vulnerabilities to Key Drivers

Permafrost melting in response to warming is expected to impact ecosystems across large areas (*high confidence*; Cheng and Wu, 2007; Tchebakova et al., 2011). The biodiversity of isolated mountains may also be particularly vulnerable to warming, because many species already have small geographical ranges that will shrink further (La Sorte and Jetz, 2010; Liu et al., 2010; Chou et al., 2011; Noroozi et al., 2011; Peh et al., 2011; Jump et al., 2012; Tanaka, N. et al., 2012; Davydov et al., 2013). Many freshwater habitats are similarly isolated and their restricted-range species may be equally vulnerable (Dudgeon, 2012). In flatter topography, higher velocities of climate change (the speeds that species need to move to maintain constant climate conditions) increase the vulnerabilities of species that are unable to keep pace, as a result of limited dispersal ability, habitat fragmentation, or other non-climatic constraints (Corlett and Westcott, 2013). In the tropics, temperature extremes above the present range are a potential threat to organisms and ecosystems (Corlett, 2011; Jevanandam et al., 2013; Mumby et al., 2013). For much of interior Asia, increases in drought stress, as a result of declining rainfall and/or rising temperatures, are the key concern. Because aridity is projected to increase in the northern Mongolian forest belt during the 21st century (Sato et al., 2007), larch cover will likely be reduced (Dulamsuren et al., 2010a). In the boreal forest region, a longer, warmer growing season will increase vulnerability to fires, although other human influences may overshadow climate impacts in accessible areas (Flannigan et al., 2009; Liu et al., 2012; Li et al., 2013; see Section 4.3.3.1.1). If droughts intensify in lowland Southeast Asia, the synergies between warmth, drought, logging, fragmentation, and fire (Daniau et al., 2012) and tree mortality (Kumagai and Porporato, 2012; Tan et al., 2013), possibly acerbated by feedbacks between deforestation, smoke aerosols, and reduced rainfall (Aragão, 2012; Tosca et al., 2012), could greatly increase the vulnerability of fragmented forest landscapes (*high confidence*).

24.4.2.5. Adaptation Options

Suggested strategies for maximizing the adaptive capacity of ecosystems include reducing non-climate impacts, maximizing landscape connectivity, and protecting "refugia" where climate change is expected to be less than the regional mean (Hannah, 2010; Game et al., 2011; Klorvuttimontara et al., 2011; Murthy et al., 2011; Ren et al., 2011; Shoo et al., 2011; Mandych et al., 2012). Additional options for inland waters include operating dams to maintain environmental flows for biodiversity, protecting catchments, and preserving river floodplains (Vörösmarty et al., 2010). Habitat restoration may facilitate species movements across climatic gradients (Klorvuttimontara et al., 2011; Hughes et al., 2012) and long-distance seed dispersal agents may need protection (McConkey et al., 2012). Assisted migration of genotypes and species is possible where movements are constrained by poor dispersal, but risks and benefits need to be considered carefully (Liu et al., 2010; Olden et al., 2010; Tchebakova et al., 2011; Dudgeon, 2012; Ishizuka and Goto, 2012; Corlett and Westcott, 2013). *Ex situ* conservation can provide backup for populations and species most at risk from climate change (Chen et al., 2009).

24.4.3. Coastal Systems and Low-Lying Areas

24.4.3.1. Sub-regional Diversity

Asia's coastline includes the global range of shore types. Tropical and subtropical coasts support approximately 45% of the world's mangrove forest (Giri et al., 2011) and low-lying areas in equatorial Southeast Asia support most of the world's peat swamp forests, as well as other forested swamp types. Intertidal salt marshes are widespread along temperate and arctic coasts, while a variety of non-forested wetlands occur inland. Asia supports approximately 40% of the world's coral reef area, mostly in Southeast Asia, with the world's most diverse reef communities in the "coral triangle" (Spalding et al., 2001; Burke et al., 2011). Seagrass beds are widespread and support most of the world's seagrass species (Green and Short, 2003). Six of the seven species of sea turtle are found in the region and five nest on Asian beaches (Spotila, 2004). Kelp forests and other seaweed beds are important on temperate coasts (Bolton, 2010; Nagai et al., 2011). Arctic sea ice supports a specialized community of mammals and other organisms (see Sections 28.2.3.3-4.).

24.4.3.2. Observed Impacts

Most of Asia's non-Arctic coastal ecosystems are under such severe pressure from non-climate impacts that climate impacts are hard to detect (see Section 5.4.2). Most large deltas in Asia are sinking (as a result of groundwater withdrawal, floodplain engineering, and trapping of sediments by dams) much faster than global sea level is rising (Syvitski et al., 2009). Widespread impacts can be attributed to climate change only for coral reefs, where the temporal and spatial patterns of bleaching correlate with higher than normal sea surface temperatures (*very high confidence*; Section 5.4.2.4; Box CC-CR). Increased water temperatures may also explain declines in large seaweed beds in temperate Japan (Nagai et al., 2011; Section 5.4.2.3). Warming coastal waters have also been implicated in the northward expansion of tropical and subtropical macroalgae and toxic phytoplankton (Nagai et al., 2011), fish (Tian et al., 2012), and tropical corals, including key reef-forming species (Yamano et al., 2011), over recent decades. The decline of large temperate seaweeds and expansion of tropical species in southwest Japan has been linked to rising sea surface temperatures (Tanaka, K. et al., 2012), and these changes have impacted fish communities (Terazono et al., 2012).

In Arctic Asia, changes in permafrost and the effects of sea level rise and sea ice retreat on storm-wave energy have increased erosion (Are et al., 2008; Razumov, 2010; Handmer et al., 2012). Average erosion rates range from 0.27 m yr^{-1} (Chukchi Sea) to 0.87 m yr^{-1} (East Siberian Sea), with a number of segments in the Laptev and East Siberian Sea experiencing rates greater than 3 m yr^{-1} (Lantuit et al., 2012).

24.4.3.3. Projected Impacts

Marine biodiversity at temperate latitudes is expected to increase as temperature constraints on warmwater taxa are relaxed (*high confidence*; see Section 6.4.1.1), but biodiversity in tropical regions may fall if, as evidence suggests, tropical species are already near their thermal maxima (*medium confidence;* Cheung et al., 2009, 2010; Nguyen et al., 2011). Individual fish species are projected to shift their ranges northward in response to rising sea surface temperatures (Tseng et al., 2011; Okunishi et al., 2012; Tian et al., 2012). The combined effects of changes in distribution, abundance, and physiology may reduce the body size of marine fishes, particularly in the tropics and intermediate latitudes (Cheung et al., 2013).

Continuation of current trends in sea surface temperatures and ocean acidification would result in large declines in coral-dominated reefs by mid-century (*high confidence*; Burke et al., 2011; Hoegh-Guldberg, 2011; see Section 5.4.2.4; Box CC-CR). Warming would permit the expansion of coral habitats to the north but acidification is expected to limit this (Yara et al., 2012). Acidification is also expected to have negative impacts on other calcified marine organisms (algae, molluscs, larval echinoderms), while impacts on non-calcified species are unclear (Branch et al., 2013; Kroeker et al., 2013; see Box CC-OA). On rocky shores, warming and acidification are expected to lead to range shifts and changes in biodiversity (see Section 5.4.2.2).

Future rates of sea level rise are expected to exceed those of recent decades (see WGI AR5 Section 13.5.1), increasing coastal flooding, erosion, and saltwater intrusion into surface and groundwaters. In the absence of other impacts, coral reefs may grow fast enough to keep up with rising sea levels (Brown et al., 2011; Villanoy et al., 2012; see Section 5.4.2.4), but beaches may erode and mangroves, salt marshes, and seagrass beds will decline, unless they receive sufficient fresh sediment to keep pace or they can move inland (Gilman et al., 2008; Bezuijen, 2011; Kintisch, 2013; see Section 5.3.2.3). Loucks et al. (2010) predict a 96% decline in tiger habitat in Bangladesh's Sunderbans mangroves with a 28 cm sea level rise if sedimentation does not increase surface elevations. Rising winter temperatures are expected to result in poleward expansion of mangrove ecosystems (see Section 5.4.2.3). Coastal freshwater wetlands may be vulnerable to saltwater intrusion with rising sea levels, but in most river deltas local subsidence for non-climatic reasons will be more important (Syvitski et al., 2009). Current trends in cyclone frequency and intensity are unclear (Section 24.3.2; Box CC-TC), but a combination of cyclone intensification and sea level rise could increase coastal flooding (Knutson et al., 2010) and losses of coral reefs and mangrove forests would exacerbate wave damage (Gedan et al., 2011; Villanoy et al., 2012).

In the Asian Arctic, rates of coastal erosion are expected to increase as a result of interactions between rising sea levels and changes in permafrost and the length of the ice-free season (*medium evidence*; *high agreement*; Pavlidis et al., 2007; Lantuit et al., 2012). The largest changes are expected for coasts composed of loose permafrost rocks and therefore subject to intensive thermal abrasion. If sea level rises by 0.5 m over this century, modeling studies predict that the rate of recession will increase 1.5- to 2.6-fold for the coasts of the Laptev Sea, East Siberian Sea, and West Yamal in the Kara Sea, compared to the rate observed in the first years of the 21st century.

24.4.3.4. Vulnerabilities to Key Drivers

Offshore marine systems are most vulnerable to rising water temperatures and ocean acidification, particularly for calcifying organisms such as corals. Sea level rise will be the key issue for many coastal areas, particularly if combined with changes in cyclone frequency or intensity, or, in Arctic Asia, with a lengthening open-water season. The expected continuing decline in the extent of sea ice in the Arctic may threaten the survival of some ice-associated organisms (see Section 28.2.2.1), with expanded human activities in previously inaccessible areas an additional concern (Post et al., 2013).

24.4.3.5. Adaptation Options

The connectivity of marine habitats and dispersal abilities of marine organisms increase the capacity for autonomous (spontaneous) adaptation in coastal systems (Cheung et al., 2009). Creating marine protected areas where sea surface temperatures are projected to change least may increase their future resilience (Levy and Ban, 2013). For coral reefs, potential indicators of future resilience include later projected onset of annual bleaching conditions (van Hooidonk et al., 2013), past temperature variability, the abundance of heat-tolerant coral species, coral recruitment rates, connectivity, and macroalgae abundance (McClanahan et al., 2012). Similar strategies may help identify reefs that are more resilient to acidification (McLeod et al., 2013). Hard coastal defenses, such as sea walls, protect settlements at the cost of preventing adjustments by mangroves, salt marshes, and seagrass beds to rising sea levels. Landward buffer zones that provide an opportunity for future inland migration could mitigate this problem (Tobey et al., 2010). More generally, maintaining or restoring natural shorelines where possible is expected to provide coastal protection and other benefits (Tobey et al., 2010; Crooks et al., 2011). Projected increases in the navigability of the Arctic Ocean because of declining sea ice suggest the need for a revision of environmental regulations to minimize the risk of marine pollution (Smith and Stephenson, 2013).

24.4.4. Food Production Systems and Food Security

It is projected that climate change will affect food security by the middle of the 21st century, with the largest numbers of food-insecure people located in South Asia (see Chapter 7).

24.4.4.1. Sub-regional Diversity

WGII AR4 Section 10.4.1.1 pointed out that there will be regional differences within Asia in the impacts of climate change on food production. Research since then has validated this divergence and new data are available especially for West and Central Asia (see Tables SM24-4, SM24-5). In WGII AR4 Section 10.4.1, climate change was projected to lead mainly to reductions in crop yield. New research shows there will also be gains for specific regions and crops in given areas. Thus, the current assessment encompasses an enormous variability, depending on the regions and the crops grown.

24.4.4.2. Observed Impacts

There are very limited data globally for observed impacts of climate change on food production systems (see Chapter 7) and this is true also for Asia. In Jordan, it was reported that the total production and average yield for wheat and barley were lowest in 1999 for the period 1996–2006 (Al-Bakri et al., 2010), which could be explained by the low rainfall during that year, which was 30% of the average (*high confidence* in detection, *low confidence* in attribution). In China, rice yield responses to recent climate change at experimental stations were assessed for the period 1981–2005 (Zhang et al., 2010). In some places, yields were positively correlated with temperature when they were also positively related with solar radiation. However, in other places, lower yield with higher temperature was accompanied by a positive correlation between yield and rainfall (*high confidence* in detection, *high confidence* in attribution). In Japan, where mean air temperature rose by about 1°C over the 20th century, effects of recent warming include phenological changes in many crops, increases in fruit coloring disorders and incidences of chalky rice kernels, reductions in yields of wheat, barley, vegetables, flowers, milk, and eggs, and alterations in the type of disease and pest (*high confidence* in detection, *high confidence* in attribution; Sugiura et al., 2012).

24.4.4.3. Projected Impacts

24.4.4.3.1. Production

WGII AR4 Section 10.4.1.1 mainly dealt with cereal crops (rice, wheat, corn). Since then, impacts of climate change have been modeled for additional cereal crops and sub-regions. It is *very likely* that climate change effects on crop production in Asia will be variable, negative for specific regions and crops in given areas and positive for other regions and crops (*medium evidence*, *high agreement*). It is also *likely* that an elevated CO_2 concentration in the atmosphere will be beneficial to most crops (*medium evidence*, *high agreement*).

In semiarid areas, rainfed agriculture is sensitive to climate change both positively and negatively (Ratnakumar et al., 2011). In the mountainous Swat and Chitral districts of Pakistan (average altitudes 960 and 1500 m above sea level, respectively), there were mixed results as well (Hussain and Mudasser, 2007). Projected temperature increases of 1.5°C and 3°C would lead to wheat yield declines (by 7% and 24%, respectively) in Swat district but to increases (by 14% and 23%) in Chitral district. In India, climate change impacts on sorghum were analyzed using the InfoCrop-SORGHUM simulation model (Srivastava et al., 2010). A changing climate was projected to reduce monsoon sorghum grain yield by 2 to 14% by 2020, with worsening yields by 2050 and 2080. In the Indo-Gangetic Plains, a large reduction in wheat yields is projected (see Section 24.4.4.3.2), unless appropriate cultivars and crop management practices are adopted (Ortiz et al., 2008). A systematic review and meta-analysis of data in 52 original publications projected mean changes in yield by the 2050s across South Asia of 16% for maize and 11% for sorghum (Knox et al., 2012). No mean change in yield was projected for rice.

In China, modeling studies of the impacts of climate change on crop productivity have had mixed results. Rice is the most important staple food in Asia. Studies show that climate change will alter productivity in China but not always negatively. For example, an ensemble-based probabilistic projection shows rice yield in eastern China would change on average by 7.5 to 17.5% (–10.4 to 3.0%), 0.0 to 25.0% (–26.7 to 2.1%), and –10.0 to 25.0% (–39.2 to –6.4%) during the 2020s, 2050s, and 2080s, respectively, in response to climate change, with (without) consideration of CO_2 fertilization effects, using all 10 combinations of two emission scenarios (A1FI and B1) and five GCMs (Hadley Centre climate prediction model 3 (HadCM3), Parallel Climate Model (PCM), CGCM2, Commonwealth Scientific and Industrial Research Organisation 2 (CSIRO2), and European Centre for Medium Range Weather Forecasts

Frequently Asked Questions

FAQ 24.2 | How will climate change affect food production and food security in Asia?

Climate change impacts on temperature and precipitation will affect food production and food security in various ways in specific areas throughout this diverse region. Climate change will have a generally negative impact on crop production Asia, but with diverse possible outcomes (*medium confidence*). For example most simulation models show that higher temperatures will lead to lower rice yields as a result of a shorter growing period. But some studies indicate that increased atmospheric CO_2 that leads to those higher temperatures could enhance photosynthesis and increase rice yields. This uncertainty on the overall effects of climate change and CO_2 fertilization is generally true for other important food crops such as wheat, sorghum, barley, and maize, among others.

Yields of some crops will increase in some areas (e.g., cereal production in north and east Kazakhstan) and decrease in others (e.g., wheat in the Indo-Gangetic Plain of South Asia). In Russia, climate change may lead to a food production shortfall, defined as an event in which the annual potential production of the most important crops falls 50% or more below its normal average. Sea level rise is projected to decrease total arable areas and thus food supply in many parts of Asia. A diverse mix of potential adaptation strategies, such as crop breeding, changing crop varieties, adjusting planting time, water management, diversification of crops, and a host of indigenous practices will all be applicable within local contexts.

and Hamburg 4 (ECHAM4)) relative to 1961–1990 levels (Tao and Zhang, 2013a). With rising temperatures, the process of rice development accelerates and reduces the duration for growth. Wassmann et al. (2009a,b) concluded that, in terms of risks of increasing heat stress, there are parts of Asia where current temperatures are already approaching critical levels during the susceptible stages of the rice plant. These include Pakistan/North India (October), South India (April/August), East India/Bangladesh (March-June), Myanmar/Thailand/Laos/Cambodia (March-June), Vietnam (April/August), Philippines (April/June), Indonesia (August), and China (July/August).

There have also been simulation studies for other crops in China. In the Huang-Hai Plain, China's most productive wheat growing region, modeling indicated that winter wheat yields would increase on average by 0.2 Mg ha^{-1} in 2015–2045 and by 0.8 Mg ha^{-1} in 2070–2099, due to warmer nighttime temperatures and higher precipitation, under A2 and B2 scenarios using the HadCM3 model (Thomson et al., 2006). In the North China Plain, an ensemble-based probabilistic projection projected that maize yield will change by –9.7 to –9.1%, –19.0 to –15.7%, and –25.5 to –24.7%, during 2020s, 2050s, and 2080s as a percentage of 1961–1990 yields (Tao et al., 2009). In contrast, winter wheat yields could increase with high probability in future due to climate change (Tao and Zhang, 2013b).

It should be noted that crop physiology simulation models may overstate the impact of CO_2 fertilization. Free Atmosphere Carbon Exchange (FACE) experiments show that measurable CO_2 fertilization effects are typically less than modeled results (see Section 7.3).

Extreme weather events are also expected to negatively affect agricultural crop production (IPCC, 2012). For example, extreme temperatures could lower yields of rice (Mohammed and Tarpley, 2009; Tian et al., 2010). With higher precipitation, flooding could also lead to lower crop production (see SREX Chapter 4).

24.4.4.3.2. Farming systems and crop areas

Since the release of the AR4 (see WGII AR4 Section 10.4.1.2), more information is available on the impacts of climate change on farming systems and cropping areas in more countries in Asia and especially in Central Asia. Recent studies validate the likely northward shifts of crop production with current croplands under threat from the impacts of climate change (*medium evidence*, *medium agreement*). Cooler regions are likely to benefit as warmer temperatures increase arable areas (*medium evidence*, *high agreement*).

Central Asia is expected to become warmer in the coming decades and increasingly arid, especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan (Lioubimtseva and Henebry, 2009). Some parts of the region could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters, and a slight increase in winter precipitation), while others could be losers (particularly western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase already extremely high water demands for irrigation, and exacerbate the already existing water crisis and human-induced desertification). In India, the Indo-Gangetic Plains are under threat of a significant reduction in wheat yields (Ortiz et al., 2008). This area produces 90 million tons of wheat grain annually (about 14 to 15% of global wheat production). Climate projections based on a doubling of CO_2 using a CCM3 model downscaled to a 30 arc-second resolution as part of the WorldClim data set showed that there will be a 51% decrease in the most favorable and high yielding area due to heat stress. About 200 million people (using the current population) in this area whose food intake relies on crop harvests would experience adverse impacts.

Rice growing areas are also expected to shift with climate change throughout Asia. In Japan, increasing irrigation water temperature (1.6°C to 2.0°C) could lead to a northward shift of the isochrones of safe transplanting dates for rice seedlings (Ohta and Kimura, 2007). As a result, rice cultivation period will be prolonged by approximately 25 to 30 days. This will allow greater flexibility in the cropping season than at present, resulting in a reduction in the frequency of cool-summer damage in the northern districts. Sea level rise threatens coastal and deltaic rice production areas in Asia, such as those in Bangladesh and the Mekong River Delta (Wassmann et al., 2009b). For example, about 7% of Vietnam's agriculture land may be submerged due to 1-m sea level rise (Dasgupta et al., 2009). In Myanmar, saltwater intrusion due to sea level rise could also decrease rice yield (Wassmann et al., 2009b).

24.4.4.3.3. Fisheries and aquaculture

Asia dominates both capture fisheries and aquaculture (FAO, 2010). More than half of the global marine fish catch in 2008 was in the West Pacific and Indian Ocean, and the lower Mekong River basin supports the largest freshwater capture fishery in the world (Dudgeon, 2011). Fish production is also a vital component of regional livelihoods, with 85.5% of the world's fishers (28 m) and fish farmers (10 m) in Asia in 2008. Many more people fish part time. Fish catches in the Asian Arctic are relatively small, but important for local cultures and regional food security (Zeller et al., 2011).

Inland fisheries will continue to be vulnerable to a wide range of ongoing threats, including overfishing, habitat loss, water abstraction, drainage of wetlands, pollution, and dam construction, making the impacts of climate change hard to detect (see also Section 24.9.1). Most concerns have centered on rising water temperatures and the potential impacts of climate change on flow regimes, which in turn are expected to affect the reproduction of many fish species (Allison et al., 2009; Barange and Perry, 2009; Bezuijen, 2011; Dudgeon, 2011; see also Section 24.4.2.3). Sea level rise is expected to impact both capture fisheries and aquaculture production in river deltas (De Silva and Soto, 2009). For marine capture fisheries, Cheung et al. (2009, 2010) used a dynamic bioclimate envelope model to project the distributions of 1066 species of exploited marine fish and invertebrates for 2005–2055, based on the SRES A1B scenario and a stable-2000 CO_2 scenario. This analysis suggests that climate change may lead to a massive redistribution of fisheries catch potential, with large increases in high-latitude regions, including Asian Russia, and large declines in the tropics, particularly Indonesia. Other studies have made generally similar predictions, with climate change impacts on marine productivity expected to be large and negative in the tropics, in part because of the vulnerability of coral reefs to both warming and ocean acidification (see also Section 24.4.3.3), and large and positive in Arctic and sub-Arctic regions, because of sea ice retreat and poleward species shifts (*high confidence*; Sumaila et al., 2011; Blanchard et al., 2012; Doney et al., 2012). Predictions of a reduction in the average maximum body weight of marine fishes by 14 to 24% by 2050 under a high-emission scenario are an additional threat to fisheries (Cheung et al., 2013).

24.4.4.3.4. Future food supply and demand

WGII AR4 Section 10.4.1.4 was largely based on global models that included Asia. There are now a few quantitative studies in Asia and its individual countries. In general, these show that the risk of hunger, food insecurity, and loss of livelihood due to climate change will *likely* increase in some regions (*low evidence*, *medium agreement*).

Rice is a key staple crop in Asia and 90% or more of the world's rice production is from Asia. An Asia-wide study revealed that climate change scenarios (using 18 GCMs for A1B, 14 GCMs for A2, and 17 GCMs for B1) would reduce rice yield over a large portion of the continent (Masutomi et al., 2009). The most vulnerable regions were western Japan, eastern China, the southern part of the Indochina peninsula, and the northern part of South Asia. In Russia, climate change may also lead to "food production shortfall," which was defined as an event in which the annual potential (i.e., climate-related) production of the most important crops in an administrative region in a specific year falls below 50% of its climate-normal (1961–1990) average (Alcamo et al., 2007). The study shows that the frequency of shortfalls in five or more of the main crop growing regions in the same year is around 2 years per decade under normal climate but could climb to 5 to 6 years per decade in the 2070s, depending on the scenario and climate model (using the GLASS, Global Agro-Ecological Zones (GAEZ), and Water-Global Assessment and Prognosis (WaterGAP-2) models and ECHAM and HadCM3 under the A2 and B2 scenarios). The increasing shortfalls were attributed to severe droughts. The study estimated that the number of people living in regions that may experience one or more shortfalls each decade may grow to 82 to 139 million in the 2070s. Increasing frequency of extreme climate events will pose an increasing threat to the security of Russia's food system.

In contrast, climate change may provide a windfall for wheat farmers in parts of Pakistan. Warming temperatures would make it possible to grow at least two crops (wheat and maize) a year in mountainous areas (Hussain and Mudasser, 2007). In the northern mountainous areas, wheat yield was projected to increase by 50% under SRES A2 and by 40% under the B2 scenario, whereas in the sub-mountainous, semiarid, and arid areas, it is *likely* to decrease by the 2080s (Iqbal et al., 2009).

24.4.4.4. Vulnerabilities to Key Drivers

Food production and food security are most vulnerable to rising air temperatures (Wassmann et al., 2009a,b). Warmer temperatures could depress yields of major crops such as rice. However, warmer temperatures could also make some areas more favorable for food production (Lioubimtseva and Henebry, 2009). Increasing CO_2 concentration in the atmosphere could lead to higher crop yields (Tao and Zhang, 2013a). Sea level rise will be a key issue for many coastal areas as rich agricultural lands may be submerged and taken out of production (Wassmann et al., 2009b).

24.4.4.5. Adaptation Options

Since AR4, there have been additional studies of recommended and potential adaptation strategies and practices in Asia (Table SM24-7) and there is new information for West and Central Asia. There are also many more crop-specific and country-specific adaptation options available. Farmers have been adapting to climate risks for generations. Indigenous and local adaptation strategies have been documented for

Southeast Asia (Peras et al., 2008; Lasco et al., 2010, 2011) and could be used as a basis for future climate change adaptation. Crop breeding for high temperature conditions is a promising option for climate change adaptation in Asia. For example, in the North China Plain, simulation studies show that using high-temperature sensitive varieties, maize yield in the 2050s could increase on average by 1.0 to 6.0%, 9.9 to 15.2%, and 4.1 to 5.6%, by adopting adaptation options of early planting, fixing variety growing duration, and late planting, respectively (Tao and Zhang, 2010). In contrast, no adaptation will result in yield declines of 13.2 to 19.1%.

24.4.5. Human Settlements, Industry, and Infrastructure

24.4.5.1. Sub-regional Diversity

Around one in every five urban dwellers in Asia lives in large urban agglomerations and almost 50% of these live in small cities (UN DESA Population Division, 2012). North and Central Asia are the most urbanized areas, with more than 63% of the population living in urban areas, with the exception of Kyrgyzstan and Tajikistan (UN-HABITAT, 2010; UN ESCAP, 2011). South and Southwest Asia are the least urbanized sub-regions, with only a third of their populations living in urban areas. However, these regions have the highest urban population growth rates within Asia, at an average of 2.4% per year during 2005–2010 (UN ESCAP, 2011). By the middle of this century, Asia's urban population will increase by 1.4 billion and will account for more than 50% of the global population (UN DESA Population Division, 2012).

24.4.5.2. Observed Impacts

Asia experienced the highest number of weather- and climate-related disasters in the world during the period 2000–2008 and suffered huge economic losses, accounting for the second highest proportion (27.5%) of the total global economic loss (IPCC, 2012). Flood mortality risk is heavily concentrated in Asia. Severe floods in Mumbai in 2005 have been attributed to both climatic factors and non-climatic factors. Strengthened capacities to address the mortality risk associated with major weather-related hazards, such as floods, have resulted in a downward trend in mortality risk relative to population size, as in East Asia, where it is now a third of its 1980 level (UNISDR, 2011).

24.4.5.3. Projected Impacts

A large proportion of Asia's population lives in low elevation coastal zones that are particularly at risk from climate change hazards, including sea level rise, storm surges, and typhoons (see Sections 5.3.2.1, 8.2.2.5; Box CC-TC). Depending on region, half to two-thirds of Asia's cities with 1 million or more inhabitants are exposed to one or multiple hazards, with floods and cyclones most important (UN DESA Population Division, 2012).

24.4.5.3.1. Floodplains and coastal areas

Three of the world's five most populated cities (Tokyo, Delhi, and Shanghai) are located in areas with high risk of floods (UN DESA Population Division, 2012). Flood risk and associated human and material losses are heavily concentrated in India, Bangladesh, and China. At the same time, the East Asia region in particular is experiencing increasing water shortages, negatively affecting its socioeconomic, agricultural, and environmental conditions, which is attributed to lack of rains and high evapotranspiration, as well as over-exploitation of water resources (IPCC, 2012). Large parts of South, East, and Southeast Asia are exposed to a high degree of cumulative climate-related risk (UN-HABITAT, 2011). Asia has more than 90% of the global population exposed to tropical cyclones (IPCC, 2012; see Box CC-TC). Damage due to storm surge is sensitive to change in the magnitude of tropical cyclones. By the 2070s, the top Asian cities in terms of population exposure (including all environmental and socioeconomic factors) to coastal flooding are expected to be Kolkata, Mumbai, Dhaka, Guangzhou, Ho Chi Minh City, Shanghai, Bangkok, Rangoon, and Hai Phòng (Hanson et al., 2011). The top Asian cities in terms of assets exposed are expected to be Guangzhou, Kolkata, Shanghai, Mumbai, Tianjin, Tokyo, Hong Kong, and Bangkok. Asia includes 15 of the global top 20 cities for projected population exposure and 13 of the top 20 for asset exposure.

24.4.5.3.2. Other issues in human settlements

Asia has a large—and rapidly expanding—proportion of the global urban exposure and vulnerability related to climate change hazards (see SREX Section 4.4.3). In line with the rapid urban growth and sprawl in many parts of Asia, the periurban interface between urban and rural areas deserves particular attention when considering climate change vulnerability (see also Section 18.4.1). Garschagen et al. (2011) find, for example, that periurban agriculturalists in the Vietnamese Mekong Delta are facing a multiple burden because they are often exposed to overlapping risks resulting from (1) socioeconomic transformations, such as land title insecurity and price pressures; (2) local biophysical degradation, as periurban areas serve as sinks for urban wastes; and (3) climate change impacts, as they do not benefit from the inner-urban disaster risk management measures. Nevertheless, the periurban interface is still underemphasized in studies on impacts, vulnerability, and adaptation in Asia.

Groundwater sources, which are affordable means of high-quality water supply in cities of developing countries, are threatened due to over-withdrawals. Aquifer levels have fallen by 20 to 50 m in cities such as Bangkok, Manila, and Tianjin and between 10 and 20 m in many other cities (UNESCO, 2012). The drop in groundwater levels often results in land subsidence, which can enhance hazard exposure due to coastal inundation and sea level rise, especially in settlements near the coast, and deterioration of groundwater quality. Cities susceptible to human-induced subsidence (developing country cities in deltaic regions with rapidly growing populations) could see significant increases in exposure (Nicholls et al., 2008). Settlements on unstable slopes or landslide-prone areas face increased prospects of rainfall-induced landslides (IPCC, 2012).

24.4.5.3.3. Industry and infrastructure

The impacts of climate change on industry include both direct impacts on industrial production and indirect impacts on industrial enterprises due to the implementation of mitigation activities (Li, 2008). The impact of climate change on infrastructure deterioration cannot be ignored, but can be addressed by changes to design procedures, including increases in cover thickness, improved quality of concrete, and coatings and barriers (Stewart et al., 2012). Climate change and extreme events may have a greater impact on large and medium-sized construction projects (Kim et al., 2007).

Estimates suggest that, by upgrading the drainage system in Mumbai, losses associated with a 1-in-100 year flood event today could be reduced by as much as 70% and, through extending insurance to 100% penetration, the indirect effects of flooding could be almost halved, speeding recovery significantly (Ranger et al., 2011). On the east coast of India, clusters of districts with poor infrastructure and demographic development are also the regions of maximum vulnerability. Hence, extreme events are expected to be more catastrophic in nature for the people living in these districts. Moreover, the lower the district is in terms of the infrastructure index and its growth, the more vulnerable it is to the potential damage from extreme events and hence people living in these regions are prone to be highly vulnerable (Patnaik and Narayanan, 2009). In 2008, the embankments on the Kosi River (a tributary of the Ganges) failed, displacing more than 60,000 people in Nepal and 3.5 million in India. Transport and power systems were disrupted across large areas. However, the embankment failure was not caused by an extreme event but represented a failure of interlinked physical and institutional infrastructure systems in an area characterized by complex social, political, and environmental relationships (Moench, 2010).

24.4.5.4. Vulnerabilities to Key Drivers

Disruption of basic services such as water supply, sanitation, energy provision, and transportation systems have implications for local economies and "strip populations of their assets and livelihoods," in some cases leading to mass migration (UN-HABITAT, 2010). Such impacts are not expected to be evenly spread among regions and cities, across sectors of the economy, or among socioeconomic groups. They tend to reinforce existing inequalities and disrupt the social fabric of cities and exacerbate poverty.

24.4.5.5. Adaptation Options

An ADB and UN report estimates that "about two-thirds of the $8 trillion needed for infrastructure investment in Asia and the Pacific between 2010 and 2020 will be in the form of new infrastructure, which creates tremendous opportunities to design, finance and manage more sustainable infrastructure" (UN ESCAP et al., 2012, p. 18). Adaptation measures that offer a "no regrets" solution are proposed for developing countries, "where basic urban infrastructure is often absent (e.g., appropriate drainage infrastructure), leaving room for actions that both increase immediate well-being and reduce vulnerability to future climate change" (Hallegatte and Corfee-Morlot, 2011). The role of urban planning and urban planners in adaptation to climate change impacts has been emphasized (Fuchs et al., 2011; IPCC, 2012; Tyler and Moench, 2012). The focus on solely adapting through physical infrastructure in urban areas requires complementary adaptation planning, management,

Frequently Asked Questions

FAQ 24.3 | Who is most at risk from climate change in Asia?

People living in low-lying coastal zones and flood plains are probably most at risk from climate change impacts in Asia. Half of Asia's urban population lives in these areas. Compounding the risk for coastal communities, Asia has more than 90% of the global population exposed to tropical cyclones. The impact of such storms, even if their frequency or severity remains the same, is magnified for low-lying and coastal zone communities because of rising sea level (*medium confidence*). Vulnerability of many island populations is also increasing due to climate change impacts. Settlements on unstable slopes or landslide-prone areas, common in some parts of Asia, face increased likelihood of rainfall-induced landslides.

Asia is predominantly agrarian, with 58% of its population living in rural areas, of which 81% are dependent on agriculture for their livelihoods. Rural poverty in parts of Asia could be exacerbated due to negative impacts from climate change on rice production, and a general increase in food prices and the cost of living (*high confidence*).

Climate change will have widespread and diverse health impacts. More frequent and intense heat waves will increase mortality and morbidity in vulnerable groups in urban areas (*high confidence*). The transmission of infectious disease, such as cholera epidemics in coastal Bangladesh, and schistosomiasis in inland lakes in China, and diarrheal outbreaks in rural children will be affected as a result of warmer air and water temperatures and altered rain patterns and water flows (*medium confidence*). Outbreaks of vaccine-preventable Japanese encephalitis in the Himalayan region and malaria in India and Nepal have been linked to rainfall. Changes in the geographical distribution of vector-borne diseases, as vector species that carry and transmit diseases migrate to more hospitable environments, will occur (*medium confidence*). These effects will be most noted close to the edges of the current habitats of these species.

governance, and institutional arrangements to be able to deal with the uncertainty and unprecedented challenges implied by climate change (Revi, 2008; Birkmann et al., 2010; Garschagen and Kraas, 2011).

24.4.6. Human Health, Security, Livelihoods, and Poverty

24.4.6.1. Sub-regional Diversity

Although rapidly urbanizing, Asia is still predominantly an agrarian society, with 57.28% of its total population living in rural areas, of which 81.02% are dependent on agriculture for their livelihoods (FAOSTAT, 2011). Rural poverty is higher than urban poverty, reflecting the heavy dependence on natural resources that are directly influenced by changes in weather and climate (Haggblade et al., 2010; IFAD, 2010). Rural poverty is expected to remain more prevalent than urban poverty for decades to come (Ravallion et al., 2007). However, climate change will also affect urbanizing Asia, where the urban poor will be impacted indirectly, as evident from the food price rises in the Middle East and other areas in 2007–2008. Certain categories of urban dwellers, such as urban wage labor households, are particularly vulnerable (Hertel et al., 2010).

Agriculture has been identified as a key driver of economic growth in Asia (World Bank, 2007). Although economic growth was impressive in recent decades, there are still gaps in development compared to the rest of the world (World Bank, 2011). Southeast Asia is the third poorest performing region after sub-Saharan Africa and southern Asia in terms of the Human Development Indicators (UN DESA Statistics Division, 2009). Impacts on human security in Asia will manifest primarily through impacts on water resources, agriculture, coastal areas, resource-dependent livelihoods, and urban settlements and infrastructure, with implications for human health and well-being. Regional disparities on account of socioeconomic context and geographical characteristics largely define the differential vulnerabilities and impacts within countries in Asia (Thomas, 2008; Sivakumar and Stefanski, 2011).

24.4.6.2. Observed Impacts

24.4.6.2.1. Floods and health

Epidemics have been reported after floods and storms (Bagchi, 2007) as a result of decreased drinking water quality (Harris et al., 2008; Hashizume et al., 2008; Solberg, 2010; Kazama et al., 2012), mosquito proliferation (Pawar et al., 2008), and exposure to rodent-borne pathogens (Kawaguchi et al., 2008; Zhou et al., 2011) and the intermediate snail hosts of *Schistosoma* (Wu et al., 2008).

Contaminated urban flood waters have caused exposure to pathogens and toxic compounds, for example, in India and Pakistan (Sohan et al., 2008; Warraich et al., 2011).

Mental disorders and posttraumatic stress syndrome have also been observed in disaster-prone areas (Udomratn, 2008) and, in India, have been linked to age and gender (Telles et al., 2009). See also Section 11.4.2 for flood-attributable deaths.

24.4.6.2.2. Heat and health

The effects of heat on mortality and morbidity have been studied in many countries, with a focus on the elderly and people with cardiovascular and respiratory disorders (Kan et al., 2007; Guo et al., 2009; Huang et al., 2010). Associations between high temperatures and mortality have been shown for populations in India and Thailand (McMichael et al., 2008) and in several cities in East Asia (Kim et al., 2006; Chung et al., 2009). Several studies have analyzed the health effects of air pollution in combination with increased temperatures (Lee et al., 2007; Qian et al., 2010; Wong et al., 2010; Yi et al., 2010). Intense heat waves have been shown to affect outdoor workers in South Asia (Nag et al., 2007; Hyatt et al., 2010).

24.4.6.2.3. Drought and health

Dust storms in Southwest, Central, and East Asia result in increased hospital admissions and worsen asthmatic conditions, as well as causing skin and eye irritations (Griffin, 2007; Hashizume et al., 2010; Kan et al., 2012). Droughts may also lead to wildfires and smoke exposure, with increased morbidity and mortality, as observed in Southeast Asia (Johnston et al., 2012). Drought can also disrupt food security, increasing malnutrition (Kumar et al., 2005) and thus susceptibility to infectious diseases.

24.4.6.2.4. Water-borne diseases

Many pathogens and parasites multiply faster at higher temperatures. Temperature increases have been correlated with increased incidence of diarrheal diseases in East Asia (Huang et al., 2008; Zhang et al., 2008; Onozuka et al., 2010). Other studies from South and East Asia have shown an association between increased incidence of diarrhea and higher temperatures and heavy rainfall (Hashizume et al., 2007; Chou et al., 2010). Increasing coastal water temperatures correlated with outbreaks of systemic *Vibrio vulnificus* infection in Israel (Paz et al., 2007) and South Korea (Kim and Jang, 2010). Cholera outbreaks in coastal populations in South Asia have been associated with increased water temperatures and algal blooms (Huq et al., 2005). The El Niño-Southern Oscillation (ENSO) cycle and Indian Ocean Dipole have been associated with cholera epidemics in Bangladesh (Pascual et al., 2000; Rodó et al., 2002; Hashizume et al., 2011).

24.4.6.2.5. Vector-borne diseases

Increasing temperatures affect vector-borne pathogens during the extrinsic incubation period and shorten vector life-cycles, facilitating larger vector populations and enhanced disease transmission, while the vector's ability to acquire and maintain a pathogen tails off (Paaijmans et al., 2012). Dengue outbreaks in South and Southeast Asia are correlated with temperature and rainfall with varying time lags (Su, 2008; Hii et al., 2009; Hsieh and Chen, 2009; Shang et al., 2010; Sriprom et al., 2010; Hashizume et al., 2012). Outbreaks of vaccine-preventable Japanese encephalitis have been linked to rainfall in studies from the Himalayan region (Partridge et al., 2007; Bhattachan et al., 2009), and to rainfall and temperature in South and East Asia (Bi et al., 2007; Murty et al., 2010). Malaria prevalence is often influenced by non-climate variability factors, but studies from India and Nepal have found correlations with rainfall (Devi and Jauhari, 2006; Dev and Dash, 2007; Dahal, 2008; Laneri et al., 2010). Temperature was linked to distribution and seasonality of malaria mosquitoes in Saudi Arabia (Kheir et al., 2010). The reemergence of malaria in central China has been attributed to rainfall and increases in temperature close to water bodies (Zhou et al., 2010). In China, temperature, precipitation, and the virus-carrying index among rodents have been found to correlate with the prevalence of hemorrhagic fever with renal syndrome (Guan et al., 2009).

24.4.6.2.6. Livelihoods and poverty

An estimated 51% of total income in rural Asia comes from non-farm sources (Haggblade et al., 2009, 2010), mostly local non-farm business and employment. The contribution of remittances to rural income has grown steadily (Estudillo and Otsuka, 2010). Significant improvements have been made in poverty eradication over the past decade (World Bank, 2007), with rapid reductions in poverty in East Asia, followed by South Asia (IFAD, 2010). A significant part of the reduction has come from population shifts, rapid growth in agriculture, and urban contributions (Janvry and Sadoulet, 2010). Climate change negatively impacts livelihoods (see Table SM24-4) and these impacts are directly related to natural resources affected by changes in weather and climate. Factors that have made agriculture less sustainable in the past include input non-responsive yields, soil erosion, natural calamities, and water and land quality related problems (Dev, 2011). These have predisposed rural livelihoods to climate change vulnerability. Livelihoods are impacted by droughts (Selvaraju et al., 2006; Harshita, 2013), floods (Nguyen, 2007; Keskinen et al., 2010; Nuorteva et al., 2010; Dun, 2011), and typhoons (Huigen and Jens, 2006; Gaillard et al., 2007; Uy et al., 2011). Drought disproportionately impacts small farmers, agricultural laborers, and small businessmen (Selvaraju et al., 2006), who also have least access to rural safety net mechanisms, including financial services (IFAD, 2010), despite recent developments in microfinance services in parts of Asia. Past floods have exposed conditions such as lack of access to alternative livelihoods, difficulty in maintaining existing livelihoods, and household debts leading to migration in the Mekong region (Dun, 2011). Similar impacts of repeated floods leading to perpetual vulnerability were found in the Tonle Sap Lake area of Cambodia (Nuorteva et al., 2010; Keskinen et al., 2010). Typhoon impacts are mainly through damage to the livelihood assets of coastal populations in the Philippines and the level of ownership of livelihood assets has been a major determinant of vulnerability (Uy et al., 2011).

24.4.6.3. Projected Impacts

24.4.6.3.1. Health effects

An emerging public health concern in Asia is increasing mortality and morbidity due to heat waves. An aging population will increase the number of people at risk, especially those with cardiovascular and respiratory disorders. Urban heat island effects have increased (Tan et al., 2010), although local adaptation of the built environment and urban planning will determine the impacts on public health. Heat stress disorders among workers and consequent productivity losses have also been reported (Lin et al., 2009; Langkulsen et al., 2010). The relationship between temperature and mortality is often U-shaped (Guo et al., 2009), with increased mortality also during cold events, particularly in rural environments, even if temperatures do not fall below 0°C (Hashizume et al., 2009). However, some studies in developing areas suggest that factors other than climate can be important, so warming may not decrease cold-related deaths much in these regions (Honda and Ono, 2009).

Climate change will affect the local transmission of many climate-sensitive diseases. Increases in heavy rain and temperature are projected to increase the risk of diarrheal diseases in, for example, China (Zhang et al., 2008). However, the impact of climate change on malaria risk will differ between areas, as projected for West and South Asia (Husain and Chaudhary, 2008; Garg et al., 2009; Majra and Gur, 2009), while a study suggested that the impact of socioeconomic development will be larger than that of climate change (Béguin et al., 2011).

Climate change is also expected to affect the spatiotemporal distribution of dengue fever in the region, although the level of evidence differs across geographical locations (Banu et al., 2011). Some studies have developed climate change-disease prevalence models; for example, one for schistosomiasis in China shows an increased northern distribution of the disease with climate change (Zhou et al., 2008; Kan et al., 2012). Impacts of climate change on fish production (Qiu et al., 2010) are being studied, along with impacts on chemical pathways in the marine environment and consequent impacts on food safety (Tirado et al., 2010), including seafood safety (Marques et al., 2010).

24.4.6.3.2. Livelihood and poverty

Floods, droughts, and changes in seasonal rainfall patterns are expected to negatively impact crop yields, food security, and livelihoods in vulnerable areas (Dawe et al., 2008; Kelkar et al., 2008; Douglas, 2009). Rural poverty in parts of Asia could be exacerbated (Skoufias et al., 2011) as a result of impacts on the rice crop and increases in food prices and the cost of living (Hertel et al., 2010; Rosegrant, 2011). The poverty impacts of climate change will be heterogeneous among countries and social groups (see Table SM24-5). In a low crop productivity scenario, producers in food exporting countries, such as Indonesia, the Philippines, and Thailand, would benefit from global food price rises and reduce poverty, while countries such as Bangladesh would experience a net increase in poverty of approximately 15% by 2030 (Hertel et al., 2010). These impacts will also differ within food exporting countries, with disproportionate negative impacts on farm laborers and the urban poor. Skoufias et al. (2011) project significant negative impacts of a rainfall shortfall on the welfare of rice farmers in Indonesia, compared to a delay in rainfall onset. These impacts may lead to global mass migration and related conflicts (Laczko and Aghazarm, 2009; Barnett and Webber, 2010; Warner, 2010; World Bank, 2010).

In North Asia, climate-driven changes in tundra and forest-tundra biomes may influence indigenous peoples who depend on nomadic tundra pastoralism, fishing, and hunting (Kumpula et al., 2011).

24.4.6.4. Vulnerabilities to Key Drivers

Key vulnerabilities vary widely within the region. Climate change can exacerbate current socioeconomic and political disparities and add to the vulnerability of Southeast Asia and Central Asia to security threats that may be transnational in nature (Jasparro and Taylor, 2008; Lioubimtseva and Henebry, 2009). Apart from detrimental impacts of extreme events, vulnerability of livelihoods in agrarian communities also arises from geographic settings, demographic trends, socioeconomic factors, access to resources and markets, unsustainable water consumption, farming practices, and lack of adaptive capacity (Acosta-Michlik and Espaldon, 2008; Allison et al., 2009; Byg and Salick, 2009; Lioubimtseva and Henebry, 2009; Salick and Ross, 2009; Salick et al., 2009; UN DESA Statistics Division, 2009; Xu et al., 2009; Knox et al., 2011; Mulligan et al., 2011). Urban wage laborers were found to be more vulnerable to cost of living related poverty impacts of climate change than those who directly depend on agriculture for their livelihoods (Hertel et al., 2010). In Indonesia, drought-associated fires increase vulnerability of agriculture, forestry, and human settlements, particularly in peatland areas (Murdiyarso and Lebel, 2007). Human health is also a major area of focus for Asia (Munslow and O'Dempsey, 2010), where the magnitude and type of health effects from climate change depend on differences in socioeconomic and demographic factors, health systems, the natural and built environment, land use changes, and migration, in relation to local resilience and adaptive capacity. The role of institutions is also critical, particularly in influencing vulnerabilities arising from gender (Ahmed and Fajber, 2009), caste and ethnic differences (Jones and Boyd, 2011), and securing climate-sensitive livelihoods in rural areas (Agrawal and Perrin, 2008).

24.4.6.5. Adaptation Options

Disaster preparedness on a local community level could include a combination of indigenous coping strategies, early-warning systems, and adaptive measures (Paul and Routray, 2010). Heat warning systems have been successful in preventing deaths among risk groups in Shanghai (Tan et al., 2007). New work practices to avoid heat stress among outdoor workers in Japan and the United Arab Emirates have also been successful (Morioka et al., 2006; Joubert et al., 2011). Early warning models have been developed for haze exposure from wildfires, in, for example, Thailand (Kim Oanh and Leelasakultum, 2011), and are being tested in infectious disease prevention and vector control programs, as for malaria in Bhutan (Wangdi et al., 2010) and Iran (Haghdoost et al., 2008), or are being developed, as for dengue fever region-wide (Wilder-Smith et al., 2012).

Some adaptation practices provide unexpected livelihood benefits, as with the introduction of traditional flood mitigation measures in China, which could positively impact local livelihoods, leading to reductions in both the physical and economic vulnerabilities of communities (Yu et al., 2009). A greater role of local communities in decision making is also proposed (Alauddin and Quiggin, 2008) and in prioritization and adoption of adaptation options (Prabhakar et al., 2010; Prabhakar and Srinivasan, 2011). Defining adequate community property rights, reducing income disparity, exploring market-based and off-farm livelihood options, moving from production-based approaches to productivity and efficiency decision-making based approaches, and promoting integrated decision-making approaches have also been suggested (Merrey et al., 2005; Brouwer et al., 2007; Paul et al., 2009; Niino, 2011; Stucki and Smith, 2011).

Climate-resilient livelihoods can be fostered through the creation of bundles of capitals (natural, physical, human, financial, and social capital) and poverty eradication (Table SM24-8). Greater emphasis on agricultural growth has been suggested as an effective means of reducing rural poverty (Janvry and Sadoulet, 2010; Rosegrant, 2011). Bundled approaches are known to facilitate better adaptation than individual adaptation options (Acosta-Michlik and Espaldon, 2008; Fleischer et al., 2011). Community-based approaches have been suggested to identify adaptation options that address poverty and livelihoods, as these techniques help capture information at the grassroots (Huq and Reid, 2007; van Aalst et al., 2008), and help integration of disaster risk reduction, development, and climate change adaptation (Heltberg et al., 2010), connect local communities and outsiders (van Aalst et al., 2008), address the location-specific nature of adaptation (Iwasaki et al., 2009; Rosegrant, 2011), help facilitate community learning processes (Baas and Ramasamy, 2008), and help design location-specific solutions (Ensor and Berger, 2009). Some groups can become more vulnerable to change after being "locked into" specialized livelihood patterns, as with fish farmers in India (Coulthard, 2008).

Livelihood diversification, including livelihood assets and skills, has been suggested as an important adaptation option for buffering climate change impacts on certain kinds of livelihoods (Selvaraju et al., 2006; Nguyen, 2007; Agrawal and Perrin, 2008; IFAD, 2010; Keskinen et al., 2010; Uy et al., 2011). The diversification should occur across assets, including productive assets, consumption strategies, and employment opportunities (Agrawal and Perrin, 2008). Ecosystem-based adaptation has been suggested to secure livelihoods in the face of climate change (Jones et al., 2012), integrating the use of biodiversity and ecosystem services into an overall strategy to help people adapt (IUCN, 2009). Among financial means, low-risk liquidity options such as microfinance programs and risk transfer products can help lift the rural poor from poverty and accumulate assets (Barrett et al., 2007; Jarvis et al., 2011).

24.4.7. Valuation of Impacts and Adaptation

Economic valuation in Asia generally covers impacts and vulnerabilities of disperse sectors such as food production, water resources, and human health (Aydinalp and Cresser, 2008; Kelkar et al., 2008; Lioubimtseva and Henebry, 2009; Su et al., 2009; Srivastava et al., 2010). Multi-sector evaluation that unpacks the relationships between and across sectors, particularly in a context of resource scarcity and competition, is very limited. Information is scarce especially for North, Central, and West Asia.

Generally, annual losses from drought are expected to increase based on various projections under diverse scenarios, but such losses are expected to be reduced if adaptation measures are implemented (ADB, 2009; Sutton et al., 2013). It is also stressed that there are great uncertainties associated with the economic aspects of climate change. In China, the total loss due to drought projected in 2030 is expected to range from US$1.1 to 1.7 billion for regions in northeast China and about US$0.9 billion for regions in north China (ECA, 2009), with adaptation measures having the potential to avert half of the losses. In India, the estimated countrywide agricultural loss in 2030—more than US$7 billion, which will severely affect the income of 10% of the population—could be reduced by 80% if cost-effective climate resilience measures are implemented (ECA, 2009).

In Indonesia, the Philippines, Thailand, and Vietnam, under the A2 scenario, the Policy Analysis for the Greenhouse Effect 2002 (PAGE2002) integrated assessment model projects a mean loss of 2.2% of GDP by 2100 on an annual basis, if only the market impact (mainly related to agriculture and coastal zones) is considered (ADB, 2009). This is well above the world's projected mean GDP loss of 0.6% each year by 2100 due to market impact alone. In addition, the mean cost for the four countries could reach 5.7% of GDP if non-market impacts related to health and ecosystems are included and 6.7% of GDP if catastrophic risks are also taken into account. The cost of adaptation for agriculture and coastal zones is expected to be about US$5 billion per year by 2020 on average. Adaptation that is complemented with global mitigation measures is expected to be more effective in reducing the impacts of climate change (IPCC, 2007; ADB, 2009; UNFCCC, 2009; MNRE, 2010; Begum et al., 2011).

24.5. Adaptation and Managing Risks

24.5.1. Conservation of Natural Resources

Natural resources are already under severe pressure from land use change and other impacts in much of Asia. Deforestation in Southeast Asia has received most attention (Sodhi et al., 2010; Miettinen et al., 2011a), but ecosystem degradation, with the resulting loss of natural goods and services, is also a major problem in other ecosystems. Land use change is also a major source of regional greenhouse gas emissions, particularly in Southeast Asia (see WGI AR5 Section 6.3.2.2, Table 6.3). Projected climate change is expected to intensify these pressures in many areas (see Sections 24.4.2.3, 24.4.3.3), most clearly for coral reefs, where increases in sea surface temperature and ocean acidification are a threat to all reefs in the region and the millions of people who depend on them (see Section 5.4.2.4; Boxes CC-CR, CC-OA). Adaptation has so far focused on minimizing non-climate pressures on natural resources and restoring connectivity to allow movements of genes and species between fragmented populations (see Section 24.4.2.5). Authors have also suggested a need to identify and protect areas that will be subject to the least damaging climate change ("climate refugia") and to identify additions to the protected area network that will allow for expected range shifts, for example, by extending protection to higher altitudes or latitudes. Beyond the intrinsic value of wild species and ecosystems, ecosystem-based approaches to adaptation aim to use the resilience of natural systems to buffer human systems against climate change, with potential social, economic, and cultural co-benefits for local communities (see Box CC-EA).

24.5.2. Flood Risks and Coastal Inundation

Many coasts in Asia are exposed to threats from floods and coastal inundation (see also Section 24.4.5.3). Responding to a large number of climate change impact studies for each Asian country over the past decade (e.g., Karim and Mimura, 2008; Pal and Al-Tabbaa, 2009), various downscaled tools to support, formulate, and implement climate change adaptation policy for local governments are under development. One of the major tools is vulnerability assessment and policy option identification with Geographical Information Systems (GIS). These tools are expected to be of assistance in assessing city-specific adaptation options by examining estimated impacts and identified vulnerability for some coastal cities and areas in Asian countries (e.g., Brouwer et al., 2007; Taylor, 2011; Storch and Downes, 2011). These tools and systems sometimes take the form of integration of top-down approaches and bottom-up (community-based) approaches (see Section 14.5). Whereas top-down approaches give scientific knowledge to local actors, community-based approaches are built on existing knowledge and expertise to strengthen coping and adaptive capacity by involving local actors (van Aalst et al., 2008). Community-based approaches may have a limitation in that they place greater responsibility on the shoulders of local people without necessarily increasing their capacity proportionately (Allen, 2006). As the nature of adaptive capacity varies depending on the formulation of social capital and institutional context in the local community, it is essential for the approaches to be based on an understanding of local community structures (Adger, 2003).

24.5.3. Economic Growth and Equitable Development

Climate change challenges fundamental elements in social and economic policy goals such as prosperity, growth, equity, and sustainable development (Mearns and Norton, 2010). Economic, social, and environmental equity is an enduring challenge in many parts of Asia. Generally, the level of wealth (typically GDP) has been used as a measure of human vulnerability of a country but this approach has serious limitations (Dellink et al., 2009; Mattoo and Subramanian, 2012). In many cases, social capital—an indicator of equity in income distribution within countries—is a more important factor in vulnerability and resilience than GDP per capita (Islam et al., 2006; Lioubimtseva and Henebry, 2009). Furthermore, political and institutional instabilities can undermine the influence of economic development (Lioubimtseva and Henebry, 2009). Poor and vulnerable countries are at greater risk of inequity and loss of livelihoods from the impacts of climate extremes as their options for coping with such events are limited. Many factors contribute to this limitation, including poverty, illiteracy, weak institutions and infrastructures, poor access to resources, information and technology, poor health care, and low investment and management capabilities. The overexploitation of land resources including forests, increases in population, desertification, and land degradation pose additional threats (UNDP, 2006). This is particularly true for developing countries in Asia with a high level of natural resource dependency. Provision of adequate resources based on the burden sharing and the equity principle will serve to strengthen appropriate adaptation policies and measures in such countries (Su et al., 2009).

24.5.4. Mainstreaming and Institutional Barriers

Mainstreaming climate change adaptation into sustainable development policies offers a potential opportunity for good practice to build resilience and reduce vulnerability, depending on effective, equitable, and legitimate actions to overcome barriers and limits to adaptation (ADB, 2005; Lim et al., 2005; Lioubimtseva and Henebry, 2009). The level of adaptation mainstreaming is most advanced in the context of official development assistance, where donor agencies and international financial institutions have made significant steps toward taking climate change adaptation into account in their loan and grant making processes (Gigli and Agrawala, 2007; Klein et al., 2007). Although some practical experiences of adaptation in Asia at the regional, national, and local level are emerging, there can be barriers that impede or limit adaptation. These include challenges related to competing national priorities, awareness and capacity, financial resources for adaptation implementation, institutional barriers, biophysical limits to ecosystem adaptation, and social and cultural factors (Lasco et al., 2009, 2012; Moser and Ekstrom, 2010). Issues with resource availability might not only result from climate change, but also from weak governance mechanisms and the breakdown of policy and regulatory structures, especially with common-pool resources (Moser and Ekstrom, 2010). Furthermore, the impact of climate change depends on the inherent vulnerability of the socio-ecological systems in a region as much as on the magnitude of the change (Evans, 2010). Recent studies linking climate-related resource scarcities and conflict call for enhanced regional cooperation (Gautam, 2012).

24.5.5. Role of Higher Education in Adaptation and Risk Management

To enhance the development of young professionals in the field of climate change adaptation, the topic could be included in higher education, especially in formal education programs. Shaw et al. (2011) mentioned that higher education in adaptation and disaster risk reduction in the Asia-Pacific region can be done through environment disaster linkage, focus on hydro-meteorological disasters, and emphasizing synergy issues between adaptation and risk reduction. Similar issues are also highlighted by other authors (Chhokar, 2010; Niu et al., 2010; Nomura and Abe, 2010; Ryan et al., 2010). Higher education should be done through lectures and course work, field studies, internships, and establishing the education-research link by exposing students to field realities. In this regard, guiding principles could include an inclusive curriculum, focus on basic theory, field orientation, multidisciplinary courses, and practical skill enhancement. Bilateral or multilateral practical research programs on adaptation and risk management by graduate students and young faculty members would expose them to real field problems.

24.6. Adaptation and Mitigation Interactions

Integrated mitigation and adaptation responses focus on either land use changes or technology development and use. Changes in land use, such as agroforestry, may provide both mitigation and adaptation benefits (Verchot et al., 2007), or otherwise, depending on how they are implemented. Agroforestry practices provide carbon storage and may decrease soil erosion, increase resilience against floods, landslides, and drought, increase soil organic matter, reduce the financial impact of crop failure, as well as have biodiversity benefits over other forms of agriculture, as shown, for example, in Indonesia (Clough et al., 2011). Integrated approaches are often needed when developing mitigation-adaptation synergies, as seen in waste-to-compost projects in Bangladesh (Ayers and Huq, 2009). Other adaptation measures that increase biomass and/or soil carbon content, such as ecosystem protection and reforestation, will also contribute to climate mitigation by carbon sequestration. However, exotic monocultures may fix more carbon than native mixtures while supporting less biodiversity and contributing less to ecological services, calling for compromises that favor biodiversity-rich carbon storage (Diaz et al., 2009). The potential for both adaptation and mitigation through forest restoration is greatest in the tropics (Sasaki et al., 2011). At higher latitudes (>45°N), reforestation can have a net warming influence by reducing surface albedo (Anderson-Teixeira et al., 2012). Expansion of biofuel crops on abandoned and marginal agricultural lands could potentially make a large contribution to mitigation of carbon emissions from fossil fuels, but could also have large negative consequences for both carbon and biodiversity if it results directly or indirectly in the conversion of carbon-rich ecosystems to cropland (Fargione et al., 2010; Qin et al., 2011). Mechanisms, such as Reduction of Emissions from Deforestation and Forest Degradation (REDD+), that put an economic price on land use emissions, could reduce the risks of such negative consequences (Thomson et al., 2010), but the incentive structures need to be worked out very carefully (Busch et al., 2012).

Forests and their management are also often emphasized for providing resilient livelihoods and reducing poverty (Chhatre and Agrawal, 2009; Noordwijk, 2010; Persha et al., 2010; Larson, 2011). Securing rights to resources is essential for greater livelihood benefits for poor indigenous and traditional people (Macchi et al., 2008) and the need for REDD+ schemes to respect and promote community forest tenure rights has been emphasized (Angelsen, 2009). It has been suggested that indigenous people can provide a bridge between biodiversity protection and climate change adaptation (Salick and Ross, 2009): a point that appears to be missing in the current discourse on ecosystem-based adaptation. There are arguments against REDD+ supporting poverty reduction due to its inability to promote productive use of forests, which may keep communities in perpetual poverty (Campbell, 2009), but there is a contrasting view that REDD+ can work in forests managed for timber production (Guariguata et al., 2008; Putz et al., 2012), especially through reduced impact logging (Guariguata et al., 2008) and other approaches such as assuring the legality of forest products, certifying responsible management, and devolving control over forests to empowered local communities (Putz et al., 2012).

On rivers and coasts, the use of hard defenses (e.g., channelization, sea walls, bunds, dams) to protect agriculture and human settlements from flooding may have negative consequences for both natural ecosystems and carbon sequestration by preventing natural adjustments to changing conditions (see Section 24.4.3.5). Conversely, setting aside landward buffer zones along coasts and rivers would be positive for both. The very high carbon sequestration potential of the organic-rich soils in mangroves (Donato et al., 2011) and peat swamp forests (Page et al., 2011) provides opportunities for combining adaptation with mitigation through restoration of degraded areas.

Mitigation measures can also result in public health benefits (Bogner et al., 2008; Haines et al., 2009). For example, sustainable cities with fewer fossil fuel-driven vehicles (mitigation) and more trees and greenery (carbon storage and adaptation to the urban heat island effect) would have a number of co-benefits, including public health—a promising strategy for "triple win" interventions (Romero-Lankao et al., 2011). Other examples include efforts to decarbonize electricity production in India and China that are projected to decrease mortality due to reduced particulate matter with aerodynamic diameter <5 µm (PM_5) and <2.5 µm ($PM_{2.5}$) (Markandya et al., 2009); policies to increase public transportation, promote walking and cycling, and reduce private cars that will increase air quality and decrease the health burden, particularly in urban environments as projected in India (Woodcock et al., 2009); and abandoning the use of biomass fuel or coal for indoor cooking and heating to improve indoor air quality and respiratory and cardiac health among, in particular, women and children in India and China (Wilkinson et al., 2009). Conversely, actions to reduce current environmental-public health issues may often have beneficial mitigation effects, like traffic emissions reduction programs in China (Wu et al., 2011) and India (Reynolds and Kandikar, 2008).

24.7. Intra-regional and Inter-regional Issues

24.7.1. Transboundary Pollution

Many Asian countries and regions face long-distance and transboundary air pollution problems. In eastern China, Japan, and the Korean Peninsula, these include dust storms that originate in the arid and semiarid regions upwind, with impacts on climate, human health, and ecosystems (Huang et al., 2013). The susceptibility of the land surface to wind erosion is strongly influenced by vegetation cover, which is in turn sensitive to climate change and other human impacts. In the humid tropics of Southeast Asia, in contrast, the major transboundary pollution issue involves smoke aerosols from burning of biomass and peatlands, mostly during clearance for agriculture (Miettinen et al., 2011b; Gautam et al., 2013). Apart from the large impact on human health, these aerosols may be having a significant effect on rainfall in equatorial regions, leading to the possibility of climate feedbacks, with fires reducing rainfall and promoting further fires (Tosca et al., 2012).

Pollutants of industrial origin are also a huge problem in many parts of the region, with well-documented impacts on human health (Section 24.4.6) and the climate (see WGI AR5 Chapters 7, 8).

24.7.2. Trade and Economy

The ASEAN Free Trade Agreement (AFTA) and the Indonesia-Japan Economic Partnership Agreement (IJEPA) have positively impacted the Indonesian economy and reduced water pollution, but increased CO_2 emissions by 0.46% compared to the business-as-usual situation, mainly due to large emission increases in the transportation sector (Gumilang et al., 2011). Full liberalization of tariffs and GDP growth concentrated in China and India have led to transport emissions growing much faster than the value of trade, as result of a shift toward distant trading partners (Cristea et al., 2013). China's high economic growth and flourishing domestic and international trade has resulted in increased consumption and pollution of water resources (Guan and Hubacek, 2007). Japanese imports from the ASEAN region are negatively correlated with per capita carbon emissions (Atici, 2012) owing to strict regulations in Japan that prevent import from polluting sectors. Export-led growth is central to the economic progress and well-being of Southeast Asian countries. Generally, as exports rise, carbon emissions tend to rise. International trading systems that help address the challenge of climate change need further investigation.

24.7.3. Migration and Population Displacement

Floods and droughts are predominant causes for internal displacement (IDMC, 2011). In 2010 alone, 38.3 million people were internally displaced: 85% because of hydrological hazards and 77% in Asia. Floods are increasingly playing a role in migration in the Mekong Delta (Warner, 2010). Often some migrants return to the vulnerable areas (Piguet, 2008) giving rise to ownership, rights of use, and other issues (Kolmannskog, 2008). Increasing migration has led to increasing migration-induced remittances contributing to Asian economies, but has had negligible effect on the poverty rate (Vargas-Silva et al., 2009). In Bangladesh, migrant workers live and work under poor conditions, such as crowded shelters, inadequate sanitation, conflict and competition with the local population, and exploitation (Penning-Rowsell et al., 2011). Forced migration can result from adaptation options such as construction of dams, but the negative outcomes could be allayed by putting proper safeguards in place (Penning-Rowsell et al., 2011). Managed retreat of coastal communities is a suggested option to address projected sea level rise (Alexander et al., 2012). A favorable approach to deal with migration is within a development framework and through adaptation strategies (Penning-Rowsell et al., 2011; ADB, 2012).

24.8. Research and Data Gaps

Studies of observed climate changes and their impacts are still inadequate for many areas, particularly in North, Central, and West Asia (Table 24-2). Improved projections for precipitation, and thus water supply, are most urgently needed. Another priority is developing water management strategies for adaptation to changes in demand and supply. More research is also needed on the health effects of changes in water quality and quantity. Understanding of climate change impacts on ecosystems and biodiversity in Asia is currently limited by the poor quality and low accessibility of biodiversity information (UNEP, 2012). National biodiversity inventories are incomplete and few sites have the baseline information needed to identify changes. For the tropics, major research gaps include the temperature dependence of carbon fixation by tropical trees, the thermal tolerances and acclimation capacities of both plants and animals, and the direct impacts of rising CO_2 (Corlett, 2011; Zuidema et al., 2013). Rising CO_2 is also expected to be important in cool-arid ecosystems, where lack of experimental studies currently limits ability to make predictions (Poulter et al., 2013). Boreal forest dynamics will be influenced by complex interactions between rising temperatures and CO_2, permafrost thawing, forest fires, and insect outbreaks (Osawa et al., 2010; Zhang et al., 2011), and understanding this complexity will require enhanced monitoring of biodiversity and species ranges, improved modeling, and greater knowledge of species biology (Meleshko and Semenov, 2008).

Rice is the most studied crop but there are still significant uncertainties in model accuracy, CO_2-fertilization effects, and regional differences (Masutomi et al., 2009; Zhang et al., 2010; Shuang-He et al., 2011). For other crops, there is even greater uncertainty. Studies are also needed of the health effects of interactions between heat and air pollution in urban and rural environments.

More generally, research is needed on impacts, vulnerability, and adaptation in urban settlements, especially cities with populations of less than 500,000, which share half the region's urban population. Greater understanding is required of the linkages between local livelihoods, ecosystem functions, and land resources for creating a positive impact on livelihoods in areas with greater dependence on natural resources (Paul et al., 2009). Increasing regional collaboration in scientific research and policy making has been suggested for reducing climate change impacts on water, biodiversity, and livelihoods in the Himalayan region (Xu et al., 2009) and could be considered elsewhere. The literature suggests that work must begin now on building understanding of the impacts of climate change and moving forward with the most cost-effective adaptation measures (ADB, 2007; Cai et al., 2008; Stage, 2010).

For devising mitigation policies, the key information needed is again the most cost-effective measures (Nguyen, 2007; Cai et al., 2008; Mathy and Guivarch, 2010).

Table 24-2 | The amount of information supporting conclusions regarding observed and projected impacts in Asia.

Sector	Topics/issues	North Asia		East Asia		Southeast Asia		South Asia		Central Asia		West Asia	
	O = Observed impacts, P = Projected Impacts	O	P	O	P	O	P	O	P	O	P	O	P
Freshwater resources	Major river runoff	/	x	/	/	/	/	/	x	x	x	x	x
	Water supply	x	x	x	x	x	x	x	x	x	x	x	x
Terrestrial and inland water systems	Phenology and growth rates	/	/	/	/	x	x	x	x	x	x	x	x
	Distributions of species and biomes	/	/	/	/	x	x	x	/	x	x	x	x
	Permafrost	/	/	/	/	/	x	/	/	/	/	/	x
	Inland waters	x	x	/	x	x	x	x	x	x	x	x	x
Coastal systems and low-lying areas	Coral reefs	NR	NR	/	/	/	/	/	/	NR	NR	/	/
	Other coastal ecosystems	x	x	/	/	x	x	x	x	NR	NR	x	x
	Arctic coast erosion	/	/	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Food production systems and food security	Rice yield	x	x	/	/	x	/	x	/	x	x	X	/
	Wheat yield	x	x	x	x	x	x	x	/	x	x	/	/
	Corn yield	x	x	x	/	x	x	x	x	x	x	x	x
	Other crops (e.g., barley, potato)	x	x	/	/	x	x	x	x	x	X	/	/
	Vegetables	x	x	/	x	x	x	x	x	x	x	x	x
	Fruits	x	x	/	x	x	x	x	x	x	x	x	x
	Livestock	x	x	/	x	x	x	x	x	x	x	x	x
	Fisheries and aquaculture production	x	/	x	/	x	/	x	x	x	x	x	x
	Farming area	x	/	x	/	x	x	x	/	x	/	x	x
	Water demand for irrigation	x	/	x	/	x	x	x	/	x	x	x	x
	Pest and disease occurrence	x	x	x	x	x	x	x	/	x	x	x	x
Human settlements, industry, and infrastructure	Floodplains	x	x	/	/	/	/	/	/	x	x	x	x
	Coastal areas	x	x	/	/	/	/	/	/	NR	NR	x	x
	Population and assets	x	x	/	/	/	/	/	/	x	x	x	x
	Industry and infrastructure	x	x	/	/	/	/	/	/	x	x	x	x
Human health, security, livelihoods, and poverty	Health effects of floods	x	x	x	x	x	x	/	x	x	x	x	x
	Health effects of heat	x	x	/	x	x	x	x	x	x	x	x	x
	Health effects of drought	x	x	x	x	x	x	x	x	x	x	x	x
	Water-borne diseases	x	x	x	x	/	x	/	x	x	x	x	x
	Vector-borne diseases	x	x	x	x	/	x	/	x	x	x	x	x
	Livelihoods and poverty	x	x	/	x	x	x	/	x	x	x	x	x
	Economic valuation	x	x	x	x	/	/	/	/	x	x	x	x

Key:
/ = Relatively abundant/sufficient information; knowledge gaps need to be addressed but conclusions can be drawn based on existing information.
x = Limited information/no data; critical knowledge gaps, difficult to draw conclusions.
NR = Not relevant.

24.9. Case Studies

24.9.1. Transboundary Adaptation Planning and Management—Lower Mekong River Basin

The Lower Mekong River Basin (LMB) covers an area of approximately 606,000 km^2 across the countries of Thailand, Laos, Cambodia, and Vietnam. More than 60 million people are heavily reliant on natural resources, in particular agriculture and fisheries, for their well-being (MRC, 2009; UNEP, 2010; Figure SM24-2). Thailand and Vietnam produced 51% of the world's rice exports in 2008, mostly in the LMB (Mainuddin et al., 2011).

Observations of climate change over the past 30 to 50 years in the LMB include an increase in temperature, an increase in rainfall in the wet season and decreases in the dry season, intensified flood and drought events, and sea level rise (ICEM, 2010; IRG, 2010). Agricultural output has been noticeably impacted by intensified floods and droughts which caused almost 90% of rice production losses in Cambodia during 1996–2001 (Brooks and Adger, 2003; MRC, 2009).Vietnam and Cambodia are two of the countries most vulnerable to climate impacts on fisheries (Allison et al., 2009; Halls, 2009).

Existing studies about future climate impacts in the Mekong Basin broadly share a set of common themes (MRC, 2009; Murphy and Sampson, 2013): increased temperature and annual precipitation; increased depth and duration of flood in the Mekong Delta and Cambodia floodplain; prolonged agricultural drought in the south and the east of the basin; and sea level rise and salinity intrusion in the Mekong delta. Hydropower dams along the Mekong River and its tributaries will also have severe impacts on fish productivity and biodiversity, by blocking critical fish migration routes, altering the habitat of non-migratory fish species, and reducing nutrient flows downstream (Costanza et al., 2011; Baran and Guerin, 2012; Ziv et al., 2012). Climate impacts, though less severe than the impact of dams, will exacerbate these changes (Wyatt and Baird, 2007; Grumbine et al., 2012; Orr et al., 2012; Räsänen et al., 2012; Ziv et al., 2012).

National climate change adaptation plans have been formulated in all four LMB countries, but transboundary adaptation planning across the LMB does not exist to date. Effective future transboundary adaptation planning and management will benefit from: a shared climate projection across the LMB for transboundary adaptation planning; improved coordination among adaptation stakeholders and sharing of best practices across countries; mainstreaming climate change adaptation into national and sub-national development plans with proper translation from national adaptation strategies into local action plans; integration of transboundary policy recommendations into national climate change plans and policies; and integration of adaptation strategies on landscape scales between ministries and different levels of government within a country (MRC, 2009; Kranz et al., 2010; Lian and Bhullar, 2011; Lebel et al., 2012).

A study of the state-of-adaptation practice in the LMB showed that only 11% (45 of 417) of climate-change related projects in the LMB were on-the-ground adaptation efforts driven by climate risks (Ding, 2012; Neo, 2012; Schaffer and Ding, 2012). Common features of "successful" projects include: robust initial gap assessment, engagement of local stakeholders, and a participatory process throughout (Brown, 2012; Khim and Phearanich, 2012; Mondal, 2012; Panyakul, 2012; Roth and Grunbuhel, 2012). A multi-stakeholder Regional Adaptation Action Network has been proposed with the intent of scaling up and improving mainstreaming of adaptation through tangible actions following the theory and successful examples of the Global Action Networks (GANs) (WCD, 2000; Waddell, 2005; Waddell and Khagram, 2007; GAVI, 2012; Schaffer and Ding, 2012).

24.9.2. Glaciers of Central Asia

In the late 20th century, central Asian glaciers occupied 31,628 km^2 (Dolgushin and Osipova, 1989). All recent basin-scale studies document multi-decadal area loss (see Figure 24-3); where multiple surveys are available, most show accelerating loss. The rate of glacier area change varies (Table SM24-9). Rates between –0.05% yr^{-1} and –0.76% yr^{-1} have been reported in the Altai (Surazakov et al., 2007; Shahgedanova et al., 2010; Yao, X.-J. et al., 2012) and Tien Shan (Lettenmaier et al., 2009; Sorg et al., 2012), and between –0.13% yr^{-1} and–0.30% yr^{-1} in the Pamir (Konovalov and Desinov, 2007; Aizen, 2011a,b,c; Yao, X.-J. et al., 2012). These ranges reflect varying sub-regional distributions of glacier size (smaller glaciers shrink faster) and debris cover (which retards shrinkage), but also varying proportions of ice at high altitudes, where as yet warming has produced little increase in melt (Narama et al., 2010).

Most studies also document mean-annual (e.g., Glazyrin and Tadzhibaeva, 2011, for 1961–1990) and summertime (e.g., Shahgedanova et al., 2010) warming, with slight cooling in the central and eastern Pamir (Aizen, 2011b). Precipitation increases have been observed more often than decreases (e.g., Braun et al., 2009; Glazyrin and Tadzhibaeva, 2011).

Aizen et al. (2007) calculated 21st-century losses of 43% of the volume of Tien Shan glaciers for an 8°C temperature increase accompanied by a 24% precipitation increase, but probable complete disappearance of glaciers if precipitation decreased by 16%; a more moderate 2°C increase led to little loss, but only if accompanied by a 24% precipitation increase. Drawing on CMIP5 simulations, Radić et al. (2013) simulated losses by 2100 of between 25 and 90% of 2006 ice volume (including Tibet Autonomous Region, China, but excluding the Altai and Sayan; range of all single-model simulations); the 14-GCM model mean losses are 55% for RCP4.5 and 75% for RCP8.5. Similarly, Marzeion et al. (2012) found 21st-century volume losses of 50% for RCP2.6, about 57% for both RCP4.5 and RCP6.0, and 67% for RCP8.5.

The glaciers have therefore been a diminishing store of water, and the diminution is projected to continue. Paradoxically, this implies more meltwater, possibly explaining limited observations of increased runoff (Sorg et al., 2012), but also an eventual decrease of meltwater yield (see Section 3.4.4). More immediately, it entails a hazard due to the formation of moraine-dammed glacial lakes (Bolch et al., 2011).

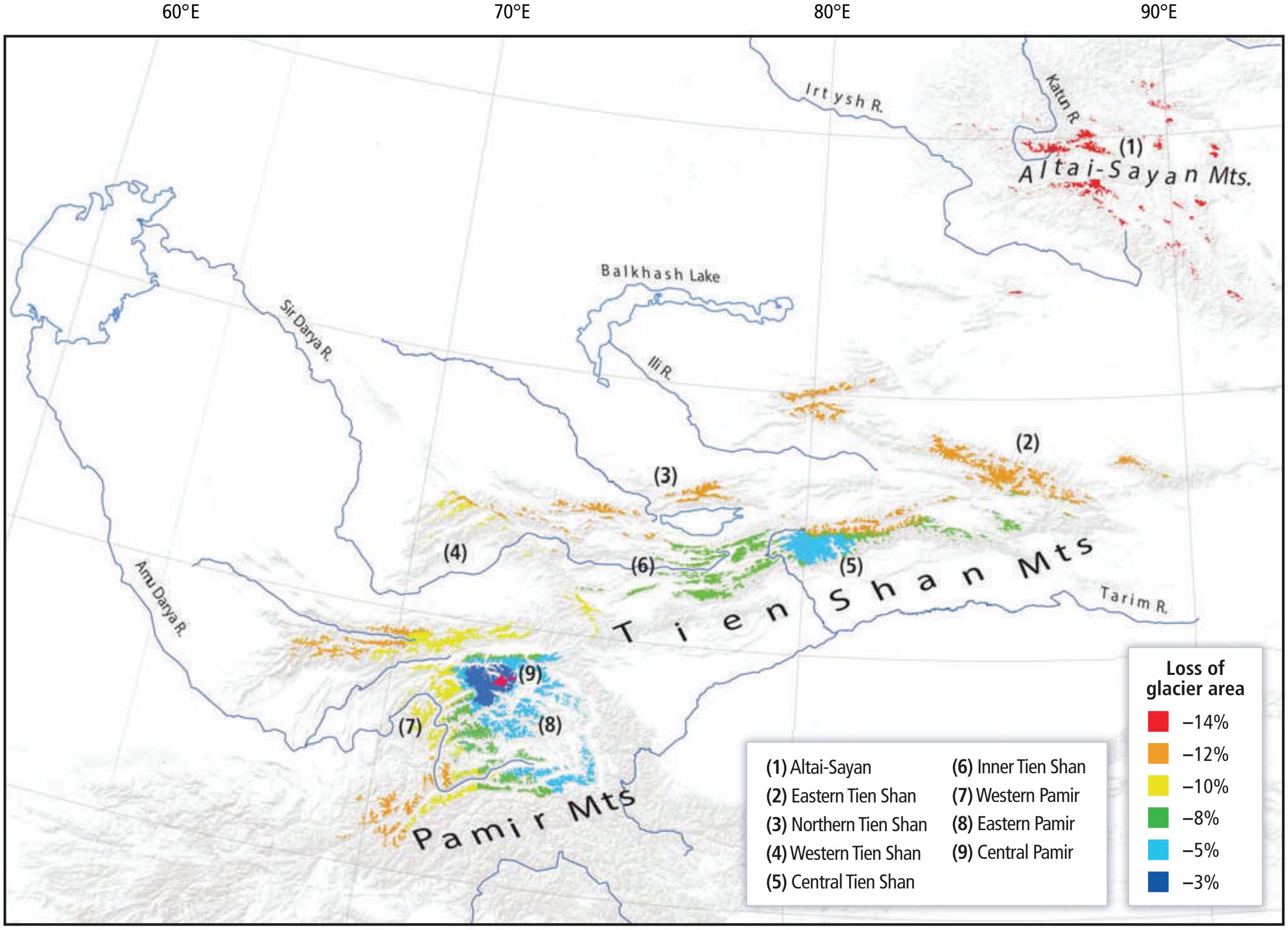


Figure 24-3 | Losses of glacier area in the Altai-Sayan, Pamir, and Tien Shan. Remote-sensing data analysis from 1960s (Corona) through 2008 (Landsat, ASTER, and Alos Prism).

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Australasia

Coordinating Lead Authors:
Andy Reisinger (New Zealand), Roger L. Kitching (Australia)

Lead Authors:
Francis Chiew (Australia), Lesley Hughes (Australia), Paul C.D. Newton (New Zealand), Sandra S. Schuster (Australia), Andrew Tait (New Zealand), Penny Whetton (Australia)

Contributing Authors:
Jon Barnett (Australia), Susanne Becken (New Zealand), Paula Blackett (New Zealand), Sarah Boulter (Australia), Andrew Campbell (Australia), Daniel Collins (New Zealand), Jocelyn Davies (Australia), Keith Dear (Australia), Stephen Dovers (Australia), Kyla Finlay (Australia), Bruce Glavovic (New Zealand), Donna Green (Australia), Don Gunasekera (Australia), Simon Hales (New Zealand), John Handmer (Australia), Garth Harmsworth (New Zealand), Alistair Hobday (Australia), Mark Howden (Australia), Graeme Hugo (Australia), Sue Jackson (Australia), David Jones (Australia), Darren King (New Zealand), Miko Kirschbaum (New Zealand), Jo Luck (Australia), Yiheyis Maru (Australia), Jan McDonald (Australia), Kathy McInnes (Australia), Johanna Mustelin (Australia), Barbara Norman (Australia), Grant Pearce (New Zealand), Susan Peoples (New Zealand), Ben Preston (USA), Joseph Reser (Australia), Penny Reyenga (Australia), Mark Stafford-Smith (Australia), Xiaoming Wang (Australia), Leanne Webb (Australia)

Review Editors:
Blair Fitzharris (New Zealand), David Karoly (Australia)

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Executive Summary

The regional climate is changing (*very high confidence*). The region continues to demonstrate long-term trends toward higher surface air and sea surface temperatures, more hot extremes and fewer cold extremes, and changed rainfall patterns. Over the past 50 years, increasing greenhouse gas concentrations have contributed to rising average temperature in Australia (*high confidence*) and New Zealand (*medium confidence*) and decreasing rainfall in southwestern Australia (*high confidence*). {25.2; Table 25-1}

Warming is projected to continue through the 21st century (*virtually certain*) along with other changes in climate. Warming is expected to be associated with rising snow lines (*very high confidence*), more frequent hot extremes, less frequent cold extremes (*high confidence*), and increasing extreme rainfall related to flood risk in many locations (*medium confidence*). Annual average rainfall is expected to decrease in southwestern Australia (*high confidence*) and elsewhere in most of far southern Australia and the northeast South Island and northern and eastern North Island of New Zealand (*medium confidence*), and to increase in other parts of New Zealand (*medium confidence*). Tropical cyclones are projected to increase in intensity but remain similar or decrease in numbers (*low confidence*), and fire weather is projected to increase in most of southern Australia (*high confidence*) and many parts of New Zealand (*medium confidence*). Regional sea level rise will *very likely* exceed the historical rate (1971–2010), consistent with global mean trends. {25.2; Table 25-1; Box 25-6; WGI AR5 13.5-6}

Uncertainty in projected rainfall changes remains large for many parts of Australia and New Zealand, which creates significant challenges for adaptation. For example, projections for average annual runoff in far southeastern Australia range from little change to a 40% decline for 2°C global warming above current levels. The dry end of these scenarios would have severe implications for agriculture, rural livelihoods, ecosystems, and urban water supply, and would increase the need for transformational adaptation (*high confidence*). {25.2, 25.5.1, 25.6.1, 25.7.2; Boxes 25-2, 25-5}

Recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (*very high confidence*), and the frequency and/or intensity of such events is projected to increase in many locations (*medium* to *high confidence*). For example, high sea surface temperatures have repeatedly bleached coral reefs in northeastern Australia (since the late 1970s) and more recently in western Australia. Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011); the Victorian heat wave (2009) increased heat-related morbidity and was associated with more than 300 excess deaths, while intense bushfires destroyed more than 2000 buildings and led to 173 deaths; and widespread drought in southeast Australia (1997–2009) and many parts of New Zealand (2007–2009; 2012–2013) resulted in substantial economic losses (e.g., regional gross domestic product (GDP) in the southern Murray-Darling Basin was below forecast by about 5.7% in 2007–2008, and New Zealand lost about NZ$3.6 billion in direct and off-farm output in 2007–2009). {25.6.2, 25.8.1; Table 25-1; Boxes 25-5, 25-6, 25-8}

Without adaptation, further changes in climate, atmospheric carbon dioxide (CO_2), and ocean acidity are projected to have substantial impacts on water resources, coastal ecosystems, infrastructure, health, agriculture, and biodiversity (*high confidence*). Freshwater resources are projected to decline in far southwest and far southeast mainland Australia (*high confidence*) and for rivers originating in the northeast of the South Island and east and north of the North Island of New Zealand (*medium confidence*). Rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure, and housing; increasing heat waves will increase risks to human health; rainfall changes and rising temperatures will shift agricultural production zones; and many native species will suffer from range contractions and some may face local or even global extinction. {25.5.1, 25.6.1-2, 25.7.2, 25.7.4; Boxes 25-1, 25-5, 25-8}

Some sectors in some locations have the potential to benefit from projected changes in climate and increasing atmospheric CO_2 (*high confidence*). Examples include reduced winter mortality (*low confidence*), reduced energy demand for winter heating in New Zealand and southern parts of Australia, and forest growth in cooler regions except where soil nutrients or rainfall are limiting. Spring pasture growth in cooler regions would also increase and be beneficial for animal production if it can be utilized. {25.7.1-2, 25.7.4, 25.8.1}

Adaptation is already occurring and adaptation planning is becoming embedded in some planning processes, albeit mostly at the conceptual rather than implementation level (*high confidence*). Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g., greening cities and recycling water) are already being implemented. Planning for

reduced water availability in southern Australia and for sea level rise in both countries is becoming adopted widely, although implementation of specific policies remains piecemeal, subject to political changes, and open to legal challenges. {25.4; Boxes 25-1, 25-2, 25-9}

Adaptive capacity is generally high in many human systems, but implementation faces major constraints, especially for transformational responses at local and community levels (*high confidence*). Efforts to understand and enhance adaptive capacity and adaptation processes have increased since the AR4, particularly in Australia. Constraints on implementation arise from: absence of a consistent information base and uncertainty about projected impacts; limited financial and human resources to assess local risks and to develop and implement effective policies and rules; limited integration of different levels of governance; lack of binding guidance on principles and priorities; different attitudes toward the risks associated with climate change; and different values placed on objects and places at risk. {25.4, 25.10.3; Table 25-2; Box 25-1}

Indigenous peoples in both Australia and New Zealand have higher than average exposure to climate change because of a heavy reliance on climate-sensitive primary industries and strong social connections to the natural environment, and face particular constraints to adaptation (*medium confidence*). Social status and representation, health, infrastructure and economic issues, and engagement with natural resource industries constrain adaptation and are only partly offset by intrinsic adaptive capacity (*high confidence*). Some proposed responses to climate change may provide economic opportunities, particularly in New Zealand related to forestry. Torres Strait communities are vulnerable even to small sea level rises (*high confidence*). {25.3, 25.8.2}

We identify eight regional key risks during the 21st century based on the severity of potential impacts for different levels of warming, uniqueness of the systems affected, and adaptation options (*high confidence*). These risks differ in the degree to which they can be managed via adaptation and mitigation, and some are more likely to be realized than others, but all warrant attention from a risk-management perspective.

- Some potential impacts can be delayed but now appear very difficult to avoid entirely, even with globally effective mitigation and planned adaptation:
  - *Significant change in community composition and structure of coral reef systems in Australia*, driven by increasing sea surface temperatures and ocean acidification; the ability of corals to adapt naturally to rising temperatures and acidification appears limited and insufficient to offset the detrimental effects. {25.6.2, 30.5; Box CC-CR}
  - *Loss of montane ecosystems and some native species in Australia*, driven by rising temperatures and snow lines, increased fire risk, and drying trends; fragmentation of landscapes, limited dispersal, and limited rate of evolutionary change constrain adaptation options. {25.6.1}
- Some impacts have the potential to be severe but can be reduced substantially by globally effective mitigation combined with adaptation, with the need for transformational adaptation increasing with the rate and magnitude of climate change:
  - *Increased frequency and intensity of flood damage to settlements and infrastructure in Australia and New Zealand*, driven by increasing extreme rainfall although the amount of change remains uncertain; in many locations, continued reliance on increased protection alone would become progressively less feasible. {25.4.2, 25.10.3; Table 25-1; Box 25-8}
  - *Constraints on water resources in southern Australia*, driven by rising temperatures and reduced cool-season rainfall; integrated responses encompassing management of supply, recycling, water conservation, and increased efficiency across all sectors are available and some are being implemented in areas already facing shortages. {25.2, 25.5.2; Box 25-2}
  - *Increased morbidity, mortality, and infrastructure damages during heat waves in Australia*, resulting from increased frequency and magnitude of extreme high temperatures; vulnerable populations include the elderly and those with existing chronic diseases; population increases and aging trends constrain effectiveness of adaptation responses. {25.8.1}
  - *Increased damages to ecosystems and settlements, economic losses, and risks to human life from wildfires in most of southern Australia and many parts of New Zealand*, driven by rising temperatures and drying trends; local planning mechanisms, building design, early warning systems, and public education can assist with adaptation and are being implemented in regions that have experienced major events. {25.2, 25.6.1, 25.7.1; Table 25-1; Box 25-6}
- For some impacts, severity depends on changes in climate variables that span a particularly large range, even for a given global temperature change. The most severe changes would present major challenges if realized:
  - *Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand from continuing sea level rise, with widespread damages toward the upper end of projected sea level rise ranges*; managed retreat is a long-term adaptation strategy for

human systems but options for some natural ecosystems are limited owing to the rapidity of change and lack of suitable space for landward migration. Risks from sea level rise continue to increase beyond 2100 even if temperatures are stabilized. {25.4.2, 25.6.1-2; Table 25-1; Box 25-1; WGI AR5 13.5}

- *Significant reduction in agricultural production in the Murray-Darling Basin and far southeastern and southwestern Australia if scenarios of severe drying are realized*; more efficient water use, allocation, and trading would increase the resilience of systems in the near term but cannot prevent significant reductions in agricultural production and severe consequences for ecosystems and some rural communities at the dry end of the projected changes. {25.2, 25.5.2, 25.7.2; Boxes 25-2, 25-5}

Significant synergies and trade-offs exist between alternative adaptation responses, and between mitigation and adaptation responses; interactions occur both within Australasia and between Australasia and the rest of the world (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, and biodiversity, but tools to understand and manage these interactions remain limited. Flow-on effects from climate change impacts and responses outside Australasia have the potential to outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*) and tourism (*limited evidence*, *high agreement*), but they remain among the least explored issues. {25.7.5, 25.9.1-2; Box 25-10}

Understanding of future vulnerability of human and mixed human-natural systems to climate change remains limited due to incomplete consideration of socioeconomic dimensions (*very high confidence*). Future vulnerability will depend on factors such as wealth and its distribution across society, patterns of aging, access to technology and information, labor force participation, societal values, and mechanisms and institutions to resolve conflicts. These dimensions have received only limited attention and are rarely included in vulnerability assessments, and frameworks to integrate social, psychological, and cultural dimensions of vulnerability with biophysical impacts and economic losses are lacking. In addition, conclusions for New Zealand in many sectors, even for biophysical impacts, are based on limited studies that often use a narrow set of assumptions, models, and data and hence have not explored the full range of potential outcomes. {25.3-4, 25.11}

25.1. Introduction and Major Conclusions from Previous Assessments

Australasia is defined here as lands, territories, offshore waters, and oceanic islands of the exclusive economic zones of Australia and New Zealand. Both countries are relatively wealthy, with export-led economies. Both have Westminster-style political systems and have a relatively recent history of non-indigenous settlement (Australia in the late 18th, New Zealand in the early 19th century). Both retain significant indigenous populations.

Principal findings from the IPCC Fourth Assessment Report (AR4) for the region were (Hennessy et al., 2007):

- Consistent with global trends, Australia and New Zealand had experienced warming of 0.4°C to 0.7°C since 1950 with changed rainfall patterns and sea level rise of about 70 mm across the region; there had also been a greater frequency and intensity of droughts and heat waves, reduced seasonal snow cover, and glacial retreat.
- Impacts from recent climate changes were evident in increasing stresses on water supply and agriculture, and changed natural ecosystems; some adaptation had occurred in these sectors but vulnerability to extreme events such as fire, tropical cyclones, droughts, hail, and floods remained high.
- The climate of the 21st century would be warmer (*virtually certain*), with changes in extreme events including more intense and frequent heat waves, fire, floods, storm surges, and droughts but less frequent frost and snow (*high confidence*), reduced soil moisture in large parts of the Australian mainland and eastern New Zealand but more rain in western New Zealand (*medium confidence*).
- Significant advances had occurred in understanding future impacts on water, ecosystems, indigenous people and health, together with an increased focus on adaptation; potential impacts would be substantial without further adaptation, particularly for water security, coastal development, biodiversity, and major infrastructure, but impacts on agriculture and forestry would be variable across the region, including potential benefits in some areas.
- Vulnerability would increase mainly due to an increase in extreme events; human systems were considered to have a higher adaptive capacity than natural systems.
- Hotspots of high vulnerability by 2050 under a medium emissions scenario included:
  - Significant loss of biodiversity in areas such as alpine regions, the Wet Tropics, the Australian southwest, Kakadu wetlands, coral reefs, and sub-Antarctic islands
  - Water security problems in the Murray-Darling basin, southwestern Australia, and eastern New Zealand
  - Potentially large risks to coastal development in southeastern Queensland and in New Zealand from Northland to the Bay of Plenty.

25.2. Observed and Projected Climate Change

Australasia exhibits a wide diversity of climates, such as moist tropical monsoonal, arid, and moist temperate, including alpine conditions. Key climatic processes are the Asian-Australian monsoon and the southeast trade winds over northern Australia, and the subtropical high pressure belt and the mid-latitude storm tracks over southern Australia and New Zealand. Tropical cyclones also affect northern Australia, and, more rarely, ex-tropical cyclones affect some parts of New Zealand. Natural climatic variability is very high in the region, especially for rainfall and over Australia, with the El Niño-Southern Oscillation (ENSO) being the most important driver (McBride and Nicholls, 1983; Power et al., 1998; Risbey et al., 2009). The southern annular mode, Indian Ocean Dipole, and the Inter-decadal Pacific Oscillation are also important regional drivers (Thompson and Wallace, 2000; Salinger et al., 2001; Cai et al., 2009b). This variability poses particular challenges for detecting and projecting anthropogenic climate change and its impacts in the region. For example, changes in ENSO in response to anthropogenic climate change are uncertain (WGI AR5 Chapter 14) but, given current ENSO impacts, any changes would have the potential to significantly influence rainfall and temperature extremes, droughts, tropical cyclones, marine conditions, and glacial mass balance (Mullan, 1995; Chinn et al., 2005; Holbrook et al., 2009; Diamond et al., 2012; Min et al., 2013).

Understanding of observed and projected climate change has received much attention since AR4, particularly in Australia, with a focus on the causes of observed rainfall changes and more systematic analysis of projected changes from different models and approaches. Climatic extremes have also been a research focus. Table 25-1 presents an assessment of this body of research for observed trends and projected changes for a range of climatic variables (including extremes) relevant for regional impacts and adaptation, including examples of the magnitude of projected change, and attribution, where possible. Most studies are based on Coupled Model Intercomparison Project Phase 3 (CMIP3) models and *Special Report on Emission Scenarios* (SRES) scenarios, but CMIP5 model results are considered where available (see also WGI AR5 Chapter 14 and Atlas; Chapter 21).

The region has exhibited warming to the present (*very high confidence*) and is *virtually certain* to continue to do so (Table 25-1). Observed and CMIP5-modeled past and projected future annual average surface temperatures are shown in Figures 25-1 and 25-2. For further details see WGI AR5 Atlas, AI.68–69. Changes in precipitation have been observed with *very high confidence* in some areas over a range of time scales, such as increases in northwestern Australia since the 1950s, the autumn/winter decline since 1970 in southwestern Australia, and, since the 1990s, in southeastern Australia, and over 1950–2004 increases in annual rainfall in the south and west of the South Island and west of the North Island of New Zealand, and decreases in the northeast of the South Island and east and north of the North Island. Based on multiple lines of evidence, annual average rainfall is projected to decrease with *high confidence* in southwestern Australia. For New Zealand, annual average rainfall is projected to decrease in the northeastern South Island and eastern and northern North Island, and increase in other parts of the country (*medium confidence*). The direction and magnitude of rainfall change in eastern and northern Australia remains a key uncertainty (Table 25-1).

This pattern of projected rainfall change is reflected in annual average CMIP5 model results (Figure 25-1), but with important additional dimensions relating to seasonal changes and spread across models (see also WGI AR5 Atlas, AI.70–71). Examples of the magnitude of projected annual change from 1990 to 2090 (percent model mean change +/–

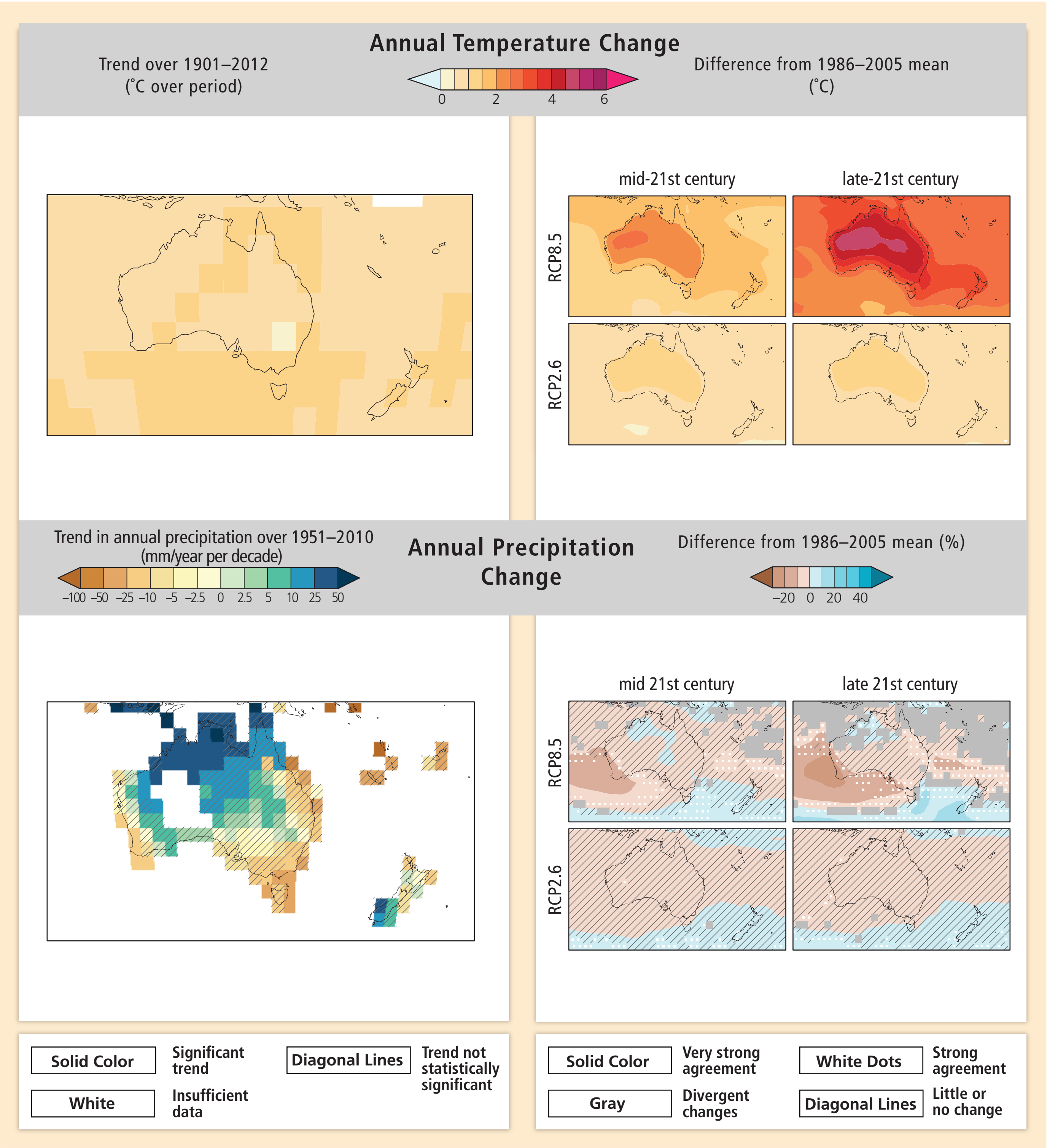

Figure 25-1 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5 Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

intermodel standard deviation) under Representative Concentration Pathway (RCP)8.5 from CMIP5 are –20 ± 13% in southwestern Australia, –2 ± 21% in the Murray-Darling Basin, and –5 ± 22% in southeast Queensland (Irving et al., 2012). Projected changes during winter and spring are more pronounced and/or consistent across models than the annual changes, for example, drying in southwestern Australia (–32 ± 11%, June to August), the Murray-Darling Basin (–16 ± 22%, June to August), and southeast Queensland (–15 ± 26%, September to November), whereas there are increases of 15% or more in the west and south of the South Island of New Zealand (Irving et al., 2012). Downscaled CMIP3 model projections for New Zealand indicate a stronger drying pattern in the southeast of the South Island and eastern and northern regions of the North Island in winter and spring (Reisinger et al., 2010) than seen in the raw CMIP5 data; based on similar broader scale changes this pattern is expected to hold once CMIP5 data are also downscaled (Irving et al., 2012).

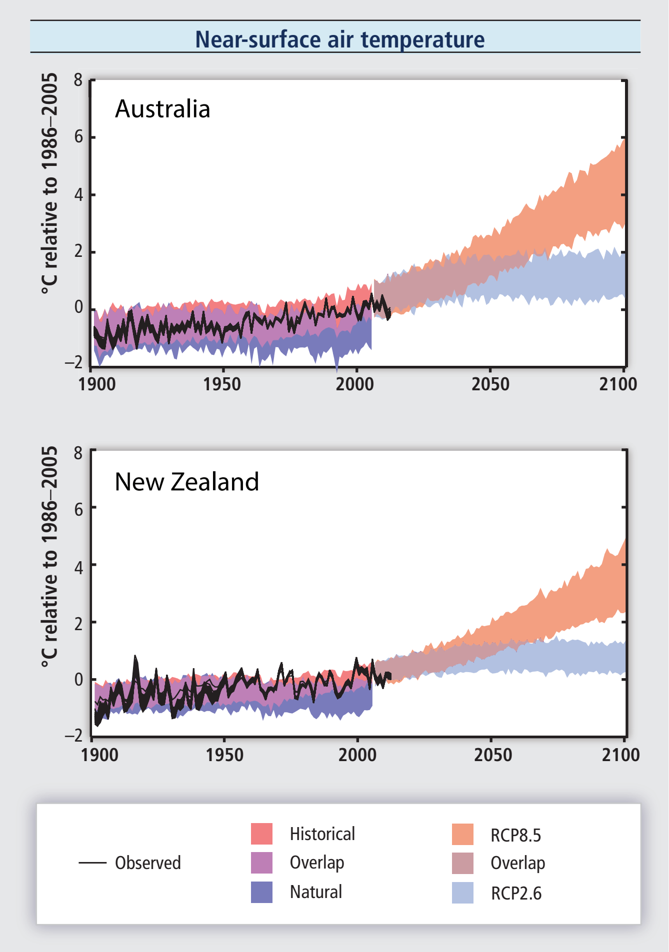

Figure 25-2 | Observed and simulated variations in past and projected future annual average near-surface air temperature over land areas of Australia (top) and New Zealand (bottom). Black lines show various estimates from observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the Representative Concentration Pathway (RCP)2.6 emissions scenario (63), and the RCP8.5 (63). Data are anomalies from the 1986–2005 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3 and Box CC-RC.

Other projected changes of at least *high confidence* include regional increases in sea surface temperature, the occurrence of hot days, fire weather in southern Australia, mean and extreme sea level, and ocean acidity (see WGI AR5 Section 6.4.4 for projections); and decreases in cold days and snow extent and depth. Although changes to tropical cyclone occurrence and that of other severe storms are potentially important for future vulnerability, regional changes to these phenomena cannot be projected with at least *medium confidence* as yet (Table 25-1).

25.3. Socioeconomic Trends Influencing Vulnerability and Adaptive Capacity

25.3.1. Economic, Demographic, and Social Trends

The economies of Australia and New Zealand rely on natural resources, agriculture, minerals, manufacturing and tourism, but the relative importance of these sectors differs between the two countries. Agriculture and mineral/energy resources accounted, respectively, for 11% and 55% (Australia) and 56% and 5% (New Zealand) of the value of total exports in 2010–2011 (ABS, 2012c; SNZ, 2012b). Water abstraction per capita in both countries is in the top half of the Organisation for Economic Co-operation and Development (OECD), decreasing since 1990 in Australia but increasing in New Zealand; more than half is used for irrigation (OECD, 2010, 2013a). Between 1970 and 2011, gross domestic product (GDP) grew by an average of 3.2% per annum in Australia and 2.4% per annum in New Zealand, with annual GDP per capita growth of 1.8% and 1.2%, respectively (SNZ, 2011; ABS, 2012d). GDP is projected to grow on average by 2.5 to 3.5% per annum in Australia and about 1.9% per annum in New Zealand to 2050 (Australian Treasury, 2010; Bell et al., 2010) but subject to significant shorter term fluctuations.

The populations of Australia and New Zealand are projected to grow significantly over at least the next several decades (*very high confidence*; ABS, 2008; SNZ, 2012a): Australia's population from 22.3 million in 2011 to 31 to 43 million by 2056 and 34 to 62 million by 2101 (ABS, 2008, 2013); New Zealand's population from 4.4 million in 2011 to 5.1 to 7.1 million by 2061 (SNZ, 2012a). The number of people aged 65 and over is projected to almost double in the next 2 decades (ABS, 2008; SNZ, 2012a). More than 85% of the Australasian population lives in urban areas and their satellite communities, mostly in coastal areas (DCC, 2009; SNZ, 2010b; UN DESA Population Division, 2012; see Box 25-9). Urban concentration and depletion of remote rural areas is expected to continue (Mendham and Curtis, 2010; SNZ, 2010c; Box 25-5), but some coastal non-urban spaces also face increasing development pressure (Freeman and Cheyne, 2008; Gurran, 2008; Box 25-1). More than 20% of Australasian residents were born overseas (OECD, 2013a).

Poverty rates and income inequality in Australia and New Zealand are in the upper half of OECD countries, and both measures increased significantly in both countries between the mid-1980s and the late 2000s (OECD, 2013a). Measurement of poverty and inequality, however, is highly contested, and it remains difficult to anticipate future changes and their effects on adaptive capacity (Peace, 2001; Scutella et al., 2009; Section 25.3.2). Indigenous peoples constitute about 2.5% and 15% of the Australian and New Zealand populations, respectively, but in

Table 25-1 | Observed and projected changes in key climate variables, and (where assessed) the contribution of human activities to observed changes. For further relevant information see WGI AR5 Chapters 3, 6 (ocean changes, including acidification), 11, 12 (projections), 13 (sea level), and 14 (regional climate phenomena). (*) *medium confidence*, (**) *high confidence*, (***) *very high confidence*, (****) *virtually certain*

Climate variable	Observed change	Direction of projected change	Examples of projected magnitude of change (relative to ~1990, unless otherwise stated)	Additional comments
Mean air temperature	Australia: Increased by 0.09 ± 0.03°C per decade since 1911[1] (***) New Zealand: Increased by 0.09 ± 0.03°C per decade since 1909[2] (***)	Australia and New Zealand: Increase[3–8] (****); greatest over inland Australia and least in coastal areas and New Zealand[5–8] (***)	Australia: 0.6–1.5°C (2030 A1B), 1.0–2.5°C (2070 B1), 2.2–5.0°C (2070 A1FI)[3] New Zealand: 0.3–1.4°C (2040 A1B), 0.7–2.3°C (2090 B1), 1.6–5.1°C (2090 A1FI)[5] Coupled Model Intercomparison Project Phase 5 (CMIP5) Representative Concentration Pathway 4.5 (RCP4.5), relative to ~1995[9]: North Australia: 0.3–1.6°C (2016–2035), 0.7–2.6°C (2046–2065) Southern Australia and New Zealand: 0.1–1.0°C (2016–2035), 0.6–1.7°C (2046–2065)	Australia: A significant contribution to observed change attributed to anthropogenic climate change[10] (**) with some regional variations attributed to atmospheric circulation variations[11,12] New Zealand: Observed change partially attributed to anthropogenic climate change[13] (*)
Sea surface temperature	Australia: Increased by about 0.12°C per decade for northwestern and northeastern Australia and by about 0.2°C per decade for southeastern Australia since 1950[14,15] (***) New Zealand: Increased by about 0.07°C per decade over 1909–2009[2] (***)	Australia and New Zealand: Increase[3,7,8] (***), with greater increase in the Tasman sea region[3,7] (*)	Australia: 0.6–1.0°C (2070 B1) and 1.6–2.0°C (2070 A1FI) for southern coastal and 1.2–1.5°C (2070 B1) and 2.2–2.5°C (2070 A1FI) elsewhere[3] New Zealand: Similar to projected changes in mean air temperature for coastal waters[5]	
Air temperature extremes	Australia and New Zealand: Significant trend since 1950: Cool extremes have become rarer and hot extremes more frequent and intense[16–19] (**). The Australian heat wave of 2012/13 was exceptional in heat, duration, and spatial extent.[20]	Australia and New Zealand: Hot days and nights more frequent and cold days and cold nights less frequent during the 21st century[3,5,21–24] (**)	Australia: Hot days in Melbourne (>35°C max.) increase by 20–40% (2030 A1B), 30–90% (2070 B1), and 70–190% (2070 A1FI)[3] New Zealand: Spring and autumn frost–free land to at least triple by 2080s[24]; up to 60 more hot days (>25°C max.) for northern areas by 2090[5]	Australia: Observed trends partly attributable to anthropogenic climate change (**) as they are consistent with mean warming and historical simulations,[18,19,21,25] although other factors may have contributed to high extremes during droughts[26–28]
Precipitation	Australia: Late autumn/winter decreases in southwestern Australia since the 1970s and in southeastern Australia since the mid–1990s, and annual increases in northwestern Australia since the 1950s[29–31] (***) New Zealand: Mean annual rainfall increased over 1950–2004 in the south and west of the South Island and west of the North Island, and decreased in the northeast of the South Island and east and north of the North Island[32] (***).	Australia: Annual decline in southwestern Australia (**), elsewhere on most of the southern (*) and northeastern (*low confidence*) continental edges, with reductions strongest in the winter half year[3,4,9,33–35] (**). Direction of annual change elsewhere is uncertain[3,35,36] (Figure 25-1) (**). New Zealand: In the South Island, annual increase in the west and south and decrease in northeast. In the North Island, increase in the west and decrease in eastern and northern regions[5,34,37] (Figure 25-1) (*)	Australia: For 2030 A1B, annual changes of –10% to +5% (northern Australia) and –10% to 0% (southern Australia); for 2070 B1, –15% to +7.5% (northern and eastern Australia) and –15% to 0% (southern Australia); and for 2070 A1FI, –30% to +20% (northern and eastern Australia) and –30% to +5% (southern Australia), with larger changes seasonally[3] New Zealand: For 2040 A1B, annual changes of –5% to +15% (southern and western) and –15% to +10% (northern and eastern) and for 2090 A1B, –10% to +25% (southern and western) and –20% to +15% (northern and eastern) based on downscaled projections with larger changes seasonally[5,37]	Australia: Observed decline in southwest is related to atmospheric circulation changes[38–40] (***) and other factors,[41] and partly attributable to anthropogenic climate change[40–43] (**). The recent southeast rainfall decline is also related to circulation changes[31,44–46] (**), with some evidence of an anthropogenic component.[47] New Zealand: Observed trends related to increased westerly winds.[32] Projected annual trends dominated by winter and spring trends related to increased westerlies[5]
Precipitation extremes	Australia: Indices of annual daily extremes (e.g., 95th and 99th percentile rainfalls) show mixed or insignificant trends,[21,48] but significant increase is evident in recent decades for shorter duration (sub-daily) events[49,50] (**). New Zealand: Extreme annual 1-day rainfall decrease in north and east and increase in west since 1930[32] (*)	Australia and New Zealand: Increase in most regions in the intensity of rare daily rainfall extremes (i.e., current 20-year return period events) and in short duration (sub-daily) extremes (*) and an increase in the intensity of 99th percentile daily extremes (*low confidence*)[5,8,21,51–56]	Australia: For 2090 A2, CMIP3 gives increases in the intensity of the 20-year daily extreme of around +200% to –25% depending on region and model.[52] New Zealand: Increases of daily extreme rainfalls of around 8% per degree Celsius are projected but with significant regional variations.[5,56]	Australia and New Zealand: The sign of observed trends mostly reflects trends in mean rainfall (e.g., there is a decrease in mean and daily extremes in southwestern Australia).[21,32,49] Similarly, future increases in intensity of extreme daily rainfall are more likely where mean rainfall is projected to increase.[3,5]
Drought	Australia: Defined using rainfall only, drought occurrence over the period 1900–2007 has not changed significantly[57] (**). New Zealand: Defined using a soil water balance model; there has been no trend in drought occurrence since 1972[58] (*).	Australia and New Zealand: Drought frequency is projected to increase in southern Australia[8,54,57,59,60] (*) and in many regions of New Zealand[58,61] (*).	Australia: Occurrence under 2070 A1B and A2 ranges from a halving to 3 times more frequent in northern Australia and 0–5 times more frequent in southern Australia.[60] New Zealand: Time spent in drought in eastern and northern New Zealand is projected to double or triple by 2040.[61]	Australia: Regional warming may have led to an increase in hydrological drought (*low confidence*).[62,63]

Table 25-1 (continued)

Climate variable	Observed change	Direction of projected change	Examples of projected magnitude of change (relative to ~1990, unless otherwise stated)	Additional comments
Winds	Australia: Significant decline in storminess over southeastern Australia since 1885[64] (*), but inconsistent trends in wind observations since 1975[65,66] New Zealand: Mean westerly flow increased during the late 20th century (1978–1998), associated with the positive phase of the Inter-decadal Pacific Oscillation[67,68]	Australia: Increases in winds in 20–30°S band, with little change to decrease elsewhere, except for winter increases over Tasmania. Decrease to little change in extremes (99th percentile) over most of Australia except Tasmania in winter[69] (*) New Zealand: Mean westerly winds and extreme winds (based on projected changes in circulation patterns) are projected to increase, especially in winter[5,70] (*).	Australia: Magnitude of simulated mean changes may exceed 10% under A1B for 2081–2100 relative to 1981–2000.[69] New Zealand: Mean westerly flow to increase by around 20% in spring and around 70% in winter, and to decrease by around 20% in summer and autumn, by 2090[5]	Australia and New Zealand: Many of past and projected changes in mean wind speed can be related to changes in atmospheric circulation.[43,67,68] New Zealand: Extreme westerlies and southerlies have slightly increased while extreme easterlies have decreased since 1960.[13,71]
Mean sea level	Australia: From 1900 to 2011 the average rate of relative sea level rise (SLR) was 1.4 ± 0.6 mm year^{-1} [72] (***). New Zealand: The average rate of relative SLR was 1.7 ± 0.1 mm year^{-1} over 1900–2009[73] (***).	Australia and New Zealand: Regional sea level rise will *very likely* exceed the 1971–2000 historical rate, consstent with global mean trends.[74] Mean sea level will continue to rise for at least several more centuries[74] (***).	Australia: Offshore regional sea level rise may exceed 10% more than global SLR; see WGI AR5 Figure 13.21.[74] New Zealand: Offshore regional sea level rise may be up to 10% more than global SLR.[75]	Australia and New Zealand: Satellite estimates of regional SLR for 1993–2009 are significantly higher than those for 1920–2000, partly reflecting climatic variability.[72,73,76,77] New Zealand: Allowing for glacial isostatic adjustment, absolute observed SLR is around 2.0 mm year^{-1}. [73,78]
Extreme sea level	Australia and New Zealand: Extreme sea levels have risen at a similar rate to global SLR.[79]	Australia and New Zealand: Projected mean SLR will lead to large increases in the frequency of extreme sea level events (***), with other changes in storm surges playing a lesser role.[80–83]	Australia: An increase of mean sea level by 0.1 m increases the frequency of an extreme sea level event by a factor of between 2 and 10 over southeastern Australia depending on location.[80–82]	
Fire weather	Australia: Increased since 1973 (**), with 24 out of 38 sites showing increases in the 90th percentile of the McArthur Forest Fire Danger Index[84]	Australia: Fire weather is expected to increase in most of southern Australia owing to hotter and drier conditions (**), based on explicit model studies carried out for southeastern Australia,[85–88] and change little or decrease in the northeast[88] (*). New Zealand: Fire danger index is projected to increase in many areas[89] (*).	Australia: Increase in days with very high and extreme fire danger index by 2–30% (2020), 5–100% (2050) (using B1 and A2 and two climate models, and 1973–2007 base)[85] New Zealand: Increase in days with very high and extreme fire danger index from around 0 to 400% (2040) and 0 to 700% (2090) (using A1B, 16 CMIP3 General Circulation Models)[89]	Australia: For the example of Canberra, the projected changes represent the current 17 days per year increasing to 18–23 days in 2020 and 20–33 days in 2050.[85]
Tropical cyclones and other severe storms	Australia: No regional change in the number of tropical cyclones (TCs) or in the proportion of intense TCs over 1981–2007[90] (*), but frequency of severe landfalling TCs in northeastern Australia has declined significantly since the late 19th century[91] and the east–west distribution has changed since 1980.[92] There has been no trend in environments suitable for severe thunderstorms.[93]	Australia: Tropical cyclones are projected to increase in intensity and stay similar or decrease in numbers,[9,94] and occur further south[94] (*low confidence*). New Zealand: Projected increase in the average intensity of cyclones in the south during winter, but a decrease elsewhere[70] (*)	Australia: One modeling study shows a 50% reduction in TC occurrence for 2051–2090 relative to 1971–2000, increases in intensity of the modeled storms, and occurence around 100 km further south.[94] New Zealand: Occurrence of conditions conducive to convective storm development is projected to increase by 3–6% by 2070–2100 (A2), relative to 1970–2000, with the largest increases over the South Island.[70]	Australia: Regional research on convective storms is limited but studies have shown a projected decrease in the frequency of cool-season tornadoes[95] and hail[3] in southern Australia, and increases in the frequency and intensity of hail in the Sydney region.[3,96]
Snow and ice	Australia: Late season significant snow depth decline at three out of four Snowy Mountain sites over 1957–2002[97] (**) New Zealand: Ice volume declined by 36–61% from the mid-late 1800s to the late 1900s[98–100], with glacier volume reducing by 15% between 1976 and 2008[101] (**).	Australia: Both snow depth and area are projected to decline[97] (***). New Zealand: Snowline elevations are projected to rise, and winter snow volume and days with low elevation snow cover are projected to decrease[5,102,103] (***).	Australia: Area with at least 30 days' cover annually is projected to decline by 14–54% (2020) and 30–93% (2050).[97] New Zealand: By 2090, peak snow accumulation is projected to decline by 32–79% at 1000 m and by 6–51% at 2000 m.[103]	New Zealand: Atmospheric circulation variations can enhance or outweigh multi-decadal trends in ice volume over time scales of up to two decades.[104,105]

References: [1]Fawcett et al. (2012); [2]Mullan et al. (2010); [3]CSIRO and BoM (2007); [4]Moise and Hudson (2008); [5]MfE (2008b); [6]AR5 WGI Atlas AI68–69; [7]AR5 WGI Ch11; [8]AR5 WGI Ch12; [9]AR5 WGI Ch14; [10]Karoly and Braganza (2005); [11]Hendon et al. (2007); [12]Nicholls et al. (2010); [13]Dean and Stott (2009); [14]Lough (2008); [15]Lough and Hobday (2011); [16]Chambers and Griffiths (2008); [17]Gallant and Karoly (2010); [18]Nicholls and Collins (2006); [19]Trewin and Vermont (2010); [20]BoM (2013); [21]Alexander and Arblaster (2009); [22]Tryhorn and Risbey (2006); [23]Griffiths et al. (2005); [24]Tait (2008); [25]Alexander et al. (2007); [26]Deo et al. (2009); [27]McAlpine et al. (2007); [28]Cruz et al. (2010); [29]Hope et al. (2010); [30]Jones et al. (2009); [31]Gallant et al. (2012); [32]Griffiths (2007); [33]Timbal and Jones (2008); [34]AR5 WGI Atlas AI70–71; [35]Irving et al. (2012); [36]Watterson (2012); [37]Reisinger et al. (2010); [38]Bates et al. (2008); [39]Frederiksen and Frederiksen (2007); [40]Hope et al. (2006); [41]Timbal et al. (2006); [42]Cai and Cowan (2006); [43]Frederiksen et al. (2011); [44]Cai et al. (2011); [45]Nicholls (2010); [46]Smith and Timbal (2010); [47]Timbal et al. (2010a); [48]Gallant et al. (2007); [49]Westra and Sisson (2011); [50]Jakob et al. (2011); [51]Abbs and Rafter (2009); [52]Rafter and Abbs (2009); [53]Kharin et al. (2013); [54]Ch3 of IPCC (2012); [55]Westra et al. (2013); [56]Carey-Smith et al. (2010); [57]Hennessy et al. (2008a); [58]Mullan et al. (2005); [59]Kirono and Kent (2010); [60]Kirono et al. (2011); [61]Clark et al. (2011); [62]Cai and Cowan (2008); [63]Nicholls (2006); [64]Alexander et al. (2011); [65]McVicar et al. (2008); [66]Troccoli et al. (2012); [67]Parker et al. (2007); [68]Mullan et al. (2001); [69]McInnes et al. (2011a); [70]Mullan et al. (2011); [71]Salinger et al. (2005); [72]Burgette et al. (2013); [73]Hannah and Bell (2012); [74]AR5 WGI Ch13; [75]Ackerley et al. (2013); [76]CSIRO and BoM (2012); [77]Meyssignac and Cazenave (2012); [78]Hannah (2004); [79]Menendez and Woodworth (2010); [80]McInnes et al. (2009); [81]McInnes et al. (2011b); [82]McInnes et al. (2012); [83]Harper et al. (2009); [84]Clarke et al. (2012); [85]Lucas et al. (2007); [86]Hasson et al. (2009); [87]Cai et al. (2009a); [88]Clarke et al. (2011); [89]Pearce et al. (2011); [90]Kuleshov et al. (2010); [91]Callaghan and Power (2011); [92]Hassim and Walsh (2008); [93]Allen and Karoly (2013); [94]Abbs (2012); [95]Timbal et al. (2010b); [96]Leslie et al. (2008); [97]Hennessy et al. (2008b); [98]Hoelzle et al. (2007); [99]Ruddell (1995); [100]Chinn (2001); [101]Chinn et al. (2012); [102]Fitzharris (2004); [103]Hendrikx et al. (2012); [104]Purdie et al. (2011); [105]Willsman et al. (2010).

Australia, their national share is growing and they constitute a much higher percentage of the population in remote and very remote regions (ABS, 2009, 2010b; SNZ, 2010a). Indigenous peoples in both countries have lower than average life expectancy, income, and education, implying that changes in socioeconomic status and social inclusion could strongly influence their future adaptive capacity (see Section 25.8.2).

25.3.2. Use and Relevance of Socioeconomic Scenarios in Adaptive Capacity/Vulnerability Assessments

Demographic, economic, and sociocultural trends influence the vulnerability and adaptive capacity of individuals and communities (see Chapters 2, 11-13, 16, 20). A limited but growing number of studies in Australasia have attempted to incorporate such information, for example, changes in the number of people and percentage of elderly people at risk (Preston et al., 2008; Baum et al., 2009; Preston and Stafford-Smith, 2009; Roiko et al., 2012), the density of urban settlements and exposed infrastructure (Preston and Jones, 2008; Preston et al., 2008; Baynes et al., 2012), population-driven pressures on water demand (Jollands et al., 2007; CSIRO, 2009), and economic and social factors affecting individual coping, planning, and recovery capacity (Dwyer et al., 2004; Khan, 2012; Roiko et al., 2012).

Socioeconomic considerations are used increasingly to understand adaptive capacity of communities (Preston et al., 2008; Smith et al., 2008; Fitzsimons et al., 2010; Soste, 2010; Brunckhorst et al., 2011) and to construct scenarios to help build regional planning capacity (Energy Futures Forum, 2006; Frame et al., 2007; Pride et al., 2010; Pettit et al., 2011; Taylor et al., 2011). Such scenarios, however, are only beginning to be used to quantify vulnerability to climate change (except, e.g., Bohensky et al., 2011; Baynes et al., 2012; Low Choy et al., 2012).

Apart from these emerging efforts, most vulnerability studies from Australasia make no or very limited use of socioeconomic factors, consider only current conditions, and/or rely on postulated correlations between generic socioeconomic indicators and climate change vulnerability. In many cases this limits confidence in conclusions regarding future vulnerability to climate change and adaptive capacity of human and mixed natural-human systems.

25.4. Cross-Sectoral Adaptation: Approaches, Effectiveness, and Constraints

25.4.1. Frameworks, Governance, and Institutional Arrangements

Adaptation responses depend heavily on institutional and governance arrangements (see Chapters 2, 14-16, 20). Responsibility for development and implementation of adaptation policy in Australasia is largely devolved to local governments and, in Australia, to State governments and Natural Resource Management bodies. Federal/central government supports adaptation mostly via provision of information, tools, legislation, policy guidance, and (in Australia) support for pilot projects. A standard risk management paradigm has been promoted to embed adaptation into decision-making practices (AGO, 2006; MfE, 2008b; Standards Australia, 2013), but broader systems and resilience approaches are used increasingly for natural resource management (Clayton et al., 2011; NRC, 2012). The Council of Australian Governments agreed a national adaptation policy framework in 2007 (COAG, 2007). This included establishing the collaborative National Climate Change Adaptation Research Facility (NCCARF) in 2008, which complemented Commonwealth Scientific and Industrial Research Organisation (CSIRO)'s Climate Adaptation Flagship. The federal government supported a first-pass national coastal risk assessment (DCC, 2009; DCCEE, 2011), is developing indicators and criteria for assessing adaptation progress and outcomes (DIICCSRTE, 2013), and commissioned targeted reports addressing impacts and management options for natural and managed landscapes (Campbell, 2008; Steffen et al., 2009; Dunlop et al., 2012), National and World Heritage areas (ANU, 2009; BMT WBM, 2011), and indigenous and urban communities (Green et al., 2009; Norman, 2010). Most State and Territory governments have also developed adaptation plans (e.g., DSE, 2013).

In New Zealand, the central government updated and expanded tools to support impact assessments and adaptation responses consistent with regulatory requirements (MfE, 2008b,c,d, 2010b), and revised key directions for coastal management (Minister of Conservation, 2010). No cross-sectoral adaptation policy framework or national-level risk assessments exist, but some departments commissioned high-level impacts and adaptation assessments after the AR4 (e.g., on agriculture and on biodiversity; Wratt et al., 2008; McGlone and Walker, 2011; Clark et al., 2012).

Public and private sector organizations are potentially important adaptation actors but exhibit large differences in preparedness, linked to knowledge about climate change, economic opportunities, external connections, size, and scope for strategic planning (Gardner et al., 2010; Taylor, B.M. et al., 2012; Johnston et al., 2013; Kuruppu et al., 2013; see also Chapters 10, 16). This creates challenges for achieving holistic societal outcomes (see also Sections 25.7-9).

Several recent policy initiatives in Australia, while responding to broader socioeconomic and environmental pressures, include goals to reduce vulnerability to climate variability and change. These include establishing the Murray-Darling Basin Authority to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011), removal of the interest rate subsidy during exceptional droughts (Productivity Commission, 2009), and management of bush fire and flood risk (VBRC, 2010; QFCI, 2012). These may be seen as examples of mainstreaming adaptation (Dovers, 2009), but they also demonstrate lag times in policy design and implementation, windows of opportunity presented by crises (e.g., the Millennium Drought of 1997–2009, the Victorian bushfires of 2009, and Queensland floods of 2011), and the challenges arising from competing interests in managing finite and changing water resources (Botterill and Dovers, 2013; Pittock, 2013; Box 25-2).

25.4.2. Constraints on Adaptation and Emerging Leading Practice Models

A rapidly growing literature since the AR4 confirms, with *high confidence*, that while the adaptive capacity of society in Australasia is generally high,

Table 25-2 | Constraints and enabling factors for institutional adaptation processes in Australasia.

Constraint	Enabling factors
Uncertainty of projections	• Improved guidance and tools to manage uncertainty and support adaptive management[1–8] • Increased focus on lead and consequence time of decisions and link with current climate variability and related risks[9–13] • Increased communication between practitioners and scientists to identify and provide decision-relevant data and context[2,3,11,13–17]
Availability and cost of data and models	• Central provision of relevant core climate and non-climate data, including regional scenarios of projected changes[4,5,7,9,18,19] • National first-pass risk assessments[4,5,7,8,18,20–24]
Limited financial and human capability and capacity; time lag in developing expertise	• Support for pilot projects[4,8,15,18,24,25] • Building capacity through institutional commitment and learning[3,5,11,17,23,26–28] • Central databases on guidance, tools, methodologies, case studies[4,5,7,18,24] • Regional partnerships and collaborations, knowledge networks[3,4,8,13,15,17,26,28–30]
Unclear problem definition and goals; unclear standards for risk assessment methodologies and decision support tools; limited monitoring and evaluation	• Explicit but iterative framing and scoping of adaptation challenge, to reflect alternative entry points for stakeholders while meeting expectations of project sponsors to ensure long-term support[3,11,17,31–34] • Tailoring decision-making frameworks to specific problems[1,2,6,17,35,36] • Criteria and tools to monitor and evaluate adaptation success[7,18,37–39]
Unclear or contradictory legislative frameworks and responsibilities, unclear liabilities	• Clear and coordinated legislative frameworks[5,8,9,15,24,40–45] • Defined responsibilities for public and private actors, including liabilities from acting and failure to act[8,9,11,24,41,44,46] • Legally binding guidance on the incorporation of climate change in planning mechanisms[5,7,8,15,38,40]
Static planning mechanisms and practice; competing mandates and fragmentation of policies; disciplinary voids or single approaches	• Whole-of-council approach to climate adaptation to break up institutional and professional silos[15,33,47] • Long-term policy commitments and implementation support[5,18,26,33,48] • Increased policy coherence across sectors, regulations, and levels of government[9,26,28,40,42,43,47] • Enabling risk-based flexible land use decisions[4,5,9,49] • Strengthening multi-disciplinarity across professional fields[14,29,48]
Lack of political leadership; short election cycles; limited community support, participation, and awareness for adaptation	• Legally binding guidance and clarification of liabilities and duty of care to reduce dependence on individual leadership[5,7–9,15,24,38,40,46,49] • Consistent but audience-specific communication of current and potential future vulnerability and implications for community values[4,5,7,26,42,43,50] • Comprehensible communication of and access to response options, and their consistency with wider development plans[7,26,28,33,39,42,43] • Clearly identified entry points for public participation[17,34,38,39,42,48,51–53]

Note: The relevance of each constraint varies among organizations, sectors, and locations. Some enabling factors are only beginning to be implemented or have only been suggested in the literature; hence their effectiveness cannot yet be evaluated. Entries for enabling factors exclude generic mechanisms, such as insurance (see Box 25-7); emergency management and early warning systems; and funding for pilot studies, capital infrastructure upgrades, or retreat schemes.

References: [1]Randall et al. (2012); [2]Verdon-Kidd et al. (2012); [3]Webb et al. (2013); [4]Mukheibir et al. (2013); [5]Lawrence et al. (2013b); [6]Nelson et al. (2008); [7]Britton (2010); [8]Gurran et al. (2008); [9]Productivity Commission (2012); [10]Stafford-Smith et al. (2011); [11]Johnston et al. (2013); [12]Park et al. (2012); [13]Power et al. (2005); [14]Reisinger et al. (2011); [15]Smith et al. (2008); [16]Stafford-Smith (2013); [17]Yuen et al. (2012); [18]Webb and Beh (2013); [19]Roiko et al. (2012); [20]DCCEE (2011); [21]DCC (2009); [22]Baynes et al. (2012); [23]Smith et al. (2010); [24]SCCCWEA (2009); [25]DSEWPC (2011); [26]Low Choy et al. (2012); [27]Gardner et al. (2010); [28]Fidelman et al. (2013); [29]Mustelin et al. (2013); [30]Serrao-Neumann et al. (2013); [31]Fünfgeld et al. (2012); [32]Kuruppu et al. (2013); [33]Britton et al. (2011); [34]Alexander et al. (2012); [35]Maru et al. (2011); [36]Preston et al. (2008); [37]Norman et al. (2013); [38]Rouse and Norton (2010); [39]Preston et al. (2011); [40]Rive and Weeks (2011); [41]Abel et al. (2011); [42]Norman (2009); [43]Gurran et al. (2006); [44]McDonald (2013); [45]Minister of Conservation (2010); [46]McDonald (2010); [47]Measham et al. (2011); [48]Rouse and Blackett (2011); [49]McDonald (2011); [50]Hine et al. (2013); [51]Burton and Mustelin (2013); [52]Hobson and Niemeyer (2011); [53]Gardner et al. (2009a).

there are formidable environmental, economic, informational, social, attitudinal, and political constraints, especially for local governments and small or highly fragmented industries. Reviews of public- and private-sector adaptation plans and strategies in Australia demonstrate strong efforts in institutional capacity building, but differences in assessment methods and weaknesses in translating goals into specific policies (White, 2009; Gardner et al., 2010; Measham et al., 2011; Preston et al., 2011; Kay et al., 2013). Similarly, local governments in New Zealand to date have focused mostly on impacts and climate-related hazards; some have developed adaptation plans, but few have committed to specific policies and steps to implementation (e.g., O'Donnell, 2007; Britton, 2010; Fitzharris, 2010; HRC, 2010; KCDC, 2012; Lawrence et al., 2013b).

Table 25-2 summarizes key constraints and corresponding enabling factors for effective institutional adaptation processes identified in Australia and New Zealand. Scientific uncertainty and resource limitations are reported consistently as important constraints, particularly for smaller councils. Ultimately more powerful constraints arise, however, from current governance and legislative arrangements and the lack of consistent tools to deal with dynamic risks and uncertainty or to evaluate the success of adaptation responses (*robust evidence*, *high agreement*; Britton, 2010; Barnett et al., 2013; Lawrence et al., 2013b; Mukheibir et al., 2013; Webb et al., 2013; see also Chapter 16).

Some constraints exacerbate others. There is *high confidence* that the absence of a consistent information base and binding guidelines that clarify governing principles and liabilities is a challenge particularly for small and resource-limited local authorities, which need to balance special interest advocacy with longer term community resilience. This heightens reliance on individual leadership subject to short-term political change and can result in piecemeal and inconsistent risk assessments and responses between levels of government and locations, and over time (Smith et al., 2008; Brown et al., 2009; Norman, 2009; Britton, 2010; Rouse and Norton, 2010; Abel et al., 2011; McDonald, 2011; Rive and Weeks, 2011; Corkhill, 2013; Macintosh et al., 2013). In these situations, planners tend to rely more on single numbers for climate projections that can be argued in court (Reisinger et al., 2011; Lawrence et al., 2013b), which increases the risk of maladaptation given

Box 25-1 | Coastal Adaptation—Planning and Legal Dimensions

Sea level rise is a significant risk for Australia and New Zealand (*very high confidence*) due to intensifying coastal development and the location of population centers and infrastructure (see Section 25.3). Under a high emissions scenario (Representative Concentration Pathway (RCP)8.5), global mean sea level would *likely* rise by 0.53 to 0.97 m by 2100, relative to 1986–2005, whereas with stringent mitigation (RCP2.6), the *likely* rise by 2100 would be 0.28 to 0.6 m (*medium confidence*). Based on current understanding, only instability of the Antarctic ice sheet, if initiated, could lead to a rise substantially above the *likely* range; evidence remains insufficient to evaluate its probability, but there is *medium confidence* that this additional contribution would not exceed several tenths of a meter during the 21st century (WGI AR5 Section 13.5). Local case studies in New Zealand (Fitzharris, 2010; Reisinger et al., 2013) and national reviews in Australia (DCC, 2009; DCCEE, 2011) demonstrate risks to large numbers of residential and commercial assets as well as key services, with widespread damages at the upper end of projected ranges (*high confidence*). In Australia, sea level rise of 1.1 m would affect more than AU$226 billion of assets, including up to 274,000 residential and 8600 commercial buildings (DCCEE, 2011), with additional intangible costs related to stress, health effects, and service disruption (HCCREMS, 2010) and ecosystems (DCC, 2009; BMT WBM, 2011). Under expected future settlement patterns, exposure of the Australian road and rail network will increase significantly once sea level rises above about 0.5 m (Baynes et al., 2012). Even if temperatures peak and decline, sea level is projected to continue to rise beyond 2100 for many centuries, at a rate dependent on future emissions (WGI AR5 Section 13.5).

Responsibility for adapting to sea level rise in Australasia rests principally with local governments through spatial planning instruments. Western Australia, South Australia, and Victoria have mandatory State planning benchmarks for 2100, with local governments determining how they should be implemented. Long-term benchmarks in New South Wales and Queensland have either been suspended or revoked, so local authorities now have broad discretion to develop their own adaptation plans. The New Zealand Coastal Policy Statement (Minister of Conservation, 2010) mandates a minimum 100-year planning horizon for assessing hazard risks, discourages hard protection of existing development, and recommends avoidance of new development in vulnerable areas. Non-binding government guidance recommends a risk-based approach, using a base value of 0.5 m sea level rise by the 2090s and considering the implications of at least 0.8 m and, for longer term planning, an additional 0.1 m per decade (MfE, 2008d).

The incorporation of climate change impacts into local planning has evolved considerably over the past 20 years, but remains piecemeal and shows a diversity of approaches (Gibbs and Hill, 2012; Kay et al., 2013). Governments have invested in high-resolution digital elevation models of coastal and flood prone areas in some regions, but many local governments still lack the resources for hazard mapping and policy design. Political commitment is variable, and legitimacy of approaches and institutions is often strongly contested (Gorddard et al., 2012), including pressure on State governments to modify adaptation policies and on local authorities to compensate developers for restrictions on current or future land uses (LGNZ, 2008; Berry and Vella, 2010; McDonald, 2010; Reisinger et al., 2011). Incremental adaptation responses can entrench existing rights and expectations about ongoing protection and development, which limit options for more transformational responses such as accommodation and retreat (*medium evidence*, *high agreement*; Gorddard et al., 2012; Barnett et al., 2013; Fletcher et al., 2013; McDonald, 2013). Strategic regional-scale planning initiatives in rapidly growing regions, like southeast Queensland, allow climate change adaptation to be addressed in ways not typically achieved by locality- or sector-specific plans, but require effective coordination across different scales of governance (Serrao-Neumann et al., 2013; Smith et al., 2013).

Courts in both countries have played an important role in evaluating planning measures. Results of litigation have varied and, in the absence of clearer legislative guidance, more litigation is expected as rising sea levels affect existing properties and adaptation responses constrain development on coastal land (MfE, 2008d; Kenderdine, 2010; Rive and Weeks, 2011; Verschuuren and McDonald, 2012; Corkhill, 2013; Macintosh, 2013).

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Box 25-1 (continued)

In addition to raising minimum floor levels and creating coastal setbacks to limit further development in areas at risk, several councils in Australia and New Zealand have consulted on or attempted to implement managed retreat policies (ECAN, 2005; BSC, 2010; HDC, 2012; KCDC, 2012). These policies remain largely untested in New Zealand, but experience in Australia has shown high litigation potential and opposing priorities at different levels of government, undermining retreat policies (SCCCWEA, 2009; DCCEE, 2010; Abel et al., 2011). Mandatory disclosure of information about future risks, community engagement, and policy stability are critical to support retreat, but existing-use rights, liability concerns, special interests, community resources, place attachment, and divergent priorities at different levels of government present powerful constraints (*high confidence*; Hayward, 2008b; Berry and Vella, 2010; McDonald, 2010; Abel et al., 2011; Alexander et al., 2012; Leitch and Robinson, 2012; Macintosh et al., 2013; Reisinger et al., 2013).

the uncertain and dynamic nature of climate risk (McDonald, 2010; Stafford-Smith et al., 2011; Gorddard et al., 2012; McDonald, 2013; Reisinger et al., 2013).

Vulnerability assessments that take mid- to late-century impacts as their starting point can inhibit actors from implementing adaptation actions, as distant impacts are easily discounted and difficult to prioritize in competition with near-term non-climate change pressures (Productivity Commission, 2012). Emerging leading practice models in Australia (Balston, 2012; HCCREMS, 2012; SGS, 2012) and New Zealand (MfE, 2008a; Britton et al., 2011) recommend a high-level scan of sectors and locations at risk and emphasize a focus on near-term decisions that influence current and future vulnerability (which could range from early warning systems to strategic and planning responses). More detailed assessment can then focus on this more tractable subset of issues, based on explicit and iterative framing of the adaptation issue (Webb et al., 2013) and taking into account the full lifetime (lead- and consequence time) of the decision/asset in question (Stafford-Smith et al., 2011).

Participatory processes help balance societal preferences with robust scientific information and ensure ownership by affected communities but rely on human capital and political commitment (*high confidence*; Hobson and Niemeyer, 2011; Rouse and Blackett, 2011; Weber et al., 2011; Leitch and Robinson, 2012). Realizing widespread and equitable participation is challenging where policies are complex, debates polarized, legitimacy of institutions contested, and potential transformational changes threaten deeply held values (Gardner et al., 2009a; Gorddard et al., 2012; Burton and Mustelin, 2013; see also Section 25.4.3). Regional approaches that engage diverse stakeholders, government, and science providers, and support the co-production of knowledge can help overcome some of these problems but require long-term institutional and financial commitments (e.g., Britton et al., 2011; DSEWPC, 2011; CSIRO, 2012; IOCI, 2012; Low Choy et al., 2012; Webb and Beh, 2013).

There is active debate about the extent to which incremental adjustments of existing planning instruments, institutions, and decision-making processes can deal adequately with the dynamic and uncertain nature of climate change and support transformational responses (Kennedy et al., 2010; Preston et al., 2011; Park et al., 2012; Dovers, 2013; Lawrence et al., 2013b; McDonald, 2013; Stafford-Smith, 2013). Recent studies suggest a greater focus on flexibility and matching decision-making frameworks to specific problems (Hertzler, 2007; Nelson et al., 2008; Dobes, 2010; Howden and Stokes, 2010; Randall et al., 2012). Limitations of mainstreamed and autonomous adaptation and the case for more proactive government intervention are being explored in Australia (Productivity Commission, 2012; Johnston et al., 2013), but have not yet resulted in new policy frameworks.

25.4.3. Psychological and Sociocultural Factors Influencing Impacts of and Adaptation to Climate Change

Adapting to climate change relies on individuals accepting and understanding changing risks and opportunities, and responding to these changes both psychologically and behaviorally (see Chapters 2, 16). The majority of Australasians accept the reality of climate change and less than 10% fundamentally deny its existence (*high confidence*; ShapeNZ, 2009; Leviston et al., 2011; Lewandowsky, 2011; Milfont, 2012; Reser et al., 2012b). Australians perceive themselves to be at higher risk from climate change than New Zealanders and citizens of many other countries, which may reflect recent experiences of climatic extremes (Gifford et al., 2009; Agho et al., 2010; Ashworth et al., 2011; Milfont et al., 2012; Reser et al., 2012c). However, beliefs about climate change and its risks vary over time, are uneven across society, and reflect media coverage and bias, political preferences, and gender (ShapeNZ, 2009; Bacon, 2011; Leviston et al., 2012; Milfont, 2012), which can influence attitudes to adaptation (Gardner et al., 2010; Gifford, 2011; Reser et al., 2011; Alexander et al., 2012; Raymond and Spoehr, 2013).

Surveys in Australia between 2007 and 2011 show moderate to high levels of climate change concern, distress, frustration, resolve, psychological adaptation, and carbon-reducing behavior (*medium evidence*, *high agreement*; Agho et al., 2010; Reser et al., 2012b,c). About two-thirds of respondents expected global warming to worsen, with about half very or extremely concerned that they or their family would be affected directly. Direct experience with environmental changes or events attributed to climate change, reported by 45% of respondents, was particularly influential, but the extent to which resulting distress and concern translate into support for planned adaptation has not been fully assessed (Reser et al., 2012a,b).

Frequently Asked Questions

FAQ 25.1 | How can we adapt to climate change if projected future changes remain uncertain?

Many existing climate change impact assessments in Australia and New Zealand focus on the distant future (2050 to 2100). When contrasted with more near-term non-climate pressures, the inevitable uncertainty of distant climate impacts can impede effective adaptation. Emerging best practice in Australasia recognizes this challenge and instead focuses on those decisions that can and will be made in the near future in any case, along with the "lifetime" of those decisions, and the risk from climate change during that lifetime. Thus, for example, the choice of next year's annual crop, even though it is greatly affected by climate, only matters for a year or two and can be adjusted relatively quickly. Even land-use change among cropping, grazing, and forestry industries has demonstrated significant flexibility in Australasia over the space of a decade. When the adaptation challenge is reframed as *implications for near-term decisions*, uncertainty about the distant future becomes less problematic and adaptation responses can be better integrated into existing decision-making processes and early warning systems.

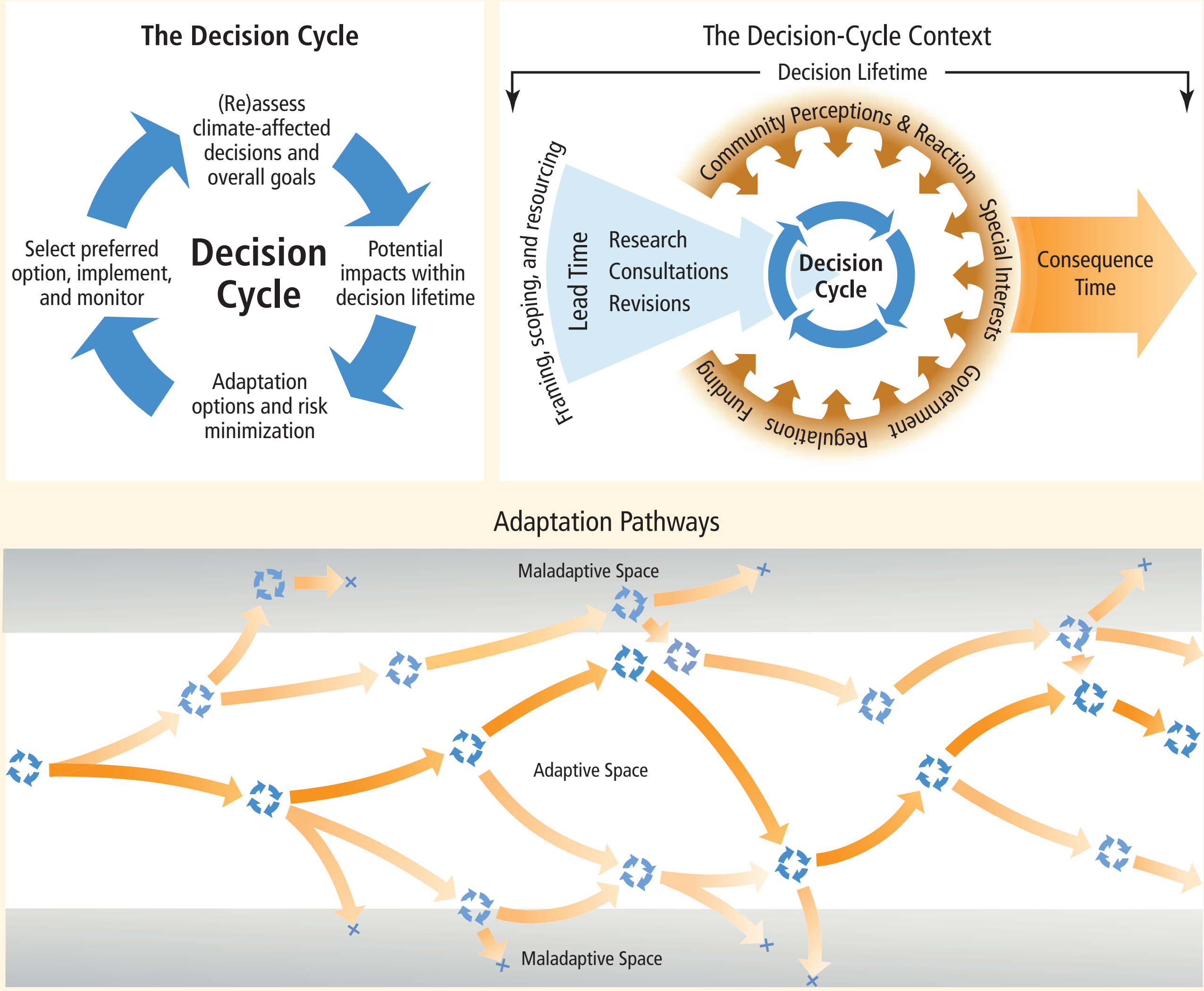

Figure 25-3 | Adaptation as an iterative risk management process. Individual adaptation decisions comprise well known aspects of risk assessment and management (top left panel). Each decision occurs within and exerts its own sphere of influence, determined by the lead and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single "correct" adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations, and goals.

Continued next page →

Frequently Asked Questions
FAQ 25.1 (continued)

Some decisions, such as those about long-lived infrastructure and spatial planning and of a public good nature, must take a long-term view and deal with significant uncertainties and trade-offs between short- and long-term goals and values. Even then, widely used techniques can help reduce challenges for decision making—including the "precautionary principle," "real options," "adaptive management," "no regrets strategies," or "risk hedging". These can be matched to the type of uncertainty but depend on a regulatory framework and institutions that can support such approaches, including the capacity of practitioners to implement them robustly.

Adaptation is not a one-off action but will take place along an evolving pathway, in which decisions will be revisited repeatedly as the future unfolds and more information comes to hand (see Figure 25-3). Although this creates learning opportunities, successive short-term decisions need to be monitored to avoid unwittingly creating an adaptation path that is not sustainable as climate change continues, or that would cope only with a limited subset of possible climate futures. This is sometimes referred to as maladaptation. Changing pathways—for example, shifting from ongoing coastal protection to gradual retreat from the most exposed areas—can be challenging and may require new types of interactions among governments, industry, and communities.

Perceived risks and potential losses from climate change depend on values associated by individuals with specific places, activities, and objects. Examples from Australia include the value placed on snow cover in the Snowy Mountains (Gorman-Murray, 2008, 2010), risks to biodiversity and recreational values in coastal South Australia (Raymond and Brown, 2011), conflicts between human uses and environmental priorities in national parks (Wyborn, 2009; Roman et al., 2010), and trade-offs between alternative water supplies and relocation in rural areas (Hurlimann and Dolnicar, 2011). These and additional studies in Australasia confirm that the more individuals identify with particular places and their natural features, the stronger the perceived potential loss but also the greater the motivation to address environmental threats (e.g., Rogan et al., 2005; McCleave et al., 2006; Collins and Kearns, 2010; Gosling and Williams, 2010; Raymond et al., 2011; Russell et al., 2013). This indicates that ecosystem-based climate change adaptation (see Box CC-EA) can provide co-benefits for subjective well-being and mental health, especially for disadvantaged and indigenous communities (Berry et al., 2010; see also Section 25.8.2).

At the same time, social and cultural values and norms can constrain adaptation options for communities by limiting the range of acceptable responses and processes (e.g., place attachment, differing values relating to near- versus long-term, private versus public, and economic versus environmental or social costs and benefits, and perceived legitimacy of institutions). Examples of this are particularly prominent in Australasia in the coastal zone (e.g., Hayward, 2008a; King et al., 2010; Gorddard et al., 2012; Hofmeester et al., 2012) and acceptance of water recycling or pricing (e.g., Pearce et al., 2007; Kouvelis et al., 2010; Mankad and Tapsuwan, 2011).

Overall, these studies give *high confidence* that the experience and threat of climate change and extreme climatic events are having appreciable psychological impacts, resulting in psychological and subsequent behavioral adaptations, reflected in high levels of acceptance and realistic concern; motivational resolve; self-reported changes in thinking, feeling, and understanding of climate change and its implications; and behavioral engagement (Reser and Swim, 2011; Reser et al., 2012a,b,c). However, adequate strategies and systems to monitor trends in psychological and social impacts, adaptation, and vulnerability are lacking, and such perspectives remain poorly integrated with and dominated by biophysical and economic characterizations of climate change impacts.

25.5. Freshwater Resources

25.5.1. Observed Impacts

Climate change impacts on water represent a cross-cutting issue affecting people, agriculture, industries, and ecosystems. The challenge of satisfying multiple demands with a limited resource is exacerbated by the high interannual and inter-decadal variability of river flows (Chiew and McMahon, 2002; Peel et al., 2004; Verdon et al., 2004; McKerchar et al., 2010) particularly in Australia. Declining river flows since the mid-1970s in far southwestern Australia have led to changed water management (see Box 11.2 in Hennessy et al., 2007). The unprecedented decline in river flows during the 1997–2009 "Millennium" drought in southeastern Australia resulted in low irrigation water allocations, severe water restrictions in urban centers, suspension of water sharing arrangements, and major environmental impacts (Chiew and Prosser, 2011; Leblanc et al., 2012).

25.5.2. Projected Impacts

Figure 25-4 shows estimated changes to mean annual runoff across Australia for a 1°C global average warming above current levels (Chiew and Prosser, 2011; Teng et al., 2012). The range of estimates arises mainly from uncertainty in projected precipitation (Table 25-1). Hydrological modelling with CMIP3 future climate projections indicates that freshwater resources in far southeastern and far southwest Australia will decline (*high confidence*; by 0 to 40% and 20 to 70%, respectively, for 2°C warming) due to the reduction in winter precipitation (Table 25-1) when most of the runoff in southern Australia occurs. The percent change in mean annual precipitation in Australia is generally amplified as a two to three times larger percent change in mean annual stream flow (Chiew, 2006; Jones et al., 2006).

This can vary, however, with unprecedented declines in flow in far southeastern Australia in the 1997–2009 drought (Cai and Cowan, 2008; Potter and Chiew, 2011; Chiew et al., 2013). Higher temperatures and associated evaporation, tree regrowth following more frequent bushfires (Kuczera, 1987; Cornish and Vertessy, 2001; Marcar et al., 2006; Lucas et al., 2007), interceptions from farm dams (van Dijk et al., 2006; Lett et al., 2009), and reduced surface-groundwater connectivity in long dry spells (Petrone et al., 2010; Hughes et al., 2012) can further accentuate declines. In the longer-term, water availability will also be affected by changes in vegetation and surface-atmosphere feedbacks in a warmer and higher CO_2 environment (Betts et al., 2007; Donohue et al., 2009; McVicar et al., 2010).

In New Zealand, precipitation changes (Table 25-1) are projected to lead to increased runoff in the west and south of the South Island and reduced runoff in the northeast of the South Island, and the east and north of the North Island (*medium confidence*). Annual flows of eastward flowing rivers with headwaters in the Southern Alps (Clutha,

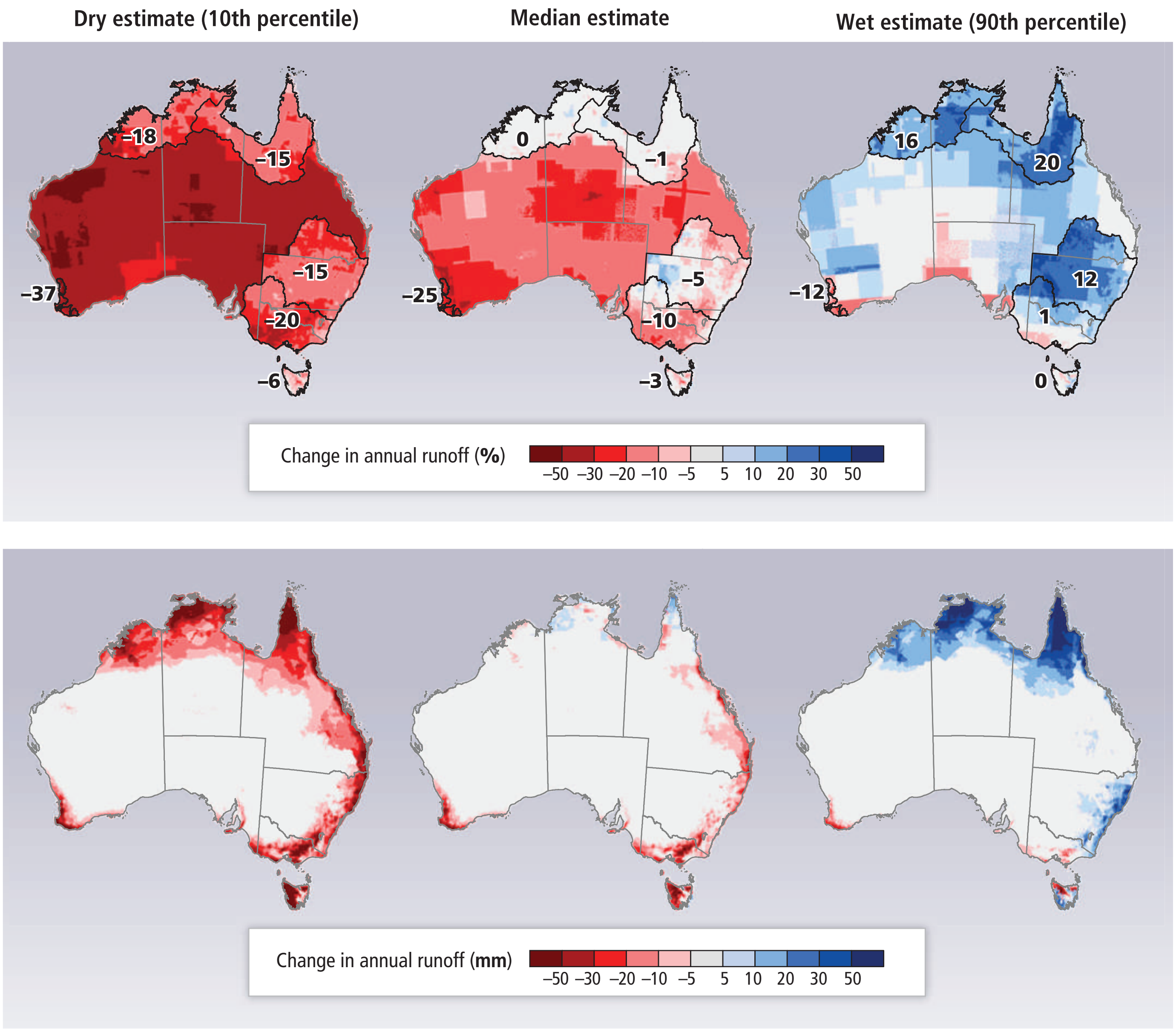

Figure 25-4 | Estimated changes in mean annual runoff for 1°C global average warming above current levels. Maps show changes in annual runoff (percentage change; top row) and runoff depth (millimeters; bottom row), for dry, median, and wet (10th to 90th percentile) range of estimates, based on hydrological modelling using 15 CMIP3 climate projections (Chiew et al., 2009; CSIRO, 2009; Petheram et al., 2012; Post et al., 2012). Projections for 2°C global average warming are about twice that shown in the maps (Post et al., 2011). (Figure adapted from Chiew and Prosser, 2011; Teng et al., 2012).

Waimakariri, Rangitata) are projected to increase by 5 to 10 % (median projection) by 2040 (Bright et al., 2008; Poyck et al., 2011; Zammit and Woods, 2011) in response to higher alpine precipitation. Most of the increases occur in winter and spring, as more precipitation falls as rain and snow melts earlier (Hendrikx et al., 2013). In contrast, the Ashley River, slightly north of this region, is projected to have little change in annual flows, with the increase in winter flows offset by reduced summer flows (Woods et al., 2008). The retreat of glaciers is expected to have only a minor impact on river flows in the first half of the century (Chinn, 2001; Anderson et al., 2008).

Climate change will affect groundwater through changes in recharge rates and the relationship between surface waters and aquifers. Dryland diffuse recharge in most of western, central, and southern Australia is projected to decrease because of the decline in precipitation, with increases in the north and some parts of the east because of projected increase in extreme rainfall intensity (*medium confidence*; Crosbie et al., 2010, 2012; McCallum et al., 2010). In New Zealand, a single study projects groundwater recharge in the Canterbury Plains to decrease by about 10% by 2040 (Bright et al., 2008). Climate change will also degrade water quality, particularly through increased material washoff following bushfires and floods (Boxes 25-6, 25-8).

25.5.3. Adaptation

The 1997–2009 drought in southeastern Australia and projected declines in future water resources in southern Australia are already stimulating adaptation (Box 25-2). In New Zealand, there is little evidence of water resources adaptation specifically to climate change. Water in New Zealand is not as scarce generally and water policy reform is driven more by pressure to maintain water quality while expanding agricultural activities, with an increasing focus on collaborative management (Memon and Skelton, 2007; Memon et al., 2010; Lennox et al., 2011; Weber et al., 2011) within national guidelines (LWF, 2010; MfE, 2011). Impacts of climate change on water supply, demand, and infrastructure have been considered by several New Zealand local authorities and consultancy reports (Jollands et al., 2007; Williams et al., 2008; Kouvelis et al., 2010), but no explicit management changes have yet resulted.

Box 25-2 | Adaptation through Water Resources Policy and Management in Australia

Widespread drought and projections of a drier future in southeastern and far southwest Australia (Bates et al., 2010; CSIRO, 2010; Potter et al., 2010; Chiew et al., 2011) saw extensive policy and management change in both rural and urban water systems (Hussey and Dovers, 2007; Bates et al., 2008; Melbourne Water, 2010; DSE, 2011; MDBA, 2011; NWC, 2011; Schofield, 2011). These management changes provide examples of adaptations, building on previous policy reforms (Botterill and Dovers, 2013). The broad policy framework is set out in the 2004 National Water Initiative and 2007 Commonwealth Water Act. The establishment of the National Water Commission (2004) and the Murray-Darling Basin Authority (2008) were major institutional reforms. The National Water Initiative explicitly recognizes climate change as a constraint on future water allocations. Official assessments (NWC, 2009, 2011) and critiques (Connell, 2007; Grafton and Hussey, 2007; Byron, 2011; Crase, 2011; Pittock and Finlayson, 2011) have discussed progress and shortcomings of the initiative, but assessment of its overall success is made difficult by other factors such as ongoing revisions to allocation plans and time lags to observable impacts.

Rural water reform in southeastern Australia, focused on the Murray-Darling Basin, is currently being implemented. The Murray-Darling Basin Plan (MDBA, 2011, 2012) will return 2750 GL yr^{-1} of consumptive water (about one-fifth of current entitlements) to riverine ecosystems and develop flexible and adaptive water sharing mechanisms to cope with current and future climates. In 2012, the Australian government committed more than AU$12 billion nationally to upgrade water infrastructure, improve water use efficiency, and purchase water entitlements for environmental use. The Basin Plan also includes an environmental watering plan to optimize environmental outcomes for the Basin. Water markets are a key policy instrument, allowing water use patterns to adapt to shifting availability and water to move toward higher value uses (NWC, 2010; Kirby et al., 2012). For example, the two-thirds reduction in irrigation water use over 2000–2009 in the Basin resulted in only 20% reduction in gross agricultural returns, mainly because water use shifted to more valuable enterprises (Kirby et al., 2012). Elsewhere, catchment management authorities and State agencies throughout southeastern Australia develop water management strategies to cope with prolonged droughts and climate change (e.g., DSE, 2011). Nevertheless, if the extreme dry end of future water projections is realized (Section 25.5.2; Figure 25-4), agriculture and ecosystems across southeastern and southwestern Australia would be threatened even with comprehensive adaptation (see Sections 25.6.1, 25.7.1-2; Connor et al., 2009; Kirby et al., 2013).

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Box 25-2 (continued)

Climate change and population growth are the two major factors that influence water planning in Australian capital cities. In Melbourne, for example, planning has centered on securing new supplies that are more resilient to major climate shocks; increasing use of alternative sources such as sewage recycling and stormwater for non-potable water; programs to reduce demand; water-sensitive urban design; and integrated planning that considers climate change impact on water supply, flood risk, and stormwater and wastewater infrastructures (DSE, 2007; Skinner, 2010; DSE, 2011; Rhodes et al., 2012). Melbourne's water augmentation program includes a desalinization plant with a 150 GL yr^{-1} capacity (about one-third of the current demand), following the lead of Perth, where a desalinization plant was established in 2006 because of declining inflows since the mid-1970s (Rhodes et al., 2012). Melbourne's water conservation strategies include water efficiency and rebate programs for business and industry, water smart gardens, dual flush toilets, grey water systems, rainwater tank rebates, free water-efficient showerheads, and voluntary residential use targets. These conservation measures, together with water use restrictions since the early 2000s, have reduced Melbourne's total per capita water use by 40% (Fitzgerald, 2009; Rhodes et al., 2012). Similar programs reduced Brisbane's per capita water use by about 50% (Shearer, 2011), while adoption of water recycling and rainwater harvesting resulted in up to 60% water savings in some parts of Adelaide (Barton and Argue, 2009).

The success of urban water reforms in the face of drought and climate change can be variously interpreted. Increasing supply through desalinization plants and water reuse schemes reduces the risk of future water shortages and helps cities cope with increasing population. Uptake of household-scale adaptation options has been locally significant but their long-term sustainability or reversibility in response to changing drivers and societal attitudes needs further research (Troy, 2008; Brown and Farrelly, 2009; Mankad and Tapsuwan, 2011). Desalinization plants can be maladaptive because of their energy demand, and the enhancement of mass supply could create a disincentive for reducing demand or increasing resilience through diversifying supply (Barnett and O'Neill, 2010; Taptiklis, 2011).

25.6. Natural Ecosystems

25.6.1. Inland Freshwater and Terrestrial Ecosystems

Terrestrial and freshwater ecosystems have suffered high rates of habitat loss and species extinctions since European settlement in both Australia and New Zealand (Kingsford et al., 2009; Bradshaw et al., 2010; McGlone et al., 2010; Lundquist et al., 2011; SoE, 2011); many reserves are small and isolated, and some key ecosystems and species under-represented (Sattler and Taylor, 2008; MfE, 2010a; SoE, 2011). Many freshwater ecosystems are pressured from over-allocation and pollution, especially in southern and eastern coastal regions in Australia (e.g., Ling, 2010). Additional stresses include erosion, changes in nutrients and fire regimes, mining, invasive species, grazing, and salinity (Kingsford et al., 2009; McGlone et al., 2010; SoE, 2011). These increase vulnerability to rapid climate change and provide challenges for both autonomous and managed adaptation (Steffen et al., 2009).

25.6.1.1. Observed Impacts

In Australian terrestrial systems, some recently observed changes in the distribution, genetics, and phenology of individual species, and in the structure and composition of some ecological communities, can be attributed to recent climatic trends (*medium* to *high confidence*; see Box 25-3). Uncertainty remains regarding the role of non-climatic drivers, including changes in atmospheric CO_2, fire management, grazing, and land use. The 1997–2009 drought had severe impacts in freshwater systems in the eastern States and the Murray-Darling Basin (Pittock and Finlayson, 2011) but, in many freshwater systems, direct climate impacts are difficult to detect above the strong signal of over-allocation, pollution, sedimentation, exotic invasions, and natural climate variability (Jenkins et al., 2011). In New Zealand, few if any impacts on ecosystems have been directly attributed to climate change rather than variability (Box 25-3; McGlone et al., 2010; McGlone and Walker, 2011). Alpine treelines in New Zealand have remained roughly stable for several hundred years (*high confidence*) despite 0.9°C average warming over the past century (McGlone and Walker, 2011; Harsch et al., 2012).

25.6.1.2. Projected Impacts

Existing environmental stresses will interact with, and in many cases be exacerbated by, shifts in mean climatic conditions and associated change in the frequency or intensity of extreme events, especially fire, drought, and floods (*high confidence*; Steffen et al., 2009; Bradstock, 2010; Murphy et al., 2012). Recent drought-related mortality has been observed for amphibians in southeast Australia (Mac Nally et al., 2009), savannah trees in northeast Australia (Fensham et al., 2009; Allen et al., 2010), Mediterranean-type eucalypt forest in southwest Western

Australia (Matusik et al., 2013), and eucalypts in sub-alpine regions in Tasmania (Calder and Kirkpatrick, 2008). Mass die-offs of flying foxes and cockatoos have been observed during heat waves (Welbergen et al., 2008; Saunders et al., 2011). These examples provide *high confidence* that extreme heat and reduced water availability, either singly or in combination, will be significant drivers of future population losses and will increase the risk of local species extinctions in many areas (e.g., McKechnie and Wolf, 2010; see also Figure 25-5).

Species distribution modeling (SDM) consistently indicates future range contractions for Australia's native species even assuming optimistic rates of dispersal, for example, Western Australian *Banksia* spp. (Fitzpatrick et al., 2008), koalas (Adams-Hosking et al., 2011), northern macropods (Ritchie and Bolitho, 2008), native rats (Green, K. et al., 2008), greater gliders (Kearney et al., 2010b), quokkas (Gibson et al., 2010), platypus (Klamt et al., 2011), birds (Garnett et al., 2013; van der Wal et al., 2013), and fish (Bond et al., 2011). In some studies, complete loss of climatically suitable habitat is projected for some species within a few decades, and therefore increased risk of local and, perhaps, global extinction (*medium confidence*). SDM has limitations (e.g., Elith et al., 2010; McGlone and Walker, 2011) but is being improved through integration with physiological (Kearney et al., 2010b) and demographic models (Keith et al., 2008; Harris et al., 2012), genetic estimates of dispersal capacity (Duckett et al., 2013), and incorporation into broader risk assessments (e.g., Williams et al., 2008; Crossman et al., 2012).

In Australia, assessments of ecosystem vulnerability have been based on observed changes, coupled with projections of future climate in relation to known biological thresholds and assumptions about adaptive capacity (e.g., Laurance et al., 2011; Murphy et al., 2012). There is *very high confidence* that one of the most vulnerable Australian ecosystems is the alpine zone because of loss of snow cover, invasions by exotic species, and changed species interactions (reviewed in Pickering et al., 2008). There is also *high confidence* in substantial risks to coastal wetlands such as Kakadu National Park subject to saline intrusion (BMT WBM, 2011); tropical savannahs subject to changed fire regimes (Laurance et al., 2011); inland freshwater and groundwater systems subject to drought, over-allocation, and altered timing of floods (Pittock et al., 2008; Jenkins et al., 2011; Pratchett et al., 2011); peat-forming wetlands along the east coast subject to drying (Keith et al., 2010); and biodiversity-rich regions such as southwest Western Australia (Yates et al., 2010a,b) and tropical and subtropical rain forests in Queensland subject to drying and warming (Stork et al., 2007; Shoo et al., 2011; Murphy et al., 2012; Hagger et al., 2013).

The very few studies of climate change impacts on biodiversity in New Zealand suggest that ongoing impacts of invasive species (Box 25-4) and habitat loss will dominate climate change signals in the short to medium term (McGlone et al., 2010), but that climate change has the potential to exacerbate existing stresses (McGlone and Walker, 2011). There is *limited evidence* but *high agreement* that the rich biota of the alpine zone is at risk through increasing shrubby growth and loss of herbs, especially if combined with increased establishment of invasive species (McGlone et al., 2010; McGlone and Walker, 2011). Some cold water-adapted freshwater fish and invertebrates are vulnerable to warming (August and Hicks, 2008; Winterbourn et al., 2008; Hitchings, 2009; McGlone and Walker, 2011) and increased spring flooding may increase risks for braided-river bird species (MfE, 2008b). For some restricted native species, suitable habitat may increase with warming (e.g., native frogs; Fouquet et al., 2010) although limited dispersal ability will limit range expansion. Tuatara populations are at risk as warming increases the ratio of males to females (Mitchell et al., 2010), although the lineage has persisted during higher temperatures in the geological past (McGlone and Walker, 2011).

25.6.1.3. Adaptation

High levels of endemism in both countries (Lindenmayer, 2007; Lundquist et al., 2011) are associated with narrow geographic ranges and associated climatic vulnerability, although there is greater scope for adaptive dispersal to higher elevations in New Zealand than in Australia. Anticipated rates of climate change, together with fragmentation of remaining habitat and limited migration options in many regions (Steffen et al., 2009; Morrongiello et al., 2011), will limit *in situ* adaptive capacity and distributional shifts to more climatically suitable areas for many species (*high confidence*). Significant local and global losses of species, functional diversity, and ecosystem services, and large-scale changes in ecological communities, are anticipated (e.g., Dunlop et al., 2012; Gallagher et al., 2012b; Murphy et al., 2012).

There is increasing recognition in Australia that rapid climate change has fundamental implications for traditional conservation objectives (e.g., Steffen et al., 2009; Prober and Dunlop, 2011; Dunlop et al., 2012; Murphy et al., 2012). Research on impacts and adaptation in terrestrial and freshwater systems has been guided by the National Adaptation Research Plans (Hughes et al., 2010; Bates et al., 2011) and by research undertaken within the CSIRO Climate Adaptation Flagship. Climate change adaptation plans developed by many levels of government and Natural Resource Management (NRM) bodies, supported by substantial Australian government funding, have identified priorities that include identification and protection of climatic refugia (Davis et al., 2013; Reside et al., 2013); restoration of riparian zones to reduce stream temperatures (Davies, 2010; Jenkins et al., 2011); construction of levees to protect wetlands from saltwater intrusion (Jenkins et al., 2011); reduction of non-climatic threats such as invasive species to increase ecosystem resilience (Kingsford et al., 2009); ecologically appropriate fire regimes (Driscoll et al., 2010); restoration of environmental flows in major rivers (Kingsford and Watson, 2011; Pittock and Finlayson, 2011); protecting and restoring habitat connectivity in association with expansion of the protected area network (Dunlop and Brown, 2008; Mackey et al., 2008; Taylor and Philp, 2010; Prowse and Brook, 2011; Maggini et al., 2013); and active interventionist strategies such as assisted colonization to reduce probability of species extinctions (Burbidge et al., 2011; McIntyre, 2011) or restore ecosystem services (Lunt et al., 2013). Few specific measures have been implemented and thus their effectiveness cannot yet be assessed. Biodiversity research and management in New Zealand to date has taken little account of climate change-related pressures and continues to focus largely on managing pressures from invasive species and predators, freshwater pollution, exotic diseases, and halting the decline in native vegetation, although a number of specific recommendations have been made to improve ecosystem resilience to future climate threats (McGlone et al., 2010; McGlone and Walker, 2011).

Climate change responses in other sectors may have beneficial as well as adverse impacts on biodiversity, but few tools to assess risks from an integrated perspective have been developed (Section 25.9.1; Box 25-10). Assessments of the impacts of climate change on the provision of ecosystem services (such as pollination and erosion control) via impacts on terrestrial and freshwater ecosystems are generally lacking. Similarly, the concept of Ecosystem-based Adaptation—the role of healthy, well-functioning ecosystems in increasing the resilience of human sectors to the impacts of climate change (see Chapters 4 and 5; Box CC-EA)—is relatively unexplored.

25.6.2. Coastal and Ocean Ecosystems

Australia's 60,000 km coastline spans tropical waters in the north to cool temperate waters off Tasmania and the sub-Antarctic islands with sovereign rights over approximately 8.1 million km^2, excluding the Australian Antarctic Territory (Richardson and Poloczanska, 2009). New Zealand has approximately 18,000 km of coastline, spanning subtropical to sub-Antarctic waters, and the world's fifth largest Exclusive Economic Zone at 4.2 million km^2 (Gordon et al., 2010). The marine ecosystems of both countries are considered hotspots of global marine biodiversity with many rare, endemic, and commercially important species (Hoegh-Guldberg et al., 2007; Blanchette et al., 2009; Gordon et al., 2010; Gillanders et al., 2011; Lundquist et al., 2011). The increasing density of coastal populations (see Section 25.3) and stressors such as pollution and sedimentation from settlements and agriculture will intensify non-climate stressors in coastal areas (*high confidence*; e.g., Russell et al., 2009). Coastal habitats provide many ecosystem services including coastal protection (Arkema et al., 2013) and carbon storage, particularly in seagrass, saltmarsh, and mangroves, which could become increasingly important for mitigation (e.g., Irving et al., 2011). Coastal ecosystems occupy less than 1% of the land mass but may account for 39% of Australia's average national annual carbon burial (estimated total: 466 millions tonnes CO_2-eq per year; Lawrence et al., 2012).

25.6.2.1. Observed Impacts

There is *high confidence* that climate change is already affecting the oceans around Australia (Pearce and Feng, 2007; Poloczanska et al., 2007; Lough and Hobday, 2011) and warming the Tasman sea in northern New Zealand (Sutton et al., 2005; Lundquist et al., 2011); average climate zones have shifted south by more than 200 km along the northeast and about 100 km along the northwest Australian coasts since 1950 (Lough, 2008). The rate of warming is even faster in southeast Australia, with a poleward advance of the East Australia Current of approximately 350 km over the past 60 years (Ridgway, 2007). Based on elevated rates of ocean warming, southwest and southeast Australia are recognized as global warming hotspots (Wernberg et al., 2011). It is *virtually certain* that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades in Australia as elsewhere (Howard et al., 2012; see also WGI AR5 Sections 3.8, 6.44).

Recently observed changes in marine systems around Australia are consistent with warming oceans (*high confidence*; Box 25-3). Examples include changes in phytoplankton productivity (Thompson et al., 2009; Johnson et al., 2011); species abundance of macroalgae (Johnson et al., 2011); growth rates of abalone (Johnson et al., 2011), southern rock lobster (Pecl et al., 2009; Johnson et al., 2011), coastal fish (Neuheimer et al., 2011), and coral (De'ath et al., 2009); life cycles of southern rock lobster (Pecl et al., 2009) and seabirds (Cullen et al., 2009; Chambers et al., 2011); and distribution of subtidal seaweeds (Johnson et al., 2011; Wernberg et al., 2011; Smale and Wernberg, 2013), plankton (Mcleod et al., 2012), fish (Figueira et al., 2009; Figueira and Booth, 2010; Last et al., 2011; Madin et al., 2012), sea urchins (Ling et al., 2009), and intertidal invertebrates (Pitt et al., 2010).

Habitat-related impacts are more prevalent in northern Australia (Pratchett et al., 2011), while distribution changes are reported more often in southern waters (Madin et al., 2012), particularly southeast Australia, where warming has been greatest. The 2011 marine heat wave in Western Australia caused the first-ever reported bleaching at Ningaloo reef (Abdo et al., 2012; Feng et al., 2013), resulting in coral mortality (Moore et al., 2012; Depczynski et al., 2013) and changes in community structure and composition (Smale and Wernberg, 2013; Wernberg et al., 2013). About 10% of the observed 50% decline in coral cover on the Great Barrier Reef since 1985 has been attributed to bleaching, the remainder to cyclones and predators (De'ath et al., 2012).

Changes in distribution and abundance of marine species in New Zealand are primarily linked to ENSO-related variability that dominates in many time series (Clucas, 2011; Lundquist et al., 2011; McGlone and Walker, 2011; Schiel, 2011), although water temperature is also important (e.g., Beentjes and Renwick, 2001). New Zealand fisheries exported more than NZ$1.5 billion worth of product in 2012 (SNZ, 2013) and variability in ocean circulation and temperature plays an important role in local fish abundance (e.g., Chiswell and Booth, 2005; Dunn et al., 2009); no climate change impacts have been reported at this stage (Dunn et al., 2009), although this may be due to insufficient monitoring.

25.6.2.2. Projected Impacts

Even though evidence of climate impacts on coastal habitats is limited to date, *confidence* is *high* that negative impacts will arise with continued climate change (Lovelock et al., 2009; McGlone and Walker, 2011; Traill et al., 2011; Chapter 6). Some coastal habitats such as mangroves are projected to expand further landward, driven by sea level rise and exacerbated by soil subsidence if rainfall declines (*medium confidence*; Traill et al., 2011), although this may be at the expense of saltmarsh and constrained in many regions by the built environment (DCC, 2009; Lovelock et al., 2009; Rogers et al., 2012). Estuarine habitats will be affected by changing rainfall or sediment discharges, as well as connectivity to the ocean (*high confidence*; Gillanders et al., 2011). Loss of coastal habitats and declines in iconic species will result in substantial impacts on coastal settlements and infrastructure from direct impacts such as storm surge, and will affect tourism (*medium confidence*; Section 25.7.5).

Changes in temperature and rainfall, and sea level rise, are expected to lead to secondary effects, including erosion, landslips, and flooding, affecting coastal habitats and their dependent species, for example, loss of habitat for nesting birds (*high confidence*; Chambers et al., 2011). Increasing ocean acidification is expected to affect many taxa (*medium confidence*; see also Box CC-OA; Chapters 6, 30) including corals (Fabricius et al., 2011), coralline algae (Anthony et al., 2008), calcareous plankton (Richardson et al., 2009; Thompson et al., 2009; Hallegraeff, 2010), reef fishes (Munday et al., 2009; Nilsson et al., 2012), bryozoans, and other benthic calcifiers (Fabricius et al., 2011). Deep-sea scleractinian corals are also expected to decline with ocean acidification (Miller et al., 2011).

The AR4 identified the Great Barrier Reef as highly vulnerable to both warming and acidification (Hennessy et al., 2007). Recent observations of bleaching (GBRMPA, 2009a) and reduced calcification in both the Great Barrier Reef and other reef systems (Cooper et al., 2008; De'ath et al., 2009; Cooper et al., 2012), along with model and experimental studies (Hoegh-Guldberg et al., 2007; Anthony et al., 2008; Veron et al., 2009) confirm this vulnerability (see also Box CC-CR). The combined impacts of warming and acidification associated with atmospheric CO_2 concentrations in excess of 450 to 500 ppm are projected to be associated with increased frequency and severity of coral bleaching, disease incidence and mortality, in turn leading to changes in community composition and structure including increasing dominance by macroalgae (*high confidence*; Hoegh-Guldberg et al., 2007; Veron et al., 2009). Other stresses, including rising sea levels, increased cyclone intensity, and nutrient-enriched and freshwater runoff, will exacerbate these impacts (*high confidence*; Hoegh-Guldberg et al., 2007; Veron et al., 2009; GBRMPA, 2013). Thermal thresholds and the ability to recover from bleaching events vary geographically and between species (e.g., Diaz-Pulido et al., 2009) but evidence of the ability of corals to adapt to rising temperatures and acidification is limited and appears insufficient to offset the detrimental effects of warming and acidification (*robust evidence*, *medium agreement*; Hoegh-Guldberg, 2012; Howells et al., 2013; Box CC-CR).

Under all SRES scenarios and a range of CMIP3 models, pelagic fishes such as sharks, tuna, and billfish are projected to move further south on the east and west coasts of Australia (*high confidence*; Hobday, 2010). These changes depend on sensitivity to water temperature, and may lead to shifts in species-overlap with implications for by-catch management (Hartog et al., 2011). Poleward movements are also projected for coastal fish species in Western Australia (Cheung et al., 2012) and a complex suite of impacts are expected for marine mammals (Schumann et al., 2013). A strengthening East Auckland Current in northern New Zealand is expected to promote establishment of tropical or subtropical species that currently occur as vagrants in warm La Niña years (Willis et al., 2007). Such shifts suggest potentially substantial changes in production and profit of both wild fisheries (Norman-Lopez et al., 2011) and aquaculture species such as salmon, mussels, and oysters (*medium confidence*; Hobday et al., 2008; Hobday and Poloczanska, 2010). Ecosystem models also project changes to habitat and fisheries production (*low confidence*; Fulton, 2011; Watson et al., 2012).

25.6.2.3. Adaptation

In Australia, research on marine impacts and adaptation has been guided by the National Adaptation Research Plan for Marine Biodiversity and Resources (Mapstone et al., 2010), programs within the CSIRO Climate Adaptation Flagship, and the Great Barrier Reef Marine Park Authority (GBRMPA, 2007). Limits to autonomous adaptation are unknown for almost all species, although limited experiments suggests capacity for response on a scale comparable to projected warming for some species (e.g., coral reef fish; Miller et al., 2012) and not others (e.g., Antarctic krill; Kawaguchi et al., 2013). Planned adaptation options include removal of human barriers to landward migration of species, beach nourishment, management of environmental flows to maintain estuaries (Jenkins et al., 2010), habitat provision (Hobday and Poloczanska, 2010), assisted colonization of seagrass and species such as turtles (e.g., Fuentes et al., 2009), and burrow modification for nesting seabirds (Chambers et al., 2011).

For southern species on the continental shelf, options are more limited because suitable habitat will not be present—the next shallow water to the south is Macquarie Island. There is *low confidence* about the adequacy of autonomous rates of adaptation by species, although recent experiments with coral reef fish suggest that some species may adapt to the projected climate changes (Miller et al., 2012).

Management actions to increase coral reef resilience include reducing fishing pressure on herbivorous fish, protecting top predators, managing runoff quality, and minimizing other human disturbances, especially through marine protected areas (Hughes et al., 2007; Veron et al., 2009; Wooldridge et al., 2012). Such actions will slow, but not prevent, long-term degradation of reef systems once critical thresholds of ocean temperature and acidity are exceeded (*high confidence*), and so novel options, including assisted colonization and shading critical reefs, have been proposed but remain untested at scale (Rau et al., 2012). Seasonal forecasting can also prepare managers for bleaching events (Spillman, 2011).

Adaptation by the fishing industry to shifting distributions of target species is considered possible by most stakeholders (e.g., southern rock lobster fishery; Pecl et al., 2009). Assisted colonization to maintain production in the face of declining recruitment may also be possible for some high value species, and has been trialed for the southern rock lobster (Green, B.S. et al., 2010). Options for aquaculture include disease management, alternative site selection, and selective breeding (Battaglene et al., 2008), but implementation is only preliminary. Marine protected area planning is not explicitly considering climate change in either country, but reserve performance will be affected by projected environment shifts and novel combinations of species, habitats, and human pressures (Hobday, 2011).

25.7. Major Industries

25.7.1. Production Forestry

Australia has about 149 Mha of forests, including woodlands. Two Mha are plantations and 9.4 Mha multiple-use native forests, and forestry contributes around AU$7 billion annually to GDP (ABARES, 2012). New Zealand's plantation estate in production forests comprises about 1.7 Mha (90% *Pinus radiata*), with recent contractions due to increased profitability of dairying (FOA and MPI, 2012; MfE, 2013).

Box 25-3 | Impacts of a Changing Climate in Natural and Managed Ecosystems

Observed changes in species, and in natural and managed ecosystems (Sections 25.6.1-2, 25.7.2) provide multiple lines of evidence of the impacts of a changing climate. Examples of observations published since the AR4 are shown in Table 25-3.

Table 25-3 | Examples of detected changes in species, natural and managed ecosystems, consistent with a climate change signal, published since the AR4. Confidence in detection of change is based on the length of study and the type, amount, and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate being a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change. (SST = sea surface temperature; EAC = East Australian Current.)

Type of change and nature of evidence	Examples	Time scale of observations	Confidence in the detection of biological change	Potential climate change driver(s)	Confidence in the role of climate vs other drivers
Morphology *Limited evidence* (one study)	Declining body size of southeast Australian passerine birds, equivalent to ~7° latitudinal shift (Gardner et al., 2009)	About 100 years	*Medium*: Trend significant for 4 out of 8 species; 2 other species show same trend but not statistically significant	Warming air temperatures about 1.0°C over same period	*Medium*: Nutritional cause discounted
Geographic distribution *High agreement, robust evidence* for many marine species and mobile terrestrial species	Southerly range extension of the barrens-forming sea urchin *Centrostephanus rodgersii* from the New South Wales coast to Tasmania; flow on impacts to marine communities including lobster fishery; shift of 160 km per decade over 30 years (Ling, 2008; Ling et al., 2008, 2009; Banks et al., 2010)	About 30–50 years (first recorded in Tasmania in late 1970s)	*High*	Increased SST, ocean warming in southeast Australia, increased southerly penetration of the EAC, 350 km over 60 years	*High*
	45 fish species, representing 27 families (about 30% of the inshore fish families occurring in the region), exhibited major distributional shifts in Tasmania (Last et al., 2011).	Distributions from late 1880s, 1980s and present (1995–now)	*High*	Increased SST in southeast Australia, increased southerly penetration of the EAC	*Medium*: Changed fishing practices have potentially contributed to trends.
	Southward range shift of intertidal species (average minimum distance 116 km) off west coast of Tasmania; 55% species recorded at more southerly sites; only 3% species expanded to more northerly sites (Pitt et al., 2010).	About 50 years; sites resampled 2007–2008, compared with 1950s	*Medium*	Increased SST in southeast Australia (average 0.22°C per decade), increased southerly penetration of the EAC, 350 km over 60 years	*Medium*
Life cycles *Robust evidence, medium agreement*; increasing documentation of advances in phenology in some species (mainly migration and reproduction in birds, emergence in butterflies, flowering in plants) but also significant trends toward later life cycle events in some taxa; see meta-analysis for Southern Hemisphere phenology (Chambers et al., 2013a)	Significant advance in mean emergence date of 1.5 days per decade (1941–2005) in the Common Brown Butterfly *Heteronympha merope* in Australia (Kearney et al., 2010)	65 years	*High*	Increase in local air temperatures of 0.16°C per decade (1945–2007)	*High*: Advance consistent with physiologically based model of temperature influence on development
	Advances in spring phenology of migratory birds, and both advances and delays in phenology in other seasons at multiple Australian sites: meta-analysis of 52 species and 145 data sets (Chambers et al., 2013b)	Multiple time periods from 1960s, all included 1990s and 2000s	*High*	Local climate trends (increasing air temperature, decreased rain days) were more important than broad-scale drivers such as the Southern Oscillation Index. Strongest associations were with decreased rain days.	*High*: No other potential confounding factors identified
	Earlier wine-grape ripening at 9 of 10 sites in Australia (Webb, L. B. et al., 2012)	Multiple time periods up to 64 years (average 41 years)	*High*	Increased length of growing season, increased average temperature, and reduced soil moisture	*Medium*: Changed husbandry techniques, resulting in lower crop yields, may have contributed to trend.
	Timing of migration of glass eels, *Anguilla* spp., advanced by several weeks in Waikato River, North Island, New Zealand (Jellyman et al., 2009).	30 years (2004–2005 compared to 1970s)	*Medium*	Warming water temperatures in spawning grounds	*Low*: Changes in discharge discounted as contributing factor

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Box 25-3 (continued)

Table 25-3 (continued)

Type of change and nature of evidence	Examples	Time scale of observations	Confidence in the detection of biological change	Potential climate change driver(s)	Confidence in the role of climate vs other drivers
Marine productivity *Limited evidence, medium agreement*	Otolith ("ear stone") analyses in long-lived Pacific fish indicates significantly increased growth rates for shallow-water species (<250 m) (3 of 3 species), reduced growth rates of deep-water (>1000 m) species (3 of 3 species); no change observed in the 2 intermediate-depth species (Thresher et al., 2007).	Birth years ranged 1861–1993 (fish 2–128 years old)	*High*	Increasing growth rates in species in top 250 m associated with warming SST, declining growth rates in species >1000 m associated with long-term cooling (as indicated by Mg/Ca ratios and change in ^{18}O in deep water corals)	*Medium*: Changed fishing pressure may have contributed to trend.
	About a 50% decline in growth rate and biomass of spring phytoplankton bloom in western Tasman Sea (Thompson et al., 2009)	60-year data set; decline recorded over period 1997–2007	*High*	Increased SST and extension of the EAC associated with reduced nutrient availability	*Medium*
Vegetation change *Limited agreement and evidence*; interacting impacts of changed land practices; altered fire regimes, increasing atmospheric CO_2 concentration and climate trends difficult to disentangle	Expansion of monsoon rainforest at expense of eucalypt savannah and grassland in Northern Territory, Australia (Banfai and Bowman, 2007; Bowman et al., 2010)	About 40 years	*Medium*	Increases in rainfall and atmospheric CO_2	*Medium*: Changes in fire regimes and land management practices may have contributed to trend.
	Net increase in mire wetland extent (10.2%) and corresponding contraction of adjacent eucalypt woodland in seven sub-catchments in southeast Australia (Keith et al., 2010)	Weather data covers >40 years (depending on parameter); vegetation mapping from 1961 to 1998.	*Medium*	Decline in evapo-transpiration	*Low*: Resource exploitation, fire history, and autogenic mire development discounted
Freshwater communities *Limited evidence* (one study)	Decline in families of macroinvertebrates that favor cooler, faster-flowing habitats in New South Wales streams and increase in families favoring warmer and more lentic conditions (Chessman, 2009)	13 years (1994–2007)	*Medium*	Increasing water temperatures and declining flows	*Low*: Variation in sampling, changes in water quality, impacts of impoundment and water extraction may have contributed to trends.
Disease *Limited evidence, robust agreement*	Emergence and increased incidence of coral diseases including white syndrome (since 1998) and black band disease (since 1993–1994) (Bruno et al., 2007; Sato et al., 2009; Dalton et al., 2010)	1998 onwards	*Medium*	Increasing SST	*High*
Coral reefs *Robust evidence, high agreement*	Multiple mass bleaching events since 1979 (see Sections 25.6.2 and 30.5)	1979 onwards	*High*	Increasing SST	*High*
	Calcification of *Porites* on GBR declined 21% (1971–2003, 4 reefs; Cooper et al., 2008); about 11% (1990–2005, 69 reefs; De'ath et al., 2009)	1971–2003; 1990–2005	*High*	Increasing SST	*High*: Changes in water quality discounted

25.7.1.1. Observed and Projected Impacts

Existing climate variability and other confounding factors have so far prevented the detection of climate change impacts on forests. Modeled projections are based on ecophysiological responses of forests to CO_2, water, and temperatures. In Australia, potential changes in water availability will be most important (*very high confidence*; e.g., reviews by Battaglia et al., 2009; Medlyn et al., 2011b). Modeling future distributions or growth rates indicate that plantations in southwest Western Australia are most at risk due to declining rainfall, and there is *high confidence* that plantation growth will be reduced by temperature increases in hotter regions, especially where species are grown at the upper range of their temperature tolerances (Medlyn et al., 2011a). Moderate reductions in rainfall and increased temperature could be offset by fertilization from increasing CO_2 (*limited evidence*, *medium agreement*; Simioni et al., 2009). In cool regions where water is not limiting, higher temperatures could benefit production (Battaglia et al., 2009). In New Zealand, temperatures are mostly sub-optimal for growth of *P. radiata* and water relations are generally less limiting (Kirschbaum and Watt, 2011). Warming is expected to increase *P. radiata* growth in the cooler south (*very high confidence*), whereas in the warmer north, temperature increases can reduce productivity, but CO_2 fertilization may offset this (*medium confidence*; Kirschbaum et al., 2012).

Modeling studies are limited by their reliance on key assumptions which are difficult to verify experimentally, for example, the degree to which photosynthesis remains stimulated under elevated CO_2 (Battaglia et al., 2009). Most studies also exclude impacts of pests, diseases, weeds, fire, and wind damage that may change adversely with climate. Fire, for instance, poses a significant threat in Australia and is expected to worsen with climate change (see Box 25-6), especially for the commercial forestry plantations in the southern winter-rainfall regions (Williams et al., 2009; Clarke et al., 2011). In New Zealand, changes in biotic factors are particularly important as they already affect plantation productivity. *Dothistroma* blight, for instance, is a serious pine disease with a temperature optimum that coincides with New Zealand's warmer, but not warmest, pine-growing regions; under climate change, its severity is, therefore, expected to reduce in the warm central North Island but increase in the cooler South Island (*high confidence*) where it could offset temperature-driven improved plantation growth (Watt et al., 2011a). There is *medium evidence* and *high agreement* of similar future southward shifts in the distribution of existing plantation weed, insect pest, and disease species in Australia (see review in Medlyn et al., 2011b).

25.7.1.2. Adaptation

Depending on the extent of climate changes and plant responses to increasing CO_2, the above studies provide *limited evidence* but *high agreement* of potential net increased productivity in many areas, but only where soil nutrients are not limiting. Adaptation strategies include changes to species or provenance selection toward trees better adapted to warmer conditions, or adopting different silvicultural options to increase resilience to climatic or biotic stresses, such as pest challenges (White et al., 2009; Booth et al., 2010; Singh et al., 2010; Wilson and Turton, 2011a). The greatest barriers to long-term adaptation planning are incomplete knowledge of plant responses to increased CO_2 and uncertainty in regional climate scenarios (*medium evidence*, *high agreement*; Medlyn et al., 2011b). The rotation time of plantation forests of about 30 years or more makes proactive adaptation important but also challenging.

25.7.2. Agriculture

Australia produces 93% of its domestic food requirements and exports 76% of agricultural production (PMSEIC, 2010a). New Zealand agriculture contributes about 56% of total export value and dairy products 27%; 95% of dairy products are exported (SNZ, 2012b). Agricultural production is sensitive to climate (especially drought; Box 25-5) but also to many non-climate factors such as management, which thus far has limited both detection and attribution of climate-related changes (see Chapters 7, 18; Webb, L.B. et al., 2012; Darbyshire et al., 2013). Because the region is a major exporter—providing, for example, more than 40% of the world trade in dairy products—changes in production conditions in the region have a major influence on world supply (OECD, 2011). This implies that climate change impacts could have consequences for food security not just locally but even globally (Qureshi et al., 2013a).

25.7.2.1. Projected Impacts and Adaptation—Livestock Systems

Livestock grazing dominates land use by area in the region. At the Australian national level, the net effect of a 3°C temperature increase (from a 1980–1999 baseline) is expected to be a 4% reduction in gross value of the beef, sheep, and wool sector (McKeon et al., 2008). Dairy productivity is projected to decline in all regions of Australia other than Tasmania under a mid-range (A1B) climate scenario by 2050 (Hanslow et al., 2013). Projected changes in national pasture production for dairy, sheep, and beef pastures in New Zealand range from an average reduction of 4% across climate scenarios for the 2030s (Wratt et al., 2008) to increases of up to 4% for two scenarios in the 2050s (Baisden et al., 2010) when the models included CO_2 fertilization and nitrogen feedbacks.

Studies modeling seasonal changes in fodder supply show greater sensitivity in animal production to climate change and elevated CO_2 than models using annual average production, with some impacts expected even under modest warming (*high confidence*) in both New Zealand (Lieffering et al., 2012) and Australia (Moore and Ghahramani, 2013). Across 25 sites in southern Australia (an area that produces 85% of sheep and 40% of beef production by value) modeled profitability declined at most sites by the 2050s because of a shorter growing season due to changes in both rainfall and temperature (Moore and Ghahramani, 2013). In New Zealand, projected changes in seasonal pasture growth drove changes in animal production at four sites representing the main areas of sheep production (Lieffering et al., 2012). In Hawke's Bay, changes in stock number and the timing of grazing were able to maintain farm income for a period in the face of variable forage supply but not in the longer term. In Southland and Waikato, projected increases in early spring pasture growth posed management problems in maintaining pasture quality, yet, if these were met, animal production could be maintained or increased. The temperature-humidity index (THI), an indicator of potential heat stress for animals, increased from 1960 to 2008 in the Murray Dairy region of Australia and further increases and reductions in milk production are projected (Nidumolu et al., 2011). Shading can substantially reduce, but not avoid, the temperature and humidity effects that produce a high THI (Nidumolu et al., 2011).

Rainfall is a key determinant of interannual variability in production and profitability of pastures and rangelands (Radcliffe and Baars, 1987; Steffen et al., 2011) yet remains the most uncertain change. In northern Australia, incremental adaptation may be adequate to manage risks of climate change to the grazing industry but an increasing frequency of droughts and reduced summer rainfall will potentially drive the requirement for transformational change (Cobon et al., 2009). Rangelands that are currently water-limited are expected to show greater sensitivity to temperature and rainfall changes than nitrogen-limited ones (Webb, N.P. et al., 2012). The "water-sparing" effect of elevated CO_2 (offsetting reduced water availability from reduced rainfall and increased temperatures) is invoked in many impact studies but does not always translate into production benefits (Kamman et al., 2005; Newton et al., 2006; Stokes and Ash, 2007; Wan et al., 2007). The impact of elevated CO_2 on forage production, quality, nutrient cycling, and water availability remains the major uncertainty in modeling system responses (McKeon et al., 2009; Finger et al., 2010); recent findings of grazing impacts on plant species composition (Newton et al., 2013) and nitrogen fixation (Watanabe et al., 2013) under elevated CO_2 have added to this uncertainty. New Zealand agro-ecosystems are subject to erosion processes strongly driven by climate; greater certainty in projections of rainfall, particularly storm frequency, are needed to better understand

Box 25-4 | Biosecurity

Biosecurity is a high priority for Australia and New Zealand given the economic importance of biologically based industries and risks to endemic species and iconic ecosystems. The biology and potential risk from invasive and native pathogenic species will be altered by climate change (*high confidence*; Roura-Pascual et al., 2011), but impacts may be positive or negative depending on the particular system.

Table 25-4 | Examples of potential consequences of climate change for invasive and pathogenic species relevant to Australia and New Zealand, with consequence categories based on Hellman et al. (2008).

Consequence	Projected change	Organism/ecosystem affected
Altered mechanisms of transport and introduction	Increased risk of introduction of Asiatic citrus psyllid (*Diaphorina citri*), vector of the disease huanglongbing[1]	Australian citrus industry and native citrus and other rutaceous species and endemic psyllid fauna
Altered distribution of existing invasive and pathogenic species	*Nassella neesiana* (Chilean needle grass): Increased droughts favor establishment.[2]	Managed pasture in New Zealand
	Warming and drying may encourage the spread of existing invasives such as *Pheidole megacephala* in New Zealand and provide suitable conditions for other exotic ant species if they invade.[3]	Human health and potentially agricultural and natural ecosystems
	Reduced climatic suitability for exotic invasive grasses in Australia (11 species including *Nassella* sp.)[4]	Australian rangeland
	Range of the invasive weed *Lantana camara* (lantana) projected to extend from north Australia to Victoria, southern Australia, and Tasmania[5]	Multiple
	Projected increases in the range of three recently naturalized subtropical plants (*Archontophoenix cunninghamiana*, *Psidium guajava*, *Schefflera actinophylla*)[6]	Native ecosystems in New Zealand
Altered climatic constraints on invasive and pathogenic species	Queensland fruit fly (*Bactrocera tryoni*) moving southwards[7]	Australian horticulture
	Significant association between amphibian declines in upland rainforests of north Queensland and three consecutive years of warm weather suggests future warming could increase the vulnerability of frogs to chytridiomycosis caused by the chytrid fungus *Batrachochytrium dendrobatadis*.[8]	Native frogs
Altered impact of existing invasive and pathogenic species	*Fusarium pseudograminearum* causing crown rot increases under elevated CO_2.[9]	Australian wheat
	Increased abundance of the root-feeding nematode *Longidorus elongatus* under elevated CO_2[10]	New Zealand pasture
	Increased severity of Swiss needle cast disease caused by *Phaeocryptopus gaeumannii*[11]	Douglas fir plantations in New Zealand, impact more severe in North Island
Altered effectiveness of management strategies	Light brown apple moth, *Epiphyas postvittana* (Walker) (*Lepidoptera: Tortricidae*) reduction in natural enemies due to asynchrony and loss of host species[12]	Australian horticulture
	Projected changes in the efficacy of five biological control systems demonstrating a range of potential disruption mechanisms[13]	Pastoral and horticultural systems in New Zealand

References: [1]Finlay et al. (2009); [2]Bourdôt et al. (2012); [3]Harris and Barker (2007); [4]Gallagher et al. (2012a); [5]Taylor, S. et al. (2012); [6]Sheppard (2012); [7]Sutherst et al. (2000); [8]Laurance (2008); [9]Melloy et al. (2010); [10]Yeates and Newton (2009); [11]Watt et al. (2011b); [12]Thomson et al. (2010); [13]Gerard et al. (2012).

climate change impacts on erosion and consequent changes in the ecosystem services provided by soils (Basher et al., 2012).

25.7.2.2. Projected Impacts and Adaptation—Cropping

Experiments with elevated CO_2 at two sites with different temperatures have shown a wide range in the response of current wheat cultivars (Fitzgerald et al., 2010). Modeling suggests there is the potential to increase New Zealand wheat yields under climate change with appropriate choices of cultivars and sowing dates (*high confidence*; Teixeira et al., 2012). In Australia, the selection of appropriate cultivars and sowing times is projected to result in increased wheat yields in high rainfall areas such as southern Victoria under climate change and in maintenance of current yields in some areas expected to be drier (e.g., northwestern Victoria; O'Leary et al., 2010). However, if extreme low rainfall scenarios are realized in areas such as South Australia then changes in cultivars and fertilizer applications are not expected to maintain current yields by 2080 (Luo et al., 2009). Under the more severe climate scenarios and without adaptation, Australia could become a net importer of wheat (Howden et al., 2010). One caveat to modeling studies is that an intercomparison of 27 wheat models found large differences between model outputs for already dry and hot Australian sites in response to increasing CO_2 and temperature (Asseng et al., 2013; Carter, 2013).

Rice production in Australia is largely dependent on irrigation, and climate change impacts will strongly depend on water availability and price (Gaydon et al., 2010). Sugarcane is also strongly water dependent (Carr and Knox, 2011); yields may increase where rainfall is unchanged or increased, but rising temperatures could drive up evapotranspiration and increase water use (*medium confidence*; Park et al., 2010).

Box 25-5 | Climate Change Vulnerability and Adaptation in Rural Areas

Rural communities in Australasia have higher proportions of older and unemployed people than urban populations (Mulet-Marquis and Fairweather, 2008). Employment and economic prospects depend heavily on the physical environment and hence are highly exposed to climate (averages, variability, and extremes) as well as changing commodity prices. These interact with other economic, social, and environmental pressures, such as changing government policies (e.g., on drought, carbon pricing; Productivity Commission, 2009; Nelson et al., 2010) and access to water resources. The vulnerability of rural communities differs within and between countries, reflecting differences in financial security, environmental awareness, policy and social support, strategic skills, and capacity for diversification (Bi and Parton, 2008; Marshall, 2010; Nelson et al., 2010; Hogan et al., 2011b; Kenny, 2011).

Climate change will affect rural industries and communities through impacts on resource availability and distribution, particularly water. Decreased availability and/or increased demand, or price, in response to climate change will increase tensions among agricultural, mining, urban, and environmental water users (*very high confidence*), with implications for governance and participatory adaptation processes to resolve conflicts (see Sections 25.4.2, 25.6.1, 25.7.2-3; Boxes 25-2, 25-10). Communities will also be affected through direct impacts on primary production, extraction activities, critical infrastructure, population health, and recreational and culturally significant sites (Kouvelis et al., 2010; Balston et al., 2012; see Sections 25.7-8).

Altered production and profitability risks and/or land use will translate into complex and interconnected effects on rural communities, particularly income, employment, service provision, and reduced volunteerism (Stehlik et al., 2000; Bevin, 2007; Kerr and Zhang, 2009). The prolonged drought in Australia during the early 2000s, for example, had many interrelated negative social impacts in rural communities, including farm closures, increased poverty, increased off-farm work, and, hence, involuntary separation of families, increased social isolation, rising stress and associated health impacts, including suicide (especially of male farmers), accelerated rural depopulation, and closure of key services (*robust evidence*, *high agreement*; Alston, 2007, 2010, 2012; Edwards and Gray, 2009; Hanigan et al., 2012; see also Box CC-GC). Positive social change also occurred, however, including increased social capital through interaction with community organizations (Edwards and Gray, 2009). While social and cultural changes have the potential to undermine the adaptive capacity of communities (Smith, W. et al., 2011), robust ongoing engagement between farmers and the local community can contribute to a strong sense of community and enhance potential for resilience (McManus et al., 2012; see also Section 25.4.3).

The economic impact of droughts on rural communities and the entire economy can be substantial. The most recent drought in Australia (2006/7–2008/9), for example, is estimated to have reduced national GDP by about 0.75% (RBA, 2006) and regional GDP in the southern Murray-Darling Basin was about 5.7% below forecast in 2007/08, along with the temporary loss of 6000 jobs (Wittwer and Griffith, 2011). Widespread drought in New Zealand during 2007–2009 reduced direct and off-farm output by about NZ$3.6 billion (Butcher, 2009). The 2012–2013 drought in New Zealand is estimated to have reduced national GDP by 0.3 to 0.6% and contributed to a significant rise in global dairy prices, which tempered even greater domestic economic losses (Kamber et al., 2013). Drought frequency and severity are projected to increase in many parts of the region (Table 25-1).

The decisions of rural enterprise managers have significant consequences for and beyond rural communities (Pomeroy, 1996; Clark and Tait, 2008). Many current responses are incremental, responding to existing climate variability (Kenny, 2011). Transformational change has occurred where industries and individuals are relocating part of their operations in response to recent and/or expectations of future climate or policy change (Kenny, 2011; see also Box 25-10), for example, rice (Gaydon et al., 2010), wine grapes (Park et al., 2012), peanuts (Thorburn et al., 2012), or changing and diversifying land use *in situ* (e.g., the recent switch from grazing to cropping in South Australia; Howden et al., 2010). Such transformational changes are expected to become more frequent and widespread with a changing climate (*high confidence*; Section 25.7.2), with positive or negative implications for the wider communities in origin and destination regions (Kiem and Austin, 2012).

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Box 25-5 (continued)

Although stakeholders within rural communities differ in their vulnerabilities and adaptive capacities, they are bound by similar dependence on critical infrastructure and resources, economic conditions, government policy direction, and societal expectations (Loechel et al., 2013). Consequently, adaptation to climate change will require an approach that devolves decision making to the level where the knowledge for effective adaptations resides, using open communication, interaction, and joint planning (Nelson et al., 2008; Kiem and Austin, 2013).

Observed trends and modeling for wine grapes suggest that climate change will lead to earlier budburst, ripening, and harvest for most regions and scenarios (*high confidence*; Grace et al., 2009; Sadras and Petrie, 2011; Webb, L.B. et al., 2012). Without adaptation, reduced quality is expected in all Australian regions (*high confidence*; Webb et al., 2008). Change in cultivar suitability in specific regions is expected (Clothier et al., 2012), with potential for development of cooler or more elevated sites within some regions (Tait, 2008; Hall and Jones, 2009) and/or expansion to new regions, with some growers in Australia already relocating (e.g., to Tasmania; Smart, 2010).

Climate change and elevated CO_2 impacts on weeds, pests, and diseases are highly uncertain (see Box 25-4). Future performance of currently effective plant resistance mechanisms under temperature and elevated CO_2 is particularly important (Melloy et al., 2010; Chakraborty et al., 2011), as is the future efficacy of widely used biocontrol—that is, the introduction or stimulation of natural enemies to control pests (Gerard et al., 2012). Australia is ranked second and New Zealand fourth in the world in the number of biological control agent introductions (Cock et al., 2010).

25.7.2.3. Integrated Adaptation Perspectives

Future water demand by the sector is critical for planning (Box 25-2). Irrigated agriculture occupies less than 1% of agricultural land in Australia but accounted for 28% of gross agricultural production value in 2010–11; almost half of this was produced within the Murray-Darling Basin, which used 68% of all irrigation water (ABS, 2012b; DAFF, 2012). Reduced inflow under dry climate scenarios is predicted to reduce substantially the value of agricultural production in the Basin (*robust evidence*, *high agreement*; Garnaut, 2008; Quiggin et al., 2010; Qureshi et al., 2013b)—for example, in one study by 12 to 44% to 2030 and 49 to 72% to 2050 (A1F1; Garnaut, 2008).

Water availability also constrains agricultural expansion: 17 Mha in northern Australia could support cropping but only 1% has appropriate water availability (Webster et al., 2009). In New Zealand, the irrigated area has risen by 82% since 1999 to more than 1 Mha; 76% is on pasture (Rajanayaka et al., 2010). The New Zealand dairy herd doubled between 1980–2009 expanding from high rainfall zones (>2000 mm annual) into drier, irrigation-dependent areas (600 to 1000 mm annual); this dependence will increase with further expansion (Robertson, 2010), which is being supported by the Government's Irrigation Acceleration Fund.

Many adaptation options—such as flexible water allocation, irrigation, and seasonal forecasting—support managing risk in the current climate (Howden et al., 2008; Botterill and Dovers, 2013) and adoption is often high (Hogan et al., 2011a; Kenny, 2011).

However, incremental on-farm adaptation has limits (Park et al., 2012) and may hinder transformational change such as diversification of land use or relocation (see Box 25-5) if it encourages persistence where climate change may take current systems beyond their response capacity (Marshall, 2010; Park et al., 2012; Rickards and Howden, 2012). In many cases, transformational change requires a greater level of commitment, access to more resources, and greater integration across all levels of decision making that encompass both on- and off-farm knowledge, processes and values (Marshall, 2010; Rickards and Howden, 2012).

25.7.3. Mining

Australia is the world's largest exporter of coking coal and iron ore and has the world's largest resources of brown coal, nickel, uranium, lead, and zinc (ABS, 2012c). Recent events demonstrated significant vulnerability to climate extremes: the 2011 floods reduced coal exports by 25 to 54 million tonnes and led to AU$5 to 9 billion revenue lost in that year (ABARES, 2011; RBA, 2011), and tropical cyclones regularly disrupted mining operations over the past decade (McBride, 2012; Sharma et al., 2013). Flood impacts were exacerbated by regulatory constraints on mine discharges, highlighting tensions among industry, social, and ecological management objectives (QRC, 2011), and by flooding affecting road and rail transport to major shipping ports (QRC, 2011; Sharma et al., 2013).

Projected changes in climate extremes imply increasing sector vulnerability without adaptation (*high confidence*; Hodgkinson et al., 2010a,b). Stakeholders have conducted initial climate risk assessments (Mills, 2009) and perceive the adaptive capacity of the industry to be high (Hodgkinson et al., 2010a; Loechel et al., 2010; QRC, 2011), but costs and broader benefits are yet to be explored along the value chain and evaluated for community support. Ongoing challenges include competition for energy and water, climate change skepticism, dealing with contrasting extremes, avoiding maladaptation, and mining-community relations regarding response options, acceptable mine discharges, and post-mining rehabilitation (Loechel et al., 2013; Sharma et al., 2013).

Box 25-6 | Climate Change and Fire

Fire during hot, dry, and windy summers in southern Australia can cause loss of life and substantial property damage (Cary et al., 2003; Adams and Attiwill, 2011). The "Black Saturday" bushfires in Victoria in February 2009, for example, burned more than 3500 km^2, caused 173 deaths, destroyed more than 2000 buildings, and caused damages of AU$4 billion (Cameron et al., 2009; VBRC, 2010). This fire occurred toward the end of a 13-year drought (CSIRO, 2010) and after an extended period of consecutive days over 30°C (Tolhurst, 2009).

Climate change is expected to increase the number of days with very high and extreme fire weather (Table 25-1), with greater changes where fire is weather-constrained (most of southern Australia; many, in particular eastern and northern, parts of New Zealand) than where it is constrained by fuel load and ignitions (tropical savannahs in Australia). Fire season length will be extended in many already high-risk areas (*high confidence*) and so reduce opportunities for controlled burning (Lucas et al., 2007). Higher CO_2 may also enhance fuel loads by increasing vegetation productivity in some regions (Donohue et al., 2009; Williams et al., 2009; Bradstock, 2010; Hovenden and Williams, 2010; King et al., 2011).

Climate change and fire will have complex impacts on vegetation communities and biodiversity (Williams et al., 2009). Greatest impacts in Australia are expected in sclerophyll forests of the southeast and southwest (Williams et al., 2009). Most New Zealand native ecosystems have limited exposure but also limited adaptations to fire (Ogden et al., 1998; McGlone and Walker, 2011). There is *high confidence* that increased fire incidence will increase risk in southern Australia to people, property, and infrastructure such as electricity transmission lines (Parsons Brinkerhoff, 2009; O'Neill and Handmer, 2012; Whittaker et al., 2013) and in parts of New Zealand where urban margins expand into rural areas (Jakes et al., 2010; Jakes and Langer, 2012); exacerbate some respiratory conditions such as asthma (Johnston et al., 2002; Beggs and Bennett, 2011); and increase economic risks to plantation forestry (Watt et al., 2008; Pearce et al., 2011). Forest regeneration following wildfires also reduces water yields (Brown et al., 2005; MDBC, 2007), while reduced vegetation cover increases erosion risk and material washoff to waterways with implications for water quality (Shakesby et al., 2007; Wilkinson et al., 2009; Smith, H.G. et al., 2011).

In Australia, fire management will become increasingly challenging under climate change, potentially exacerbating conflicting management objectives for biodiversity conservation versus protection of property (*high confidence*; O'Neill and Handmer, 2012; Whittaker et al., 2013). Current initiatives center on planning and regulations, building design to reduce flammability, fuel management, early warning systems, and fire detection and suppression (Handmer and Haynes, 2008; Preston et al., 2009; VBRC, 2010; O'Neill and Handmer, 2012). Some Australian authorities are taking climate change into account when rethinking approaches to managing fire to restore ecosystems while protecting human life and properties (Preston et al., 2009; Adams and Attiwill, 2011). Improved understanding of climate drivers of fire risk is assisting fire management agencies, landowners, and communities in New Zealand (Pearce et al., 2008, 2011), although changes in management to date show little evidence of being driven by climate change.

25.7.4. Energy Supply, Demand, and Transmission

Energy demand is projected to grow by 0.5 to 1.3% per annum in Australasia over the next few decades in the absence of major new policies (MED, 2011; Syed, 2012). Australia's predominantly thermal power generation is vulnerable to drought-induced water restrictions, which could require dry-cooling and increased water use efficiency where rainfall declines (Graham et al., 2008; Smart and Aspinall, 2009). Depending on carbon price and technology costs, renewable electricity generation in Australia is projected to increase from 10% in 2010–11 to approximately 33 to 50% by 2030 (Hayward et al., 2011; Stark et al., 2012; Syed, 2012), but few studies have explored the vulnerability of these new energy sources to climate change (Bryan et al., 2010; Crook et al., 2011; Odeh et al., 2011). New Zealand's predominantly hydroelectric power generation is vulnerable to precipitation variability. Increasing winter precipitation and snow melt, and a shift from snowfall to rainfall will reduce this vulnerability (*medium confidence*) as winter/spring inflows to main hydro lakes are projected to increase by 5 to 10% over the next few decades (McKerchar and Mullan, 2004; Poyck et al., 2011). Further reductions in seasonal snow and glacial melt as glaciers diminish, however, would compromise this benefit (Chinn, 2001; Renwick et al., 2009; Srinivasan et al., 2011). Increasing wind power generation (MED, 2011) would benefit from projected increases in mean westerly winds but face increased risk of damages and shutdown during extreme winds (Renwick et al., 2009).

Climate warming would reduce annual average peak electricity demands by 1 to 2% per degree Celsius across New Zealand and 2(±1)% in New South Wales, but increase by 1.1(±1.4)% and 4.6(±2.7)% in Queensland and South Australia due to air conditioning demand (Stroombergen et al., 2006; Jollands et al., 2007; Thatcher, 2007; Nguyen et al., 2010). Increased summer peak demand, particularly in Australia (see also Figure 25-5), will place additional stress on networks and can result in blackouts (*very high confidence*; Jollands et al., 2007; Thatcher, 2007; Howden and Crimp, 2008; Wang et al., 2010a). During the 2009 Victorian heat wave, demand rose by 24% but electrical losses from transmission lines increased by 53% due to higher peak currents (Nguyen et al., 2010), and successive failures of the overloaded network temporarily left more than 500,000 people without power (QUT, 2010). Various adaptation options to limit increasing urban energy demand exist and some are being implemented (see Box 25-9).

There is *limited evidence* but *high agreement* that without additional adaptation, distribution networks in most Australian states will be at high risk of failure by 2031–2070 under non-mitigation scenarios due to increased bushfire risk and potential strengthening and southward shift of severe cyclones in tropical regions (Maunsell and CSIRO, 2008; Parsons Brinkerhoff, 2009). Adaptation costs have been estimated at AU$2.5 billion to 2015, with more than half to meet increasing demand for air conditioning and the remainder to increase resilience to climate-related hazards; underground cabling would reduce bushfire risk but has large investment costs that are not included (Parsons Brinkerhoff, 2009). Decentralized ownership of assets constitutes a significant adaptation constraint (ATSE, 2008; Parsons Brinkerhoff, 2009). In New Zealand, increasing high winds and temperatures have been identified qualitatively as the most relevant risks to transmission (Jollands et al., 2007; Renwick et al., 2009).

25.7.5. Tourism

Tourism contributes 2.6 to 4% of GDP to the economies of Australia and New Zealand (ABS, 2010a; SNZ, 2011). The net present value of the Great Barrier Reef alone over the next 100 years has been estimated at AU$51.4 billion (Oxford Economics, 2009). Most Australasian tourism is exposed to climate variability and change (see Section 25.2 for projected trends), and some destinations are highly sensitive to extreme events (Hopkins et al., 2012). The 2011 floods and Tropical Cyclone Yasi, for example, cost the Queensland tourism industry about AU$590 million, mainly due to cancellations and damage to the Great Barrier Reef (PwC, 2011); and drought in the Murray-Darling Basin caused an estimated AU$70 million loss in 2008 due to reduced visitor days (TRA, 2010).

25.7.5.1. Projected Impacts

Future impacts on tourism have been modeled for several Australian destinations. The Great Barrier Reef is expected to degrade under all climate change scenarios (Sections 25.6.2, 30.5; Box CC-CR), reducing its attractiveness (Marshall and Johnson, 2007; Bohensky et al., 2011; Wilson and Turton, 2011b). Ski tourism is expected to decline in the Australian Alps due to snow cover reducing more rapidly than in New Zealand (Pickering et al., 2010; Hendrikx et al., 2013) and greater perceived attractiveness of New Zealand (Hopkins et al., 2012). Higher temperature extremes in the Northern Territory are projected with *high confidence* to increase heat stress and incur higher costs for air conditioning (Turton et al., 2009). Sea level rise places pressures on shorelines and long-lived infrastructure but implications for tourist resorts have not been quantified (Buckley, 2008).

Economic modeling suggests that the Australian alpine region would be most negatively affected in relative terms due to limited alternative activities (Pham et al., 2010), whereas the competitiveness of some destinations (e.g., Margaret River in Western Australia) could be enhanced by higher temperatures and lower rainfall (Jones et al., 2010; Pham et al., 2010). An analog-based study suggests that, in New Zealand, warmer and drier conditions mostly benefit but wetter conditions and extreme climate events undermine tourism (Wilson and Becken, 2011). *Confidence* in outcomes is *low*, however, owing to uncertain future tourist behaviour (Scott et al., 2012; see also Section 25.9.2).

25.7.5.2. Adaptation

Both New Zealand and Australia have formalized adaptation strategies for tourism (Becken and Clapcott, 2011; Zeppel and Beaumont, 2011). In Australia, institutions at various levels also promote preparation for extreme events (Tourism Queensland, 2007, 2010; Tourism Victoria, 2010) and strengthening ecosystem resilience to maintain destination attractiveness (GBRMPA, 2009b). Snow-making is already broadly adopted to increase reliability of skiing (Bicknell and McManus, 2006; Hennessy et al., 2008b), but its future effectiveness depends on location. In New Zealand, even though warming will significantly reduce the number of days suitable for snow-making (Hendrikx and Hreinsson, 2012), sufficient snow could be made in all years until the end of the 21st century to maintain current minimum operational skiing conditions. Options for resorts in Australia's Snowy Mountains are far more limited (Hendrikx et al., 2013), where maintaining skiing conditions until at least 2020 would require AU$100 million in capital investment into 700 snow guns and 2.5 to 3.3 GL of water per month (Pickering and Buckley, 2010).

Short investment horizons, high substitutability, and a high proportion of human capital compared with built assets give *high confidence* that the adaptive capacity of the tourism industry is high overall, except for destinations where climate change is projected to degrade core natural assets and diversification opportunities are limited (Evans et al., 2011; Morrison and Pickering, 2011). Strategic adaptation decisions are constrained by uncertainties in regional climatic changes (Turton et al., 2010), limited concern (Bicknell and McManus, 2006), lack of leadership, and limited coordinated forward planning (Sanders et al., 2008; Turton et al., 2009; Roman et al., 2010; White and Buultjens, 2012). An integrated assessment of tourism vulnerability in Australasia is not yet possible owing to limited understanding of future changes in tourism and community preferences (Scott et al., 2012), including the flow-on effects of changing travel behavior and tourism preferences in other world regions (see Section 25.9.2).

25.8. Human Society

25.8.1. Human Health

25.8.1.1. Observed Impacts

Life expectancy in Australasia is high, but shows substantial ethnic and socioeconomic inequalities (Anderson et al., 2006). Mortality increases in hot weather in Australia (*robust evidence*, *high agreement*; Bi and Parton, 2008; Vaneckova et al., 2008) with air pollution exacerbating this association. The last 4 decades have seen a steady increase in the ratio of summer to winter mortality in Australia, indicating a health effect from climatic warming (Bennett et al., 2013). Exceptional heat wave conditions in Australia have been associated with substantial increases in mortality and hospital admissions in several regional towns and capital cities (*high confidence*; Khalaj et al., 2010; Loughnan et al., 2010; Tong et al., 2010a,b). For example, during the heat wave in January and February 2009 in southeastern Australia (BoM, 2009), total emergency cases increased by 46% over the three hottest days: direct heat-related health problems increased 34-fold, 61% of these being in people aged 75 years or older, and there were an estimated 374 excess deaths, a 62% increase in all-cause mortality (Victorian Government, 2009a). Mental health admissions increased across all age groups by 7.3% in metropolitan South Australia during heat waves (1993–2006; Hansen et al., 2008). Mortality attributed to mental and behavioral disorders increased in the 65- to 74-year age group and in persons with existing mental health problems (Hansen et al., 2008). Experience of extreme events also strongly affects psychological well-being (see Section 25.4.3).

25.8.1.2. Projected Impacts

Projected increases in heat waves (Figure 25-5) will increase heat-related deaths and hospitalizations, especially among the elderly, compounded by population growth and aging (*high confidence*; Bambrick et al., 2008;

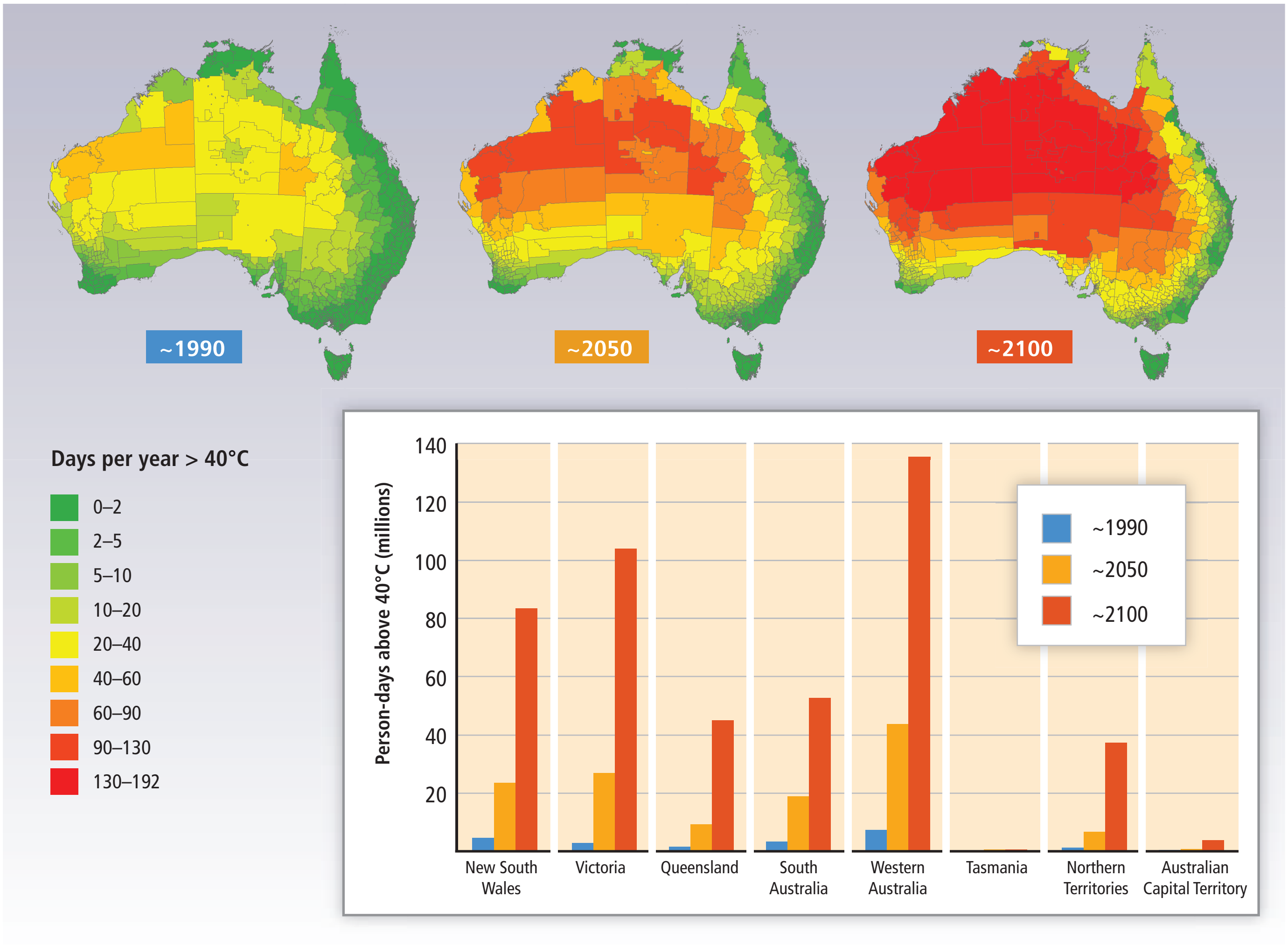

Figure 25-5 | Projected changes in exposure to heat under a high emissions scenario (A1FI). Maps show the average number of days with peak temperatures >40°C, for approximately 1990 (based on available meteorological station data for the period 1975–2004), approximately 2050, and approximately 2100. Bar charts show the change in population heat exposure, expressed as person-days exposed to peak temperatures >40°C, aggregated by State/Territory and including projected population growth for a default scenario. Future temperatures are based on simulations by the Geophysical Fluid Dynamics Laboratory Coupled Model version 2 (GFDL-CM2) global climate model (Meehl et al., 2007), re-scaled to the A1FI scenario; simulations based on other climate models could give higher or lower results. Data from Baynes et al. (2012).

Box 25-7 | Insurance as a Climate Risk Management Tool

Insurance helps spread the risk from extreme events across communities and over time and therefore enhances the resilience of society to disasters (see Section 10.7). In Australia, insured losses are dominated by meteorological hazards, including the 2011 Queensland floods and the 1999 Sydney hailstorm (ICA, 2012) with estimated claims of AU$3 billion per annum (IAA, 2011b). In New Zealand, floods and storms are the second most costly natural hazards after earthquakes (ICNZ, 2013). The number of damaging insured events (up to a certain loss value) has increased significantly in the Oceania region since 1980 (Schuster, 2013). Normalized losses in Australia show no significant trend from at least 1967 to 2006 (Crompton and McAneney, 2008; Crompton et al., 2010; Table 10-4), consistent with the global conclusion (IPCC, 2012) that increasing exposure of people and economic assets has been the major cause of long-term increases in economic losses from weather- and climate-related disasters. Issues relating to data quality and methodological choices prevent definitive conclusions regarding the role of climate change in loss trends (Crompton et al., 2011; Nicholls, 2011; IPCC, 2012).

There is *high confidence* that, without adaptive measures, projected increases in extremes (Table 25-1) and uncertainties in these projections will lead to increased insurance premiums, exclusions, and non-coverage in some locations (IAG, 2011), which will reshape the distribution of vulnerability, for example, through unaffordability or unavailability of cover in areas at highest risk (IAA, 2011a,b; NDIR, 2011; Booth and Williams, 2012). Restriction of cover occurred in some locations following the 2011 flood events in Queensland (Suncorp, 2013).

Insurance can contribute positively to risk reduction by providing incentives to policy holders to reduce their risk profile (O'Neill and Handmer, 2012), for example, through resilience ratings given to buildings (TGA, 2009; Edge Environment, 2011; IAG, 2011). Apart from constituting an autonomous private sector response to extreme events, insurance can also be framed as a form of social policy to manage climate risks, similar to New Zealand's government insurance scheme (Glavovic et al., 2010); government measures to reduce or avoid risks also interact with insurance companies' willingness to provide cover (Booth and Williams, 2012). Yet insurance can also act as a constraint on adaptation, if those living in climate-risk prone localities pay discounted or cross-subsidized premiums or policies fail to encourage betterment after damaging events by requiring replacement of "like for like," constituting a missed opportunity for risk reduction (NDIR, 2011; QFCI, 2012; Reisinger et al., 2013; see also Section 10.7). The effectiveness of insurance thus depends on the extent to which it is linked to a broader national resilience approach to disaster mitigation and response (Mortimer et al., 2011).

Gosling et al., 2009; Huang et al., 2012). In the southern states of Australia and parts of New Zealand, this may be partly offset by reduced deaths from cold at least for modest rises in temperature (*low confidence*; Bambrick et al., 2008; Kinney, 2012). With strong mitigation, climate change is projected to result in 11% fewer temperature-related deaths in both 2050 and 2100 in Australia, but 14% and 100% more deaths in 2050 and 2100, respectively, without mitigation under a hot, dry A1FI scenario (Bambrick et al., 2008; see Chapter 11 for detail on temperature-related health trade-offs). Net results were driven almost entirely by increased mortality in the north, especially Queensland, consistent with Huang et al. (2012). In a separate study that accounted for increased daily temperature variability, a threefold increase in heat-related deaths is projected for Sydney by 2100 for the A2 scenario, assuming no adaptation (Gosling et al., 2009). The number of hot days when physical labor in the sun becomes dangerous is also projected to increase substantially in Australia by 2070, leading to economic costs from lost productivity, increased hospitalizations, and occasional deaths (*medium confidence*; Hanna et al., 2011; Maloney and Forbes, 2011).

Water- and food-borne diseases are projected to increase, but the complexity of their relationship to climate and non-climate drivers means there is *low confidence* in specific projections. For Australia, 205,000 to 335,000 new cases of bacterial gastroenteritis by 2050, and 239,000 to 870,000 cases by 2100, are projected under a range of emission scenarios (Bambrick et al., 2008; Harley et al., 2011). Based on their observed positive relationship with temperature, notifications of salmonellosis notifications are projected to increase 15% for every 1°C increase in average monthly temperatures (Britton et al., 2010a). Water-borne zoonotic diseases such as cryptosporidiosis and giardiasis have more complex relationships with climate and are amenable to various adaptations, making future projections more difficult (Britton et al., 2010b; Lal et al., 2012).

Understanding the combined effects of climate change and socioeconomic development on the distribution of vector-borne diseases has improved since the AR4. Australasia is projected to remain malaria free under the A1B emission scenario until at least 2050 (Béguin et al., 2011) and

Box 25-8 | Changes in Flood Risk and Management Responses

Flood damages across eastern Australia and both main islands of New Zealand in 2010 and 2011 revealed a significant adaptation deficit (ICA, 2012; ICNZ, 2013). For example, the Queensland floods in January 2011 resulted in 35 deaths, three-quarters of the State including Brisbane declared a disaster zone, and damages to public infrastructure of AU$5 to 6 billion (Queensland Government, 2011). These floods were associated with a strong monsoon and the strongest La Niña on record (Cai et al., 2012; CSIRO and BoM, 2012; Evans and Boyer-Souchet, 2012). Flood frequency and severity exhibit strong decadal variability with no significant long-term trend in Australasia to date (Kiem et al., 2003; Smart and McKerchar, 2010; Ishak et al., 2013).

Flood risk is projected to increase in many regions due to more intense extreme rainfall events driven by a warmer and wetter atmosphere (*medium confidence*; Table 25-1). High-resolution downscaling (Carey-Smith et al., 2010), and dynamic catchment hydrological and river hydraulic modeling in New Zealand (Gray, W. et al., 2005; McMillan et al., 2010; MfE, 2010b; Ballinger et al., 2011; Duncan and Smart, 2011; McMillan et al., 2012) indicate that the 50-year and 100-year flood peaks for rivers in many parts of the country will increase by 5 to 10% by 2050 and more by 2100 (with large variation between models and emissions scenarios), with a corresponding decrease in return periods for specific flood levels. Studies for Queensland show similar results (DERM et al., 2010). In Australia, flood risk is expected to increase more in the north (driven by convective rainfall systems) than in the south (where more intense extreme rainfall may be compensated by drier antecedent moisture conditions), consistent with confidence in heavy rainfall projections (Table 25-1; Alexander and Arblaster, 2009; Rafter and Abbs, 2009).

Flood risk near river mouths will be exacerbated by storm surge associated with higher sea level and potential change in wind speeds (McInnes et al., 2005; MfE, 2010b; Wang et al., 2010b). Higher rainfall intensity and peak flow will also increase erosion and sediment loads in waterways (Prosser et al., 2001; Nearing et al., 2004) and exacerbate problems from aging stormwater and wastewater infrastructure in cities (Howe et al., 2005; Jollands et al., 2007; CCC, 2010; WCC, 2010; see also Box 25-9). However, moderate flooding also has benefits through filling reservoirs, recharging groundwater, and replenishing natural environments (Hughes, 2003; Chiew and Prosser, 2011; Oliver and Webster, 2011).

Adaptation to increased flood risk from climate change is starting to happen (Wilby and Keenan, 2012) through updating guidelines for design flood estimation (MfE, 2010b; Westra, 2012), improving flood risk management (O'Connell and Hargreaves, 2004; NFRAG, 2008; Queensland Government, 2011), accommodating risk in flood prone areas (options include raising floor levels, using strong piled foundations, using water-resistant insulation materials, and ensuring weather tightness), and risk reduction and avoidance through spatial planning and managed relocation (Trotman, 2008; Glavovic et al., 2010; LVRC, 2012; QFCI, 2012). Adaptation options in urban areas also include ecosystem-based approaches such as retaining floodplains and floodways, restoring wetlands, and retrofitting existing systems to attenuate flows (Howe et al., 2005; Skinner, 2010; WCC, 2010; see also Box 25-9).

The recent flooding in eastern Australia and the projected increase in future flood risk have resulted in changes to reservoir operations to mitigate floods (van den Honert and McAneney, 2011; QFCI, 2012) and insurance practice to cover flood damages (NDIR, 2011; Phelan, 2011; see also Box 25-7). However, the magnitude of potential future changes in flood risk and limits to incremental adaptation responses in urban areas suggest that more transformative approaches based on altering land use and avoidance of exposure to future flooding may be needed in some locations, especially if changes in the upper range of projections are realized (*high confidence*; Lawrence and Allan, 2009; DERM et al., 2010; Glavovic et al., 2010; Wilby and Keenan, 2012; Lawrence et al., 2013a).

sporadic cases could be treated effectively. The area climatically suitable for transmission of dengue will expand in Australasia (*high confidence*; Bambrick et al., 2008; Åström et al., 2012), but changes in socioeconomic factors, especially domestic water storage, may have a more important influence on disease incidence than climate (Beebe et al., 2009; Kearney et al., 2009). Impacts of climate change on Barmah Forest Virus in Queensland depend on complex interactions between rainfall and temperature changes, together with tidal and socioeconomic factors, and thus will vary substantially among different coastal regions (Naish et al., 2013). The effects of climate change combined with frequent travel within and outside the region, and recent incursions of exotic mosquito species, could expand the geographic range of other important arboviruses such as Ross River Virus (*medium confidence*; Derraik and Slaney, 2007; Derraik et al., 2010).

A growing literature since the AR4 has focused on the psychological impacts of climate change, based on impacts of recent climate variability and extremes (Doherty and Clayton, 2011; see also Section 25.4.3). These studies indicate significant mental health risks associated with climate-related disasters, in particular persistent and severe drought, floods, and storms; climate impacts may be especially acute in rural communities where climate change places additional stresses on livelihoods (*high confidence*; Edwards et al., 2011; see also Box 25-5).

Projected population growth and urbanization could further increase health risks indirectly via climate-related stress on housing, transport and energy infrastructure, and water supplies (*low confidence*; Howden-Chapman, 2010; see also Box 25-9).

25.8.1.3. Adaptation

Research since the AR4 has mainly focused on climate change impacts, although some adaptation strategies have received attention in Australia. These include improving health care services, social support for those most at risk, improving community awareness to reduce adverse exposures, developing early warning and emergency response plans (Wang and McAllister, 2011), and understanding perceptions of climatic risks to health as they affect adaptive behaviors (Akompad et al., 2013). In New Zealand, central Government health policies do not identify specific measures to adapt to climate change (Wilson, 2011). In both countries, policies to reduce risks from extreme events such as floods and fires will have co-benefits for health (see Boxes 25-6, 25-8).

A review of the southern Australian heat wave of 2009 identified a range of issues including communication failures with no clear public information or warning strategy, and no clear thresholds for initiating public information campaigns (Kiem et al., 2010). Emergency services were underprepared and relied on reactive solutions (QUT, 2010). The Victorian government has since developed a heat wave plan to coordinate a state-wide response, maintain consistent community-wide understanding through a Heat Health alert system, build capacity of councils to support communities most at risk, support a Heat Health Intelligence surveillance system, and distribute public health information (Victorian Government, 2009b).

25.8.2. Indigenous Peoples

25.8.2.1. Aboriginal and Torres Strait Islanders

Work since the AR4 includes a national Indigenous adaptation research action plan (Langton et al., 2012), regional risk studies (Green et al., 2009; DNP, 2010; TSRA, 2010; Nursey-Bray et al., 2013) and scrutiny from an Indigenous rights perspective (ATSISJC, 2009). Socioeconomic disadvantage and poor health (SCRGSP, 2011) indicate a disproportionate climate change vulnerability of Indigenous Australians (McMichael et al., 2009) although there are no detailed assessments. In urban and regional areas, where 75% of the Indigenous population lives (ABS, 2010b), assessments have not specifically addressed risks to Indigenous people (e.g., Guillaume et al., 2010). In other regions, all remote, there is limited empirical evidence of vulnerability (Maru et al., 2012). However, there is *medium evidence* and *high agreement* for significant future impacts from increasing heat stress, extreme events, and increased disease (Campbell et al., 2008; Spickett et al., 2008; Green et al., 2009).

The Indigenous estate comprises more than 25% of the Australian land area (Altman et al., 2007; NNTR, 2013). There is *high agreement* but *limited evidence* that natural resource dependence (e.g., Bird et al., 2005; Gray, M.C. et al., 2005; Kwan et al., 2006; Buultjens et al., 2010) increases Indigenous exposure and sensitivity to climate change (Green et al., 2009); climate change-induced dislocation, attenuation of cultural attachment to place, and loss of agency will disadvantage Indigenous mental health and community identity (Fritze et al., 2008; Hunter, 2009; McIntyre-Tamwoy and Buhrich, 2011); and, housing, infrastructure, services, and transport, often already inadequate for Indigenous needs especially in remote Australia (ABS, 2010c), will be further stressed (Taylor and Philp, 2010). Torres Strait island communities and livelihoods are vulnerable to major impacts from even small sea level rises (*high confidence*; DCC, 2009; Green, D. et al., 2010a; TSRA 2010).

Little adaptation of Indigenous communities to climate change is apparent to date (cf. Burroughs, 2010; GETF 2011; Nursey-Bray et al., 2013; Zander et al., 2013). Plans and policies that are imposed on Indigenous communities can constrain their adaptive capacity (Ellemor, 2005; Petheram et al., 2010; Veland et al., 2010; Langton et al., 2012) but participatory development of adaptation strategies is challenged by multiple stressors and uncertainty about causes of observed changes (Leonard, S. et al., 2010; Nursey-Bray et al., 2013). Adaptation planning would benefit from a robust typology (Maru et al., 2011) across the diversity of Indigenous life experience (McMichael et al., 2009). Indigenous re-engagement with environmental management (e.g., Hunt et al., 2009; Ross et al., 2009) can promote health (Burgess et al., 2009) and may increase adaptive capacity (Berry et al., 2010; Davies et al., 2011). There is emerging interest in integrating Indigenous observations of climate change (Green, D. et al., 2010b; Petheram et al., 2010) and developing inter-cultural communication tools (Leonard, S. et al., 2010; Woodward et al., 2012). Extensive land ownership in northern and inland Australia and land management traditions mean that Indigenous people are well situated to provide greenhouse gas abatement and carbon sequestration services that may also support their livelihood aspirations (Whitehead et al., 2009; Heckbert et al., 2012).

25.8.2.2. New Zealand Māori

The projected impacts of climate change on Māori society are expected to be highly differentiated, reflecting complex economic, social, cultural, environmental, and political factors (*high confidence*). Since the AR4, studies have been either sector-specific (e.g., Insley, 2007; Insley and Meade, 2008; Harmsworth et al., 2010; King et al., 2012) or more general, inferring risk and vulnerability based on exploratory engagements with varied stakeholders and existing social, economic, political, and ecological conditions (e.g., MfE, 2007b; Te Aho, 2007; King et al., 2010).

The Māori economy depends on climate-sensitive primary industries with vulnerabilities to climate conditions (*high confidence*; Packman et al., 2001; NZIER, 2003; Cottrell et al., 2004; TPK, 2007; Tait et al., 2008b; Harmsworth et al., 2010; King et al., 2010; Nana et al., 2011a). Much of Māori-owned land is steep (>60%) and susceptible to damage from high intensity rainstorms, while many lowland areas are vulnerable to flooding and sedimentation (Harmsworth and Raynor, 2005; King et al., 2010). Land in the east and north is also drought prone, and this increases uncertainties for future agricultural performance, product quality, and investment (*medium confidence*; Cottrell et al., 2004; Harmsworth et al., 2010; King et al., 2010). The fisheries and aquaculture sector faces substantial risks (and uncertainties) from changes in ocean temperature and chemistry, potential changes in species composition, condition, and productivity levels (*medium confidence*; King et al., 2010; see also Section 25.6.2). At the community and individual level, Māori regularly utilize the natural environment for hunting and fishing, recreation, the maintenance of traditional skills and identity, and collection of cultural resources (King and Penny, 2006; King et al., 2012). Many of these activities are already compromised due to resource competition, degradation, and modification (Woodward et al., 2001; King et al., 2012). Climate change driven shifts in natural ecosystems will further challenge the capacities of some Māori to cope and adapt (*medium confidence*; King et al., 2012).

Māori organizations have sophisticated business structures, governance (e.g., trusts, incorporations), and networks (e.g., Iwi leadership groups) across the state and private sectors (Harmsworth et al., 2010; Insley, 2010; Nana et al., 2011b), critical for managing and adapting to climate change risks (Harmsworth et al., 2010; King et al., 2012). Future opportunities will depend on partnerships in business, science, research, and government (*high confidence*; Harmsworth et al., 2010; King et al., 2010) as well as innovative technologies and new land management practices to better suit future climates and use opportunities from climate policy, especially in forestry (Carswell et al., 2002; Harmsworth, 2003; Funk and Kerr, 2007; Insley and Meade, 2008; Tait et al., 2008b; Penny and King, 2010). Māori knowledge of environmental processes and hazards (King et al., 2005, 2007) as well as strong social-cultural networks are vital for adaptation and ongoing risk management (King et al., 2008); however, choices and actions continue to be constrained by insufficient resourcing, shortages in social capital, and competing values (King et al., 2012). Combining traditional ways and knowledge with new and untried policies and strategies will be key to the long-term sustainability of climate-sensitive Māori communities, groups, and activities (*high confidence*; Harmsworth et al., 2010; King et al., 2012).

25.9. Interactions among Impacts, Adaptation, and Mitigation Responses

The AR4 found that individual adaptation responses can entail synergies or trade-offs with other adaptation responses and with mitigation, but that integrated assessment tools were lacking in Australasia (Hennessy et al., 2007). Subsequent studies provide detail on such interactions and can inform a balanced portfolio of climate change responses, but evaluation tools remain limited, especially for local decision making (Park et al., 2011). A review of 25 specific climate change-associated land use plans from Australia, for example, found that 14 exhibited potential for conflict between mitigation and adaptation (Hamin and Gurran, 2009).

25.9.1. Interactions among Local-Level Impacts, Adaptation, and Mitigation Responses

Table 25-6 shows examples of adaptation responses that are either synergistic or entail trade-offs with other impacts and/or adaptation responses and goals. Adapting proactively to projected climate changes, particularly extremes such as floods or drought, can increase near-term resilience to climate variability and be a motivation for adopting adaptation measures (Productivity Commission, 2012). However, exclusive reliance on near-term benefits can increase trade-offs and

Box 25-9 | Opportunities, Constraints, and Challenges to Adaptation in Urban Areas

Considerable opportunities exist for Australasian cities and towns to reduce climate change impacts and, in some regions, benefit from projected changes such as warmer winters and more secure water supply (Fitzharris, 2010; Australian Government, 2012). Many tools and practices developed for sustainable resource management or disaster risk reduction in urban areas are co-beneficial for climate change adaptation, and vice versa, and can be integrated with mitigation objectives (Hamin and Gurran, 2009). Despite the abundance of potential adaptation options, however, social, cultural, institutional, and economic factors frequently constrain their implementation (*high confidence*; see also Section 25.4.2). The form and longevity of cities and towns, with their concentration of hard and critical infrastructure such as housing, transport, energy, stormwater and wastewater systems, telecommunications, and public facilities provide additional challenges (see also Chapters 8, 10; Sections 25.7.4, 25.8.1; Boxes 25-1, 25-2, 25-8). Transport infrastructure is vulnerable to extreme heat and flooding (QUT, 2010; Taylor and Philp, 2010) but quantification of future risks remains limited (Gardiner et al., 2009; Balston et al., 2012; Baynes et al., 2012). Table 25-5 summarizes some adaptation options, co-benefits, and constraints on their adoption in Australasia.

Continued next page →

Box 25-9 (continued)

Table 25-5 | Examples of co-beneficial climate change adaptation options for urban areas and barriers to their adoption. Options in italics are already widely implemented in Australia and New Zealand urban areas.

Climate impact	Adaptation options	Co-benefits	Barriers to adoption
Hot days and heat waves[1–8]	Greening cities/roofs; *more green spaces; well-designed energy efficient buildings*; occupant behavioral change; standards for new and retrofitting of existing infrastructure and assets; new methods and material for transport infrastructure to withstand higher extreme temperature	Energy efficiency; reduced risk of blackouts; fewer health impacts; resilient infrastructure and assets; resilient community	Lack of standards; high installation costs; limited understanding of benefits; high individual discount rate; split of private costs and public benefits
Decreased water supply and drought (see Box 25-2 for more)	Supply augmentation (*water recycling, rainwater harvesting, increased storage*, desalinization); *demand management; infrastructure upgrades; integrated water-sensitive urban design*	Water self-sufficiency for current and future demand/population; less pipe/storage leakage; reduced environmental impacts from abstraction	Potential health impacts of recycled water; lower than expected uptake of demand options and relaxation after crises; trade-offs between supply and demand management; cost and environmental impacts of some augmentation options
River and local flooding, coastal erosion and inundation (see Boxes 25-1 and 25-8 for more)	New standards and improvements to *building, water infrastructure (e.g., drainage and sewerage)* and transport infrastructure; *upgrades of protection systems; retaining floodplains/floodways*; restoring wetlands; buffers from hazard-prone areas; *raising minimum floor levels*; rezoning/relocation	Reduced damages to homes and infrastructure and loss of life; decreased insurance premiums; habitat protection	High implementation cost especially if retrospective on existing stock; rezoning/relocation can affect property prices and are highly contested.
Severe storms and tropical cyclones[9–12]	New building design to withstand higher wind pressures; rezoning/relocation	Reduced damages to homes and infrastructure and loss of life; decreased insurance premiums	High implementation cost; rezoning/relocation can affect property prices and are highly contested.
Corrosion from increased atmospheric CO$_2$ levels[13,14]	Improved standards for construction using concrete; application of coatings for existing building stock	Reduced rates of carbonation-induced corrosion of concrete	Effectiveness of coatings varies with age and condition of concrete.

References: [1]BRANZ (2007); [2]Coutts et al. (2010); [3]Moon and Han (2011); [4]Stephenson et al. (2010); [5]Williams et al. (2010); [6]CSIRO et al. (2007); [7]Taylor and Philp (2010); [8]QUT (2010); [9]Mason and Haynes (2010); [10]Wang et al. (2010b); [11]Stewart and Wang (2011); [12]Mason et al. (2013); [13]Stewart et al. (2012); [14]Wang et al. (2012).

Overall, the implementation of climate change adaptation policy for urban settlements in Australia and New Zealand has been mixed. The Australian National Urban Policy encourages adaptation, and many urban plans include significant adaptation policies (e.g., City of Melbourne, 2009; City of Port Phillip, 2010; ACT Government, 2012; City of Adelaide, 2012). New Zealand also promotes urban adaptation through strategies, plans, and guidance documents (MfE, 2008b; CCC, 2010; WCC, 2010; Auckland Council, 2012; NIWA et al., 2012). Many examples of incremental urban adaptation exist (Box 25-2; Table 25-5), particularly where these include co-benefits and respond to other stressors, like prolonged drought in southern Australia and recurrent floods. Experience is much scarcer with more flexible land uses, managed relocation, and ecosystem-based adaptation that could transform existing settlement patterns and development trends, and where maintaining flexibility to address long-term climate risks can run against near-term development pressures (see Boxes 25-1, 25-2, 25-8, CC-EA). Decision-making models that support such adaptive and transformative changes (Section 25.4.2; Box 25-1) have not yet been implemented widely in urban contexts; increased coordination among different levels of government may be required to spread costs and balance public and private, near- and long-term, and local and regional benefits (Norman, 2009, 2010; Britton, 2010;Abel et al., 2011; Lawrence et al., 2013a; McDonald, 2013; Palutikof et al., 2013; Reisinger et al., 2013).

result in long-term maladaptation (*high confidence*). For example, enhancing protection measures after major flood events, combined with rapid re-building, accumulates fixed assets that can become increasingly costly to protect as climate change continues, with attendant loss of amenity and environmental values (Glavovic et al., 2010; Gorddard et al., 2012; McDonald, 2013). Similarly, deferring adoption of increased design wind speeds in cyclone-prone areas delays near-term investment costs but also reduces the long-term benefit/cost ratio of the strategy (Stewart and Wang, 2011).

Mitigation actions can contribute to but also counteract local adaptation goals. Energy-efficient buildings, for example, reduce network and health risks during heat waves, but urban densification to reduce transport energy demand intensifies urban heat islands and, hence, heat-related health risks (Sections 25.7.4, 25.8.1). Specific adaptations can also make achievement of mitigation targets harder or easier. Increased use of air conditioning, for example, increases energy demand, but energy efficiency and building design can reduce heat exposure as well as energy demand (Section 25.7.4, Box 25-9). Table 25-7 gives further

Table 25-6 | Examples of interactions between impacts and adaptation measures in different sectors. In each case, impacts or responses in one sector have the potential to conflict (cause negative impacts) or be synergistic (have co-benefits) with impacts or responses in another sector, or with another type of response in the same sector.

Primary goal	Sector(s) affected	Examples of interactions between impacts and adaptation responses
Reduction of bushfire risk in natural landscapes	Biodiversity, tourism	Potential for greater conflict between conservation managers and other park users in Kosciuszko National Park if increasing fire incidence causes park closures, either to reduce risk, or to rehabilitate vegetation after fires (Wyborn, 2009), e.g., objectives of the Wildfire Management Overlay (WMO) in Victoria conflict with vegetation conservation (Hughes and Mercer, 2009).
Reduction of risk to energy transmission from bushfires	Biodiversity, energy	Underground cabling would reduce both the susceptibility of transmission networks to fire and ignition sources for wild fires, thus reducing risks to ecosystems and settlements; constraints include significant investment cost, diverse ownership of assets, and lack of an overarching national strategy (ATSE, 2008; Parsons Brinkerhoff, 2009; Linnenluecke et al., 2011).
Protection of coastal infrastructure	Biodiversity, tourism	Seawalls may provide habitat but these communities have different diversity and structure from those developing on natural substrates (Jackson et al., 2008); groynes potentially alter beach fauna diversity and community structure (Walker et al., 2008); continuing hard protection against sea level rise results in long-term loss of coastal amenities (Gorddard et al., 2012).
Avoidance of risks from sea level rise via relocation	Indigenous communities	Relocation can avoid increasing local pressures on communities from sea level rise but raises complex cultural, land rights, legal, and economic issues, e.g., potential relocation of Torres Strait islander communities (Green, D. et al., 2010a; McNamara et al., 2011).
Allocating scarce water resources via market instruments	Rural areas, agriculture, mining	Market based instruments such as water trading help allocation of scarce water resources to the highest value uses. The negative implications of this include potential loss of access to lower value users, which in some areas includes agriculture and drinking water supplies, with potentially significant social, environmental, and wider economic consequences (Kiem and Austin, 2012).
Increased water security via augmentation of supply for urban and agricultural systems	Biodiversity, water demand management	Water storage can buffer urban settlements and agricultural systems against high variability in river flows, but altered flow regimes can have significant negative impacts on freshwater ecosystems (Bond et al., 2008; Pittock et al., 2008; Kingsford, 2011). Discharge from desalination plants (e.g. in Perth and Sydney) can lead to substantial local increases in salinity and temperature, and the accumulation of metals, hydrocarbons, and toxic anti-fouling compounds in receiving waters (Roberts et al., 2010); increasing supply can reduce the effectiveness of demand-side measures (Barnett and O'Neill, 2010; Taptiklis, 2011; Box 25-2).

examples, and Box 25-10 explores the multiple and complex benefits and trade-offs in changing land use to simultaneously adapt to and mitigate climate change.

25.9.2. Intra- and Inter-regional Flow-on Effects among Impacts, Adaptation, and Mitigation

Recent studies strengthen conclusions from the AR4 (Hennessy et al., 2007) that flow-on effects from climate change impacts occurring in other world regions can exacerbate or counteract projected impacts in Australasia. Modeling suggests Australia's terms of trade would deteriorate by about 0.23% in 2050 and 2.95% in 2100 as climate change impacts without mitigation reduce economic activity and demand for coal, minerals, and agricultural products in other world regions (A1FI scenario; Harman et al., 2008). As a result, Australian Gross National Product (GNP) is expected to decline more strongly than GDP because of climate change, especially toward the end of the 21st century (Gunasekera et al., 2008). These conclusions, however, merit only *medium confidence*, because they rely on simplified assumptions

Table 25-7 | Examples of interactions between adaptation and mitigation measures (green rows denote synergies where multiple benefits may be realized; yellow rows denote potential trade-offs and conflicts; blue row gives an example of complex, mixed interactions). The primary goal may be adaptation or mitigation.

Primary goal	Sector(s) affected	Examples of interactions between adaptation and mitigation responses
Adaptation to decreasing snowfall	Biodiversity, energy use, water use	Snowmaking in the Australian Alps would require large additional energy and water resources by 2020 of 2500–3300 Ml of water per month, more than half the average monthly water consumption by Canberra in 2004–2005. Increased snowmaking negatively affects vegetation, soils, and hydrology of subalpine–alpine areas (Pickering and Buckley, 2010; Morrison and Pickering, 2011; ABS, 2012a).
Air conditioning for heat stress	Health, energy use	Rising temperatures degrade building energy efficiency (Wang et al., 2010a) and increase energy demand and associated CO_2 emissions if summer cooling needs are met by increased air conditioning (Stroombergen et al., 2006; Thatcher, 2007; Wang et al., 2010a).
Renewable wind energy production	Biodiversity	Wind-farms can have localized negative effects on bats and birds. However, risk assessment of the potential negative impacts of wind turbines on threatened bird species in Australia indicated low to negligible impacts on all species modeled (Smales, 2006).
Urban densification	Biodiversity, water, health	Higher urban density to reduce energy consumption from transport and infrastructure can result in loss of permeable surfaces and tree cover, intensify flood risks, and exacerbate discomfort and health impacts of hotter summers (Hamin and Gurran, 2009).
Water supply from desalination	Energy demand	Meeting increasing urban water demand via desalination plants increases energy demand and CO_2 emissions if this demand is met by increased fossil fuel energy generation (Barnett and O'Neill, 2010; Stamatov and Stamatov, 2010).
Secure food production in a warming climate	Nitrous oxide and methane emissions	Net greenhouse gas emissions intensity from dairy systems in southern Australia have been estimated to increase in future in several locations due to a changing climate and management responses (Cullen and Eckard, 2011; Eckard and Cullen, 2011). A shift toward perennial C4 grasses would increase methane emissions from grazing ruminants due to lower feed quality, but studies in southwest Australia suggest this could be more than offset by increased soil carbon storage (Thomas et al., 2012; Bradshaw et al., 2013).
Housing design to reduce peak energy demand	Energy use, infrastructure, health	Reducing peak energy demand through building design and demand management reduces vulnerability of electricity networks and transmission losses during heat waves (Parsons Brinkerhoff, 2009; Nguyen et al., 2010), reduces heat stress during summer, and provides health benefits during winter (Strengers, 2008; Howden-Chapman, 2010; Strengers and Maller, 2011; Ren et al., 2012).
Energy from second-generation biofuels	Biodiversity, rural areas, agriculture	New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services including reducing erosion (Cocklin and Dibden, 2009; Giltrap et al., 2009; McHenry, 2009).
Reduced emissions from fires	Biodiversity, livelihoods	Improved management of savannah fires to reduce the extent of high-intensity late season fires could substantially reduce emissions as well as having significant benefits for biodiversity and indigenous employment (Russell-Smith et al., 2009; Bradshaw et al., 2013).
Reduce methane emissions from feral camels	Biodiversity, agriculture	Feral camels in Australia are projected to double from 1 to 2 million by 2020. Controlling their numbers to reduce methane emissions could have significant biodiversity benefits (NRMMC, 2010; Bradshaw et al., 2013). Economic benefits of reduced grazing competition, infrastructure damage, and greenhouse gases could outweigh costs of camel reductions (Drucker et al., 2010).

Box 25-10 | Land-based Interactions among Climate, Energy, Water, and Biodiversity

Climate, water, biodiversity, food, and energy production and use are intertwined through complex feedbacks and trade-offs (see also Box CC-WE). This could make alternative uses of natural resources within rural landscapes increasingly contested, yet decision support tools to manage competing objectives are limited (PMSEIC, 2010b).

Various policies in Australasia support increased biofuel production and biological carbon sequestration via, for example, mandatory renewable energy targets and incentives to increase carbon storage. Impacts of increased biological sequestration activities on biodiversity depend on their implementation. Benefits arise from reduced erosion, additional habitat, and enhanced ecosystem connectivity, while risks or lost opportunities are associated with large-scale monocultures especially if replacing more diverse landscapes (Brockerhoff et al., 2008; Giltrap et al., 2009; Steffen et al., 2009; Todd et al., 2009; Bradshaw et al., 2013).

Photosynthesis transfers water to the atmosphere, so increased sequestration is projected to reduce catchment yields particularly in southern Australia and affect water quality negatively (CSIRO, 2008; Schrobback et al., 2011; Bradshaw et al., 2013). Accounting for this water use in water allocations for sequestration activities would increase their cost and limit the potential of sequestration-driven land use change (Polglase et al., 2011; Stewart et al., 2011). Large-scale land-cover changes also affect local and regional climates and soil moisture through changing albedo, evaporation, plant transpiration, and surface roughness (McAlpine et al., 2009; Kirschbaum et al., 2011b), but these feedbacks have rarely been included in analyses of changing water demands and availability.

Biological carbon sequestration in New Zealand is less water-challenged than in Australia, except where catchments are projected to become drier and/or are already completely allocated (MfE, 2007a; Rutledge et al., 2011), and would mostly improve water quality through reduced erosion (Giltrap et al., 2009). Policies to protect water quality by limiting nitrogen discharge from agriculture have reduced livestock production and greenhouse gas emissions in the Lake Taupo and Rotorua catchments and supported land-use change toward sequestration (OECD, 2013b).

Trade-offs between biofuel and food production and ecosystem services depend strongly on the type of sequestration activity and their management relies on the use of consistent principles to evaluate externalities and benefits of alternative land uses (PMSEIC, 2010b). First-generation biofuels have been modeled in Australia as directly competing with agricultural production (Bryan et al., 2010). In contrast, production of woody biofuels in New Zealand is projected to occur on marginal land, not where the most intense agriculture occurs (Todd et al., 2009). Falling costs and increasing efficiency of solar energy may limit future biofuel demand, given the limited efficiency of plants in converting solar energy into usable fuel (e.g., Reijnders and Huijbregts, 2007).

about global climate change impacts, economic effects, and policy responses.

For New Zealand, there is *limited evidence* but *high agreement* that higher global food prices driven by adverse climate change impacts on global agriculture and some international climate policies would increase commodity prices and hence producer returns. Agriculture and forestry producer returns, for example, are estimated to increase by 14.6% under the A2 scenario by 2070 (Saunders et al., 2010) and real gross national disposable income by 0.6 to 2.3% under a range of non-mitigation scenarios (Stroombergen, 2010) relative to baseline projections in the absence of global climate change.

Some climate policies such as biofuel targets and agricultural mitigation in other regions would also increase global commodity prices and hence returns to New Zealand farmers (Saunders et al., 2009; Reisinger et al., 2012). Depending on global implementation, these could more than offset projected average domestic climate change impacts on agriculture (Tait et al., 2008a). In contrast, higher international agricultural commodity prices appear insufficient to compensate for the more severe effects of climate change on agriculture in Australia (see Section 25.7.2; Gunasekera et al., 2007; Garnaut, 2008).

Climate change could affect international tourism to Australasia through international destination and activity preferences (Kulendran and Dwyer, 2010; Rosselló-Nadal et al., 2011; Scott et al., 2012), climate policies, and oil prices (Mayor and Tol, 2007; Becken, 2011; Schiff and Becken, 2011). These potentially significant effects remain poorly quantified, however, and are not well integrated into local vulnerability studies (Hopkins et al., 2012).

Climate change has the potential to change migration flows within Australasia, particularly because of coastal changes (e.g., from the Torres Straits islands to mainland Australia), although reliable estimates of such movements do not yet exist (see Section 12.4; Green, D. et al., 2010a; McNamara et al., 2011; Hugo, 2012). Migration within countries, and from New Zealand to Australia, is largely economically driven and sustained by transnational networks, though the perceived more attractive current climate in Australia is reportedly a factor in migration from New Zealand (Goss and Lindquist, 2000; Green, A.E. et al., 2008; Poot, 2009). The impacts of climate change in the Pacific may contribute to an increase in the number of people seeking to move to nearby countries (Bedford and Bedford, 2010; Hugo, 2010; McAdam, 2010; Farbotko and Lazrus, 2012; Bedford and Campbell, 2013) and affect political stability and geopolitical rivalry within the Asia-Pacific region, although there is no clear evidence of this to date and causal theories are scarce (Dupont, 2008; Pearman, 2009; see Sections 12.4-5). Increasing climate-driven disasters, disease, and border control will stimulate operations other than war for Australasia's armed forces; integration of security into adaptation and development assistance for Pacific island countries can therefore play a key role in moderating the influence of climate change on forced migration and conflict (*robust evidence*, *high agreement*; Dupont and Pearman, 2006; Bergin and Townsend, 2007; Dupont, 2008; Sinclair, 2008; Barnett, 2009; Rolfe, 2009).

25.10. Synthesis and Regional Key Risks

25.10.1. Economy-wide Impacts and the Potential of Mitigation to Reduce Risks

Globally effective mitigation could reduce or delay some of the risks associated with climate change and make adaptation more feasible beyond about 2050, when projected climates begin to diverge substantially between mitigation and non-mitigation scenarios (see also Section 19.7). Literature quantifying these benefits for Australasia has increased since the AR4 but remains very sparse. Economy-wide net costs for Australia are modeled to be substantially greater in 2100 under unmitigated climate change (A1FI; GNP loss 7.6%) than under globally effective mitigation (GNP loss less than 2% for stabilization at 450 or 550 ppm CO_2-eq, including costs of mitigation and residual impacts; Garnaut, 2008). These estimates, however, are highly uncertain and depend strongly on valuation of non-market impacts, treatment of potentially catastrophic outcomes, and assumptions about adaptation, global changes, and flow-on effects for Australia and effectiveness and implementation of global mitigation efforts (Garnaut, 2008). No estimates of climate change costs across the entire economy exist for New Zealand.

The benefits of mitigation in terms of reduced risks have been quantified for some individual sectors in Australia, for example, for irrigated agriculture in the Murray-Darling Basin (Quiggin et al., 2008, 2010; Valenzuela and Anderson, 2011; Scealy et al., 2012) and for net health outcomes (Bambrick et al., 2008). Although quantitative estimates from individual studies are highly assumption-dependent, multiple lines of evidence (see Sections 25.7-8) give *very high confidence* that globally effective mitigation would significantly reduce many long-term risks from climate change to Australia. Benefits differ, however, between States for some issues, for example, heat- and cold-related mortality (Bambrick et al., 2008). Few studies consider mitigation benefits explicitly for New Zealand, but scenario-based studies give *high confidence* that, if global emissions were reduced from a high (A2) to a medium-low (B1) emissions scenario, this would markedly lower the projected increase in flood risks (Ballinger et al., 2011; McMillan et al., 2012) and reduce risks to livestock production in the most drought-prone regions (Tait et al., 2008a; Clark et al., 2011). Mitigation would also reduce the projected benefits to production forestry, however, though amounts depend on the response to CO_2 fertilization (Kirschbaum et al., 2011a; see also Section 25.7.1).

25.10.2. Regional Key Risks as a Function of Mitigation and Adaptation

The Australia/New Zealand chapter of the AR4 (Hennessy et al., 2007) concluded with an assessment of aggregated vulnerability for a range of sectors as a function of global average temperature. Building on recent additional insights, Table 25-8 shows eight key risks within those sectors that can be identified with *high confidence* for the 21st century, based on the multiple lines of evidence presented in the preceding sections and selected using the framework for identifying key risks set out in Chapter 19 (see also Box CC-KR). This combines consideration of biophysical impacts, their likelihood, timing, and persistence, with vulnerability of the affected system, based on exposure, magnitude of harm, significance of the system, and its ability to cope with or adapt to projected biophysical changes. These key risks differ in the extent to which they can be managed through adaptation and mitigation and their evolution over time, and some are more likely than others, but all warrant attention from a risk-management perspective.

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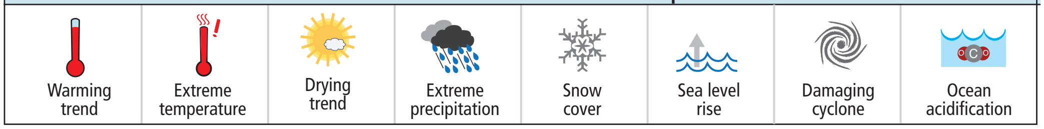
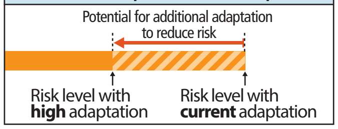
Table 25-8 | Key regional risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized on a scale from very low to very high and presented in three timeframes: the present, near-term (2030–2040), and long-term (2080–2100). For the near-term era of committed climate change (here, for 2030–2040), projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. For the longer-term era of climate options (here, for 2080–2100), risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.

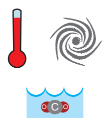
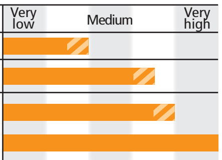
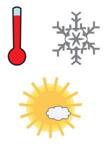
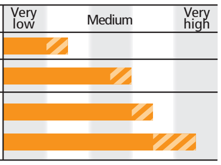
Climate-related drivers of impacts



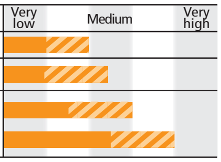
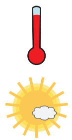
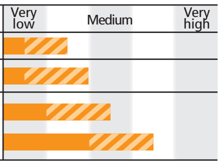
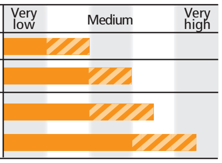
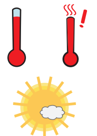
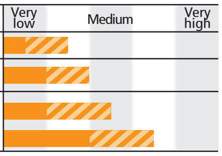
Level of risk & potential for adaptation



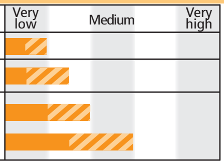
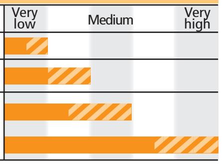
Impacts can be delayed but now appear very difficult to avoid entirely, even with combined globally effective mitigation and planned adaptation

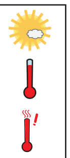
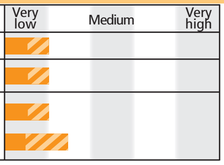
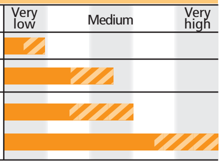
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Significant change in community composition and structure of coral reef systems in Australia (*high confidence*) [25.6.2, 30.5, Boxes CC-CR, CC-OA]	Ability of corals to adapt naturally appears limited and insufficient to offset the detrimental effects of rising temperatures and acidification.Other options are mostly limited to reducing other stresses (water quality, tourism, fishing) and early warning systems; direct interventions such as assisted colonization and shading have been proposed but remain untested at scale.		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	
Loss of montane ecosystems and some native species in Australia (*high confidence*) [25.6.1]	Direct adaptation options are limited, but reducing other stresses such as pests and diseases, predator control and enhancing connectivity of habitats provides immediate co-benefits; need to consider facilitating migration and assisted colonisation.		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	

Impacts have the potential to be severe but can be reduced substantially by globally effective mitigation combined with adaptation

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*) [Table 25-1, Boxes 25-8, 25-9]	Significant adaptation deficit in some regions to current flood risk. Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	
Constraints on water resources in southern Australia (*high confidence*) [25.5.1, Boxes 25-2, 25-9]	Water resources already struggling to meet unrestrained demand in many locations and exacerbated by projected population growth; effective adaptation relies on combination of demand and supply mechanisms.		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	
Increased morbidity, mortality and infrastructure damages during heat waves in Australia (*high confidence*) [25.7.4, 25.8.1]	Vulnerability is exacerbated by population growth and aging; transport and power infrastructure already severely stressed during heat waves in many regions, with significant financial costs from future upgrades.		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	
Wild fire damages to ecosystems and settlements and risks to human life in southern Australia and many parts of New Zealand (*high confidence*) [Table 25-1, Box 25-6]	Part of integrated landscape management; trade-offs between different management objectives and settlement patterns and goals (biodiversity versus protection of human life and property).		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	

Impacts whose severity depends on changes in climate variables that span a particularly large range; the most severe end would present major challenges

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Moderate sea level rise	Timeframe	High end sea level rise
				(AR5 WGI 13.5; Box 25-2)		
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damages toward the upper end of projected sea level rise ranges (*high confidence*) [25.6, 25.10, Box 25-1]	Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Wet end of scenario	Timeframe	Dry end of scenario
				(25.2, 25.5.2, Figure 25-4)		
Significant reduction in agriculture production in the Murray-Darling Basin and far south-eastern and south-western Australia (*high confidence*) [25.2, 25.6.1, 25.7.2, Table 25-1, Boxes 25-2, 25-5]	Immediate co-benefits from improved management of over-allocated water resources and balancing competing demands, but the extreme dry end would threaten agricultural production as well as ecosystems and some rural communities.		Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C		Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	

One set of key risks comprises damages to natural ecosystems (significant change in community structure of coral reefs and loss of some montane ecosystems) that can be moderated by globally effective mitigation but to which some damage now seems inevitable. For some species and ecosystems, climatically constrained ecological niches, fragmented habitats, and limited adaptive movement collectively present hard limits to adaptation to further climate change (*high confidence*). A second set of key risks (increase in flood risk, water scarcity, heat waves, and wildfire) comprises damages that could be severe but can be reduced substantially by globally effective mitigation combined with adaptation, with the need for transformational adaptation increasing with the rate and amount of climate change. A third set of key risks (coastal damages from sea level rise, and loss of agriculture production from severe drying) comprises potential impacts whose scale remains highly uncertain within the 21st century, even for a given global temperature change, and where alternative scenarios materially affect levels of concern, adaptation needs, and strategies. Even though scenarios of severe drying (see Section 25.5.2) or rapid sea level rise approaching 1 m or more by 2100 (see Box 25-2; WGI AR5 Section 13.5) have low or currently unknown probabilities, the associated impacts would so severely challenge adaptive capacity, including transformational changes, that they constitute important risks.

A first comparative assessment for Australia of exposure and damages from different hazards up to 2100 indicates that river flooding will continue to be the most costly source of direct damages to infrastructure, even though the largest value of assets is exposed to bush fire. Exposure to and damages from coastal inundation are currently smaller, but would rise most rapidly beyond mid-century if sea level rise exceeds 0.5 m (Baynes et al., 2012).

An *emerging risk* is the compounding of extreme events, none of which would constitute a key risk in its own right, but that collectively and cumulatively across space and time could stretch emergency response and recovery capacity and hamper regional economic development, including through impacts on insurance markets or multiple concurrent needs for major infrastructure upgrades (NDIR, 2011; Phelan, 2011; Baynes et al., 2012; Booth and Williams, 2012; Karoly and Boulter, 2013). Efforts are underway to better understand the potential importance of cumulative impacts and responses, including the challenges arising from impacts and responses across different levels of government (Leonard, M. et al., 2010; CSIRO, 2011), but evidence is as yet too limited to identify this as a *key risk* consistent with the definitions adopted in this report (see Chapter 19).

Climate change is projected to bring benefits to some sectors and parts of Australasia, at least under limited warming scenarios associated with globally effective mitigation (*high confidence*). Examples include an extended growing season for agriculture and forestry in cooler parts of New Zealand and Tasmania, reduced winter mortality (*low confidence*), and reduced winter energy demand in most of New Zealand and southern States of Australia, and increased winter hydropower potential in New Zealand's South Island (Sections 25.7.1-2, 25.7.4, 25.8.1).

The literature supporting this assessment of key risks is uneven among sectors and between Australia and New Zealand; for the latter, conclusions in many sectors are based on limited studies that often use a narrow set of assumptions, models, and data and that, accordingly, have not explored the full range of potential outcomes.

25.10.3. Challenges to Adaptation in Managing Key Risks, and Limits to Adaptation

Two key and related challenges for regional adaptation are apparent: to identify when and where adaptation may imply transformational rather than incremental changes; and, where specific interventions are needed to overcome adaptation constraints, in particular to support transformational responses that require coordination across different spheres of governance and decision making (Productivity Commission, 2012; Palutikof et al., 2013). The magnitude of climate change, especially under scenarios of limited mitigation, and constraints to adaptation suggest that incremental and autonomous responses will not deliver the full range of available adaptation options nor ensure the continued function of natural and human systems if some key risks are realized (*high confidence*; see also Section 25.4).

Most incremental adaptation measures in natural ecosystems focus on reducing other non-climate stresses but, even with scaled-up efforts, conserving the current state and composition of the ecosystems most at risk appears increasingly infeasible (Sections 25.6.1-2). Maintenance of key ecosystem functions and services requires a radical reassessment of conservation values and practices related to assisted colonization and the values placed on "introduced" species (Steffen et al., 2009). Divergent views regarding intrinsic and service values of species and ecosystems imply the need for a proactive discussion to enable effective decision making and resource allocation.

In human systems, incremental adjustments of current risk management tools, planning approaches, and early warning systems for floods, fire, drought, water resources, and coastal hazards can increase resilience to climate variability and change, especially in the near term (IPCC, 2012; Productivity Commission, 2012; Dovers, 2013). A purely incremental approach, however, which generally aims to preserve current management objectives, governance, and institutional arrangements, can make later transformational changes increasingly difficult and costly (*medium evidence*, *high agreement*; e.g., Howden et al., 2010; Park et al., 2012; McDonald, 2013; Stafford-Smith, 2013). Examples of transformational changes include: shifting emphasis from protection to accommodation or avoidance of flood risk, including managed retreat from eroding coasts; the translocation of industries in response to increasing drought, flood, and fire risks or water scarcity; and the associated transformation of the economic and social base and governance of some rural communities (Boxes 25-1, 25-2, 25-5 to 25-9; Nelson et al., 2010; Linnenluecke et al., 2011; Kiem and Austin, 2012; O'Neill and Handmer, 2012; McDonald, 2013; Palutikof et al., 2013).

Consideration of transformational adaptation becomes critical where long life- or lead-times are involved, and where high up-front costs or multiple interdependent actors create constraints that require coordinated and proactive interventions (Stafford-Smith et al., 2011; Productivity Commission, 2012; Palutikof et al., 2013). Deferring such adaptation decisions because of uncertainty about the future will not necessarily minimize costs or ensure adequate flexibility for future responses,

Frequently Asked Questions

FAQ 25.2 | What are the key risks from climate change to Australia and New Zealand?

Our assessment identifies eight key regional risks from climate change. Some impacts, especially on ecosystems, are by now difficult to avoid entirely. Coral reef systems have a limited ability to adapt naturally to further warming and an increasingly acidic ocean. Similarly, the habitat for some mountain or high elevation ecosystems and their associated species is shrinking inexorably with rising temperatures. This implies substantial impacts and some losses even under scenarios of limited warming. Other risks, however, can be reduced substantially by adaptation, combined with globally effective mitigation. These include potential flood damages from more extreme rainfall in most parts of Australia and New Zealand; constraints on water resources from reducing rainfall in southern Australia; increased health risks and infrastructure damages from heat waves in Australia; and increased economic losses, risks to human life, and ecosystem damage from wildfires in southern Australia and many parts of New Zealand. A third set of risks is particularly challenging to manage robustly because the severity of potential impacts varies widely across the range of climate projections, even for a given temperature increase. These concern damages to coastal infrastructure and low-lying ecosystems from continuing sea level rise, where damages would be widespread if sea level turns out to be at the upper end of current scenarios; and threats to agricultural production in both far southeastern and far southwestern Australia, which would affect ecosystems and rural communities severely at the dry end of projected rainfall changes. Even though some of these key risks are more likely to materialize than others, and they differ in the extent that they can be managed by adaptation and mitigation, they all warrant attention from a risk management perspective, given their potential major consequences for the region.

although up-front investment and opportunity costs of adaptation can present powerful arguments for delayed or staged responses (Stewart and Wang, 2011; Gorddard et al., 2012; Productivity Commission, 2012; McDonald, 2013). Whether transformational responses are seen as success or failure of adaptation depends on the extent to which actors accept a change in, or wish to maintain, current activities and management objectives, and the degree to which the values and institutions underpinning the transformation are shared or contested across stakeholders (Park et al., 2012; Stafford-Smith, 2013). These views will differ not only between communities and industries but also from person to person depending on their individual value systems, perceptions of and attitude to risk, and ability to capitalize on opportunities (see also Section 25.4.3).

25.11. Filling Knowledge Gaps to Improve Management of Climate Risks

The wide range of projected rainfall changes (averages and extremes) and their hydrological amplification are key uncertainties affecting the scale and urgency of adaptation in agriculture, forestry, water resources, some ecosystems, and wildfire and flood risks. For ecosystems, agriculture, and forestry, these uncertainties are compounded by limited knowledge of responses of vegetation to elevated CO_2, changes in ocean pH, and interactions with changing climatic conditions. The uncertainties in future impacts are most critical for decisions with long lifetimes, such as capital infrastructure investment or large-scale changes in land and water use. Uncertainties about the rate of sea level rise, and changes in storm paths and intensity, add to challenges for infrastructure design. The use of multi-model means and a narrow set of emissions scenarios in many past studies implies that the full set of climate-related risks and management options remains incompletely explored.

Understanding of ecological and physiological thresholds that, once exceeded, would result in rapid changes in species, ecosystems, and their services is still very limited. The literature is noticeably sparse in New Zealand and for arid Australia. These knowledge gaps are compounded by limited information about the effect of global climate change on patterns of natural climate variability, such as ENSO. Better understanding the effect of evolving natural climate variability and long-term trends, along with rising CO_2 concentrations, on pests, invasive species, and native and managed ecosystems could support more robust ecosystem-based adaptation strategies.

Vulnerability of human and managed systems depends critically on future socioeconomic characteristics. Research into psychological, economic, social, and cultural dimensions of vulnerability, adaptive capacity, and underpinning values remains limited and poorly integrated with biophysical studies. This limits the level of confidence in conclusions regarding future vulnerabilities and the feasibility and effectiveness of adaptation strategies.

These multiple, persistent, and structural uncertainties imply that, in most cases, adaptation requires an iterative risk management process. Though decision-support frameworks are being developed, it remains unclear to what extent existing governance and institutional arrangements will be able to support more transformational responses, particularly where competing public and private interests and particularly vulnerable groups are involved. The enabling or constraining influences on adaptation from interactions among market forces, institutions, governance, policy, and regulatory environments have only recently begun to attract research attention, mostly in Australia.

Climate change impacts, adaptation, and mitigation responses in other world regions will affect Australasia, but our understanding of this remains very limited. Existing studies suggest that transboundary effects, mediated mostly via trade but potentially also migration, can be of similar if not larger scale than direct domestic impacts of climate change for economically important sectors such as agriculture and tourism. However, scenarios used in such studies tend to be highly simplified. Effective management of risks and opportunities in these sectors would benefit from better integration of relevant global scenarios of climatic and socioeconomic changes into studies of local vulnerability and adaptation options.

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North America

Coordinating Lead Authors:

Patricia Romero-Lankao (Mexico), Joel B. Smith (USA)

Lead Authors:

Debra J. Davidson (Canada), Noah S. Diffenbaugh (USA), Patrick L. Kinney (USA), Paul Kirshen (USA), Paul Kovacs (Canada), Lourdes Villers Ruiz (Mexico)

Contributing Authors:

William Anderegg (USA), Jessie Carr (USA), Anthony Cheng (USA), Thea Dickinson (Canada), Ellen Douglas (USA), Hallie Eakin (USA), Daniel M. Gnatz (USA), Mary Hayden (USA), Maria Eugenia Ibarraran Viniegra (Mexico), Blanca E. Jiménez Cisneros (Mexico), Rob de Loë (Canada), Michael D. Meyer (USA), Catherine Ngo (USA), Amrutasri Nori-Sarma (India), Greg Oulahen (Canada), Diana Pape (USA), Ana Peña del Valle (Mexico), Roger Pulwarty (USA), Ashlinn Quinn (USA), Fabiola S. Sosa-Rodriguez (Mexico), Daniel Runfola (USA), Landy Sánchez Peña (Mexico), Bradley H. Udall (USA), Fiona Warren (Canada), Kate Weinberger (USA), Tom Wilbanks (USA)

Review Editors:

Ana Rosa Moreno (Mexico), Linda Mortsch (Canada)

Volunteer Chapter Scientist:

William Anderegg (USA)

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Executive Summary

Overview

North America's climate has changed and some societally relevant changes have been attributed to anthropogenic causes (*very high confidence*). {Figure 26-1} Recent climate changes and individual extreme events demonstrate both impacts of climate-related stresses and vulnerabilities of exposed systems (*very high confidence*). {Figure 26-2} Observed climate trends in North America include an increased occurrence of severe hot weather events over much of the USA, decreases in frost days, and increases in heavy precipitation over much of North America (*high confidence*). {26.2.2.1} The attribution of observed changes to anthropogenic causes has been established for some climate and physical systems (e.g., earlier peak flow of snowmelt runoff and declines in the amount of water stored in spring snowpack in snow-dominated streams and areas of western USA and Canada (*very high confidence*). {Figure 26-1} Evidence of anthropogenic climatic influence on ecosystems, agriculture, water resources, infrastructure, and urban and rural settlements is less clearly established, though, in many areas, these sectors exhibit substantial sensitivity to climate variability (*high confidence*). {26.3.1-2, 26.4.2.1-2, 26.4.3.1, 26.5.1, 26.7.1.1, 26.7.2, 26.8.1; Figure 26-2; Box 26-3}

Many climate stresses that carry risk—particularly related to severe heat, heavy precipitation, and declining snowpack—will increase in frequency and/or severity in North America in the next decades (*very high confidence*). Global warming of approximately 2°C (above the preindustrial baseline) is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low-snow years, and shifts toward earlier snowmelt runoff over much of the western USA and Canada. {26.2.2.2} Together with climate hazards such as higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability, these changes are projected to lead to increased stresses to water, agriculture, economic activities, and urban and rural settlements (*high confidence*). {26.3.2, 26.5.2, 26.7.1.2, 26.8.3} Global warming of approximately 4°C is *very likely* to cause larger changes in extreme heat events, daily-scale precipitation extremes and snow accumulation and runoff, as well as emergence of a locally novel temperature regime throughout North America. {26.2.2.2} This higher level of global temperature change is *likely* to cause decreases in annual precipitation over much of the southern half of the continent and increases in annual precipitation over much of the northern half of the continent. {26.2.2.2} The higher level of warming would present additional and substantial risks and adaptation challenges across a range of sectors (*high confidence*). {26.3.3, 26.5.2, 26.6.2, 26.7.2.2, 26.8.3}

We highlight below key findings on impacts, vulnerabilities, projections, and adaptation responses relevant to specific North American sectors: ecosystems, water, agriculture, human health, urban and rural settlements, infrastructure, and the economy. We then highlight challenges and opportunities for adaptation, and future risks and adaptive capacity for three key climate-related risks.

Sector-Specific Climate Risks and Adaptation Opportunities

North American ecosystems are under increasing stress from rising temperatures, carbon dioxide (CO_2) concentrations, and sea levels, and are particularly vulnerable to climate extremes (*very high confidence*). Climate stresses occur alongside other anthropogenic influences on ecosystems, including land use changes, non-native species, and pollution, and in many cases will exacerbate these pressures (*very high confidence*). {26.4.1, 26.4.3}. Evidence since the Fourth Assessment Report (AR4) highlights increased ecosystem vulnerability to multiple and interacting climate stresses in forest ecosystems, through wildfire activity, regional drought, high temperatures, and infestations (*medium confidence*); {26.4.2.1; Box 26-2} and in coastal zones due to increasing temperatures, ocean acidification, coral reef bleaching, increased sediment load in runoff, sea level rise (SLR), storms, and storm surges (*high confidence*). {26.4.3.1} In the near term, conservation and adaptation practices can buffer against climate stresses to some degree in these ecosystems, both through increasing system resilience, such as forest management to reduce vulnerability to infestation, and in reducing co-occurring non-climate stresses, such as careful oversight of fishing pressure (*medium confidence*). {26.4.4}

Water resources are already stressed in many parts of North America due to non-climate change anthropogenic forces, and are expected to become further stressed due to climate change (*high confidence*). {26.3} Decreases in snowpacks are already influencing seasonal streamflows (*high confidence*). {26.3.1} Though indicative of future conditions, recent floods, droughts, and changes in mean flow conditions cannot yet be attributed to climate change (*medium* to *high confidence*). {26.3.1-2} The 21st century is projected to witness decreases in water quality and increases in urban drainage flooding throughout most of North America under climate change as well as a decrease in instream uses such as hydropower in some regions (*high confidence*). {26.3.2.2-4} In addition, there will be decreases in water supplies for urban areas and irrigation in North America except in general for southern tropical Mexico, northwest coastal USA, and west coastal Canada (*high* to *medium confidence*). {26.3.2.1} Many adaptation options currently available can address water supply deficits; adaptation responses to flooding and water quality concerns are more limited (*medium confidence*). {26.3.3}

Effects of temperature and climate variability on yields of major crops have been observed (*high confidence*). {25.5.1} Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st century without adaptation, although the rate of decline varies by model and scenario, and some regions, particularly in the north, may benefit (*very high confidence*). {26.5.2} Given that North America is a significant source of global food supplies, projected productivity declines here may affect global food security (*medium confidence*). At 2°C, adaptation has high potential to offset projected declines in yields for many crops, and many strategies offer mitigation co-benefits; but effectiveness of adaptation would be reduced at 4°C (*high confidence*). {26.5.3} Adaptation capacity varies widely among producers, and institutional support—currently lacking in some regions—greatly enhances adaptive potential (*medium confidence*). {26.5.4}

Human health impacts from extreme climate events have been observed, although climate change-related trends and attribution have not been confirmed to date. Extreme heat events currently result in increases in mortality and morbidity in North America (*very high confidence*), with impacts that vary by age, location, and socioeconomic factors (*high confidence*). {26.6.1.2} Extreme coastal storm events can cause excess mortality and morbidity, particularly along the East Coast of the USA, and the Gulf Coast of both Mexico and the USA (*high confidence*). {26.6.1.1} A range of water-, food-, and vector-borne infectious diseases, air pollutants, and airborne pollens are influenced by climate variability and change (*medium confidence*). {26.6.1.3-6} Further climate warming in North America will impose stresses on the health sector through more severe extreme events such as heat waves and coastal storms, as well as more gradual changes in climate and CO_2 levels. {26.6.2} Human health impacts in North America from future climate extremes can be reduced by adaptation measures such as targeted and sustainable air conditioning, more effective warning and response systems, enhanced pollution controls, urban planning strategies, and resilient health infrastructure (*high confidence*). {26.6.3}

Observed impacts on livelihoods, economic activities, infrastructure, and access to services in North American urban and rural settlements have been attributed to SLR, changes in temperature and precipitation, and occurrences of such extreme events as heat waves, droughts, and storms (*high confidence*). {26.8.2.1} Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific social and environmental factors and processes that contribute to risk, vulnerability, and adaptive capacity such as hazard magnitude, populations access to assets, built environment features, and governance (*high confidence*). {26.8.2.1-2}. Some of these processes (e.g., the legacy of previous and current stresses) are common to urban and rural settlements, while others are more pertinent to some types of settlements than others. For example, human and capital risks are highly concentrated in some highly exposed urban locations, while in rural areas, geographic isolation and institutional deficits are key sources of vulnerability. Among the most vulnerable are indigenous peoples due to their complex relationship with their ancestral lands and higher reliance on subsistence economies, and those urban centers where high concentrations of populations and economic activities in risk-prone areas combine with several socioeconomic and environmental sources of vulnerability (*high confidence*). {26.8.2.1-2} Although larger urban centers would have higher adaptation capacities, future climate risks from heat waves, droughts, storms, and SLR in cities would be enhanced by high population density, inadequate infrastructures, lack of institutional capacity, and degraded natural environments (*medium evidence*, *high agreement*). {26.8.3}

Much of North American infrastructure is currently vulnerable to extreme weather events and, unless investments are made to strengthen them, would be more vulnerable to climate change (*medium confidence*). Water resources and transportation infrastructure are in many cases deteriorating, thus more vulnerable to extremes than strengthened ones (*high confidence*). Extreme events have caused significant damage to infrastructure in many parts of North America; risks to infrastructure are particularly acute in Mexico but are a big concern in all three countries (*high confidence*). {26.7}

Most sectors of the North American economy have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). {Figure 26-2} Despite a growing experience with reactive adaptation, there are few examples of proactive adaptation anticipating future climate change impacts, and these are largely found in sectors with longer term decision making, including energy and public infrastructure. Knowledge about lessons learned and best adaptive practices by industry sector are not well documented in the published literature. {26.7} There is an emerging concern that dislocation in one sector of the economy may have an adverse impact on other sectors as a result of supply chain interdependency (*medium confidence*). {26.7} Slow-onset perils—such as SLR, drought, and permafrost thaw—are an emerging concern for some sectors, with large regional variation in awareness and adaptive capacity (*medium confidence*).

Adaptation Responses

Adaptation—including through technological innovation, institutional strengthening, economic diversification, and infrastructure design—can help to reduce risks in the current climate, and to manage future risks in the face of climate change (*medium confidence*). {26.8.4, 26.9.2} There is increasing attention to adaptation among planners at all levels of government but particularly at the municipal level, with many jurisdictions engaging in assessment and planning processes. These efforts have revealed the significant challenges and sources of resistance facing planners at both the planning and implementation stages, particularly the adequacy of informational, institutional, financial, and human resources, and lack of political will (*medium confidence*). {26.8.4.2, 26.9.3} Specific strategies introduced into policy to date tend to be incremental rather than transformational. Fiscal constraints are higher for Mexican jurisdictions and sectors than for Canada or the USA. The literature on sectoral-level adaptation is stronger in the areas of technological and engineering adaptation strategies than in social, behavioral, and institutional strategies. Adaptation actions have the potential to result in synergies or trade-offs with mitigation and other development actions and goals (*high confidence*). {26.8.4.2, 26.9.3}

26.1. Introduction

This chapter assesses literature on observed and projected impacts, vulnerabilities, and risks as well as on adaptation practices and options in three North American countries: Canada, Mexico, and the USA. The North American Arctic region is assessed in Chapter 28: Polar Regions. North America ranges from the tropics to frozen tundra, and contains a diversity of topography, ecosystems, economies, governance structures, and cultures. As a result, risk and vulnerability to climate variability and change differ considerably across the continent depending on geography, scale, hazard, socio-ecological systems, ecosystems, demographic sectors, cultural values, and institutional settings. This chapter seeks to take account of this diversity and complexity as it affects and is projected to affect vulnerabilities, impacts, risks, and adaptation across North America.

No single chapter would be adequate to cover the range and scope of the literature about climate change vulnerabilities, impacts, and adaptations in the three focus countries of this assessment. (Interested readers are encouraged to review these reports: Lemmen et al., 2008; INECC and SEMARNAT, 2012a; NCADAC, 2013.) We therefore attempt to take a more integrative and innovative approach. In addition to describing current and future climatic and socioeconomic trends of relevance to understanding risk and vulnerability in North America (Section 26.2), we contrast climate impacts, vulnerabilities, and adaptations across and within the three countries in the following key sectors: water resources and management (Section 26.3); ecosystems and biodiversity (Section 26.4); agriculture and food security (Section 26.5); human health (Section 26.6); and key economic sectors and services (Section 26.7). We use a comparative and place-based approach to explore the factors and processes associated with differences and commonalities in vulnerability, risk, and adaptation between urban and rural settlements (Section 26.8); and to illustrate and contrast the nuanced challenges and opportunities adaption entails at the city, subnational, and national levels (Sections 26.8.4, 26.9; Box 26-3). We highlight two case studies that cut across sectors, systems, or national boundaries. The first, on wildfires (Box 26-2), explores some of the connections between climatic and physical and socioeconomic process (e.g., decadal climatic oscillation, droughts, wildfires land use, and forest management) and across systems and sectors (e.g., fires direct and indirect impacts on local economies, livelihoods, built environments, and human health). The second takes a look at one of the world's longest borders between a high-income (USA) and middle-income country (Mexico) and briefly reflects on the challenges and opportunities of responding to climate change in a transboundary context (Box 26-1). We close with a section (26.10) summarizing key multi-sectoral risks and uncertainties and discussing some of the knowledge gaps that will need to be filled by future research.

Findings from the Fourth Assessment Report

This section summarizes key findings on North America, as identified in Chapter 13 of the Fourth Assessment Report (AR4) focused on Mexico (Magrin et al., 2007) and Chapter 14 on Canada and the USA (Field et al., 2007). It focuses on observed and projected impacts, vulnerabilities, and risks, as well as on adaptation practices and options, and highlights areas of agreement and difference between the AR4's two chapters and our consolidated North American chapter.

Observed Impacts and Processes Associated with Vulnerability

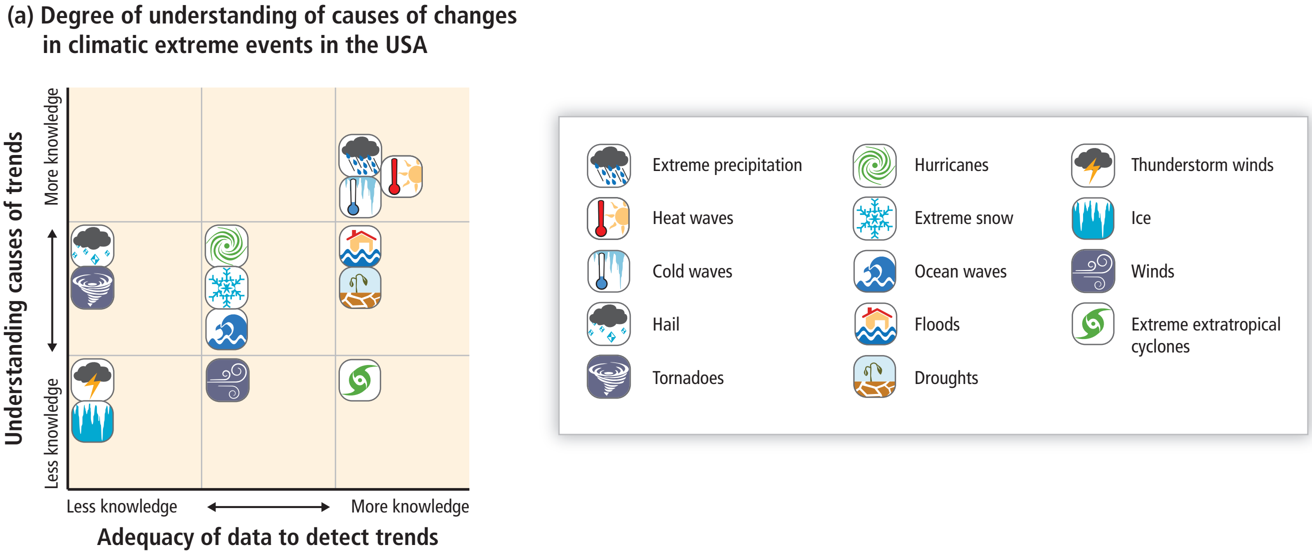
Both WGII AR4 Section 14.2 and our chapter (Figure 26-2) find that, over the past decades, economic damage from severe weather has increased dramatically. Our chapter confirms that although Canada and the USA have considerably more adaptive capacity than Mexico, their vulnerability depends on the effectiveness and timing of adaptation and the distribution of capacity, which vary geographically and between sectors (WGII AR4 Sections 14.2.6, 14.4-5; Sections 26.2.2, 26.8.2).

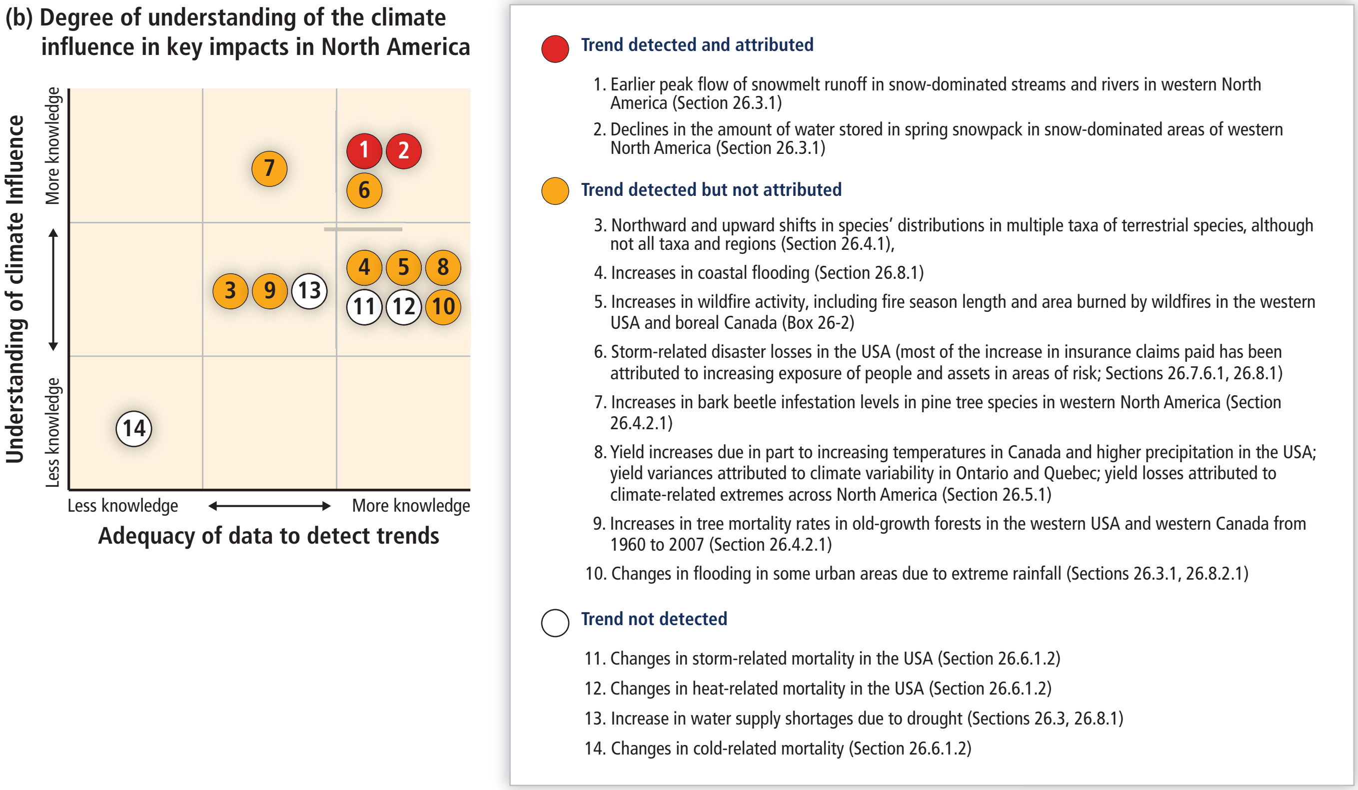
WGII AR4 Chapters 13 and 14 did not assess impacts, vulnerabilities, and risks in urban and rural settlements, but rather assessed literature on future risks in the following sectors:

- *Ecosystems*: Both AR4 and our chapter find that ecosystems are under increased stress from increased temperatures, climate variability, and other climate stresses (e.g., sea level rise (SLR) and storm-surge flooding), and that these stresses interact with developmental and environmental stresses (e.g., as salt intrusion, pollution, population growth, and the rising value of infrastructure in coastal areas) (WGII AR4 Sections 13.4.4, 14.2.3, 14.4.3). Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections would alter ecosystem structure, function, and services in terrestrial ecosystems (WGII AR4 Sections 14.2, 14.4). Both reports show that dry soils and warm temperatures are associated with increased wildfire activity and insect outbreaks in Canada and the USA (WGII AR4 Sections 14.2, 14.4; Section 26.4.2.1).
- *Water resources*: AR4 projects millions in Mexico to be at risk from the lack of adequate water supplies due to climate change (WGII AR4 Section 13.4.3); our chapter, however, finds that water resources are already stressed by non-climatic factors, such as population pressure that will be compounded by climate change (Section 26.3.1). Both reports find that in the USA and Canada rising temperatures would diminish snowpack and increase evaporation (Section 26.2.2.1), thus affecting seasonal availability of water (WGII AR4 Section 14.2.1; Section 26.3.1). The reports also agree that these effects will be amplified by water demand from economic development, agriculture, and population growth, thus imposing further constraints to over-allocated water resources and increasing competition among agricultural, municipal, industrial, and ecological uses (WGII AR4 Sections 14.4.1, 14.4.6; Section 26.3.3). Both agree water quality will be further stressed (WGII AR4 Sections 13.4.3, 14.4.1; Section 26.3.2.2). There is more information available now on water adaptation than in AR4 (WGII AR4 Sections 13.5.1.3, 14.5.1; Section 26.3.3), and it is possible to attribute changes in extreme precipitation, snowmelt, and snowpack to climate change (WGII AR4 Sections 13.2.4, 14.2.1; Section 26.3.1).
- *Agriculture*: The AR4 noted that while increases in grain yields in the USA and Canada are projected by most scenarios (WGII AR4 Section 14.4.4), in Mexico the picture is mixed for wheat and maize, with different projected impacts depending on scenario used (WGII AR4 Section 13.4.2). Research since the AR4 has offered more cautious projections of yield change in North America due to shifts in temperature and precipitation, particularly by 2100; and significant harvest losses due to recent extreme weather events have been observed (Section 26.5.1). Furthermore, our chapter reports on recent research that underscores the context-specific nature of adaptation

capacity and of institutional support and shows that these factors, which greatly enhance adaptive potential, are currently lacking in some regions (Section 26.5.3).

- *Health*: AR4 focused primarily on a set of future health risks. These include changes in the geographical distribution and transmission of diseases such as dengue (WGII AR4 Section 13.4.5) and increases in respiratory illness, including exposure to pollen and ozone (WGII AR4 Section 14.4) and in mortality from hot temperatures and extreme weather in Canada and the USA. AR4 also projects that climate change impacts on infrastructure and human health in cities of Canada and the USA would be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth, and an aging population (WGII AR4 Sections 14.4-5). Without increased investments in measures such


(a) Degree of understanding of causes of changes in climatic extreme events in the USA


(b) Degree of understanding of the climate influence in key impacts in North America

🔴 **Trend detected and attributed**

1. Earlier peak flow of snowmelt runoff in snow-dominated streams and rivers in western North America (Section 26.3.1)
2. Declines in the amount of water stored in spring snowpack in snow-dominated areas of western North America (Section 26.3.1)

🟠 **Trend detected but not attributed**

3. Northward and upward shifts in species' distributions in multiple taxa of terrestrial species, although not all taxa and regions (Section 26.4.1),
4. Increases in coastal flooding (Section 26.8.1)
5. Increases in wildfire activity, including fire season length and area burned by wildfires in the western USA and boreal Canada (Box 26-2)
6. Storm-related disaster losses in the USA (most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk; Sections 26.7.6.1, 26.8.1)
7. Increases in bark beetle infestation levels in pine tree species in western North America (Section 26.4.2.1)
8. Yield increases due in part to increasing temperatures in Canada and higher precipitation in the USA; yield variances attributed to climate variability in Ontario and Quebec; yield losses attributed to climate-related extremes across North America (Section 26.5.1)
9. Increases in tree mortality rates in old-growth forests in the western USA and western Canada from 1960 to 2007 (Section 26.4.2.1)
10. Changes in flooding in some urban areas due to extreme rainfall (Sections 26.3.1, 26.8.2.1)

○ **Trend not detected**

11. Changes in storm-related mortality in the USA (Section 26.6.1.2)
12. Changes in heat-related mortality in the USA (Section 26.6.1.2)
13. Increase in water supply shortages due to drought (Sections 26.3, 26.8.1)
14. Changes in cold-related mortality (Section 26.6.1.2)

Figure 26-1 | (a) Detection and attribution of climate change impacts. Comparisons of the adequacy of currently available data to detect trends and the degree of understanding of causes of those changes in climatic extreme events in the USA (Peterson et al., 2013), and (b) degree of understanding of the climate influence in key impacts in North America. Note that "climate influence" means that the impact has been documented to be sensitive to climate, not that it has been attributed to climate change. Red circles indicate that formal detection and attribution to climate change has been performed for the given impact; yellow circles indicate that a trend has been detected from background variability in the given impact, but formal attribution to climate change has not occurred and the trend could be due to other drivers; and white circles indicate that a trend has not currently been detected.

as early warning and surveillance systems, air conditioning, and access to health care, hot temperatures and extreme weather in Canada and the USA are predicted to result in increased adverse health impacts (WGII AR4 Sections 14.4-5). Our chapter provides a more detailed assessment of these future risks (Section 26.6), besides assessing a richer literature on observed health impacts (Section 26.6.1).

- *Adaptation*: AR4 found that Mexico has early warning and risk management systems, yet it faces planning and management barriers. In Canada and the USA, a decentralized response framework has resulted in adaptation that tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems (WGII AR4 Section 14.5). Both chapters see "mainstreaming" climate issues into decision making as key to successful adaptation (WGII AR4 Sections 13.5, 14.5). The current chapter provides a summary of the growing empirical literature on emerging opportunities and constraints associated with recent institutional adaptation planning activities since the AR4 (Sections 26.3.3, 26.4.4, 26.5.4, 26.6.3, 26.8.4, 26.9).

In summary, scholarship on climate change impacts, adaptation, and vulnerability has grown considerably since the AR4 in North America, particularly in Canada and the USA. It is possible now not only to detect and attribute to anthropogenic climate change some impacts such as changes in extreme precipitation, snowmelt, and snowpack, but also to examine trends showing increased insect outbreaks, wildfire events, and coastal flooding. These latter trends have been shown to be sensitive to climate, but, like the local climate patterns that cause them, have not yet been positively attributed to anthropogenic climate change (see Figure 26-1).

26.2. Key Trends Influencing Risk, Vulnerability, and Capacities for Adaptation

26.2.1. Demographic and Socioeconomic Trends

26.2.1.1. Current Trends

Canada, Mexico, and USA share commonalities but also differ in key dimensions shaping risk, vulnerability, and adaptation such as population dynamics, economic development, and institutional capacity. During the last years, the three countries, particularly the USA, have suffered economic losses from extreme weather events (Figure 26-2). Hurricanes, droughts, floods, and other climate-related hazards produce risk as they interact with increases in exposed populations, infrastructure, and other assets and with the dynamics of such factors shaping vulnerability as wealth, population size and structure, and poverty (Figures 26-2 and SPM.1). Population growth has been slower in Canada and USA than in Mexico (UN DESA Population Division, 2011). Yet population growth in Mexico also decreased from 3.4% between 1970 and 1980 to 1.5% yearly during 2000–2010. Populations in the three countries are aging at different

Box 26-1 | Adapting in a Transboundary Context: The Mexico-USA Border Region

Extending over 3111 km (1933 miles; U.S. Census Bureau, 2011), the border between the USA and Mexico, which can be defined in different ways (Varady and Ward, 2009), illustrates the challenges and opportunities of responding to climate change in a transboundary context. Changing regional climate conditions and socioeconomic processes combined shape differentiated vulnerabilities of exposed populations, infrastructure, and economic activities.

Since at least 1999, the region has experienced high temperatures and aridity anomalies leading to drought conditions (Woodhouse et al., 2010; Wilder et al., 2013) affecting large areas on both sides of the border, and considered the most extreme in over a century of recorded precipitation patterns for the area (Cayan et al., 2010; Seager and Vecchi, 2010; Nielsen-Gammon, 2011). Streamflow in already oversubscribed rivers such as the Colorado and Rio Grande (Nakaegawa et al., 2013) has decreased. Climatological conditions for the area have been unprecedented, with sustained high temperatures that may have exceeded any experienced for 1200 years. Although these changes cannot conclusively be attributed to anthropogenic climate change, they are consistent with climate change projections (Woodhouse et al., 2010).

The population of the Mexico-USA border is rapidly growing and urbanizing, doubling from just under 7 million in 1983 to more than 15 million in 2012 (Peach and Williams, 2000). Since 1994, rapid growth in the area has been fueled by rapid economic development subsequent to passage of the North American Free Trade Agreement (NAFTA). Between 1990 and 2001 the number of assembly factories or maquiladoras in Mexico grew from 1700 to nearly 3800, with 2700 in the border area. By 2004, it was estimated that more than 1 million Mexicans were employed in more than 3000 maquiladoras located along the border (Border Indicators Task Force, 2011; EPA and SEMARNAT, 2012).

Continued next page →

Box 26-1 (continued)

Notwithstanding this growth, challenges to adaptive capacity include high rates of poverty in a landscape of uneven economic development (Wilder et al., 2013). Large sections of the urban population, particularly in Mexico, live in informal housing lacking the health and safety standards needed to respond to hazards, and with no insurance (Collins et al., 2011). Any effort to increase regional capacity to respond to climate needs to take existing gaps into account. In addition, there is a prevalence of incipient or actual conflict (Mumme, 1999), given by currently or historically contested allocation of land and water resources (e.g., an over-allocated Colorado River ending in Mexico above the Sea de Cortes (Getches, 2003)). Climate change, therefore, would bring additional significant consequences for the region's water resources, ecosystems, and rural and urban settlements.

The impacts of regional climatic and non-climatic stresses compound existing urban vulnerabilities that are different across countries. For instance, besides degrading highly diverse ecosystems (Wilder et al., 2013), residential growth in flood-prone areas in Ciudad Juárez has not been complemented with the provision of determinants of adaptive capacity to residents, such as housing, health care, and drainage infrastructure. As a result, although differences in mean hazard scores are not significant between Ciudad Juárez (Mexico) and El Paso (USA), social vulnerability and average risk are three times and two times higher in Ciudad Juárez than in El Paso respectively (Collins, 2008).

Projected warming and drying would impose additional burdens on already stressed water resources and ecosystems and compound existing vulnerabilities for populations, infrastructure, and economic activities (Wilder et al., 2013). The recent drought in the region illustrated the multiple dimensions of climate-related events, including notable negative impacts on the agricultural sector, water supplies, food security, and risk of wildfire (discussed in Box 26-2) (Wehner et al., 2011; Hoerling et al., 2012; Schwalm et al., 2012).

Adaptation opportunities and *constraints* are shared across international borders, creating the need for cooperation among local, national, and international actors. Although there are examples of efforts to manage transborder environmental issues, such as the USA-Mexico International Boundary and Water Commission agreement (United States and Mexico International Boundary and Water Commission, 2012), constraints to effective cooperation and collaboration include different governance structures (centralized in Mexico, decentralized in the USA), institutional fragmentation, asymmetries in the use and dissemination of information, and language (Wilder et al., 2010, 2013; Megdal and Scott, 2011).

rates (Figure 26-2). In 2010, 14.1% of the population in Canada was 60 years and older, compared to 12.7% in the USA and 6.1% in Mexico (UN DESA Population Division, 2011). Urban populations have grown faster than rural populations, resulting in a North America that is highly urbanized (Canada 84.8%, Mexico 82.8%, and USA 85.8%). Urban populations are also expanding into peri-urban spaces, producing rapid changes in population and land use dynamics that can exacerbate risks from such hazards as floods and wildfires (Eakin et al., 2010; Romero-Lankao et al., 2012a). Mexico has a markedly higher poverty rate (34.8%) than Canada (9.1%) and the USA (12.5%) (Figure 26-2), with weather events and climate affecting poor people's livelihood assets, including crop yields, homes, food security, and sense of place (Chapter 13; Section 26.8.2). Between 1970 and 2012, a 10% increase in single-person households—who can be vulnerable because of isolation and low income and housing quality (Roorda et al., 2010)—has been detected in the USA (Vespa et al., 2013).

While concentrations of growing populations, water, sanitation, transportation and energy infrastructure, and industrial and service sectors in urban areas can be a source of risk, geographic isolation and high dispersion of rural populations also introduce risk because of long distances to essential services (Section 26.8.2). Rural populations are more vulnerable to climate events due to smaller labor markets, lower income levels, and reduced access to public services. Rural poverty could also be aggravated by changes in agricultural productivity, particularly in Mexico, where 65% of the rural population is poor, agricultural income is seasonal, and most households lack insurance (Scott, 2007). Food price increases, which may also result from climate events, would contribute to food insecurity (Lobell et al., 2011; World Bank, 2011).

Migration is a key trend affecting North America, recently with movements between urban centers and from rural Mexico into Mexico's cities, and in the USA. Rates of migration from rural Mexico are positively associated with natural disaster occurrence and increased poverty trends (Saldaña-Zorilla and Sandberg, 2009), and with decreasing precipitation (Nawrotski et al., 2013). Studies of migration induced by past climate variability and change indicate a preference for short-range domestic movement, a complex relationship to assets with indications that the poorest are less able to migrate, and the role of preexisting immigrant networks in facilitating international migration (Oppenheimer, 2013).

North America has become more economically integrated following the 1994 North American Free Trade Agreement. Prior to a 2007–2008 reduction in trade, the three countries registered dynamic growth in industry, employment, and global trade of agricultural and manufactured goods (Robertson et al., 2009). Notwithstanding North America's economic dynamism, increased socioeconomic disparities (Autor et al., 2008) have affected such determinants of vulnerability as differentiated human development and institutional capacity within and across countries.

26.2.1.2. Future Trends

The North American population is projected to continue growing, reaching between 531.8 (SRES B2) and 660.1 (A2) million by 2050 (IIASA, 2007).

(a) Significant weather events taking place during 1993–2012

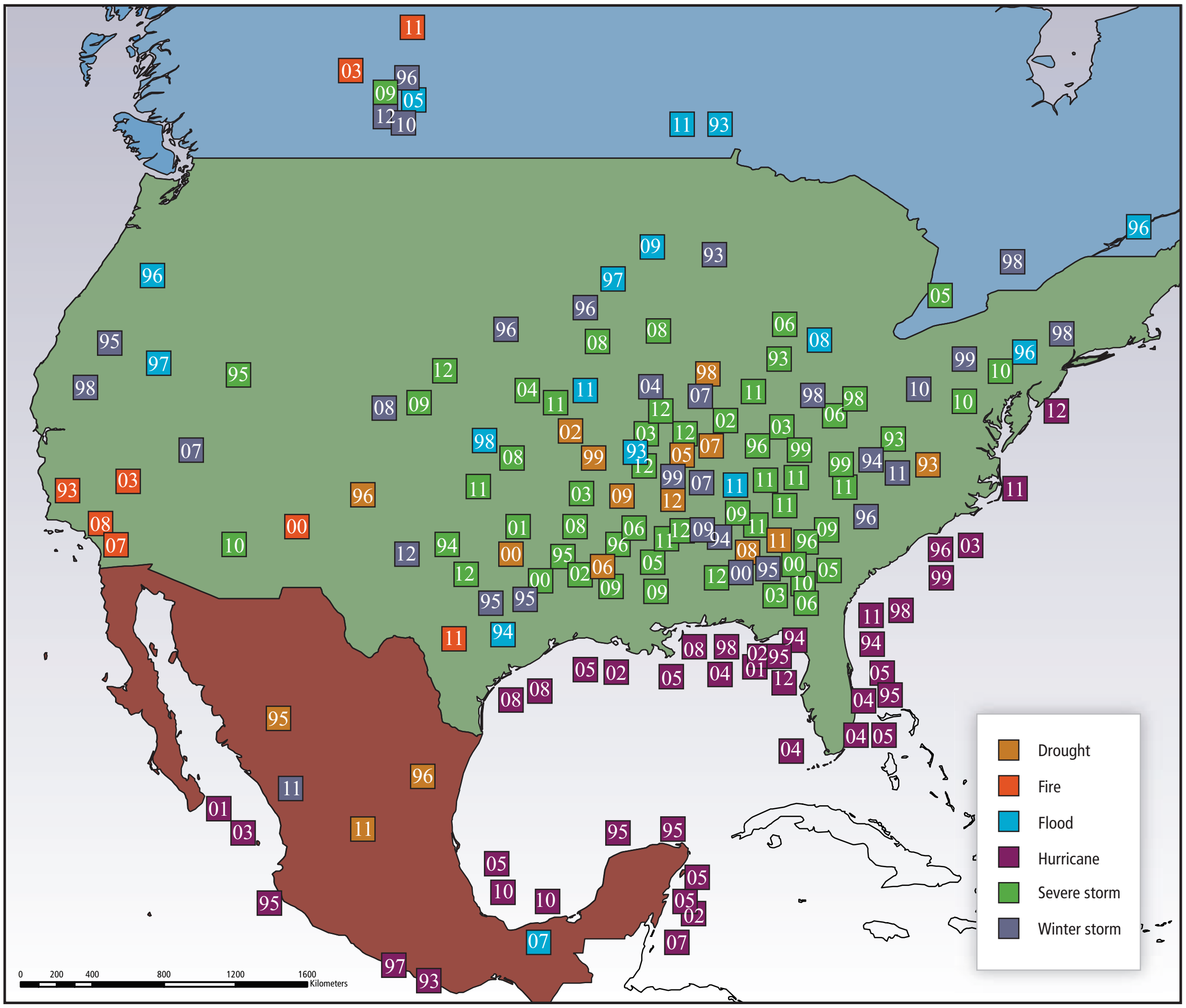


Figure 26-2 | Extreme events illustrating vulnerabilities for Mexico, the USA, and Canada. This figure offers a graphic illustration of location of extreme events and relevant vulnerability trends. The observed extreme events have not been attributed to anthropogenic climate change, yet they are climate-sensitive sources of impact illustrating vulnerability of exposed systems, particularly if projected future increases in the frequency and/or intensity of such events should materialize. The figure contains three elements. (a) A map with significant weather and climate events taking place during 1993–2012 (data derived from NatCatSERVICE, 2013). The categories "Severe storm" and "Winter storm" are aggregations of multiple types of storms; e.g., hailstorms are shown as Winter storms and tornadoes as Severe storms. Boxed numbers refer to the years in which the extreme events occurred. Hurricanes are placed offshore of the point of initial landfall, and placement of all other boxes (which may span multiple subnational jurisdictions) is weighted towards areas with the highest expected impacts (defined by estimated affected populations when finer subnational detail was not available). The map includes only events with overall losses ≥ US\$1 billion in the USA, or ≥US\$500 million in Mexico and Canada, adjusted to 2012 values; hence, it does not include events of small and medium impact. Additionally, losses do not capture the impacts of disasters on populations' livelihoods and well-being. (b) A map (facing page) with population density per ~0.0083˚ gridbox at 1-km resolution highlighting exposure and represented using 2011 Landsat data (Bright et al., 2012). Note that a ~0.0083˚ grid box is approximately1 km^2, but this approximation varies by latitude. (c) Four panels (facing page) with trends in socio-demographic indicators used in the literature to measure vulnerability to hazards (Romero-Lankao et al., 2012b): poverty rates, percentage of elderly, GDP per capita and total population (U.S. Census Bureau, 2011; Statistics Canada, 2012, CEPAL, 2013).

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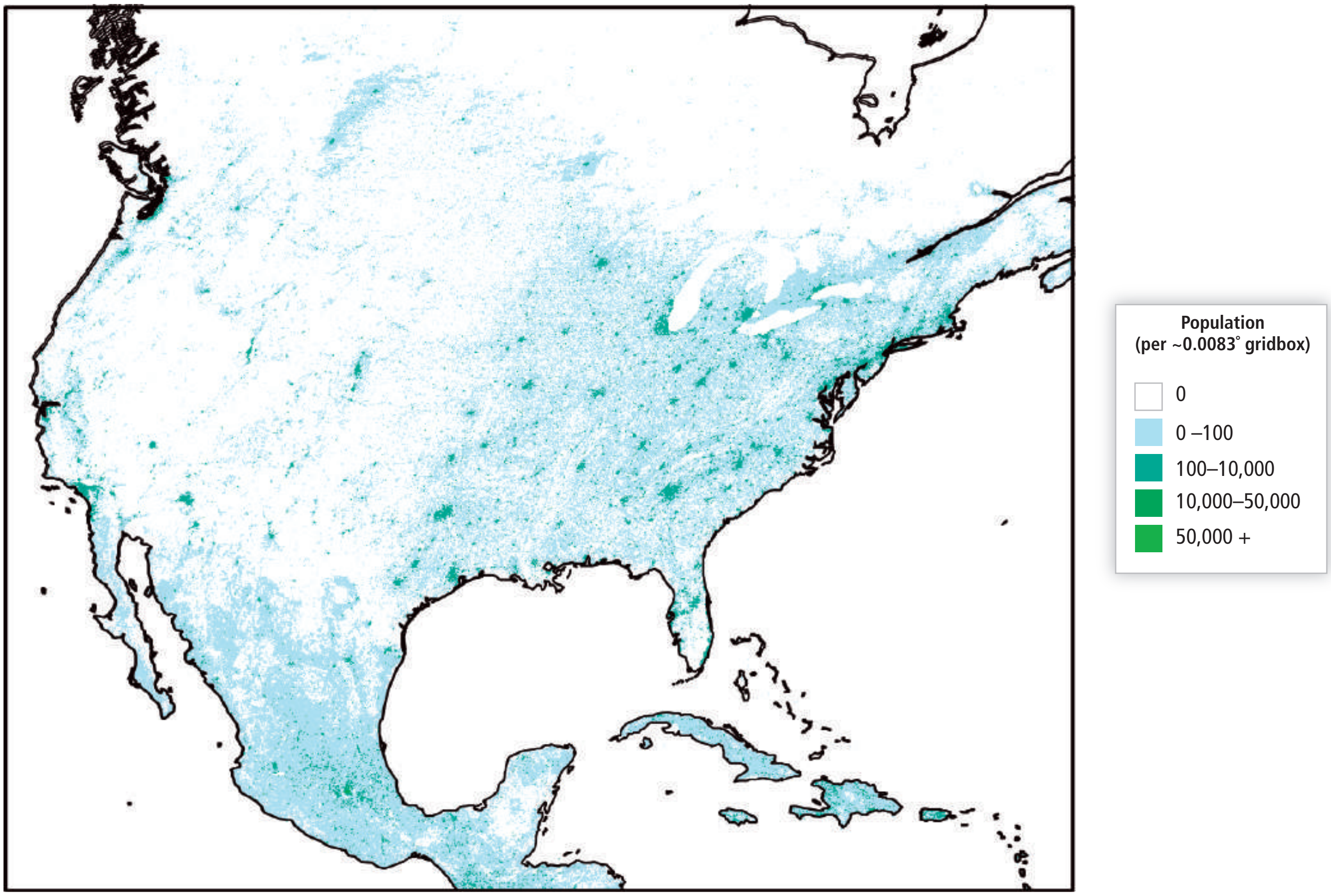
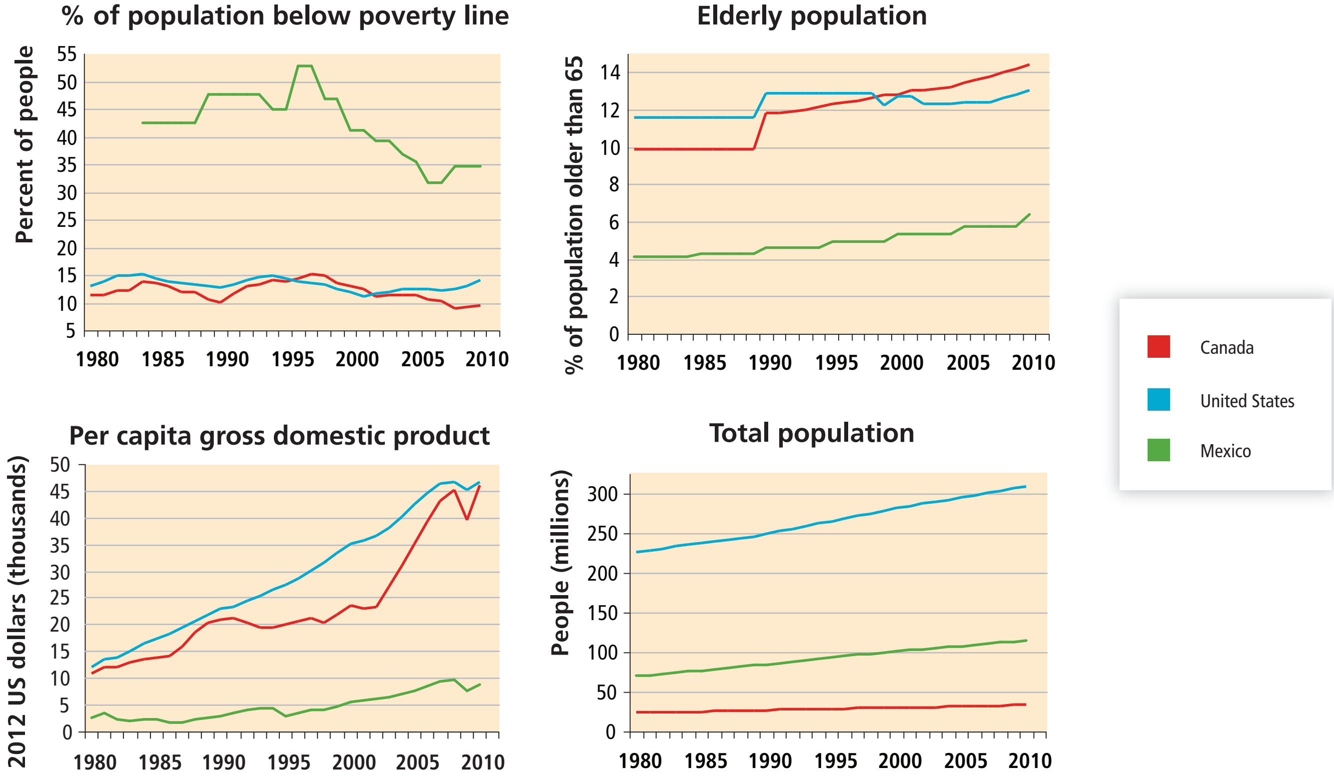
Figure 26-2 (continued)

(b) Population density at 1 km resolution



(c) Trends in socioeconomic indicators



The percentage of elderly people (older than 64 years) is also projected to continue to increase, by 23.4 to 26.9% in Canada, 12.4 to 18.4% in Mexico, and 17.3 to 20.9% in the USA by 2050 (B2 and A2, respectively) (IIASA, 2007). The elderly are highly vulnerable to extreme weather events (heat waves in particular, Figure 26-2) (Martiello and Giacchi, 2010; Diffenbaugh and Scherer, 2011; Romero-Lankao, 2012; White-Newsome et al., 2012). Numbers of single-person households and female-headed households—both of which are vulnerable because of low income and housing quality—are anticipated to increase (Roorda et al., 2010). Institutional capacity to address the demands posed by increasing numbers of vulnerable populations may also be limited, with resulting stress on health and the economy.

Three other shifts are projected to influence impacts, vulnerabilities, and adaptation to climate change in North America: urbanization, migration, and socioeconomic disparity. With small differences between countries, both the concentration of growing populations in some urban areas and the dispersion of rural populations are projected to continue to define North America by 2050. Assuming no change in climate, between 2005 and 2030 the population of Mexico City Metro Area will increase by 17.5%, while between 2007 and 2030 available water will diminish by 11.2% (Romero-Lankao, 2010). Conversely, education, a key determinant of adaptive capacity (Chapter 13), is expected to expand to low-income households, minorities, and women, which could increase the coping capacity of households and have a positive impact on economic growth (Goujon et al., 2004). However, the continuation of current patterns of economic disparity and poverty would hinder future adaptive capacity. Inequality in Mexico is larger (Figure 26-2), having a Gini coefficient (according to which the higher the number the higher economic disparity) of 0.56, in contrast to 0.317 for Canada and 0.389 for the USA (OECD, 2010). Mexico is one of five countries in the world that is projected to experience the highest increases in poverty due to climate-induced extreme events (52% increase in rural households, 95.4% in urban wage-labor households; Coupled Model Intercomparison Project Phase 3 (CMIP3), A2) (Ahmed et al., 2009).

Some studies project increased North American migration in response to climate change. Feng, Krueger, and Oppenheimer (2010) estimated the emigration of an additional 1.4 to 6.7 million Mexicans by 2080 based on projected maize yield declines, range depending on model (B1, United Kingdom Meteorological Office (UKMO), and Geophysical Fluid Dynamics Laboratory (GFDL)). Oppenheimer speculates that the indirect impacts of migration "could be as substantial as the direct effects of climate change in the receiving area," because the arrival migrants can increase pressure on climate sensitive urban regions (Oppenheimer, 2013, p. 442).

26.2.2. Physical Climate Trends

Some processes important for climate change in North America are assessed eslewhere in the Fifth Assessment Report, including WGI AR5 Chapter 2 (Observations: Atmosphere and Surface), WGI AR5 Chapter 4 (Observations: Cryosphere), WGI AR5 Chapter 12 (Long-term Climate Change: Projections, Commitments, and Irreversibility), WGI AR5 Chapter 14 (Climate Phenomena and Their Relevance for Future Regional Climate Change), WGI AR5 Annex I (Atlas of Global and Regional Climate Projections), and Chapter 21 of this volume (Regional Context). In addition, comparisons of emissions, concentrations, and radiative forcing in the Representative Concentration Pathways (RCPs) and *Special Report on Emission Scenarios* (SRES) scenarios can be found in WGI AR5 Annex II (Climate System Scenario Tables).

26.2.2.1. Current Trends

It is *very likely* that mean annual temperature has increased over the past century over most of North America (WGI AR5 Figure SPM.1b; Figure 26-3). Observations also show increases in the occurrence of severe hot events over the USA over the late 20th century (Kunkel et al., 2008), a result in agreement with observed late-20th-century increases in extremely hot seasons over a region encompassing northern Mexico, the USA, and parts of eastern Canada (Diffenbaugh and Scherer, 2011). These increases in hot extremes have been accompanied by observed decreases in frost days over much of North America (Alexander et al., 2006; Brown et al., 2010; see also WGI AR5 Section 2.6.1), decreases in cold spells over the USA (Kunkel et al., 2008; see also WGI AR5 Section 2.6.1), and increasing ratio of record high to low daily temperatures over the USA (Meehl et al., 2009). However, warming has been less pronounced and less robust over areas of the central and southeastern USA (e.g., Alexander et al., 2006; Peterson et al., 2008; see also WGI AR5 Section 2.6.1; WGI AR5 Figure SPM.1b; Figure 26-3). It is possible that this pattern of muted temperature change has been influenced by changes in the hydrologic cycle (e.g., Pan et al., 2004; Portmann et al., 2009), as well as by decadal-scale variability in the ocean (e.g., Meehl et al., 2012; Kumar et al., 2013b).

It is *very likely* that annual precipitation has increased over the past century over areas of the eastern USA and Pacific Northwest (WGI AR5 Figure 2.29; Figure 26-3). Observations also show increases in heavy precipitation over Mexico, the USA, and Canada between the mid-20th and the early 21st century (DeGaetano, 2009; Peterson and Baringer, 2009; Pryor et al., 2009; see also WGI AR5 Section 2.6.2). Observational analyses of changes in drought are more equivocal over North America, with mixed sign of trend in dryness over Mexico, the USA, and Canada (Dai, 2011; Sheffield et al., 2012; see also WGI AR5 Section 2.6.2; WGI AR5 Figure 2.42). There is also evidence for earlier occurrence of peak flow in snow-dominated rivers globally (Rosenzweig, 2007; WGI AR5 Section 2.6.2). Observed snowpack and snow-dominated runoff have been extensively studied in the western USA and western Canada, with observations showing primarily decreasing trends in the amount of water stored in spring snowpack from 1960 to 2002 (with the most prominent exception being the central and southern Sierra Nevada; Mote, 2006) and primarily earlier trends in the timing of peak runoff over the 1948–2000 period (Stewart et al., 2006; WGI AR5 Section 4.5; WGI AR5 Figure 4.21). Observations also show decreasing mass and length of glaciers in North America (WGI AR5 Section 4.3; WGI AR5 Figures 4.9, 4.10, 4.11). Further, in assessing changes in the hydrology of the western USA, it has been concluded that "up to 60% of the climate-related trends of river flow, winter air temperature, and snowpack between 1950 and 1999 are human-induced" (Barnett et al., 2008, p. 1080).

Observational limitations prohibit conclusions about trends in severe thunderstorms (WGI AR5 Section 2.6.2) and tropical cyclones (WGI AR5

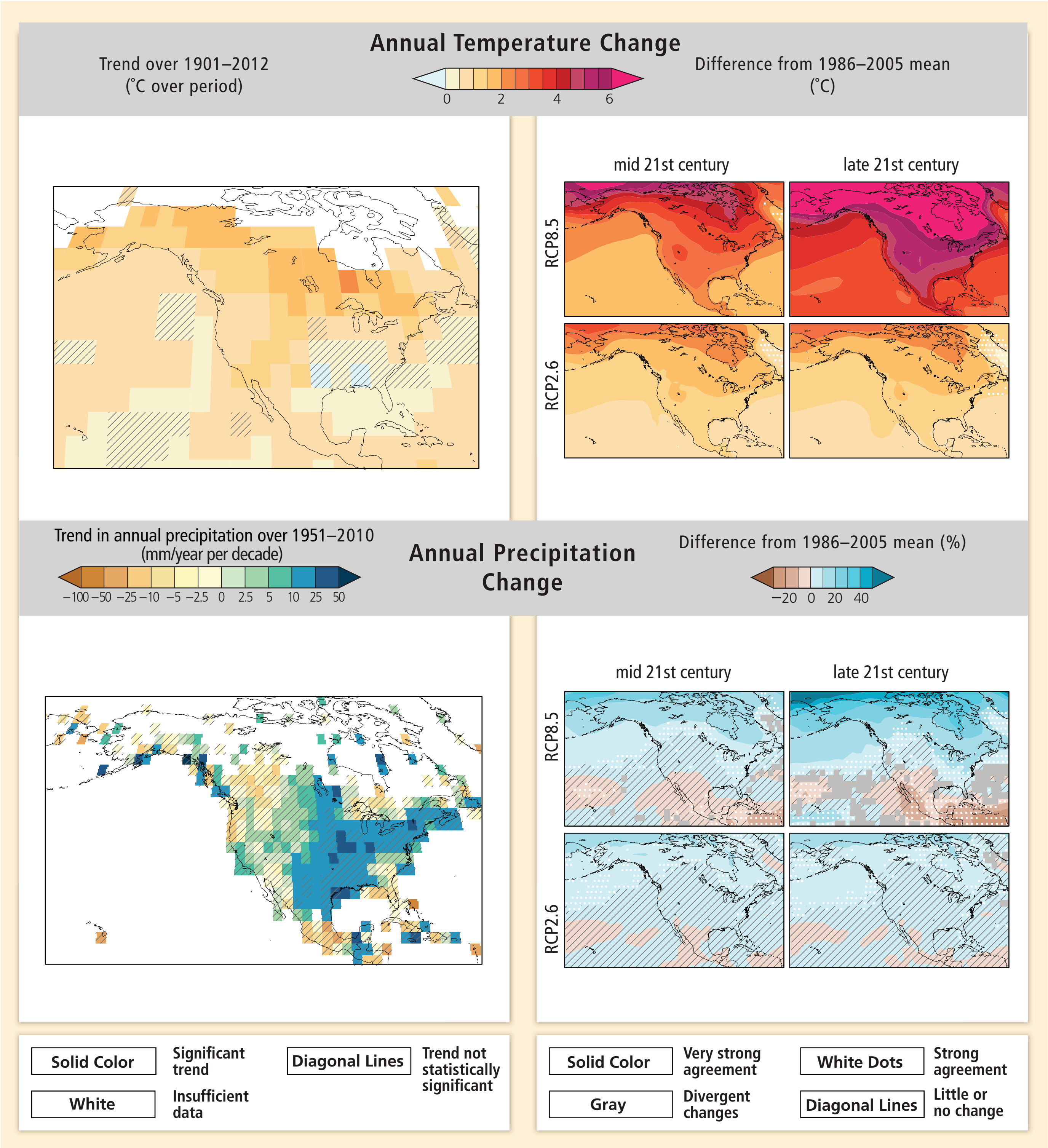


Figure 26-3 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5 Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

Section 2.6.3) over North America. The most robust trends in extratropical cyclones over North America are determined to be toward more frequent and intense storms over the northern Canadian Arctic and toward less frequent and weaker storms over the southeastern and southwestern coasts of Canada over the 1953–2002 period (Wang et al., 2006; see also WGI AR5 Section 2.7.4).

WGI concludes that "Global mean sea level (GMSL) has risen by 0.19 (0.17 to 0.21) m over the period 1901–2010" and that "it is *very likely* that the mean rate was 1.7 (1.5 to 1.9) mm yr^{-1} between 1901 and 2010 and increased to 3.2 (2.8 to 3.6) mm yr^{-1} between 1993 and 2010" (WGI AR5 Chapter 3 ES). In addition, observed changes in extreme sea level have been caused primarily by increases in mean sea level (WGI AR5 Section 3.7.5). Regional variations in the observed rate of SLR can result from processes related to atmosphere and ocean variability (such as lower rates along the west coast of the USA) or vertical land motion (such as high rates along the US Gulf Coast), but the persistence of the observed regional patterns is unknown (WGI AR5 Section 3.7.3).

26.2.2.2. Climate Change Projections

WGI AR5 Chapters 11 and 12 assess near- and long-term future climate change, respectively. WGI AR5 Chapter 14 assesses processes that are important for regional climate change, with WGI AR5 Section 14.8.3 focused on North America. Many of the WGI AR5 conclusions are drawn from Annex I of the WGI contribution to the AR5.

The CMIP5 ensemble projects *very likely* increases in mean annual temperature over North America, with *very likely* increases in temperature over all land areas in the mid- and late-21st-century periods in RCP2.6 and RCP8.5 (Figure 26-3). Ensemble-mean changes in mean annual temperature exceed 2°C over most land areas of all three countries in the mid-21st-century period in RCP8.5 and the late-21st-century period in RCP8.5, and exceed 4°C over most land areas of all three countries in the late-21st-century period in RCP8.5. However, ensemble-mean changes in mean annual temperature remain within 2°C above the late-20th-century baseline over most North American land areas in both the mid- and late-21st-century periods in RCP2.6. The largest changes in mean annual temperature occur over the high latitudes of the USA and Canada, as well as much of eastern Canada, including greater than 6°C in the late-21st-century period in RCP8.5. The smallest changes in mean annual temperature occur over areas of southern Mexico, the Pacific Coast of the USA, and the southeastern USA.

The CMIP5 ensemble projects warming in all seasons over North America beginning as early as the 2016–2035 period in RCP2.6, with the greatest warming occurring in winter over the high latitudes (WGI AR5 Annex I; Figure 26-3) (Diffenbaugh and Giorgi, 2012). The CMIP5 and CMIP3 ensembles suggest that the response of warm-season temperatures to elevated radiative forcing is larger as a fraction of the baseline variability than the response of cold-season temperatures (Diffenbaugh and Scherer, 2011; Kumar et al., 2013b), and the CMIP3 ensemble suggests that the response of temperature in low-latitude areas of North America is larger as a fraction of the baseline variability than the response of temperature in high-latitude areas (Diffenbaugh and Scherer, 2011). In addition, CMIP3 and a high-resolution climate model ensemble suggest that the signal-to-noise ratio of 21st century warming is far greater over the western USA, northern Mexico, and the northeastern USA than over the central and southeastern USA (Diffenbaugh et al., 2011), a result that is similar to the observed pattern of temperature trend significance in the USA (Figure 26-3).

Most land areas north of 45°N exhibit *likely* or *very likely* increases in mean annual precipitation in the late-21st-century period in RCP8.5 (Figure 26-3). The high-latitude areas of North America exhibit *very likely* changes in mean annual precipitation throughout the illustrative RCP periods, with *very likely* increases occurring in the mid-21st-century period in RCP2.6 and becoming generally more widespread at higher levels of forcing. In contrast, much of Mexico exhibits *likely* decreases in mean annual precipitation beginning in the mid-21st-century period in RCP8.5, with the area of *likely* decreases expanding to cover most of Mexico and parts of the south-central and southwestern USA in the late-21st-century period in RCP8.5. *Likely* changes in mean annual precipitation are much less common at lower levels of forcing. For example, *likely* changes in mean annual precipitation in the mid- and late-21st-century periods in RCP2.6 are primarily confined to increases over areas of Canada and Alaska, with no areas of Mexico and very few areas of the contiguous USA exhibiting differences that exceed the baseline variability in more than 66% of the models.

CMIP5 projects increases in winter precipitation over Canada and Alaska, consistent with projections of a poleward shift in the dominant cold-season storm tracks (Yin, 2005; see also WGI AR5 Section 14.8.3), extratropical cyclones (Trapp et al., 2009), and areas of moisture convergence (WGI AR5 Section 14.8.3), as well as with projections of a shift toward positive North Atlantic Oscillation (NAO) trends (Hori et al., 2007; see also WGI AR5 Section 14.8.3). CMIP5 also projects decreases in winter precipitation over the southwestern USA and much of Mexico associated with the poleward shift in the dominant stormtracks and the expansion of subtropical arid regions (Seager and Vecchi, 2010; see WGI AR5 Section 14.8.3). However, there are uncertainties in hydroclimatic change in western North America associated with the response of the tropical Pacific sea surface temperatures (SSTs) to elevated radiative forcing (particularly given the influence of tropical SSTs on the Pacific North American (PNA) pattern and north Pacific storm tracks; Cayan et al., 1999; Findell and Delworth, 2010; Seager and Vecchi, 2010; see also WGI AR5 Section 14.8.3), and not all CMIP5 models simulate the observed recent hydrologic trends in the region (Kumar et al., 2013a).

For seasonal-scale extremes, CMIP5 projects substantial increases in the occurrence of extremely hot seasons over North America in early, middle, and late-21st-century periods in RCP8.5 (Diffenbaugh and Giorgi, 2012; Figure 26-4). For example, during the 2046–2065 period in RCP8.5, more than 50% of summers exceed the respective late-20th-century maximum seasonal temperature value over most of the continent. CMIP3 projects similar increases in extremely hot seasons, including greater than 50% of summers exceeding a mid-20th-century baseline throughout much of North America by the mid-21st-century in the A2 scenario (Duffy and Tebaldi, 2012), and greater than 70% of summers exceeding the highest summer temperature observed on record over much of the western USA, southeastern USA, and southern Mexico by the mid-21st-century in the A2 scenario (Battisti and Naylor, 2009). CMIP5 also projects substantial decreases in snow accumulation over

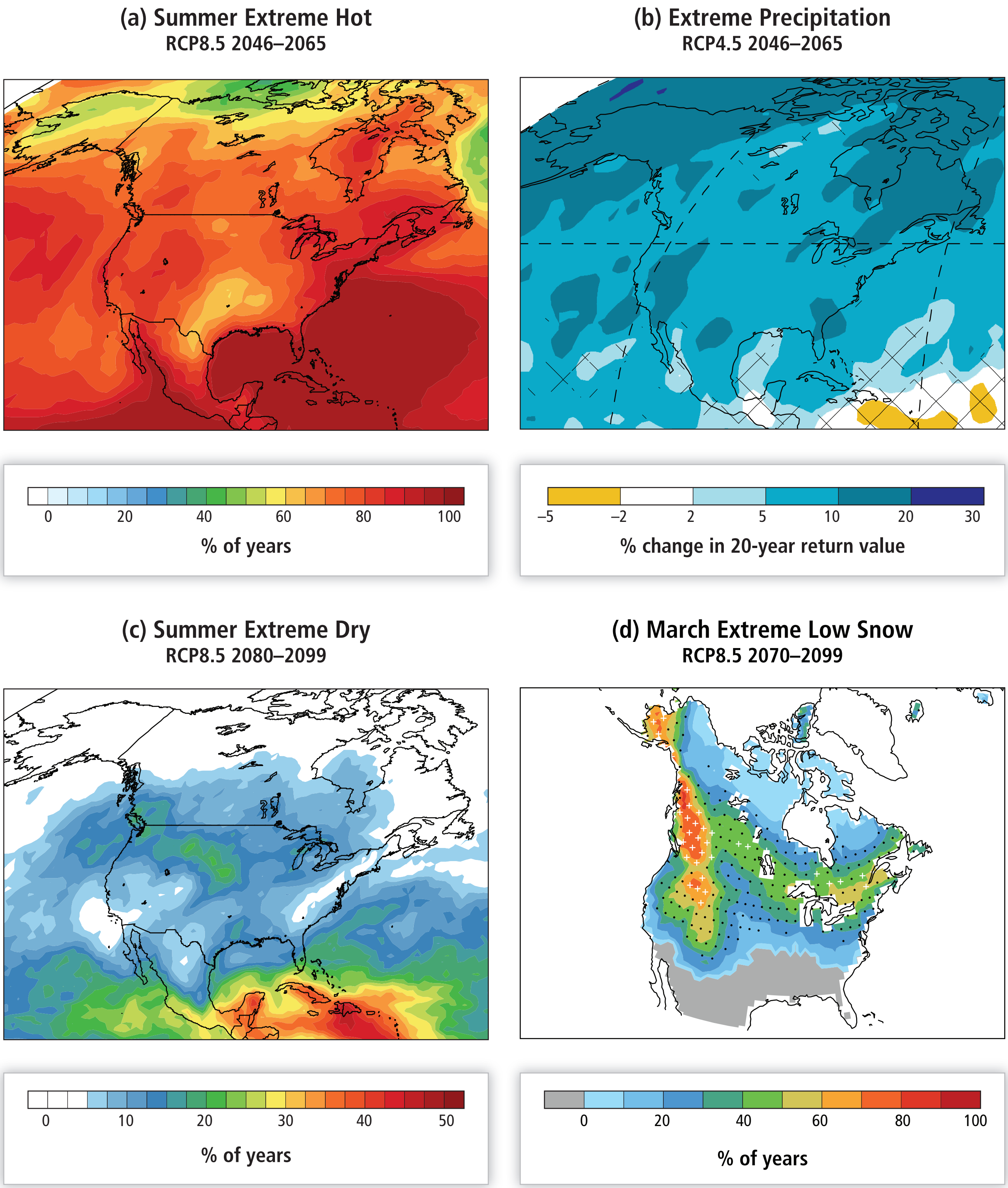


Figure 26-4 | Projected changes in extremes in North America. (a) The percentage of years in the 2046–2065 period of Representative Concentration Pathway 8.5 in which the summer temperature is greater than the respective maximum summer temperature of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 2012). (b) The percentage difference in the 20-year return value of annual precipitation extremes between the 2046–2065 period of RCP4.5 and the 1986–2005 baseline period (Kharin et al., 2013). The hatching indicates areas where the differences are not significant at the 5% level. (c) The percentage of years in the 2080–2099 period of RCP8.5 in which the summer precipitation is less than the respective minimum summer precipitation of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 2012). (d) The percentage of years in the 2070–2099 period of RCP8.5 in which the March snow water equivalent is less than the respective minimum March snow water equivalent of the 1976–2005 period (Diffenbaugh et al., 2012). The black (white) stippling indicates areas where the multi-model mean exceeds 1.0 (2.0) standard deviations of the multi-model spread. (a-d) The RCPs and time periods are those used in the peer-reviewed studies in which the panels appear. The 2046–2065 period of RCP8.5 and the 2046–2065 period of RCP4.5 exhibit global warming in the range of 2°C to 3°C above the preindustrial baseline (WGI AR5 Figure 12.40). The 2080–2099 and 2070–2099 periods of RCP8.5 exhibit global warming in the range of 4°C to 5°C above the preindustrial baseline (WGI AR5 Figure 12.40).

the USA and Canada (Diffenbaugh et al., 2012; Figure 26-4), suggesting that the increases in cold-season precipitation over these regions reflect a shift towards increasing fraction of precipitation falling as rain rather than snow (Diffenbaugh et al., 2012). Over much of the western USA and western Canada, greater than 80% of years exhibit March snow amount that is less than the late-20th-century median value beginning in the mid-21st-century period in RCP8.5, with the ensemble-mean change exceeding 2 standard deviations of the ensemble spread. Likewise, greater than 60% of years exhibit March snow amount that is less than the late-20th-century minimum value in the late-21st-century period in RCP8.5, with the ensemble-mean change exceeding 2 standard deviations of the ensemble spread (Diffenbaugh and Giorgi, 2012; Figure 26-4). CMIP5 also projects increases in the occurrence of extremely dry summer seasons over much of Mexico, the USA, and southern Canada (Figure 26-4). The largest increases occur over southern Mexico, where greater than 30% of summers in the late-21st-century period in RCP8.5 exhibit seasonal precipitation that is less than the late-20th-century minimum summer precipitation.

For daily-scale extremes, almost all areas of North America exhibit *very likely* increases of at least 5°C in the warmest daily maximum temperature by the late-21st-century period in RCP8.5. Likewise, most areas of Canada exhibit *very likely* increases of at least 10°C in the coldest daily minimum temperature by the late-21st-century period in RCP8.5, while most areas of the USA exhibit *very likely* increases of at least 5°C and most areas of Mexico exhibit *very likely* increases of at least 3°C (Sillmann et al., 2013; see also WGI AR5 Figure 12.13). In addition, almost all areas of North America exhibit *very likely* increases of 5 to 20% in the 20-year return value of extreme precipitation by the mid-21st-century period in RCP4.5 (Figure 26-4), while most areas of the USA and Canada exhibit *very likely* increases of at least 5% in the maximum 5-day precipitation by the late-21st-century period in RCP8.5 (Sillmann et al., 2013; see also WGI AR5 Figure 12.13). Further, almost all areas of Mexico exhibit *very likely* increases in the annual maximum number of consecutive dry days by the late-21st-century period in RCP8.5 (Sillmann et al., 2013; see also WGI AR5 Figure 12.13).

26.3. Water Resources and Management

Water withdrawals are exceeding stressful levels in many regions of North America such as the southwestern USA, northern and central Mexico (particularly Mexico City), southern Ontario, and the southern Canadian Prairies (CONAGUA, 2010; Romero-Lankao, 2010; Sosa-Rodriguez, 2010; Averyt et al., 2011; Environment Canada, 2013a). Water quality is also a concern with 10 to 30% of the surface monitoring sites in Mexico having polluted water (CONAGUA, 2010), and about 44% of assessed stream miles and 64% of assessed lake areas in the USA not clean enough to support their uses (EPA, 2004). Stations in Canada's 16 most populated drainage basins reported at least fair quality, with many reporting good or excellent quality (Environment Canada, 2013b). In basins outside of the populated areas there are some cases of declining water quality where impacts are related to resource extraction, agriculture, and forestry (Hebben, 2009).

Water management infrastructure in most areas of North America is in need of repair, replacement, or expansion (Section 26.7). Climate change, land use changes and population growth, and demand increases will add to these stresses (Karl et al., 2009).

26.3.1. Observed Impacts of Climate Change on Water Resources

26.3.1.1. Droughts and Floods

As reported in WGI AR5 Chapter 10 and in Section 26.2.2.1, it is not possible to attribute changes in drought frequency in North America to anthropogenic climate change (Prieto-González et al., 2011; Axelson et al., 2012; Orlowsky and Senevirantne, 2013; Figure 26-1). Few discernible trends in flooding have been observed in the USA (Chapter 3). Changes in the magnitude or frequency of flood events have not been attributed to climate change. Floods are generated by multiple mechanisms (e.g., land use, seasonal changes, and urbanization); trend detection is confounded by flow regulation, teleconnections, and long-term persistence (Section 26.2.2.1; Collins, 2009; Kumar et al., 2009; Smith et al., 2010; Villarini and Smith, 2010; Villarini et al., 2011; Hirsch and Ryberg, 2012; INECC and SEMARNAT, 2012a; Prokoph et al., 2012; Peterson et al., 2013).

26.3.1.2. Mean Annual Streamflow

Whereas annual precipitation and runoff increases have been found in the midwestern and northwestern USA, decreases have been observed in southern states (Georgakakos et al., 2013). Chapter 3 notes the correlation between changes in streamflow and observed regional changes in temperature and precipitation. Kumar et al. (2009) suggest that human activities have influenced observed trends in streamflow, making attribution of changes to climate difficult in many watersheds. Nonetheless, earlier peak flow of snowmelt runoff in snow-dominated streams and rivers in western North America has been formally detected and attributed to anthropogenic climate change (Barnett et al., 2008; Das et al., 2011; Figure 26-1).

26.3.1.3. Snowmelt

Warm winters produced earlier runoff and discharge but less snow water equivalent and shortened snowmelt seasons in many snow-dominated areas of North America (Barnett et al., 2005; Rood et al., 2008; Reba et al., 2011; see also Section 26.2.2; Chapter 3).

26.3.2. Projected Climate Change Impacts and Risks

26.3.2.1. Water Supply

Most of this assessment focuses on surface water as there are few groundwater studies (Tremblay et al., 2011; Georgakakos et al., 2013). Impacts and risks vary by region and model used.

In arid and semiarid western USA and Canada and in most of Mexico, except the southern tropical area, water supplies are projected to be further stressed by climate change, resulting in less water availability and increased drought conditions (Seager et al., 2007; Cayan et al., 2010; MacDonald, 2010; Martínez Austria and Patiño Gómez, 2010; Montero Martínez et al., 2010; CONAGUA, 2011; Prieto-González et al., 2011; Bonsal et al., 2012; Diffenbaugh and Field, 2013; Orlowsky and Seneviratne, 2013; Sosa-Rodriguez, 2013). Compounding factors include saltwater intrusion, and increased groundwater and surface water pollution (Leal Asencio et al., 2008).

In the southwest and southeast USA, ecosystems and irrigation are projected to be particularly stressed by decreases in water availability due to the combination of climate change, growing water demand, and water transfers to urban and industrial users (Seager et al., 2009; Georgakakos et al., 2013). In the Colorado River basin, crop irrigation requirements for pasture grass are projected to increase by 20% by 2040 and by 31% by 2070 (Dwyer et al., 2012). In the Rio Grande basin, New Mexico, runoff is projected to decrease by 8 to 30% by 2080 due to climate change. Water transfers may entail significant transaction costs associated with adjudication and potential litigation, and might have economic, environmental, social, and cultural impacts that vary by water user (Hurd and Coonrod, 2012). In Mexico, water shortages combined with increased water demands are projected to increase surface and groundwater over-exploitation (CONAGUA, 2011).

Other parts of North American are projected to have different climate risks. The vulnerability of water resources over the tropical southern region of Mexico is projected to be low for 2050: precipitation decreases from 10 to 5% in the summer and no precipitation changes in the winter. After 2050, greater winter precipitation is projected, increasing the possibility of damaging hydropower and water storage dams by floods, while precipitation is projected to decrease by 40 to 35% in the summer (Martínez Austria and Patiño Gómez, 2010).

Throughout the 21st century, cities in northwest Washington are projected to have drawdown of average seasonal reservoir storage in the absence of demand reduction because of less snowpack even though annual streamflows increase. Without accounting for demand increases, projected reliability of all systems remains above 98% through mid- and late-21st century (Vano et al., 2010a; CONAGUA, 2011). Throughout the eastern USA, water supply systems will be negatively impacted by lost snowpack storage, rising sea levels contributing to increased storm intensities and saltwater intrusion, possibly lower streamflows, land use and population changes, and other stresses (Sun et al., 2008; Obeysekera et al., 2011).

In Canada's Pacific Northwest region, cool season flows are expected to increase, while warm seasons flows would decrease (Hamlet, 2011). Southern Alberta, where approximately two-thirds of Canadian irrigated land is located, is projected to experience declines in mean annual streamflow, especially during the summer (Shepherd et al., 2010; Poirier and de Loë, 2012; Tanzeeba and Gan, 2012). In the Athabasca River basin in northern Alberta, modeling results consistently indicate large projected declines in mean annual flows (Kerkhoven and Gan, 2011). In contrast, modeling results for basins in Manitoba indicate an increase in mean annual runoff (Choi et al., 2009). Some model results for the Fraser River basin in British Columbia indicate increases in mean annual runoff by the end of the 21st century, while others indicate decreases (Kerkhoven and Gan, 2011). In central Quebec, J. Chen et al. (2011) project a general increase in discharge during November to April, and a general decrease in summer discharge under most climate change conditions.

26.3.2.2. Water Quality

Many recent studies project water quality declines due to the combined impacts of climate change and development (Daley et al., 2009; Tu, 2009; Praskievicz and Chang, 2011; Wilson and Weng, 2011; Tong et al., 2012). Increased wildfires linked to a warming climate are expected to affect water quality downstream of forested headwater regions (Emelko et al., 2011).

Model simulation of lakes under a range of plausible higher air temperatures (Tahoe, Great Lakes, Lake Onondaga, and shallow polymictic lakes), depending on the system, predict a range of impacts such as increased phytoplankton, fish,and cyanobacteria biomass; lengthened stratification periods with risks of significant hypolimnetic oxygen deficits in late summer with solubilization of accumulated phosphorus and heavy metals with accelerated reaction rates; and decreased lake clarity (Dupuis and Hann, 2009; Trumpickas et al., 2009; Sahoo et al., 2011; Taner et al., 2011). Model simulations have found seasonal climate change impacts on nonpoint source pollution loads, while others have found no impact (Marshall and Randhir, 2008; Tu, 2009; Taner et al., 2011; Praskievicz and Chang, 2011).

Changes in physical-chemical-biological parameters and micropollutants are predicted to negatively affect drinking water treatment and distribution systems (Delpla et al., 2009; Carriere et al., 2010; Emelko et al., 2011). Wastewater treatment plants would be more vulnerable as increases in rainfall and wet weather lead to higher rates of inflow and infiltration (King County Department of Natural Resources and Parks, 2008; New York City Department of Environmental Protection, 2008; Flood and Cahoon, 2011). They would also face reduced hydraulic capacities due to higher sea levels and increased river and coastal flooding (Flood and Cahoon, 2011), with higher sea levels also threatening sewage collection systems (Rosenzweig et al., 2007; King County Department of Natural Resources and Parks, 2008).

26.3.2.3. Flooding

Projected increases in flooding (Georgakakos et al., 2013) may affect sectors ranging from agriculture and livestock in southern tropical Mexico (CONAGUA, 2010) to urban and water infrastructure in areas such as Dayton (Ohio), metro Boston, and the Californian Bay-Delta region (NRC, 1995; Kirshen et al., 2006; DWR, 2009; Wu, 2010). Floods could begin earlier, and have earlier peaks and longer durations (e.g., southern Quebec basin). Urbanization can compound the impacts of increased flooding due to climate change, particularly in the absence of flood management infrastructure that takes climate change into account (Hejazi and Markus, 2009; Mailhot and Duchesne, 2010; Sosa-Rodriguez, 2010). Ntelekos et al. (2010) estimate that annual riverine flood losses in the USA could increase from approximately US$2 billion now to US$7 to US$19 billion annually by 2100 depending on emission scenario and economic growth rate.

26.3.2.4 Instream Uses

Projections of climate impacts on instream uses vary by region and time frame. Hydropower generation, affected by reduced lake levels, is projected to decrease in arid and semiarid areas of Mexico (CICC, 2009; Sosa-Rodriguez, 2013) and in the Great Lakes (Buttle et al., 2004; Mortsch et al., 2006; Georgakakos et al., 2013). In the US Pacific Northwest under several emissions scenarios, it is projected to increase in 2040 by approximately 5% in the winter and decrease by approximately 13% in the summer, with annual reductions of approximately 2.5%. Larger increases and decreases are projected by 2080 (Hamlet et al., 2010). On the Peribonka River system in Quebec, annual mean hydropower production will similarly decrease in the short term and increase by as much as 18% in the late-21st century (Minville et al., 2009). Navigation on the Great Lakes, Mississippi River, and other inland waterways may benefit from less ice cover but will be hindered by increased floods and low river levels during droughts (Georgakakos et al., 2013).

26.3.3. Adaptation

A range of structural and non-structural adaptation measures are being implemented, many of which are no-regret policies. For instance, in preparation for more intense storms, New York City is using green infrastructure to capture rainwater before it can flood the combined sewer system and is elevating boilers and other equipment above ground (Bloomberg, 2012). The Mexican cities of Monterrey, Guadalajara, Mexico City, and Tlaxcala are reducing leaks from water systems (CICC, 2009; CONAGUA, 2010; Romero-Lankao, 2010; Sosa-Rodriguez, 2010). Regina, Saskatchewan, has increased urban water conservation efforts (Lemmen et al., 2008).

The 540-foot high, 1300-foot long concrete Ross Dam in the state of Washington, USA, was built on a special foundation so it could later be raised in height (Simmons, 1974). Dock owners in the Trent-Severn Waterway in the Great Lakes have moved their docks into deeper water to better manage impacts on shorelines (Coleman, 2005). The South Florida Water Management District is assessing the vulnerability to sea level rise of its aging coastal flood control system and exploring adaptation strategies, including a strategy known as forward pumping (Obeysekera et al., 2011). In Cambridge, Ontario, extra-capacity culverts are being installed in anticipation of larger runoff (Scheckenberger et al., 2009).

Water meters have been installed to reduce consumption by different users such as Mexican and Canadian farmers and in households of several Canadian cities (INE and SEMARNAT, 2006; Lemmen et al., 2008). Agreements and regulations are underway such as the 2009 SECURE Water Act, which establishes a federal climate change adaptation program with required studies to assess future water supply risks in the western USA (42 USC § 10363). One such large, multi-year study was recently completed in the USA for the Colorado River (Bureau of Reclamation, 2013), and others are planned. Agreements and regulations are underway, such as the 2007 Shortage Sharing Agreement for the management of the Colorado River, driven by concerns about water conservation, planning, better reservoir coordination, and preserving flexibility to respond to climate change (Bureau of Reclamation, 2007). Quebec Province is requiring dam safety inspections every 10 years to account for new knowledge on climate change impacts (Centre d'Expertise Hydrique du Québec, 2003). Expanded beyond flood and hydropower management to now include climate change, the Columbia River Treaty is a good example of an international treaty to manage a range of water resources challenges (U.S. Army Corps of Engineers and Bonneville Power Administration, 2013).

26.4. Ecosystems and Biodiversity

26.4.1. Overview

Recent research has documented gradual changes in physiology, phenology, and distributions in North American ecosystems consistent with warming trends (Dumais and Prévost, 2007). Changes in phenology and species' distributions, particularly in the USA and Canada, have been attributed to rising temperatures, which have in turn been attributed to anthropogenic climate change via joint attribution (Root et al., 2005; Vose et al., 2012). Concomitant with 20th-century temperature increases, northward and upward shifts in plant, mammal, bird, lizard, and insect species' distributions have been documented extensively in the western USA and eastern Mexico (Parmesan, 2006; Kelly and Goulden, 2008; Moritz et al., 2009; Tingley et al., 2009; Sinervo et al., 2010). These distribution shifts consistent with climate change interact with other environmental changes such as land use change, hindering the ability of species to respond (Ponce-Reyes et al., 2013).

A range of techniques have been applied to assess the vulnerability of North American ecosystems and species to changes in climate (Anderson et al., 2009; Loarie et al., 2009; Glick and Stein, 2011). A global risk analysis based on dynamic global vegetation models identified boreal forest in Canada as notably vulnerable to ecosystem shift (Scholze et al., 2006). Since the AR4, the role of extreme events, including droughts, flood, hurricanes, storm surges, and heat waves, is a more prominent theme in studies of climate change impacts on North American ecosystems (Chambers et al., 2007; IPCC, 2012).

A number of ecosystems in North America are vulnerable to climate change. For example, species in alpine ecosystems are at high risk due to limited geographic space into which to expand (Villers Ruiz and Castañeda-Aguado, 2013). Many forest ecosystems are susceptible to wildfire and large-scale mortality and infestation events (Section 26.4.1). Across the continent, potentially rapid rates of climate change may require location shifts at velocities well outside the range in historical reconstructions (Sandel et al., 2011; Schloss et al., 2012). Changes in temperature, precipitation amount, and CO_2 concentrations can have different effects across species and ecological communities (Parmesan, 2006; Matthews et al., 2011), leading to ecosystem disruption and reorganization (Dukes et al., 2011; Smith et al., 2011), as well as movement or loss.

The following subsections focus in more depth on climate vulnerabilities in forests and coastal ecosystems. These ecosystems, spanning all three North American countries, are illustrative cases of where understanding opportunities for conservation and adaptation practices is important, and recent research advances on and new evidence of increased vulnerabilities since AR4 motivate further exploration. Further treatment of grasslands and shrublands can be found in Section 4.3.3.2.2; wetlands and peatlands in Section 4.3.3.3; and tundra, alpine, and permafrost systems in Section 4.3.3.4. Additional synthesis of climate change impacts on terrestrial, coastal, and ocean ecosystems can be found in Chapter 8 of the U.S. National Climate Assessment (Groffman et al., 2013).

26.4.2. Tree Mortality and Forest Infestation

26.4.2.1. Observed Impacts

Droughts of unusual severity, extent, and duration have affected large parts of western and southwestern North America and resulted in regional-scale forest dieback in Canada, the USA, and Mexico. Extensive tree mortality has been related to drought exacerbated by high summertime temperatures in trembling aspen (*Populus tremuloides*), pinyon pine (*Pinus edulis*), and lodgepole pine (*Pinus contorta*) since the early 2000s (Breshears et al., 2005; Hogg et al., 2008; Raffa et al., 2008; Michaelian et al., 2011; Anderegg et al., 2012). In 2011 and 2012, forest dieback in northern and central Mexico was associated with extreme temperatures and severe droughts (Comisión Nacional Forestal, 2012a). Widespread forest-mortality events triggered by extreme climate events can alter ecosystem structure and function (Phillips et al., 2009; Allen et al., 2010; Anderegg et al., 2013). Similarly, multi-decadal changes in demographic rates, particularly mortality, indicate climate-mediated changes in forest communities over longer periods (Hogg and Bernier, 2005; Williamson et al., 2009). Average annual mortality rates increased from less than 0.5% of trees per year in the 1960s in forests of western Canada and the USA to, respectively, 1.5 to 2.5% (Peng et al., 2011), and 1.0 to 1.5% in the 2000s in the USA (van Mantgem et al., 2009).

The influences of climate change on ecosystem disturbance, such as insect outbreaks, have become increasingly salient and suggest that these disturbances could have a major influence on North American ecosystems and economy in a changing climate. In terms of carbon stores these outbreaks have the potential to turn forests into carbon sources (Kurz et al., 2008a,b; Hicke et al., 2012). Warm winters in western Canada and USA have increased winter survival of the larvae of bark beetles, helping drive large-scale forest infestations and forest die-off in western North America since the early 2000s (Bentz et al., 2010). Beginning in 1994, mountain pine beetle outbreaks have severely affected more than 18 million hectares of pine forests in British Columbia, and outbreaks are expanding northwards (Energy, Mines and Resources, 2012).

26.4.2.2. Projected Impacts and Risks

Projected increases in drought severity in southwestern forests and woodlands in USA and in northwestern Mexico suggest that these ecosystems may be increasingly vulnerable, with impacts including vegetation mortality (Overpeck and Udall, 2010; Seager and Vecchi, 2010; Williams et al., 2010) and an increase of biological agents such as beetles, borers, pathogenic fungi, budworms, and other pests (Drake et al., 2005). An index of forest drought stress calibrated from tree rings indicates that projected drought stress by the 2050s in the SRES A2 scenario from the CMIP3 model ensemble, due primarily to warming-induced rises in vapor pressure deficit, exceeds the most severe droughts of the past 1000 years (Williams et al., 2013).

Under a scenario with large changes in global temperature (SRES A2) increases in growing-season temperature in forest soils in southern Quebec are as high as 5.0°C toward the end of the century and decreases of soil water content reach 20 to 40% due to elevated evapotranspiration rates (Houle et al., 2012). More frequent droughts in tropical forests may change forest structure and regional distribution, favoring a higher prevalence of deciduous species in the forests of Mexico (Drake et al., 2005; Trejo et al., 2011).

Shifts in climate are expected to lead to changes in forest infestation, including shifts of insect and pathogen distributions into higher latitudes and elevations (Bentz et al., 2010). Predicted climate warming is expected to have effects on bark beetle population dynamics in the western USA, western Canada, and northern Mexico that may include increases in developmental rates, generations per year, and changes in habitat suitability (Waring et al., 2009). As a result, the impacts of bark beetles on forest resources are expected to increase (Waring et al., 2009).

Wildfire, a potentially powerful influence on North American forests in the 21st century, is discussed in Box 26-2.

26.4.3. Coastal Ecosystems

Highly productive estuaries, coastal marshes, and mangrove ecosystems are present along the Gulf Coast and the East and West Coasts of North America. These ecosystems are subject to a wide range of non-climate stressors, including urban and tourist developments and the indirect effects of overfishing (Bhatti et al., 2006; Mortsch et al., 2006; CONABIO et al., 2007; Lund et al., 2007). Climate change adds risks from SLR, warming, ocean acidification, extratropical cyclones, altered upwelling, and hurricanes and other storms.

26.4.3.1. Observed Climate Impacts and Vulnerabilities

SLR, which has not been uniform across the coasts of North America (Crawford et al., 2007; Kemp et al., 2008; Leonard et al., 2009; Zavala-Hidalgo et al., 2010; Sallenger, Jr. et al., 2012), is directly related to flooding and loss of coastal dunes and wetlands, oyster beds, seagrass, and mangroves (Feagin et al., 2005; Cooper et al., 2008; Najjar et al., 2010; Ruggiero et al., 2010; Martinez Arroyo et al., 2011; McKee, 2011).

Increases in sea surface temperature in estuaries alter metabolism, threatening species, especially coldwater fish (Crawford et al., 2007). Historical warm periods have coincided with low salmon abundance and restriction of fisheries in Alaska (Crozier et al., 2008; Karl et al., 2009). North Atlantic cetaceans and tropical coral reefs in the Gulf of California and the Caribbean have been affected by increases in the incidence of diseases associated with warm waters and low water quality (ICES, 2011; Mumby et al., 2011).

Increased concentrations of CO_2 in the atmosphere due to human emissions are causing ocean acidification (Chapters 5 ES, 6 ES; FAQ 5.1). Along the temperate coasts of North America acidification directly affects calcareous organisms, including colonial mussel beds, with indirect influences on food webs of benthic species (Wootton et al., 2008). Increased acidity in conjunction with high temperatures has been identified as a serious threat to coral reefs and other marine ecosystems in the Bahamas and the Gulf of California (Doney et al., 2009; Hernández et al., 2010; Mumby et al., 2011).

Tropical storms and hurricanes can have a wide range of effects on coastal ecosystems, potentially altering hydrology, geomorphology (erosion), biotic structure in reefs, and nutrient cycling. Hurricane impacts on the coastline change dramatically the marine habitat of sea turtles, reducing feeding habitats, such as coral reefs and areas of seaweed, and nesting places (Liceaga-Correa et al., 2010; Montero Martínez et al., 2010).

26.4.3.2. Projected Impacts and Risks

Projected increases in sea levels, particularly along the coastlines of Florida, Louisiana, North Carolina, and Texas (Kemp et al., 2008; Leonard et al., 2009; Weiss et al., 2011), will threaten many plants in coastal ecosystems through increased inundation, erosion, and salinity levels. In settings where landward shifts are not possible, a 1 m rise in sea level will result in loss of wetlands and mangroves along the Gulf of Mexico of 20% in Tamaulipas to 94% in Veracruz (Flores Verdugo et al., 2010).

Projected impacts of increased water temperatures include contraction of coldwater fish habitat and expansion of warmwater fish habitat (Mantua et al., 2010), which can increase the presence of invasive species that threaten resident populations (Janetos et al., 2008). Depending on scenario, Chinook salmon in the Pacific Northwest may decline by 20 to 50% by 2040–2050 (Battin et al., 2007; Crozier et al., 2008), integrating across restrictions in productivity and abundance at the southern end of their range and expansions at the northern end (Azumaya et al., 2007), although habitat restoration and protection particularly at lower elevations may help mitigate declines in abundance.

Continuing ocean acidification will decrease coral growth and interactions with temperature increases will lead to increased risk of coral bleaching, leading to declines in coral ecosystem biodiversity (Veron et al., 2009; see also Section 5.4.2.4; Box CC-OA). Oyster larvae in the Chesapeake Bay grew more slowly when reared with CO_2 levels between 560 and 480 ppm compared to current environmental conditions (Gazeau et al., 2007; Miller et al., 2009; Najjar et al., 2010).

Although future trends in thunderstorms and tropical cyclones are uncertain (Section 26.2.2), any changes, particularly an increase in the frequency of category 4 and 5 storms (Bender et al., 2010; Knutson et al., 2010), could have profound impacts on mangrove ecosystems, which require 25 years for recovery from storm damage (Kovacs et al., 2004; Flores Verdugo et al., 2010).

26.4.4. Ecosystems Adaptation, and Mitigation

In North America, a number of adaptation strategies are being applied in novel and flexible ways to address the impacts of climate change (Mawdsley et al., 2009; NOAA, 2010; Gleeson et al., 2011; Poiani et al., 2011). The best of these are based on detailed knowledge of the vulnerabilities and sensitivities of species and ecosystems, and with a focus on opportunities for building resilience through effective ecosystem management. Government agencies and nonprofit organizations have established initiatives that emphasize the value of collaborative dialog between scientists and practitioners, indigenous communities, and grass-roots organizations to develop no-regrets and co-benefits adaptation strategies (Ogden and Innes, 2009; Gleeson et al., 2011; Halofsky et al., 2011; Cross et al., 2012, 2013; INECC and SEMARNAT, 2012b).

Examples of adaptation measures implemented to respond to climate change impacts on ecosystems are diverse. They include programs to reduce the incidence of Canadian forest pest infestations (Johnston et al., 2010); breeding programs for resistance to diseases and insect pests (Yanchuk and Allard, 2009); use of forest programs to reduce the incidence of forest fires and encourage agroforestry in areas of Mexico (Sosa-Rodriguez, 2013); and selection by forest or fisheries managers of activities that are more adapted to new climatic conditions (Vasseur

Box 26-2 | Wildfires

Wildfire is a natural process, critical to nutrient cycling, controlling populations of pests and pathogens, biodiversity, and fire-adapted species (Bond and Van Wilgen, 1996). However, since the mid-1980s large wildfire activity in North America has been marked by increased frequency and duration, and longer wildfire seasons (Westerling et al., 2006; Williamson et al., 2009). Recent wildfires in western Canada, the USA, and Mexico relate to long and warm spring and summer droughts, particularly when they are accompanied by winds (Holden et al., 2007; Comisión Nacional Forestal, 2012b). Interacting processes such as land use changes associated with the expansion of settlements and activities in peri-urban areas or forested areas, combined with the legacies of historic forest management that prescribed fire suppression, also substantially increase wildfire risk (Radeloff et al., 2005; Peter et al., 2006; Fischlin et al., 2007; Theobald and Romme, 2007; Gude et al., 2008; Collins and Bolin, 2009; Hammer et al., 2009; Brenkert-Smith, 2010).

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Box 26-2 (continued)

Drought conditions are strongly associated with wildfire occurrence, as dead fuels such as needles and dried stems promote the incidence of firebrands and spot fires (Keeley and Zedler, 2009; Liu et al., 2012). Drought trends vary across regions (Groisman et al., 2007; Girardin et al., 2012): The western USA has experienced drier conditions since the 1970s (Peterson et al., 2013); drought periods in Alberta and Idaho have coincided with large burned areas (Pierce and Meyer, 2008; Kulshreshtha, 2011); and heterogeneous patterns of drought severity and a reduction of wildfire risk have been detected for the circumboreal region (Girardin et al., 2009). Decadal climatic oscillations also contribute to differences in drought, and thus in wildfire occurrences. The areas burned in the continent boreal forest and in northwest and central Mexico correlate with the dynamics of seasonal land/ocean temperature variability (Macias Fauria and Johnson, 2006; Skinner et al., 2006; Villers Ruíz and Hernández-Lozano, 2007; Girardin and Sauchyn, 2008; Macias Fauria and Johnson, 2008), which is shifting toward hotter temperatures and longer droughts. Such human practices as slash-and-burn agriculture can have negative impacts on Mexican forests (Bond and Keeley, 2005; CONANP and The Nature Conservancy, 2009).

Drought index projections and climate change regional models show increases in wildfire risk during the summer and fall on the southeast Pacific Coast, Northern Plains, and the Rocky Mountains (Liu et al., 2012). In places like Sierra Nevada, mixed conifer forests, which have a natural cycle of small, non-crown fires, are projected to have massive crown fires (Bond and Keeley, 2005; see also Table 26-1).

While healthy forests (Davis, 2004) and many fire-maintained systems that burn at lower intensities can provide carbon sequestration and thus mitigation co-benefits (e.g., longleaf pine savanna, Sierra mixed-conifer; Fried et al., 2008; North et al., 2012), forests affected by pests and fires are less effective carbon sinks, and wildfires themselves are a source of emissions.

Wildfires pose a direct threat to human lives, property, and health. Over the last 30 years, 155 people were killed in wildfires across North America, including 103 in the USA, 50 in Mexico, and 2 in Canada (Centre for Research on the Epidemiology of Disasters, 2012). Direct effects include injury and respiratory effects from smoke inhalation, with firefighters at increased risk (Naeher et al., 2007; Reisen and Brown, 2009; Reisen et al., 2011). Wildfire activity causes impacts on human health (Section 26.6).

Minimizing adverse effects of wildfires involves short- and long-term strategies such as planned manipulation of vegetation composition and stand structure (Girardin et al., 2012; Terrier et al., 2013), suppression of fires where required, fuel treatments, use of fire-safe materials in construction, community planning, and reduction of arson. Not all negative consequences of fire can be avoided, though a mixture of techniques can be used to minimize adverse effects (Girardin et al., 2012). Prescribed fire may be an important tool for managing fire risk in Canada and the USA (Hurteau and North, 2010; Wiedinmyer and Hurteau, 2010; Hurteau et al., 2011). Managers in the USA have encouraged reduction of flammable vegetation around structures with different levels of success (Stewart et al., 2006). However, such efforts depend largely on land use planning; the socioeconomic capacity of communities at risk; the extent of resource dependence; community composition; and the risk perceptions, attitudes, and beliefs of decision makers, private property owners, and affected populations (McFarlane, 2006; Repetto, 2008; Collins and Bolin, 2009; Martin et al., 2009; Trainor et al., 2009; Brenkert-Smith, 2010). Indigenous peoples are at higher risk from wildfire and may have unique requirements for adaptation strategies (Carroll et al., 2010; Christianson et al., 2012a,b).

Effective forest management requires stakeholder involvement and investment. The provision of adequate information on smoke, prescribed fire, pest management, and forest thinning is crucial, as is building trust between stakeholders and land managers (Dombeck et al., 2004; Flint et al., 2008; Chang et al., 2009). Institutional shifts from reliance on historical records toward incorporation of climate forecasting in forest management is also crucial to effective adaptation (McKenzie et al., 2004; Millar et al., 2007; Kolden and Brown, 2010).

and Catto, 2008). Example programs have addressed commercial fishing, mass tourism (Pratchett et al., 2008), and enforcement mechanisms for using water regulation technologies to maintain quantity and quality in wetlands around the Great Lakes and San Francisco, California (Mortsch et al., 2006; Okey et al., 2012). Assisted migration is increasingly discussed as a potential management option to maintain health and productivity of forests; yet the technique has logistical and feasibility challenges (Keel, 2007; Hoegh-Guldberg et al., 2008; Winder et al., 2011).

Several lines of evidence indicate that effective adaptation requires changes in approach and becomes much more difficult if warming exceeds 2°C above preindustrial levels (CONABIO et al., 2007; Mansourian et al., 2009; U.S. Forest Service, 2010; Glick and Stein, 2011; March et al., 2011; INECC and SEMARNAT, 2012b). Even though options for effective adaptation are increasingly constrained at warming over 2°C, some opportunities will remain. In particular, efforts to maintain or increase forest carbon stocks can lead to numerous benefits, including not only benefits for atmospheric CO_2 (Anderson and Bell, 2009; Anderson et al., 2011). Even where there are opportunities, managers face challenges in designing management practices that favor carbon stocks, while at the same time maintaining biodiversity, recognizing the rights of indigenous people, and contributing to local economic development (FAO, 2012).

26.5. Agriculture and Food Security

Projected declines in global agricultural productivity (Chapter 7) have implications for food security among North Americans. Because North America is a major exporter (FAO, 2009; Schlenker and Roberts, 2009), shifts in agricultural productivity here may have implications for global food security. Canada and the USA are relatively food secure, although households living in poverty are vulnerable. 17.6% of Mexicans are food insecure (Monterroso et al., 2012). Indigenous peoples are highly vulnerable due to high reliance on subsistence (Chapter 12). While this section focuses on agricultural production, food security is related to multiple factors (see Chapter 7).

26.5.1. Observed Climate Change Impacts

Historic yield increases are attributed in part to increasing temperatures in Canada and higher precipitation in the USA (*medium evidence*, *high agreement*; Pearson et al., 2008; Nadler and Bullock, 2011; Sakurai et al., 2011), although multiple non-climatic factors affect historic production rates. In many North American regions optimum temperatures have been reached for dominant crops; thus continued regional warming would diminish rather than enhance yields (*high confidence*; Jones et al., 2005). Regional yield variances over time have been attributed to climate variability, for example Ontario (Cabas et al., 2010) and Quebec (Almaraz et al., 2008). Since 1999 a marked increase in crop losses attributed to climate-related events such as drought, extreme heat, and storms has been observed across North America (Hatfield et al., 2013), with significant negative economic effects (*high confidence*; Swanson et al., 2007; Chen and McCarl, 2009; Costello et al., 2009). In Mexico, agriculture accounted for 80% of weather-related financial losses since 1990 (Saldaña-Zorrilla, 2008; Figure 26-2).

26.5.2. Projected Climate Change Risks

Studies project productivity gains in northern regions and where water is not projected to be a limiting factor, across models, time frames, and scenarios (*high confidence*; Hatfield et al., 2008; Pearson et al., 2008; Stöckle et al., 2010; Wheaton et al., 2010). Overall yields of major crops in North America are projected to decline modestly by mid-century and more steeply by 2100 among studies that do not consider adaptation (*very high confidence*). Certain regions and crops may experience gains in the absence of extreme events, and projected yields vary by climate model (Paudel and Hatch, 2012; Liu et al., 2013).

Among studies projecting yield declines, two factors stand out: exceedance of temperature thresholds and water availability. Yields of several important North American agriculture sectors—including grains, forage, livestock, and dairy—decline significantly above temperature thresholds (Wolfe et al., 2008; Schlenker and Roberts, 2009; Craine et al., 2010). Temperature increases affect product quality as well, for example, coffee (Lin, 2007), wine grapes (Hayhoe et al., 2004; Jones et al., 2005), wheat (Porter and Semenov, 2005), fruits and nuts (Lobell et al., 2006), and cattle forage (Craine et al., 2010). Projected temperature increases would reduce corn, soy, and cotton yields by 2020, with declines ranging from 30 to 82% by 2099 depending on crop and scenario (steepest decline for corn, A1; Schlenker and Roberts, 2009). Studies also project increasing interannual yield variability over time (Sakurai et al., 2011; Urban et al., 2012). Several studies focus on California, one of North America's most productive agricultural regions. Modest and variable yield changes among several California crops are projected to 2026, with yield declines from 9 to 29% by 2097 (A2, DAYCENT model). Lee et al. (2011) and Lobell and Field (2011) found little negative effect for California perennials by 2050 due to projected climate change, assuming irrigation access (General Circulation Model (GCM) ensemble, A2 and B1). Hannah et al. (2013), however, project large declines in land suitability for California viticulture by 2050 (with increases further north) with RCP4.5 and RCP8.5 (GCM ensemble); declines are greater under RCP8.5. Heat-induced livestock stress, combined with reduced forage quality, would reduce milk production and weight gain in cattle (Wolfe et al., 2008; Hernández et al., 2011).

Precipitation increases offset but do not entirely compensate for temperature-related declines in productivity (Kucharik and Serbin, 2008). In regions projected to experience increasing temperatures combined with declining precipitation, declines in yield and quality are more acute (Craine et al., 2010; Monterroso Rivas et al., 2011).

Projected change in climate will reduce soil moisture and water availability in the US West/Southwest, the Western Prairies in Canada, and central and northern Mexico (*very high confidence*; Pearson et al., 2008; Cai et al., 2009; Karl et al., 2009; Sanchez-Torres Esqueda, 2010; Vano et al., 2010b; Kulshreshtha, 2011). CMIP5 models indicate soil moisture decreases across the continent in spring and summer under RCP8.5, with *high agreement* (Dirmeyer et al., 2013). Based on a combined exposure/consumptive water use model, the US Great Plains is identified as one of four global future vulnerability hotspots for water availability from the 2030s and beyond, where anticipated water withdrawals would exceed 40% of freshwater resources (Liu et al., 2013). In western USA and Canada, projected earlier spring snowmelt and reduced snowpack would affect productivity negatively regardless of precipitation, as water availability in summer and fall are reduced (Schlenker et al., 2007; Forbes et al., 2011; Kienzle et al., 2012).

Projected increases in extreme heat, drought, and storms affect productivity negatively (Chen and McCarl, 2009; Kulshreshtha, 2011). The northeastern and southeastern USA have been identified as "vulnerability hotspots" for corn and wheat production respectively by 2045 with vulnerability worsening thereafter, using a combined drought exposure and adaptive capacity assessment, with only slight differences between A1B and B2 scenarios (Fraser et al., 2013). Central North America is identified as among the globe's regions of highest risk of heat stress by 2070 (National Institute for Environmental Studies (NIES) GCM, A1B; Teixeira et al., 2013).

26.5.3. A Closer Look at Mexico

Much of Mexico's land base is already marginal for two of the country's major crops: corn and beef (Buechler, 2009). Severe desertification in Mexico due to non-climate drivers further compromises productivity (Huber-Sannwald et al., 2006). Land classified suitable for rain-fed corn is projected to decrease from 6.2% currently to between 3 and 4.3% by 2050 (UKHadley B2, European Centre for Medium Range Weather Forecasts and Hamburg 5 (ECHAM5)/Max Planck Institute (MPI) A2; Monterroso Rivas et al., 2011). The distribution of most races of corn is expected to be reduced and some eliminated by 2030 (A2, three climate models; Ureta et al., 2012). Precipitation declines of 0 to 30% are projected over Mexico by 2040, with the most acute declines in northwestern Mexico, the primary region of irrigated grain farming (declines steeper in A2 than A1B, 18-model ensemble).

Although projected increases in precipitation may contribute to increase in rangeland productivity in some regions (Monterroso Rivas et al., 2011), a study in Veracruz indicates that the effects of projected maximum summer temperatures on livestock heat stress are expected to reach the "danger level" (at which losses can occur) by 2020 and continue to rise (A2, B2, three GCMs; Hernández et al., 2011). Coffee, an economically important crop supporting 500,000 primarily indigenous households (González Martínez, 2006), is projected to decline 34% by 2020 in Veracruz if historic temperature and precipitation trends continue (Gay et al., 2006); see also Schroth et al. (2009), on declines in Chiapas.

Many of Mexico's agricultural communities are also considered highly vulnerable, due to high sensitivity and/or low adaptive capacity (Monterroso et al., 2012). The agriculture sector here consists primarily of small farmers (Claridades Agropecuarias, 2006), who face high livelihood risks due to limited access to credit and insurance (Eakin and Tucker, 2006; Wehbe et al., 2008; Saldaña-Zorilla and Sandberg, 2009; Walthall et al., 2012).

26.5.4. Adaptation

The North American agricultural industry has the adaptive capacity to offset projected yield declines and capitalize on opportunities under 2°C warming. Butler and Huybers (2012) project a reduction in US corn yield loss from 14 to 6% with 2°C warming, with spatial shifts in varietal selection (not accounting for variability in temperature and precipitation). Incremental strategies, such as planting varieties better suited to future climate conditions and changing planting dates, have been observed across the continent (Bootsma et al., 2005; Conde et al., 2006; Eakin and Appendini, 2008; Coles and Scott, 2009; Nadler and Bullock, 2011; Paudel and Hatch, 2012; Campos et al., 2013). In some sectors we are seeing multi-organizational investments in adaptation. International coffee retailers and non-governmental organizations, for example, are engaged in enhancing coffee farmers' adaptive capacity (Schroth et al., 2009; Soto-Pinto and Anzueto, 2010). Other strategies specifically recommended for Mexico include soil remediation, improved use of climate information, rainwater capture, and drip irrigation (Sosa-Rodriguez, 2013). New crop varieties better suited to future climates, including genetically modified organisms (GMOs), are under development in the USA (e.g., Chen et al., 2012), although potential risks have been noted (Quist and Chapela, 2001). Current trends in agricultural practices in commercial regions such as the midwestern USA, however, amplify productivity risks posed by climate change (Hatfield et al., 2013). Incremental strategies will have reduced effectiveness under a 2099/4°C warming scenario, which would require more systemic adaptation, including production and livelihood diversification (Howden et al., 2007; Asseng et al., 2013; Mehta et al., 2013; Smith and Gregory, 2013).

Some adaptive strategies impose financial costs and risks onto producers (Wolfe et al., 2008; Craine et al., 2010), which may be beyond the means of smallholders (Mercer et al., 2012) or economically precluded for low-value crops. Technological improvements improve yields under normal conditions but do not protect harvests from extremes (Karl et al., 2009; Wittrock et al., 2011). Others may have maladaptive effects (e.g., increased groundwater and energy consumption). Crop-specific weather index insurance, for example (widely implemented in Mexico to support small farmers), may impose disincentives to invest in diversification and irrigation (Fuchs and Wolff, 2010).

Many strategies have co-benefits, however. In fact, investments in agricultural adaptation represent a cost-effective mitigation strategy (Lobell et al., 2013). Low- and no-till practices reduce soil erosion and runoff, protect crops from extreme precipitation (Zhang and Nearing, 2005), retain soil moisture, reduce biogenic and geogenic greenhouse gas emissions (Nelson et al., 2009; Suddick et al., 2010), and build soil organic carbon (Aguilera et al., 2013). Planting legumes and weed management on pastures enhance both forage productivity and soil carbon sequestration (Follett and Reed, 2010). Shade perennials increase soil moisture retention (Lin, 2010) and contribute to local cooling (Georgescu et al., 2011). Crop diversification mediates the impacts of climate and market shocks (Eakin and Appendini, 2008) and enhances management flexibility (Chhetri et al., 2010).

Barriers and Enablers

Market forces and technical feasibility alone are insufficient to foster sectoral-level adaptation (Kulshreshtha, 2011). Institutional support is key, but found to be inadequate in many contexts (*high confidence*; Bryant et al., 2008; Klerkx and Leeuwis, 2009; Jacques et al., 2010; Tarnoczi and Berkes, 2010; Brooks and Loevinsohn, 2011; Alam et al., 2012; Anderson and McLachlan, 2012). Many suggested adaptation strategies with anticipated economic benefits are often not adopted by farmers, suggesting the need for more attention to culture and behavior (Moran et al., 2013). Attitudinal studies among US farmers indicate limited acknowledgment of anthropogenic climate change, associated with lower levels of support for adaptation (*medium evidence*, *high agreement*; Arbuckle, Jr. et al., 2013; Gramig et al., 2013).

Other key enablers are access to and quality of information (Tarnoczi and Berkes, 2010; Tarnoczi, 2011; Baumgart-Getz et al., 2012; Tambo and Abdoulaye, 2012), particularly regarding optimum crop management, production inputs, and optimum crop-specific geographic information. Social networks are important for information dissemination and farmer support (Chiffoleau, 2009; Wittrock et al., 2011; Baumgart-Getz et al., 2012). Networks among producers may be especially important to the level of awareness and concern farmers hold about climate change (Frank et al., 2010; Sánchez-Cortés and Chavero, 2011), while also enabling extensive farmer-to-farmer exchange of adaptation strategies (Eakin et al., 2009).

26.6. Human Health

Large national assessments of climate and health have been carried out in the USA and Canada (Bélanger et al., 2008; see references in Section 26.1). These have highlighted the potential for changes in impacts of extreme storm and heat events, air pollution, pollen, and infectious diseases, drawing from a growing North American research base analyzing observed and projected relationships among weather, vulnerability, and health. The causal pathways leading from climate to health are complex, and can be modified by factors including economic status, preexisting illness, age, other health risk factors, access to health care, built and natural environments, adaptation actions, and others. Human health is an important dimension of adaptation planning at the local level, much of which has so far focused on warning and response systems to extreme heat events (New York State Climate Action Council, 2012).

26.6.1. Observed Impacts, Vulnerabilities, and Trends

26.6.1.1. Storm-Related Impacts

The magnitude of health impacts of extreme storms depends on interactions between exposure and characteristics of the affected communities (Keim, 2008). Coastal and low-lying infrastructure and populations can be vulnerable owing to flood-related interruptions in communications, health care access, and mobility. Health impacts can arise through direct pathways of traumatic death and injury (e.g., drowning, impacts of blowing and falling objects, contact with power wires) as well as more indirect, longer term pathways related to damage to health and transportation infrastructure, contamination of water and soil, vector-borne diseases, respiratory diseases, and mental health (CCSP, 2008a). Infectious disease impacts from flooding include creation of breeding sites for vectors (Ivers and Ryan, 2006) and bacterial transmission through contaminated water and food sources causing gastrointestinal disease. Chemical toxins can be mobilized from industrial or contaminated sites (Euripidou and Murray, 2004). Elevated indoor mold levels associated with flooding of buildings and standing water are identified as risk factors for cough, wheeze, and childhood asthma (Bornehag et al., 2001; Jaakkola et al., 2005). Mental health impacts can arise as a result of the stress of evacuation, property damage, economic loss, and household disruption (Weisler et al., 2006; CCSP, 2008a; Berry et al., 2010, 2011). Since 1970, there has been no clear trend in US hurricane deaths, once the singular Katrina event is set aside (Blake et al., 2007).

26.6.1.2. Temperature Extremes

Studies throughout North America have shown that high temperatures can increase mortality and/or morbidity (e.g., Medina-Ramon and Schwartz, 2007; Kovats and Hajat, 2008; Anderson and Bell, 2009; Deschênes et al., 2009; Knowlton et al., 2009; O'Neill and Ebi, 2009; Hajat and Kosatsky, 2010; Kenny et al., 2010; Cueva-Luna et al., 2011; Hurtado-Díaz et al., 2011; Romero-Lankao et al., 2012b). Extremely cold temperatures have also been associated with increased mortality (Medina-Ramon and Schwartz, 2007), an effect separate from the seasonal phenomenon of excess winter mortality, which does not appear to be directly related to cold temperatures (Kinney, 2012). To date, trends over time in cold-related deaths have not been investigated.

Most available North American evidence derives from the USA and Canada, though one study reported significant heat- and cold-related mortality impacts in Mexico City (McMichael et al., 2008). US EPA has tracked the death rate in the USA from 1979 to 2009 for which death certificates list the underlying cause of death as heat related (EPA, 2012). No clear trend upwards or downwards is yet apparent in this indicator. Note that this case definition is thought to significantly underestimate the total impacts of heat on mortality.

26.6.1.3. Air Quality

Ozone and particulate matter (e.g., particulate matter with aerodynamic diameter <2.5 µm ($PM_{2.5}$) and PM_{10}) have been associated with adverse health effects in many locations in North America (Romero-Lankao et al., 2013b). Emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorological variables such as temperature, humidity, wind speed and direction, and mixing height (Kinney, 2008). Although air pollution emission trends will play a dominant role in future pollution levels, climate change may make it harder to achieve some air quality goals (Jacob and Winner, 2009). Forest fire is a source of particle emissions in North America, and can lead to increased cardiac and respiratory disease incidence, as well as direct mortality (Rittmaster et al., 2006; Ebi et al., 2008). The indoor environment also can affect health in many ways, for example, via penetration of outdoor pollution, emissions or pollutants indoors, moisture-related problems, and transmission of respiratory infections. Indoor moisture leads to mold growth, a problem that is exacerbated in colder regions such as northern North America in the winter (Potera, 2011). Climate variability and change will affect indoor air quality, but with direction and magnitude that remains largely unknown (Institute of Medicine, 2011).

26.6.1.4. Pollen

Exposure to pollen has been associated with a range of allergic outcomes, including exacerbations of allergic rhinitis (Cakmak et al., 2002; Villeneuve et al., 2006) and asthma (Delfino, 2002). Temperature and precipitation in the months prior to the pollen season affect production of many types of tree and grass pollen (Reiss and Kostic, 1976; Minero et al., 1998; Lo and Levetin, 2007; EPA, 2008). Ragweed pollen production is responsive to temperatures and to CO_2 concentrations (Ziska and Caulfield, 2000; Wayne et al., 2002; Ziska et al., 2003; Singer et al., 2005). Because pollen production and release can be affected by temperature, precipitation, and CO_2 concentrations, pollen exposure and allergic disease morbidity could change in response to climate change. However, to date, the timing of the pollen season is the only evidence for observed climate-related impacts. Many studies have indicated that pollen seasons are beginning earlier (Emberlin et al., 2002; Rasmussen, 2002; Clot, 2003; Teranishi et al., 2006; Frei and Gassner, 2008; Levetin and de Water, 2008; Ariano et al., 2010). Ragweed season length has increased at some monitoring stations in the USA (Ziska et al., 2011). Research on trends in North America has been hampered by the lack of long-term, consistently collected pollen records (EPA, 2008).

26.6.1.5. Water-borne Diseases

Water-borne infections are an important source of morbidity and mortality in North America. Commonly reported infectious agents in US and Canadian outbreaks include *Legionella* bacterium, the cryptosporidium parasite *Campylobacter*, and *Giardia* (Bélanger et al., 2008; Centers for Disease Control and Prevention, 2011). Cholera remains an important agent in Mexico (Greer et al., 2008). Risk of water-borne illness is greater among the poor, infants, elderly, pregnant women, and immune-compromised individuals (Rose et al., 2001; CCSP, 2008a). In Mexico City, declining water quality has led to ineffective disinfection of drinking water supplies (Mazari-Hiriart et al., 2005; Sosa-Rodriguez, 2010).

Changes in temperature and hydrological cycles can influence the risk of water-borne diseases (Curriero et al., 2001; Greer et al., 2008; Harper et al., 2011). Severe storms have been shown to play a role in water-borne disease risks in Canada (Thomas et al., 2006). Floods enhance the potential for runoff to carry sediment and pollutants to water supplies (CCSP, 2008b). Disparities in access to treated water were identified as a key determinant of under age-5 morbidity due to water-borne illnesses in the central State of Mexico (Jiménez-Moleón and Gómez-Albores, 2011).

26.6.1.6. Vector-borne Diseases

The extent to which climate change has altered, and will alter, the geographic distribution of vectors of infectious disease remains uncertain because of the inherent complexity of the ecological system. Spatial and temporal distribution of disease vectors depend not only on climate factors, but also on land use/change, socioeconomic and sociocultural factors, prioritization of vector control, access to health care, and human behavioral responses to perception of disease risk, among other factors (Lafferty, 2009; Wilson, 2009). Although temperature drives important biological processes in these organisms, climate variability on a daily, seasonal, or interannual scale may result in organism adaptation and shifts, though not necessarily expansion, in geographic range (Lafferty, 2009; Tabachnick, 2010; McGregor, 2011). Range shifts may alter the incidence of disease depending on host receptiveness and immunity, as well as the ability of the pathogen to evolve so that strains are more effectively and efficiently acquired (Reiter, 2008; Beebe et al., 2009; Rosenthal, 2009; Russell, 2009; Epstein, 2010).

North Americans are currently at risk from a number of vector-borne diseases, including Lyme disease (Ogden et al., 2008; Diuk-Wasser et al., 2010), dengue fever (Jury, 2008; Ramos et al., 2008; Johansson et al., 2009; Degallier et al., 2010; Kolivras, 2010; Lambrechts et al., 2011; Riojas-Rodriguez et al., 2011; Lozano-Fuentes et al., 2012), West Nile virus (Gong et al., 2011; Morin and Comrie, 2010), and Rocky Mountain spotted fever, to name a few. Risk is increasing from invasive vector-borne pathogens, such as chikungunya (Ruiz-Moreno et al., 2012) and Rift Valley fever viruses (Greer et al., 2008). Mexico is listed as high risk for dengue fever by the World Health Organization (WHO). There has been an increasing number of cases of Lyme disease in Canada, and Lyme disease vectors are spreading along climate-determined trajectories (Koffi et al., 2012; Leighton et al., 2012).

26.6.2. Projected Climate Change Impacts

Projecting future consequences of climate warming for heat-related mortality and morbidity is challenging, due in large part to uncertainties in the nature and pace of adaptations that populations and societal infrastructure will undergo in response to long-term climate change (Kinney et al., 2008). Additional uncertainties arise from changes over time in population demographics, economic well-being, and underlying disease risk, as well as in the model-based predictions of future climate and our understanding of the exposure-response relationship for heat-related mortality. However, climate warming will lead to continuing health stresses related to extreme high temperatures, particularly for the northern parts of North America. The health implications of warming winters remain uncertain (Kinney, 2012).

Several recent studies have projected future health impacts due to air pollution in a changing climate (Knowlton et al., 2004; Bell et al., 2007; Tagaris et al., 2009, 2010; Chang et al., 2010). There is a large literature examining future climate influences on outdoor air quality in North America, particularly for ozone (Murazaki and Hess, 2006; Steiner et al., 2006; Kunkel et al., 2007;Tao et al., 2007; Holloway et al., 2008; Lin et al., 2008, 2010; Nolte et al., 2008; Wu et al., 2008; Avise et al., 2009; Chen et al., 2009; Liao et al., 2009; Racherla and Adams, 2009; Tai et al., 2010). This work suggests with *medium confidence* that ozone concentrations could increase under future climate change scenarios if emissions of precursors were held constant (Jacob and Winner, 2009). However, analyses show that future increases can be offset through measures taken to limit emission of pollutants (Kelly et al., 2012). The literature for $PM_{2.5}$ is more limited than that for ozone, and shows a more complex pattern of climate sensitivities, with no clear net influence of warming temperatures (Liao et al., 2007; Tagaris et al., 2008; Avise et al., 2009; Pye et al., 2009; Mahmud et al., 2010). On the other hand, $PM_{2.5}$ plays a crucial role in potential health co-benefits of some climate mitigation measures. Regarding outdoor pollen, warming will lead to further changes in the seasonal timing of pollen release (*high confidence*). Another driver of future pollen could be changing spatial patterns of vegetation as a result of climate change. Regarding clean water supplies, extreme precipitation can overwhelm combined sewer systems and lead to overflow events that threaten human health (Patz et al., 2008). Conditional on a future increase in such events, we can anticipate increasing risks related to water-borne diseases.

Whether future warmer winters in the USA and Canada will promote transmission of diseases like dengue and malaria is uncertain, in part because of access to amenities such as screening and air-conditioning that provide barriers to human-vector contact. Socioeconomic factors also play important roles in determining risks. Better longitudinal data sets and empirical models are needed to address research gaps on climate-sensitive infectious diseases, as well as to provide a better mechanism for weighting the roles of external drivers such as climate change on a macro/micro scale, human-environmental changes on a regional to local scale, and extrinsic factors in the transmission of vector-borne infectious diseases (Wilson, 2009; McGregor, 2011).

26.6.3. Adaptation Responses

Early warning and response systems can be developed to build resilience to events like heat waves, storms, and floods (Ebi, 2011) and protect susceptible populations, which include infants, children, the elderly, individuals with pre-existing diseases, and those living in socially and/or economically disadvantaged conditions (Pinkerton et al., 2012). Adaptation planning at all scales to build resilience for health systems in the face of a changing climate is a growing priority (Kinney et al., 2011). Adaptation to heat events can occur via physiologic mechanisms, indoor climate control, urban-scale cooling initiatives, and with implementation of warning and response systems (Romero-Lankao et al., 2012b). Additional research is needed on the extent to which warning systems prevent deaths (Harlan and Ruddell, 2011). Efforts to reduce GHG emissions could provide health co-benefits, including reductions in heat-related and respiratory illnesses (Luber et al., 2014).

26.7. Key Economic Sectors and Services

There is mounting evidence that many economic sectors across North America have experienced climate impacts and are adapting to the risk of loss and damage from weather perils. This section covers the literature for the energy, transportation, mining, manufacturing, construction and housing, and insurance sectors in North America. Recent studies find a range of adaptive practices and adaptation responses to experience with extreme events, and only an emerging consideration of proactive adaptation in anticipation of future global warming.

26.7.1. Energy

26.7.1.1. Observed Impacts

Energy demand for cooling has increased as building stock and air conditioning penetration have increased (Wilbanks et al., 2012). Extreme weather currently poses risk to the energy system (Wilbanks et al., 2012). For example, Hurricane Sandy resulted in a loss of power to 8.5 million customers in the northeastern USA (NOAA, 2013). Energy consumption is a major user of water resources in North America, with 49% of the water withdrawals in the USA for thermoelectric power (Kenny et al., 2009).

26.7.1.2. Projected Impacts

Demand for summer cooling is projected to increase and demand for winter heating is projected to decrease. Total energy demand in North America is projected to increase in coming decades because of non-climate factors (Galindo, 2009; National Energy Board, 2011; EIA, 2013). Climate change is projected to have varying geographic impacts. In Canada, a net decrease in residential annual energy demand is projected by 2050 and by 2100 (Isaac and Van Vuuren, 2009; Schaeffer et al., 2012). It is difficult to project changes in net energy demand in the USA because of uncertainties in such factors as climate change, and change in technology, population, and energy prices. Peak demand for electricity is projected to increase more than the average demand for electricity, with capacity expansion needed in many areas (Wilbanks et al., 2012). Given the projected increases in energy demand in the southern USA from climate change (Auffhammer and Aroonruengsawat, 2011, 2012), it is reasonable to conclude that Mexico will have a net increase in demand.

Major water resource-related concerns include effects of increased cooling and other demands for water and water scarcity in the west; effects of extreme weather events, SLR, hurricanes, and seasonal droughts in the southeast; and effects of increased cooling demands in the northern regions (CCSP, 2007; MacDonald et al., 2012; Wilbanks et al., 2012; DOE-PI, 2013).

The magnitude of projected impacts on hydropower potential will vary significantly between regions and within drainage basins (Desrochers et al., 2009; Kienzle et al., 2012; Shrestha et al., 2012). Annual mean hydropower production in the Peribonka River in Quebec is estimated to increase by approximately 10% by mid-century and 20% late in the century under the A2 scenario (Minville et al., 2009).

Higher temperatures and increased climate variability can have adverse impacts on renewable energy production such as wind and solar (DOE-PI, 2013). Changing cloud cover affects solar energy resources, changes in winds affect wind power potentials, and temperature change and water availability can affect biomass production (CCSP, 2007; DOE-PI, 2013).

26.7.1.3. Adaptation

Many adaptations are underway to reduce vulnerability of the energy sector to extreme climate events such as heat, drought, and flooding (DOE-PI, 2013). Adaptation includes many approaches such as increased supply and demand efficiency (e.g., through more use of insulation), more use of urban vegetation and reflective surfaces, improved electric grid, reduced reliance on above-ground distribution systems, and distributed power (Wilbanks et al., 2012). Important barriers to adaptation include uncertainty about future climate change, inadequate information on costs of adaptation, lack of climate resilient energy technologies, and limited price signals (DOE-PI, 2013). Strategies resulting in energy demand reduction would reduce GHG emissions and reduce the vulnerability of the sector to climate change.

26.7.2. Transportation

26.7.2.1. Observed Impacts

Much of the transportation infrastructure across North America is aging, or inadequate (Mexico), which may make it more vulnerable to damage from extreme events and climate change. Approximately 11% of all US bridges are structurally deficient, 20% of airport runways are in fair or poor condition, and more than half of all locks are more than 50 years old (U.S. Department of Transportation, 2013). More than US$2 trillion is needed to bring infrastructure in the USA up to "good condition" (ASCE, 2009, p. 6). Canadian infrastructure had an investment deficit of CA$125 billion in the 1980s and 1990s (Mirza and Haider, 2003).

Some transportation systems have been harmed (Figure 26-2). For example, in 2008, Hurricane Ike caused US$2.4 billion in damages to ports and waterways in Texas (MacDonald et al., 2012). The "superflood" in Tennessee and Kentucky in 2010 caused US$2.3 billion in damage (NOAA, 2013).

Hurricane Sandy flooded portions of New York City's subway system, overtopped runways at La Guardia airport, and caused US$400 million in damage to the New Jersey transit system (NOAA, 2013).

26.7.2.2. Projected Impacts

Scholarship on projected climate impacts on transportation infrastructure focuses mostly on USA and Canada. Increases in high temperatures, intense precipitation, drought, sea level, and storm surge could affect transportation across the USA. The greatest risks would be to coastal transportation infrastructure, but there could be benefits to marine and lake transportation in high latitudes from less ice cover (TRB, 2008). A 1-m SLR combined with a 7-m storm surge could inundate over half of the highways, arterials, and rail lines in the US Gulf Coast (CCSP, 2008c). Declining water levels in the Great Lakes would increase shipping costs by restricting vessel drafts and reducing vessel cargo volume (Millerd, 2011). In southern Canada by the 2050s, cracking of roads from freeze and thaw would decrease under the B2 and A2 scenarios, structures would freeze later and thaw earlier, while higher extreme temperatures could increase rutting (Mills et al., 2009) and related maintenance and rehabilitation costs (Canadian Council of Professional Engineers, 2008).

A 1°C to 1.5°C increase in global mean temperature would increase the costs of keeping paved and unpaved roads in the USA in service by, respectively, US$2 to US$3 billion per year by 2050 (Chinowsky et al., 2013). Tens of thousands to more than 100,000 bridges in the USA could be vulnerable to increasing peak river flows in the mid- and late-21st century under the A1B and A2 scenarios. Strengthening vulnerable bridges to be less vulnerable to climate change is estimated to cost approximately US$100 to US$250 billion (Wright et al., 2012).

26.7.2.3. Adaptation

Adaptation steps are being taken in North America, particularly to protect transportation infrastructure from SLR and storm surge in coastal regions. Almost all of the major river and bay bridges destroyed by Hurricane Katrina surge waters were rebuilt at higher elevations, and the design of the connections between the bridge decks and piers were strengthened (Grenzeback and Luckmann, 2006).

Adaptation actions include protecting coastal transportation from SLR and more intense coastal storms or possibly relocating infrastructure. Many midwestern states are examining channel protection and drainage designs, while transportation agencies in Canada and the USA have been preparing to manage the aftermath of extreme weather events (Meyer et al., 2013). In addition, new materials may be needed so pavement and rail lines can better withstand more extreme temperatures.

26.7.3. Mining

26.7.3.1. Observed Impacts

Climatic sensitivities of mining activities, including exploration, extraction, processing, operations, transportation, and site remediation, have been noted in the limited literature (Chiotti and Lavender, 2008; Furgal and Prowse, 2008; Meza-Figueroa et al., 2009; Ford et al., 2010a; Gómez-Álvarez et al., 2011; Kirchner et al., 2011; Locke et al., 2011; Pearce et al., 2011; Stratos Inc. and Brodie Consulting Ltd., 2011). Drought-like conditions have affected the mining sector by limiting water supply for operations (Pearce et al., 2011), enhancing dust emissions from quarries (Pearce et al., 2011), and increasing concentrations of heavy metals in sediments (Gómez-Álvarez et al., 2011). Heavy precipitation events have caused untreated mining wastewater to be flushed into river systems (Pearce et al., 2011). High loads of contamination (from metals, sulfate, and acid) at three mine sites in the USA were measured during rainstorm events following dry periods (Nordstrom, 2009).

26.7.3.2. Projected Impacts

Climate change is perceived by Canadian mine practitioners as an emerging risk and, in some cases, a potential opportunity (Ford et al., 2010a, 2011; Pearce et al., 2011; NRTEE, 2012), with potential impacts on transportation (Ford et al., 2011) and limited water availability (Acclimatise, 2009) from projected drier conditions (Sun et al., 2008; Seager and Vecchi, 2010) being identified as key issues.

An increase in heavy precipitation events projected for much of North America (Warren and Egginton, 2008; Nordstrom, 2009) would adversely affect the mining sector. A study on acid rock damage drainage in Canada concluded that an increase in heavy precipitation events presented a risk of both environmental impacts and economic costs

(Stratos Inc. and Brodie Consulting Ltd., 2011) Damage to mining infrastructure from extreme events, for active and post-operation mines, is also a concern (Pearce et al., 2011). Climate change impacts that affect the bottom-line of mining companies (through direct impacts or associated costs of adaptation), would have consequences for employment, for both the mining sectors and local support industries (Backus et al., 2013).

26.7.3.3. Adaptation

Despite increasing awareness, there are presently few documented examples of proactive adaptation planning within the mining sector (Acclimatise, 2009; Ford et al., 2010a, 2011). However, adjustments to management practices to deal with short-term water shortages, including reducing water intake, increasing recycling, and establishing infrastructure to move water from tailing ponds, pits, and quarries, have worked successfully in the past (Chiotti and Lavender, 2008). Integrating climate change considerations at the mine planning and design phase increases the opportunity for effective and cost-efficient adaptation (Stratos Inc. and Brodie Consulting Ltd., 2011).

26.7.4. Manufacturing

26.7.4.1. Observed Impacts

There is little literature focused on climate change and manufacturing, although one study suggested that manufacturing is among the most sensitive sectors to weather in the USA (Lazo et al., 2011). Weather affects the supply of raw material, production process, transportation of goods, and demand for certain products. In 2011, automobile manufacturers in North America experienced production losses associated with shortages of components due to flooding in Thailand (Kim, 2011). In 2013, reduced cattle supply and higher feed prices associated with drought in Texas led to a decision to close a beef processing plant (Beef Today Editors, 2013). Drought also caused delays for barge shipping on the Mississippi River in 2012 (Polansek, 2012). Major storms, like Hurricanes Sandy, Katrina, and Andrew, significantly disrupted manufacturing activities, including plant shutdowns due to direct damages and/or loss of electricity and supply disruptions due to unavailability of parts, and difficulties delivering products due to compromised transportation networks (Baade et al., 2007; Dolfman et al., 2007).

26.7.4.2. Projected Impacts

The drier conditions (Sun et al., 2008; Seager and Vecchi, 2010; Wehner et al., 2011) would present challenges, especially for manufacturers located in regions already experiencing water stress. This could lead to increased conflicts over water between sectors and regions, and affect the ability of regions to attract new facilities or retain existing operations. A study of the effect of changes in precipitation (A1B scenario) on 70 industries in the USA between 2010 and 2050 found potentially significant losses in production and employment due to declines in water availability and the interconnectedness of different industries (Backus et al., 2013).

Another potential concern for manufacturing relates to impacts of heat on worker safety and productivity. Several studies suggest that higher temperatures and humidity would lead to decreased productivity and increased occupational health risks (e.g., Kjellstrom et al., 2009; Hanna et al., 2011; Kjellstrom and Crowe, 2011).

26.7.4.3. Adaptation

Some companies are beginning to recognize the risks climate change presents to their manufacturing operations, and consider strategies to build resilience (NRTEE, 2012). Coca Cola has a water stewardship strategy focusing on improving water use efficiency at its manufacturing plants, while Rio Tinto Alcan is assessing climate change risks for their operations and infrastructure, which include vulnerability of transport systems, increased maintenance costs, and disruptions due to extreme events (NRTEE, 2012). Air conditioning is a viable and effective adaptation option to address some of the impacts of warming, though it does incur greater demands for electricity and additional costs (Scott et al., 2008a). Sourcing raw materials from different regions and relocating manufacturing plants are other adaptation strategies that can be used to increase resiliency and reduce vulnerability.

26.7.5. Construction and Housing

26.7.5.1. Observed Impacts

The risk of damage from climate change is important for construction industries, though little research has systematically explored the topic (Morton et al., 2011). Private data from insurance companies report a significant increase in severe weather damage to buildings and other insured infrastructure over several decades (Munich Re, 2012).

26.7.5.2. Projected Impacts

Most studies project a significant further increase in damage to homes, buildings, and infrastructure (Bjarndadottir et al., 2011; IPCC, 2012). Affordable adaptation in design and construction practices could reduce much of the risk of climate damage for new buildings and infrastructure, involving reform in building codes and other standards (Kelly et al., 2012). However, adaptation best practices in design and construction are often prohibitively expensive to apply to existing buildings and infrastructure, so much of the projected increase in climate damage risk involves existing buildings and infrastructure.

26.7.5.3. Adaptation

Engineering and construction knowledge exists to design and construct new buildings to accommodate the risk of damage from historic extremes and anticipated changes in severe weather (IBHS, 2008; Kelly, 2010; Ministry of Municipal Affairs and Housing, 2011). Older buildings may be retrofit to increase resilience, but these changes are often more expensive to introduce into an existing structure than if they were included during initial construction.

The housing and construction industries have made advances toward climate change mitigation by incorporating energy efficiency in building design (Heap, 2007). Less progress has been made in addressing the risk of damage from extreme weather events (Kenter, 2010). In some markets, such as the Gulf Coast of the USA, change is underway in the design and construction of new homes in reaction to recent hurricanes (Levina et al., 2007; Kunreuther and Michel-Kerjan, 2009; IBHS, 2011), but in most markets across North America there has been little change in building practices. The cost of adaptation measures combined with limited long-term liability for future buildings has influenced some builders to take a wait-and-see attitude (Morton et al., 2011). Exploratory work is underway to consider implementation of building codes that would focus on historic weather experience and also introduce expected future weather risks (Auld et al., 2010; Ontario Ministry of Environment, 2011).

26.7.6. Insurance

26.7.6.1. Observed Impacts

Property insurance and reinsurance companies across North America experienced a significant increase in severe weather damage claims paid over the past 3 or 4 decades(Cutter and Emrich, 2005; Bresch and Spiegel, 2011; Munich Re, 2011). Most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk (Pielke, Jr. et al., 2008; Barthel and Neumayer, 2012). A role for climate change has not been excluded, but the increase to date in damage claims is largely due to growth in wealth and population (IPCC, 2012).

Severe weather and climate risks have emerged over the past decade as the leading cost for property insurers across North America, resulting in significant change in industry practices. The price of insurance increased in regions where the risk of loss and damage has increased. Discounts have been introduced where investments in adaptation have reduced the risk of future weather losses (Mills, 2012). Further detailed discussion on the insurance sector and climate change can be found in Section 10.7.

26.7.6.2. Projected Impacts

Without adaptation, there is an expectation that severe weather insurance damage claims would increase significantly over the next several decades across North America (World Bank, 2010). The risk of damage is expected to rise due to continuing growth in wealth, the population living at risk, and climate change. There is also an expectation that some weather perils in North America will increase in severity, including Atlantic hurricanes and the area burned by wildfire (Karl et al., 2008; Balshi et al., 2009), and other perils in frequency, including intense rainfall events (IPCC, 2012).

26.7.6.3. Adaptation

The insurance industry is one of the most studied sectors in North America in terms of climate impacts and adaptation. Most adaptation in the insurance industry has been in response to an increase in severe weather damage, with little evidence of proactive adaptation in anticipation of future climate change (Mills and Lecomte, 2006; Mills, 2007, 2009; Kunreuther and Michel-Kerjan, 2009; AMF, 2011; Leurig, 2011; Gallagher, 2012). In addition to pricing decisions based on an actuarial analysis of historic loss experience, many insurance companies in the USA and Canada now use climate model information to help determine the prices they charge and discounts they offer. Most insurance companies have established specialized claims handling procedures for responding to catastrophic events (Kovacs, 2005; Mills, 2009).

A recent study of more than 2000 major catastrophes since 1960 found that insurance is a critical adaptive tool available to help society minimize the adverse economic consequences of natural disasters (von Peter et al., 2012). Government insurance programs for coverage of flood in the USA have been affected by recent hurricanes and previously subsidized premiums have been changed to more accurately reflect risk (FEMA, 2013). In the USA and Canada, homeowners make extensive use of insurance to manage a broad range of risks, and those with insurance recover quickly following most extreme weather events. However, the majority of public infrastructure is not insured and it frequently takes more than a decade before government services fully recover. In contrast, Mexico has a well-developed program for financing the rebuilding of public infrastructure following a disaster (Fondo de Desastres Naturales (FONDEN)) but insurance markets are only beginning to emerge for homeowners and businesses. In 2012, per capita spending on property and casualty insurance was US$2239.20 in the USA, US$2040.40 in Canada, and US$113.00 in Mexico (Swiss Re, 2013).

Insurance companies are also working to influence the behavior of their policyholders to reduce the risk of damage from climate extremes (Kovacs, 2005; Anderson et al., 2006; Mills, 2009). For example, the industry supports the work of the Insurance Institute for Business and Home Safety in the USA, and the Institute for Catastrophic Loss Reduction in Canada, in working to champion change in the building code and communicate to property owners, governments, and other stakeholders best practices for reducing the risk of damage from hurricanes, tornadoes, winter storms, wildfire, flood, and other extremes.

26.8. Urban and Rural Settlements

Recently a growing body of literature and national assessments have focused on climate-related impacts, vulnerabilities, and risks in North American settlements (e.g., US-NCA Chapters 11, 14; Chapters 8, 9).

26.8.1. Observed Weather and Climate Impacts

Observed impacts on lives, livelihoods, economic activities, infrastructure, and access to services in North American human settlements have been attributed to SLR (Section 26.2.2.1), changes in temperature and precipitation, and occurrences of extreme events such as heat waves, droughts, and storms (Figure 26-2).

Only a handful of these impacts have been attributed to anthropogenic climate change, such as shifts in Pacific Northwest marine ecosystems, which have restricted fisheries and thus affected fishing communities (Karl et al., 2009). As well, MacKendrick and Parkins (2005), Parkins and MacKendrick (2007), Parkins (2008), and Holmes (2010) identified 30 communities and 25,000 families in British Columbia negatively affected by the mountain pine beetle outbreak (see Section 26.4.1.1).

While *droughts* are among the more notable extreme events affecting North American urban and rural settlements recently, with severe occurrences in the Canadian Prairies causing economic and employment losses (2001–2002; Wheaton et al., 2007), changes in drought frequency in North America have not been attributed to anthropogenic climate change (Figure 26-1). The 2010–2012 drought across much of the USA and northern Mexico was considered the most severe in a century (MacDonald, 2010). It affected 80% of agricultural land in the USA, with 2000 counties designated disaster zones by September (USDA ERS, 2012). Impacts include the loss of 3.2 million tons of maize in Mexico, placing 2.5 million at risk of food insecurity (DGCS, 2012). Among the most severely affected were indigenous peoples, such as the Rarámuri of Chihuahua (DGCS, 2012). Closely associated with droughts, the impacts of recent wildfires have been significant (see Box 26-2), and have intensified inequalities in vulnerability between amenity migrants and low-income residents in peri-urban areas of California and Colorado (Collins and Bolin, 2009).

Other extreme events include heat waves, resulting in excess urban mortality (O'Neill and Ebi, 2009; Romero-Lankao et al., 2012b) and affecting infrastructure and built environments. For example, road pavement in Chicago buckled under temperatures higher than 100°F (CBS Chicago, 2012); in Colorado two wildfires burned more than 600 homes (NOAA NCDC, 2013).

Extreme storms and extreme precipitation have also impacted several North American regions (Figures 26-1, 26-2). Flood frequency has increased in some cities, a trend sometimes associated with more intense precipitation (e.g., Mexico City and Charlotte, North Carolina, USA; Villarini et al., 2009; Magana, 2010), while in others this trend is associated with a transition from flood events dominated by snowmelt to those caused by warm-season thunderstorms (e.g., Québec, Canada, and Milwaukee, Wisconsin, USA; Ouellet et al., 2012; Yang et al., 2013). As illustrated by Hurricane Sandy (Neria and Shultz, 2012; Powell et al., 2012), storms impact human health and health care access (Section 26.6.1.1), and impacts on infrastructure and the built environment have been costly. Heavy precipitation, storm surges, flash floods, and wind—including flooding on the US East Coast and Midwest (2011), hurricanes and floods in the city of Villa Hermosa (Galindo et al., 2009) and other urban areas in southern Mexico (2004–2005)—have compromised homes and businesses (Comfort, 2006; Kirshen et al., 2008; Jonkman et al., 2009; Romero-Lankao, 2010). Hurricane Wilma alone caused US$1.8 billion in damage, among the biggest insurance losses in Latin American history (Galindo et al., 2009).

The impacts of interacting hazards compound vulnerabilities (Section 26.8.2). Coastal settlements are at risk from the combined occurrence of coastal erosion, health effects, infrastructure, and economic damage from storm surges. Earlier thaw (Friesinger and Bernatchez, 2010), SLR, and coastal flooding have been detected along the Mid-Atlantic, Gulf of Mexico, and St. Lawrence (Kirshen et al., 2008; Friesinger and Bernatchez, 2010; Zavala-Hidalgo et al., 2010; Rosenzweig et al., 2011; Tebaldi et al., 2012).

Climate impacts on the ecosystem function and services (e.g., water supplies, biodiversity, or flood protection) provided to human settlements are another concern. While acknowledged in some places (e.g., Mexico City Climate Action Plan), they have received relatively less scholarship attention (Hunt and Watkiss, 2011).

26.8.2. Observed Factors and Processes Associated with Vulnerability

Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific vulnerability factors and processes (Table 26-1; Cutter et al., 2013), some of which are common to many settlements, while others are more pertinent to some types of settlements than others. Human settlements simultaneously face a multi-level array of non-climate-related hazards (e.g., economic, industrial, technological) that contribute to climate change vulnerability (McGranahan et al., 2007; Satterthwaite et al., 2007; Romero-Lankao and Dodman, 2011). In the following subsections we highlight key sources of vulnerability for urban and rural systems.

26.8.2.1. Urban Settlements

Hazard risks in urban settlements are enhanced by the *concentration* of populations, economic activities, cultural amenities, and built environments particularly when they are in highly exposed locations such as coastal and arid areas. Cities of concern include those in the Canadian prairies and USA-Mexico border region; and major urban areas including Boston, New York, Chicago, Washington DC, Los Angeles, Villa Hermosa, Mexico City, and Hermosillo (Bin et al., 2007; Collins, 2008; Kirshen et al., 2008; Collins and Bolin, 2009; Galindo et al., 2009; Gallivan et al., 2009; Hayhoe et al., 2010; Romero-Lankao, 2010; Rosenzweig et al., 2010; Wittrock et al., 2011).

Risks may also be heightened by *multiple interacting hazards*. Slow-onset events such as urban heat islands, for instance, interact with poor air quality in large North American cities to exacerbate climate impacts on human health (Romero-Lankao et al., 2013a). As illustrated by recent weather events (Figure 26-2), however, hazard interactions can also follow individual, high-magnitude extreme events of short duration, with cascading effects across interconnected energy, transportation, water, and health infrastructures and services to contribute to and compound urban vulnerability (Gasper et al., 2011). Wildfire vulnerability in the southwest has been compounded by peri-urban growth (Collins and Bolin, 2009; Brenkert-Smith, 2010). Under current financial constraints in many cities, climate-related economic losses can reduce resources available to address social issues, thus threatening institutional capacity and urban livelihoods (Kundzewicz et al., 2008).

The *urbanization process* and *urban built-environments* of North America can amplify climate impacts as they change land use and land surface physical characteristics (e.g., surface albedo; Chen, F. et al., 2011). A 34% increase in US urban land development (Alig et al., 2004) between

1982 and 1997 had implications for water supplies and extreme event impacts. Effects on water are of special concern (Section 26.3), as urbanization can enhance or reduce precipitation, depending on climate regime; geographical location; and regional patterns of land, energy, and water use (Cuo et al., 2009). Urbanization also has significant impacts on flood climatology through atmospheric processes tied to the urban heat island (UHI), the urban canopy layer (UCL), and the aerosol composition of airsheds (Ntelekos et al., 2010). The UHI can also increase health risks differentially, due to socio-spatial inequalities across and within North American cities (Harlan et al., 2008; Miao et al., 2011).

Urbanization imposes path dependencies that can amplify or attenuate vulnerability (Romero-Lankao and Qin, 2011). The overexploitation of Mexico City's aquifer by 19.1 to 22.2 $m^3 s^{-1}$, for example, has reduced groundwater levels and caused subsidence, undermining building foundations and infrastructure and increasing residents' vulnerability to earthquakes and heavy rains (Romero-Lankao, 2010).

Elements of the *built-environment* such as housing stock, urban form, the condition of water and power infrastructures, and changes in urban and ecological services also affect vulnerability. Large, impermeable surfaces and buildings disrupt drainage channels and accelerate runoff (Walsh et al., 2005). Damage from floods can be much more catastrophic if drainage or waste collection systems are inadequate to accommodate peak flows (Richardson, 2010; Sosa-Rodriguez, 2010). While many Canadian and US cities are in need of infrastructure adaptation upgrades (Doyle et al., 2008; Conrad, 2010), Mexican cites are faced with existing infrastructure deficits (Niven et al., 2010; Hardoy and Romero-Lankao, 2011), and high levels of socio-spatial segregation (Smolka and Larangeira, 2008; see also Section 26.7).

Recent weather hazards (Figure 26-2) illustrate that economic activities and highly valued physical capital of cities (real estate, interconnected infrastructure systems) are very sensitive to climate-related disruptions that can result in high impacts; activities in some urban areas are particularly exposed to key resource constraints (e.g., water in the USA-Mexico border; oil industry in Canada, USA, and Mexico; Conrad, 2010; Levy et al., 2010); others are dependent upon climate-sensitive sectors (e.g., tourism; Lal et al., 2011). Disruptions to production, services, and livelihoods, and changes in the costs of raw materials, also impact the economic performance of cities (Hunt and Watkiss, 2011).

Cities are relatively better endowed than rural populations with individual and neighborhood assets such as income, education, quality of housing, and access to infrastructure and services that offer protection from climate hazards. However, intra-urban socio-spatial differences in access to these assets shape response capacities (Harlan and Ruddell, 2011; Romero-Lankao et al., 2013a). All this means that class and socio-spatial segregation are key determinants not only of vulnerability but also of inequalities in risk generation and distribution within cities. Economic elites are better positioned to access the best land and enjoy the rewards of environmental amenities such as clean air, safe drinking water, open space, and tree shade (Morello-Frosch et al., 2002; Harlan et al., 2006, 2008; Ruddell et al., 2011). Although wealthy sectors are moving into risk prone coastal and forested areas (Collins, 2008), and certain hazards (air pollution) affect both rich and poor alike (Romero-Lankao et al., 2013a), climate risks tend to be disproportionally borne by the poor or otherwise marginalized populations (Cutter et al., 2008; Collins and Bolin, 2009; Romero-Lankao, 2010; Wittrock et al., 2011). In some cities, marginalized populations are moving to peri-urban areas with inadequate services, a portfolio of precarious livelihood mechanisms, and inappropriate risk-management institutions (Collins and Bolin, 2009; Eakin et al., 2010; Monkkonen, 2011; Romero-Lankao et al., 2012a).

Although cities have comparatively higher access than rural municipalities to determinants of institutional capacity such as human resources and revenue pools, their governance arrangements are often hampered by jurisdictional conflicts, asymmetries in information and communication access, fiscal constraints on public services including emergency personnel, and top-down decision making. These governance issues exacerbate urban vulnerabilities and constrain urban adaptation planning (Carmin et al., 2012; Romero-Lankao et al., 2013a).

26.8.2.2. Rural Settlements

The legacy of previous and current stressors in North American rural communities, including rapid population growth or loss, reduced employment, and degradation of local knowledge systems, can increase vulnerability (Brklacich et al., 2008; Coles and Scott, 2009; McLeman, 2010). North American rural communities have a higher proportion of lower income and unemployed populations and higher poverty than cities (Whitener and Parker, 2007; Lal et al., 2011; Skoufias et al., 2011). 55% of Mexico's rural residents live in poverty, and the livelihood of 72% of these is in farming (Saldaña-Zorrilla, 2008). US and Canadian rural communities have older populations (McLeman, 2010) and lower education levels (Lal et al., 2011). Indigenous communities have lower education levels and high levels of poverty, but are younger than average populations (Downing and Cuerrier, 2011). The legacy of their colonial history, furthermore, has stripped Indigenous communities of land and many sources of social and human capital (Brklacich et al., 2008; Hardess et al., 2011). Conversely, rural and Indigenous community members possess valuable local and experiential knowledge regarding regional ecosystem services (Galloway McLean et al., 2011).

Rural economies have limited economic diversity and relatively high dependence on climate-sensitive sectors (Johnston et al., 2008; Lemmen et al., 2008; Molnar, 2010); they are sensitive to climate-induced reductions in resource supply and productivity, in addition to direct exposure to climate hazards (Daw et al., 2009). Single-sector economic dependence contributes significantly to vulnerability (Cutter et al., 2003). Engagement in export markets presents opportunity but also exposure to economic volatility (Eakin, 2006; Saldaña-Zorilla and Sandberg, 2009), and economic downturns take attention away from climate change adaptation. Farming and fishing provide both economic and food security, the impacts of climate thus posing a double threat to livelihood (Badjek et al., 2010), particularly among women (Bee et al., 2013). Inter-related factors affecting vulnerability in forestry and fishing communities include over-harvesting and the cumulative environmental effects of multiple land use activities (Brklacich et al., 2008).

Many tourism-based communities are dominated by seasonal economies and low-wage, service-based employment (Tufts, 2010), and small businesses that lack resources for emergency planning (Hystad and

Keller, 2006, 2008). Non-renewable resource industries are sensitive to power, water, and transportation disruptions associated with hazards.

Geographic isolation can be a key source of vulnerability for rural communities in North America, imposing long commutes to essential services like hospitals and non-redundant transportation corridors that can be compromised during extreme events (Chouinard et al., 2008). Many Indigenous communities are isolated, raising the costs and limiting the diversity of imported food, fuel, and other supplies, rendering the ability to engage in subsistence harvesting especially critical for both cultural and livelihood well-being (Andrachuk and Pearce, 2010; Hardess et al., 2011). Many Indigenous peoples also maintain strong cultural attachment to ancestral lands, and thus are especially sensitive to declines in the ability of that land to sustain their livelihoods and cultural well-being (Downing and Cuerrier, 2011).

Rural physical infrastructure is often inadequate to meet service needs or is in poor condition (McLeman and Gilbert, 2008; Krishnamurthy et al., 2011), especially for Indigenous communities (Brklacich et al., 2008; Hardess et al., 2011; Lal et al., 2011; see also Section 26.9). A lack of redundant power and communication services can compromise hazard response capacity.

26.8.3. Projected Climate Risks on Urban and Rural Settlements

Urbanization, migration, economic disparity, and institutional capacity will influence future impacts and adaptation to climate change in North American human settlements (Section 26.2.1). Water-related concerns are assessed in Sections 26.3.2.1, 26.3.2.3). We describe below a variety of future climate risks identified in the literature, many of which focus on cities (Chapters 8, 9) and, with the exception of larger centers such as New York and Boston, are qualitative in nature (Hunt and Watkiss, 2011). This is due in part to the difficulty in downscaling the shifts in key trends in climate parameters to an appropriate scale.

Model-based SLR projections of future risks to cities are characterized by large uncertainties due to global factors (e.g., the dynamics of polar ice sheets) and regional factors (e.g., regional shifts in ocean circulation, high of the adjacent ocean and local land elevation; Blake et al., 2011; see WGI AR5 Chapter 3). The latter will determine differential SLR impacts on regional land development of coastal settlements (GAO, 2007; Yin et al., 2009; Conrad, 2010; Millerd, 2011; Biasutti et al., 2012), making some areas particularly vulnerable to inundation (Cooper and Sehlke, 2012). SLR can also exacerbate vulnerability to extreme events such as hurricanes (Frazier et al., 2010).

Temperature increases would lead to additional health hazards. Baseline warmer temperatures in cities are expected to be further elevated by extreme heat events whose intensity and frequency is projected to increase during the 21st century (Section 26.2.2), particularly in northern mid-latitude cities (Jacob and Winner, 2009).

Participation in some outdoor activities would increase as a result of projected increases in warm days (Scott and McBoyle, 2007). Projected snowfall declines in Canada and the northeastern USA would reduce length of winter sport seasons and thus affect the economic well-being of some communities (McBoyle et al., 2007; Scott et al., 2008b).

Any increase in frequency of extreme events, such as intense precipitation, flooding, and prolonged dry periods, would affect particularly the populations, economic activities, infrastructures, and services on coasts, flood-prone deltas, and arid regions (Kirshen et al., 2008; Nicholls et al., 2008; Richardson, 2010; Weiss et al., 2011). For example, by the end of this century, New York City is projected to experience nearly twice as many extreme precipitation days compared to today (A2, mean ensemble of 17 models). Ntelekos et al. (2010) and Cayan et al. (2010) project an increase in the number and duration of droughts in the southwestern USA, with most droughts expected to last more than 5 years by 2050 (GDFL CM2.1 and National Centre for Meteorological Research (CNRM) CM3, A2 and B1). Assuming no adaptation, total losses from river flooding in metropolitan Boston are estimated to exceed US$57 billion by 2100, of which US$26 billion is attributed to climate change (Kirshen et al., 2008; Nicholls et al., 2008; Richardson, 2010; Weiss et al., 2011).

Future climate risks on lives and livelihoods have been relatively less studied. A handful of studies focused on forestry are notable, indicating potentially substantial shifts in livelihood options without adaptation. Sohngen and Sedjo (2005) estimate losses from climate change in the Canadian/US timber sector of US$1.4 to US$2.1 billion per year over the next century. Anticipated future supply reductions in British Columbia as a consequence of the pine beetle outbreak vary from 10 to 62% (Patriquin et al., 2007). Substantial declines in suitable habitat for valued tree species in Mexico have been projected (Gómez-Mendoza and Arriaga, 2007; Gómez Diaz et al., 2011).

Scholars are starting to project future risks from interacting hazards. For instance, by 2070 with a 0.5 m rise in sea level and under scenarios of socioeconomic growth, storm surges, and subsidence, populations at risk in New York, Miami, and New Orleans might increase three-fold, while asset exposure will increase more than 10-fold (Hanson et al., 2011).

Essential *infrastructure and services* are key concerns (Sections 26.3, 26.7). Increased occurrence of drought affecting water availability is projected for southwestern USA/northern Mexico, the southern Canadian Prairies and central Mexico, combined with projected increases in water demand due to rapid population growth and agriculture (Schindler and Donahue, 2006; MacDonald, 2010; Lal et al., 2011). Using A1B and A2 scenarios, Escolero-Fuentes et al. (2009) projected that, by 2050, Mexico City and its watersheds will experience a more intense hydrological cycle and a reduction of between 10 to 17% in per capita available water. SLR is predicted to threaten water and electricity infrastructure with inundation and increasing salinity (Sharp, 2010).

26.8.4. Adaptation

26.8.4.1. Evidence of Adaptation

26.8.4.1.1. What are populations doing? Autonomous adaptation

As illustrated by recent extreme events (Figure 26-2), individuals and households in North America not only have been affected by extremes, but have also been responding to climate impacts mostly through incremental actions, for example, by purchasing additional insurance or reinforcing homes to withstand extreme weather (Simmons and Sutter, 2007; Romero-Lankao et al., 2012a). Some individuals respond by diversifying livelihoods (Newland et al., 2008; Rose and Shaw, 2008) or migrating (see Section 26.1.1; Black et al., 2011).

The propensity to respond to climate and weather hazards is strongly influenced not only by access to household assets, but also by community and governmental support. The emergency response to Hurricane Sandy illustrates this. Although New York and New Jersey witnessed vivid scenes of "medical humanitarianism," because of inadequate communication and coordination among agencies, public health support did not always reach those most in need (Abramson and Redlener, 2013).

The perceived risks of climate change among individuals are equally important. Strong attachment to place and occupation may motivate willingness to support incremental adaptation, enhance coping capacity, and foster adaptive learning (Collins and Bolin, 2009; Romero-Lankao, 2010; Aguilar and Santos, 2011; Wittrock et al., 2011). They have also been found to serve as barriers to transformational adaptation (Marshall et al., 2012). Residents of the USA stand out in international research as holding lower levels of perceived risk of climate change (AXA Group and Ipsos Research, 2012), which may limit involvement in household-level adaptation or support for public investments in adaptation.

26.8.4.1.2. What are governments doing? Planned adaptation

Leadership in adaptation is far more evident locally than at other tiers of government in North America (Richardson, 2010; Vasseur, 2011; Vrolijks et al., 2011; Carmin et al., 2012; Henstra, 2012). Few municipalities have moved into the implementation stage, however; most programs are in the process of problem diagnosis and planning (Perkins et al., 2007; Moser and Satterthwaite, 2008; Romero-Lankao and Dodman, 2011). Systematic assessments of vulnerability are rare, particularly in relation to population groups (Vrolijks et al., 2011). Surveys of municipal leaders showed adaptation is rarely incorporated into planning, due to lack of resources, information, and expertise (Horton and Richardson, 2011), and the prevalence of other issues considered higher priority, suggesting the need for subnational and federal-level facilitation in the form of resources and enabling regulations.

Climate change policies have been motivated by concerns for local economic or energy security and the desire to play leadership roles (Rosenzweig et al., 2010; Anguelovski and Carmin, 2011; Romero-Lankao et al., 2013a). Some policies constitute "integrated" strategies (New York; Perkins et al., 2007; Rosenzweig et al., 2010), and coordinated participation of multiple municipalities (Vancouver; Richardson, 2010). Sector-specific climate risk management plans have also emerged (e.g., water conservation in Phoenix, USA and Regina, Canada; wildfire protection in Kamloops, Canada and Boulder, USA). Municipalities affected by the mountain pine beetle have taken many steps toward adaptation (Parkins, 2008), and coastal communities in eastern Canada are investing in saltwater marsh restoration to adapt to rising sea levels (Marlin et al., 2007). Green roofs, forest thinning, and urban agriculture have all been expanding (Chicago, New York, Kamloops, Mexico City), as have flood protection (New Orleans, Chicago), private and governmental insurance policies (Browne and Hoyt, 2000; Ntelekos et al., 2010; see also Section 26.10), saving schemes (common in Mexico), air pollution controls (Mexico City), and hazard warning systems (Collins and Bolin, 2009; Coffee et al., 2010; Romero-Lankao, 2010; Aguilar and Santos, 2011).

26.8.4.2. Opportunities and Constraints

Adaptation in human settlements is influenced by local access to resources, political will, and the capacity for institutional-level attention and multi-level/sectoral coordination (Burch, 2010; Romero-Lankao et al., 2013a).

26.8.4.2.1. Adaptation is path-dependent

Adaptation options are constrained by past settlement patterns and decisions. The evolution of cities as economic hubs, for example, affects vulnerability and resilience (Leichenko, 2011). Urban expansion into mountain, agricultural, protected, and otherwise risk-prone areas (Boruff et al., 2005; McGranahan et al., 2007; Collins and Bolin, 2009; Conrad, 2010) invariably alters regional environments. Development histories foreclose some resilience pathways. Previous water development, for example, can result in irreversible over-exploitation and degradation of water resources.

26.8.4.2.2. Institutional capacity

At all levels of governance, adaptation in North America is affected by numerous determinants of institutional capacity. Three have emerged in the literature as particularly significant challenges for urban and rural settlements:

- *Economic resources*: Rural communities face limited revenues combined with higher costs of supplying services (Williamson et al., 2008; Posey, 2009). Small municipal revenue pools translate into fiscal constraints necessary to support public services, including emergency personnel and health care (Lal et al., 2011). Although large cities tend to have greater fiscal capacity, most do not receive financial support for adaptation (Carmin et al., 2012), yet face the risk of higher economic losses.
- *Information and social capital*: Differences in access and use of information, and capacity for learning and innovation, affect adaptive capacity (Romero-Lankao et al., 2013a). Levels of knowledge and prioritization can be low among municipal planners. Information access can be limited, even among environmental planners (Picketts et al., 2012). The relationship between trust and participation in support networks (social capital) and adaptive capacity is generally positive; however, strong social bonds may support narratives that underestimate climate risk (Wolf et al., 2010; Romero-Lankao et al., 2012b).
- *Participation*: Considering the overlap among impacts and sources of vulnerability in North American human settlements, long-term effectiveness of local adaptation hinges on inclusion of all stakeholders. Stakeholder involvement lengthens planning time frames, may elicit conflicts, and power relationships can constrain

Box 26-3 | Climate Responses in Three North American Cities

With populations of 20.5, 14, and 2.3 million people, respectively, the metropolitan areas of Mexico City, New York, and Vancouver are facing multiple risks that climate change is projected to aggravate. These risks range from sea level rise, coastal flooding, and storm surges in New York and Vancouver to heat waves, heavy rains and associated flooding, air pollution, and heat island effects in all three cities (Leon and Neri, 2010; Rosenzweig and Solecki, 2010; City of Vancouver, 2012). Many of these risks result not only from long-term global and regional processes of environmental change, but also from local changes in land and water uses and in atmospheric emissions induced by urbanization (Leon and Neri, 2010; Romero-Lankao, 2010; Kinney et al., 2011; Solecki, 2012).

The three cities have been frontrunners in the climate arena. In Mexico City, the Program of Climate Action 2008–2012 (PAC) and the 2011 Law for Mitigation and Adaptation to Climate Change are parts of a larger 15-year "Green Agenda," with most of designated funds committed to reducing 7 million tonnes of CO_2-equivalent by 2012 (Romero-Lankao et al., 2013). New York City and Vancouver's plans are similarly mitigation centered. As of 2007 New York's long-term sustainability plan included adaptation (Solecki, 2012; Ray et al., 2013), while Vancouver launched its municipal adaptation plan in July 2012. The shifts in focus from mitigation to adaptation have followed as it has become increasingly clear that even if mitigation efforts are wholly successful, some adverse impacts due to climate change are unavoidable.

Urban leaders in all three cities have emerged as global leaders in sustainability. Mayor Bloomberg of New York, Mayor Ebrard of Mexico City, and David Cadman of Vancouver have, respectively, led the C40, World Mayors Council on Climate Change, and International Council for Local Environmental Initiatives (ICLEI). Scientists, private sector actors, and non-governmental organizations have been of no lesser importance. To take advantage of a broad-based interaction between various climate change actors, Mexico City has set up a Virtual Climate Change Center to serve as a repository of knowledge, models, and data on climate change impacts, vulnerability, and risks (Romero-Lankao et al., 2013a). Information sharing by climate change actors has also taken place in New York, where scientists and insurance and risk management experts have served on the Panel on Climate Change to advise the city on the science of climate change impacts and "protection levels specific to the city's critical infrastructure" (Solecki, 2012, p. 564).

The climate plans of the three cities are far reaching, including mitigation and adaptation strategies related to their sustainability goals. The three cities emphasize different priorities in their climate action plans. Mexico City seeks to reduce water consumption and transportation emissions through such actions as improvements in infrastructure and changes in the share of public transport. Vancouver has prioritized the separation of sanitary and storm water systems, yet this adaptation is not expected to be complete until 2050 (City of Vancouver, 2012). It will also take New York much time, money, and energy to expand adaptation strategies beyond the protection of water systems to include all essential city infrastructure (Ray et al., 2013). Overall, few proposed actions will result in immediate effects, and instead call for additional planning, highlighting the significant effort necessary for comprehensive responses. Overall, adaptation planning in the three cities faces many challenges. In all three regions, multi-jurisdictional governance structures with differing approaches to climate change challenge the ability for coordinated responses (Solecki, 2012; Romero-Lankao et al., 2013a). Conflicts in priorities and objectives between various actors and sectors are also prevalent (Burch, 2010). For instance, authorities in Mexico City concerned with avoiding growth into risk-prone and conservation areas (Aguilar and Santos, 2011) compete for regulatory space within a policy agenda that is already coping with a wide range of economic and developmental imperatives (Romero-Lankao et al., 2013a).

Climate responses require new types of localized scientific information, such as vulnerability analyses and flood risk assessments, which are not always available (Romero-Lankao et al., 2012a; Ray et al., 2013). Little is known, for instance, about how to predict and respond to common and differential levels of risk experienced by different human settlements. Comprehensive planning is still limited as well. For example, although scholarship exists on disparities in household- and population-level vulnerability and adaptive capacity (Cutter et al., 2003; Villeneuve and Burnett, 2003; Douglas et al., 2012; Romero-Lankao et al., 2013b), equity concerns have received relatively less attention by the three cities. Even when local needs are identified, such as the need to protect higher risk homeless and low-income populations (Vancouver), they are often not addressed in action plans.

access (Few et al., 2007; Colten et al., 2008). However, effective stakeholder engagement has tremendously enhanced adaptation planning, eliciting key sources of information regarding social values, securing legitimacy (Aguilar and Santos, 2011), and fostering adaptive capacity of involved stakeholders.

26.9. Federal and Subnational Level Adaptation

Along with many local governments (Section 26.8.4), federal, and subnational tiers of government across North America are developing climate change adaptation plans. These initiatives, which began at the subnational levels (e.g., Nunavut Department of Sustainable Development, 2003), appear to be preliminary and relatively little has been done to implement specific measures.

26.9.1. Federal Level Adaptation

All three national governments are addressing adaptation to some extent, with a national strategy and a policy framework (Mexico), a federal policy framework (Canada), and the USA having delegated all federal agencies to develop adaptation plans.

In 2005, the Mexican government created the Inter-Secretarial Commission to Climate Change (Comisión Inter-Secretarial de Cambio Climático (CICC)) to coordinate national public policy on climate change (CICC, 2005; Sosa-Rodriguez, 2013). The government's initiatives are being delivered through the *National Strategy for Climate Change 2007–2012* (Intersecretarial Commission on Climate Change, 2007) and, the *Special Programme on Climate Change 2009–2012*, which identify priorities in research, cross-sectoral action such as developing early warning systems, and capacity development to support mitigation and adaptation actions (CICC, 2009). The *Policy Framework for Medium Term Adaptation* (CICC, 2010) aims at framing a single national public policy approach on adaptation with a time horizon up to 2030. The General Law of Climate Change requires state governments to implement mitigation and adaptation actions (Diario Oficial de la Federación, 2012).

Canada is creating a Federal Adaptation Policy Framework intended to mainstream climate risks and impacts into programs and activities to help frame government priorities (Government of Canada, 2011). In 2007, the federal Government made a 4-year adaptation commitment to develop six Regional Adaptation Collaboratives (RAC) in provinces across Canada, ranging in size and scope, from flood protection and drought planning, to extreme weather risk management; and assessing the vulnerability of Nunavut's mining sector to climate change (Natural Resources Canada, 2011). In 2011, the federal government renewed financial support for several adaptation programs and provided new funding to create a Climate Adaptation and Resilience Program for Aboriginals and Northerners, and Enhancing Competitiveness in a Changing Climate program (Environment Canada, 2011). Canada recently launched an Adaptation Platform to advance adaptation priorities across the country (Natural Resources Canada, 2013).

The US government embarked in 2009 on a government-wide effort to have all federal agencies address adaptation; to apply understanding of climate change to agency missions and operations; to develop, prioritize, and implement actions; and to evaluate adaptations and learn from experience (The White House, 2009; Bierbaum et al., 2012). A 2013 plan issued by the president enhanced the US government effort supporting adaptation (Executive Office of the President, 2013). The US government provides technical and information support for adaptation by non-federal actors, but does not provide direct financial support for adaptation (Parris et al., 2010).

Some federal agencies took steps to address climate change adaptation prior to this broader interagency effort. In 2010, the US Department of Interior created Climate Science Centers to integrate climate change information and management strategies in eight regions and 21 Landscape Conservation Cooperatives (Secretary of the Interior, 2010), while the US Environmental Protection Agency's Office of Water developed a climate change strategy (EPA, 2011).

26.9.2. Subnational Level Adaptation

A number of states and provinces in all three countries have developed adaptation plans. For example, in Canada, Quebec's 2013–2020 adaptation strategy outlines 17 objections covering a number of managed sectors and ecosystems (Government of Quebec, 2012). British Columbia is modernizing its Water Act to alter water allocation during drought to reduce agricultural crop and livestock loss and community conflict, while protecting aquatic ecosystems (BC Ministry of the Environment, 2010).

In the USA, California was the first state to publish an adaptation plan calling for a 20% reduction in per capita water use by 2020 (California Natural Resources Agency, 2009). Maryland first developed a plan on coastal resources and then broadened it to cover human health, agriculture, ecosystems, water resources, and infrastructure (Maryland Commission on Climate Change, 2008, 2010). The State of Washington is addressing environment, infrastructure, and communities; human health and security; ecosystems, species, and habitat; and natural resources (Built Environment: Infrastructure & Communities Topic Advisory Group, 2011; Human Health and Security Topic Advisory Group, 2011; Natural Resources Working Lands and Waters Topic Advisory Group, 2011; Species, Habitats and Ecosystems Topic Advisory Group, 2011).

Of the three national governments, only Mexico requires that states develop adaptation plans. In Mexico, seven of 31 states—Veracruz, Mexico City, Nuevo León, Guanajuato, Puebla, Tabasco, and Chiapas—have developed their *State Programmes for Climate Change Action* (Programas Estatales de Acción ante el Cambio Climático (PEACC)), while Baja California Sur, Hidalgo, and Campeche are in the final stage and 17 states are still in the planning and development stage (Instituto de Ecología del Estado de Guanajuato, 2011). The proposed adaptation actions focus mainly on: (1) reducing physical and social vulnerability of key sectors and populations; (2) conservation and sustainable management of ecosystems, biodiversity, and ecosystem services; (3) developing risk management strategies; (4) strengthening water management; (5) protecting human health; and (6) improving current urban development strategies, focusing on settlements and services, transport, and land use planning.

26.9.3. Barriers to Adaptation

Chapter 16 provides a more in-depth discussion on adaptation barriers and limits. Adaptation plans tend to exist as distinct documents and are often not integrated into other planning activities (Preston et al., 2011). Most adaptation activities have only involved planning for climate change rather than specific actions, and few measures have been implemented (Preston et al., 2011; Bierbaum et al., 2012).

Even though Canada and the USA are relatively well endowed in their capacity to adapt, there are significant constraints on adaptation, with financing being a significant constraint in all three countries (Carmin et al., 2012). Barriers include legal constraints (e.g., Jantarasami et al., 2010), lack of coordination across different jurisdictions (Smith et al., 2009; NRC, 2010; INECC and SEMARNAT, 2012b), leadership (Smith et al., 2009; Moser and Ekstrom, 2010), and divergent perceptions about climate change (Bierbaum et al., 2012; Moser, 2013). Although obtaining accurate scientific data was ranked less important by municipalities (Carmin et al., 2012), an important constraint is lack of access to scientific information and capacity to manage and use it (Moser and Ekstrom, 2010; INECC and SEMARNAT, 2012b). Adaptation activities in developed countries such as the USA tend to address hazards and propose adaptations that tend to protect current activities rather than facilitate long-term change. In addition, the adaptation plans generally do not attempt to increase adaptive capacity (Eakin and Patt, 2011). However, making changes to institutions needed to enable or promote adaptations can be costly (Marshall, 2013).

Although multi-level and multi-sectoral coordination is a key component of effective adaptation, it is constrained by factors such as mismatch between climate and development goals, political rivalry, and lack of national support to regional and local efforts (Brklacich et al., 2008; Brown, 2009; Sander-Regier et al., 2009; Sydneysmith et al., 2010; Craft and Howlett, 2013; Romero-Lankao et al., 2013a). Traditionally, environmental or engineering agencies are responsible for climate issues (e.g., Mexico City, Edmonton and London, Canada), but have neither the decision-making power nor the resources to address all dimensions involved. Adaptation planning requires long-term investments by government, business, grassroots organizations, and individuals (e.g., Romero-Lankao, 2007; Burch, 2010; Croci et al., 2010; Richardson, 2010).

26.9.4. Maladaptation, Trade-Offs, and Co-Benefits

Adaptation strategies may introduce trade-offs or maladaptive effects for policy goals in mitigation, industrial development, energy security, and health (Hamin and Gurran, 2009; Laukkonen et al., 2009). Snow-making equipment, for example, mediates snowpack reductions, but has high water and energy requirements (Scott et al., 2007). Irrigation and air conditioning have immediate adaptive benefits for North American settlements, but are energy-consumptive. Sea walls protect coastal properties, yet negatively affect coastal processes and ecosystems (Richardson, 2010).

Conventional sectoral approaches to risk management and adaptation planning undertaken at different temporal and spatial scales have exacerbated vulnerability in some cases, for example, peri-urban areas in Mexico (Eakin et al., 2010; Romero-Lankao, 2012). Approaches that delegate response planning to residents in the absence of effective knowledge exchange have resulted in maladaptive effects (Friesinger and Bernatchez, 2010).

Other strategies offer synergies and co-benefits. Policies addressing air pollution (Harlan and Ruddell, 2011) or housing for the poor, particularly in Mexico (Colten et al., 2008), can often be adapted at low or no cost to fulfill adaptation and sustainability goals (Badjek et al., 2010). Efforts to temper declines in production or competitiveness in rural communities could involve mitigation innovations, including carbon sequestration forest plantations (Holmes, 2010). Painting roofs white reduces the effects of heat and lowers energy demand for cooling (Akbari et al., 2009).

Adaptation planning can be greatly enhanced by incorporating regionally or locally specific vulnerability information (Clark et al., 1998; Barsugli et al., 2012; Romsdahl et al., 2013). Methods for mapping vulnerability have been improved and effectively utilized (Romero-Lankao et al., 2013b). Similarly, strategies supporting cultural preservation and subsistence livelihood needs among Indigenous peoples would enhance adaptation (Ford et al., 2010b), as would integrating traditional culture with other forms of knowledge, technologies, education, and economic development (Hardess et al., 2011).

26.10. Key Risks, Uncertainties, Knowledge Gaps, and Research Needs

26.10.1. Key Multi-sectoral Risks

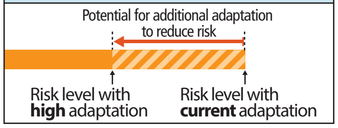
We close this chapter with our assessment of key current and future regional risks from climate change with an evaluation of the potential for risk reduction through adaptation (Table 26-1). Two of the three examples, wildfires and urban floods, illustrate that multiple climate drivers can result in multiple impacts (e.g., loss of ecosystems integrity, property damage, and health impacts due to wildfires and urban floods). The three risks evaluated in Table 26-1 also show that relative risks depend on the context-specific articulation and dynamics of such factors as the following:

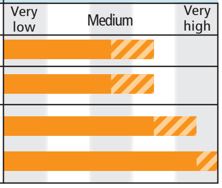
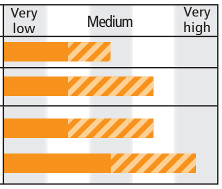
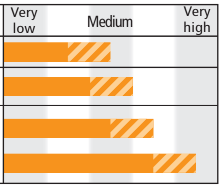
- The magnitude and rate of change of relevant climatic and non-climatic drivers and hazards. For instance, the risk of urban floods depends not only on global climatic conditions (current vs. future global mean temperatures of 2°C and 4°C), but also on urbanization, a regional source of hazard risk that can enhance or reduce precipitation, as it affects the hydrologic cycle and, hence, has impacts on flood climatology (Section 26.8.2.1).
- The internal properties and dynamics of the system being stressed. For example, some ecosystems are more fire adapted than others. Some populations are more vulnerable to heat stress because of age, preexisting medical conditions, working conditions and lifestyles (e.g., outdoor workers, athletes).
- Adaptation potentials and limits. For example, while residential air conditioning can effectively reduce health risk, availability and usage is often limited among the most vulnerable individuals. Furthermore, air conditioning is sensitive to power failures and its use has mitigation implications.

Table 26-1 | Key risks from climate change and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of this chapter, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Climate-related drivers of impacts						
🌡 Warming trend	🌡! Extreme temperature	☀ Drying trend	🌧 Extreme precipitation	🌧 Precipitation	🌀 Damaging cyclone	🌊 Sea level

Level of risk & potential for adaptation



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Wildfire-induced loss of ecosystem integrity, property loss, human morbidity, and mortality as a result of increased drying trend and temperature trend (*high confidence*) [26.4, 26.8, Box 26-2]	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity. • Agroforestry can be an effective strategy for reduction of slash and burn practices in Mexico.	🌡 ☀	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Heat-related human mortality (*high confidence*) [26.6, 26.8]	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is highly variable and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, early heat warning systems, cooling centers, greening, and high-albedo surfaces.	🌡!	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Urban floods in riverine and coastal areas, inducing property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment, due to sea level rise, extreme precipitation, and cyclones (*high confidence*) [26.2-4, 26.8]	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions. • Conservation of wetlands, including mangroves, and land-use planning strategies can reduce the intensity of flood events.	🌧 🌀 🌊	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

The judgments about risk conveyed by the Table 26-1 are based on assessment of the literature and expert judgment by chapter authors living under current socioeconomic conditions. Therefore, risk levels are estimated for each time frame, assuming a continuation of current adaptation potentials and constraints. Yet over the course of the 21st century, socioeconomic and physical conditions can change considerably for many sectors, systems, and places. The dynamics of wealth generation and distribution, technological innovations, institutions, and even culture can substantially affect North American levels of risk tolerance within the social and ecological systems considered (see also Box TS.8).

26.10.2. Uncertainties, Knowledge Gaps, and Research Needs

The literature on climate impacts, adaptation, and vulnerability in North America has grown considerably, as has the diversity of sectors and topics covered (e.g., urban and rural settlements; food security; and adaptation at local, state, and national levels). However, limitations in the topical and geographical scope of this literature are still a challenge (e.g., more studies have focused on insurance than on economic sectors such as industries, construction, and transportation). It is also challenging to summarize results across many studies and identify trends in the literature when there are differences in methodology, theoretical frameworks, and causation narratives (e.g., between outcome and contextual approaches), making it hard to compare "apples to oranges" (Romero-Lankao et al., 2012b). While the USA and Canada have produced large volumes of literature, Mexico lags well behind. It was, therefore, difficult to devote equal space to observed and projected impacts, vulnerabilities, and adaptations in Mexico in comparison with its northern neighbors. With its large land area, population, and important, albeit under-studied, climate change risks and vulnerabilities, more climate change research focusing on Mexico is direly needed.

The literature on North America tends to be dominated by sector level analyses. Yet, climate change interacts with other physical and social processes to create differential risks and impact levels. These differences are mediated by context-specific physical and social factors shaping the vulnerability of exposed systems and sectors. Furthermore, while studies often focus on isolated sectoral effects, impacts happen in communities, socio-ecologic systems, and regions, and shocks and dislocations in one sector or region often affect other sectors and regions as a result of social and physical interdependencies. This point is illustrated by Boxes 26-1 and 26-2 and the human settlements section, which discuss place-based impacts, vulnerabilities, and adaptations. Unfortunately, literature using placed-based or integrated approaches to these complexities is limited. Indeed, although in early drafts the authors of this chapter attempted to put more emphasis on place-based analysis and comparisons, the literature was inadequate to support such an effort. The IPCC includes chapters on continents and large regions to make it possible to assess

Frequently Asked Questions

FAQ 26.1 | What impact are climate stressors having on North America?

Recent climate changes and extreme events such as floods and droughts depicted in Figure 26-2 demonstrate clear impacts of climate-related stresses in North America (*high confidence*). There has been increased occurrence of severe hot weather events over much of the USA and increases in heavy precipitation over much of North America (*high confidence*). Such events as droughts in northern Mexico and south-central USA, floods in Canada, and hurricanes such as Sandy demonstrate exposure and vulnerability to extreme climate (*high confidence*). Many urban and rural settlements, agricultural production, water supplies, and human health have been observed to be vulnerable to these and other extreme weather events (Figure 26-2). Forest ecosystems have been stressed through wildfire activity, regional drought, high temperatures, and infestations, while aquatic ecosystems are being affected by higher temperatures and sea level rise.

Many decision makers, particularly in the USA and Canada, have the financial, human, and institutional capacity to invest in resilience, yet a trend of rising losses from extremes has been evident across the continent (Figure 26-2), largely due to socioeconomic factors, including a growing population, equity issues, and increased property value in areas of high exposure. In addition, climate change is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low snow years, and shifts toward earlier snowmelt runoff over much of the western USA and Canada (*high confidence*). These changes combined with higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability are projected to lead to increased stresses to water, agriculture, economic activities, and urban and rural settlements (*high confidence*).

Frequently Asked Questions

FAQ 26.2 | Can adaptation reduce the adverse impacts of climate stressors in North America?

Adaptation—including land use planning, investments in infrastructure, emergency management, health programs, and water conservation—has significant capacity to reduce risks from current climate and climate change (Figure 26-3). There is increasing attention to adaptation among planners at all levels of government but particularly at the municipal level, with many jurisdictions engaging in assessment and planning processes. Yet, there are few documented examples of implementation of proactive adaptation and these are largely found in sectors with longer term decision making, including energy and public infrastructure (*high confidence*). Adaptation efforts have revealed the significant challenges and sources of resistance facing planners at both the planning and implementation stages, particularly the adequacy of informational, institutional, financial, and human resources, and lack of political will (*medium confidence*). While there is high capacity to adapt to climate change across much of North America, there are regional and sectoral disparities in economic resources, governance capacity, and access to and ability to utilize information on climate change, which limit adaptive capacity in many regions and among many populations such as the poor and Indigenous communities. For example, there is limited capacity for many species to adapt to climate change, even with human intervention. At lower levels of temperature rise, adaptation has high potential to offset projected declines in yields for many crops, but this effectiveness is expected to be much lower at higher temperatures. The risk that climate stresses will cause profound impacts on ecosystems and society—including the possibility of species extinction or severe adverse socioeconomic shocks—highlights limits to adaptation.

how multiple climate change impacts can affect these large areas. However, this macro view gives insufficient detail on context-specific local impacts and risks, missing the on-the-ground reality that the effects of climate change are and will be experienced at much smaller scales, and those smaller scales are often where meaningful mitigation and adaptation actions can be generated. To give local actors relevant information on which to base these local actions, more research is needed to understand better the local and regional effects of climate change across sectors.

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Central and South America

Coordinating Lead Authors:
Graciela O. Magrin (Argentina), José A. Marengo (Brazil)

Lead Authors:
Jean-Phillipe Boulanger (France), Marcos S. Buckeridge (Brazil), Edwin Castellanos (Guatemala), Germán Poveda (Colombia), Fabio R. Scarano (Brazil), Sebastián Vicuña (Chile)

Contributing Authors:
Eric Alfaro (Costa Rica), Fabien Anthelme (France), Jonathan Barton (UK), Nina Becker (Germany), Arnaud Bertrand (France), Ulisses Confalonieri (Brazil), Amanda Pereira de Souza (Brazil), Carlos Demiguel (Spain), Bernard Francou (France), Rene Garreaud (Chile), Iñigo Losada (Spain), Melanie McField (USA), Carlos Nobre (Brazil), Patricia Romero Lankao (Mexico), Paulo Saldiva (Brazil), Jose Luis Samaniego (Mexico), María Travasso (Argentina), Ernesto Viglizzo (Argentina), Alicia Villamizar (Venezuela)

Review Editors:
Leonidas Osvaldo Girardin (Argentina), Jean Pierre Ometto (Brazil)

Volunteer Chapter Scientist:
Nina Becker (Germany)

This chapter should be cited as:

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Executive Summary

Significant trends in precipitation and temperature have been observed in Central America (CA) and South America (SA) (*high confidence*). In addition, changes in climate variability and in extreme events have severely affected the region (*medium confidence*). Increasing trends in annual rainfall in southeastern South America (SESA; 0.6 mm day^{-1} 50 yr^{-1} during 1950–2008) contrast with decreasing trends in CA and central-southern Chile (–1 mm day^{-1} 50 yr^{-1} during 1950–2008). Warming has been detected throughout CA and SA (near 0.7°C to 1°C 40 yr^{-1} since the mid-1970s), except for a cooling off the Chilean coast of about –1 °C 40 yr^{-1}. Increases in temperature extremes have been identified in CA and most of tropical and subtropical SA (*medium confidence*), while more frequent extreme rainfall in SESA has favored the occurrence of landslides and flash floods (*medium confidence*). {27.2.1.1; Table 27-1; Box 27-1}

Climate projections suggest increases in temperature, and increases or decreases in precipitation for CA and SA by 2100 (*medium confidence*). In post-Fourth Assessment Report (AR4) climate projections, derived from dynamic downscaling forced by Coupled Model Intercomparison Project Phase 3 (CMIP3) models for various Special Report on Emission Scenarios (SRES) scenarios, and from different global climate models from the CMIP5 for various Representative Concentration Pathways (RCPs) (4.5 and 8.5), warming varies from +1.6°C to +4.0°C in CA, and +1.7°C to +6.7°C in SA (*medium confidence*). Rainfall changes for CA range between –22 and +7% by 2100, while in SA rainfall varies geographically, most notably showing a reduction of –22% in northeast Brazil, and an increase of +25% in SESA (*low confidence*). By 2100 projections show an increase in dry spells in tropical SA east of the Andes, and in warm days and nights in most of SA (*medium confidence*). {27.2.1.2; Table 27-2}

Changes in streamflow and water availability have been observed and projected to continue in the future in CA and SA, affecting already vulnerable regions (*high confidence*). The Andean cryosphere is retreating, affecting the seasonal distribution of streamflows (*high confidence*). {Table 27-3} Increasing runoffs in the La Plata River basin and decreasing ones in the Central Andes (Chile, Argentina) and in CA in the second half of the 20th century were associated with changes in precipitation (*high confidence*). Risk of water supply shortages will increase owing to precipitation reductions and evapotranspiration increases in semi-arid regions (*high confidence*) {Table 27-4}, thus affecting water supply for cities (*high confidence*) {27.3.1.1, 27.3.5}, hydropower generation (*high confidence*) {27.3.6, 27.6.1}, and agriculture. {27.3.1.1} Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability (*medium confidence*). Ongoing constitutional and legal reforms toward more efficient and effective water resources management and coordination constitute another adaptation strategy (*medium confidence*). {27.3.1.2}

Land use change contributes significantly to environmental degradation, exacerbating the negative impacts of climate change (*high confidence*). Deforestation and land degradation are attributed mainly to increased extensive and intensive agriculture. The agricultural expansion, in some regions associated with increases in precipitation, has affected fragile ecosystems, such as the edges of the Amazon forest and the tropical Andes. Even though deforestation rates in the Amazon have decreased substantially since 2004 to a value of 4,656 km^2 yr^{-1} in 2012, other regions such as the Cerrado still present high levels of deforestation, with average rates as high as 14,179 km^2 yr^{-1} for the period 2002–2008. {27.2.2.1}

Conversion of natural ecosystems is the main cause of biodiversity and ecosystem loss in the region, and is a driver of anthropogenic climate change (*high confidence*). Climate change is expected to increase the rates of species extinction (*medium confidence*). For instance, vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains. In Brazil, distribution of some groups of birds and plants will be dislocated southward, where there are fewer natural habitats remaining. However, CA and SA have still large extensions of natural vegetation cover for which the Amazon is the main example. {27.3.2.1} Ecosystem-based adaptation practices are increasingly common across the region, such as the effective management and establishment of protected areas, conservation agreements, and community management of natural areas. {27.3.2.2}

Socioeconomic conditions have improved since AR4; however, there is still a high and persistent level of poverty in most countries, resulting in high vulnerability and increasing risk to climate variability and change (*high confidence*). Poverty levels in most countries remain high (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade. The Human Development Index varies greatly between countries, from Chile and Argentina with the highest values to Guatemala and Nicaragua with the lowest values in 2007. The economic inequality translates into inequality in access to water, sanitation, and adequate housing, particularly for the most vulnerable groups, translating into low adaptive capacities to climate change. {27.2.2.2}

Sea level rise (SLR) and human activities on coastal and marine ecosystems pose threats to fish stocks, corals, mangroves, recreation and tourism, and control of diseases (*high confidence*). SLR varied from 2 to 7 mm yr^{-1} between 1950 and 2008. Frequent coral bleaching events associated with ocean warming and acidification occur in the Mesoamerican Coral Reef. In CA and SA, the main drivers of mangrove loss are deforestation and land conversion to agriculture and shrimp ponds. {27.3.3.1} Brazilian fisheries' co-management (a participatory multi-stakeholder process) is an example of adaptation as it favors a balance between conservation of marine biodiversity, the improvement of livelihoods, and the cultural survival of traditional populations. {27.3.3.2}

Changes in agricultural productivity with consequences for food security associated with climate change are expected to exhibit large spatial variability (*medium confidence*). In SESA, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (*medium confidence*; SRES: A2, B2). {Table 27-5} In CA, northeast of Brazil, and parts of the Andean region, increases in temperature and decreases in rainfall could decrease the productivity in the short term (by 2030), threatening the food security of the poorest population (*medium confidence*). {Table 27-5} Considering that SA will be a key food-producing region in the future, one of the challenges will be to increase the food and bioenergy quality and production while maintaining environmental sustainability under climate change. {27.3.4.1} Some adaptation measures include crop, risk, and water use management along with genetic improvement (*high confidence*). {27.3.4.2}

Renewable energy based on biomass has a potential impact on land use change and deforestation and could be affected by climate change (*medium confidence*). Sugarcane and soy are likely to respond positively to CO_2 and temperature changes, even with a decrease in water availability, with an increase in productivity and production (*high confidence*). The expansion of sugarcane, soy, and oil palm may have some effect on land use, leading to deforestation in parts of the Amazon and CA, among other regions, and loss of employment in some countries (*medium confidence*). {27.3.6.1} Advances in second-generation bioethanol from sugarcane and other feedstocks will be important as a measure of mitigation. {27.3.6.2}

Changes in weather and climatic patterns are negatively affecting human health in CA and SA, by increasing morbidity, mortality, and disabilities (*high confidence*), and through the emergence of diseases in previously non-endemic areas (*high confidence*). With *very high confidence,* climate-related drivers are associated with respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), hantaviruses and rotaviruses, chronic kidney diseases, and psychological trauma. Air pollution is associated with pregnancy-related outcomes and diabetes, among others. {27.3.7.1} Vulnerabilities vary with geography, age, gender, race, ethnicity, and socioeconomic status, and are rising in large cities (*very high confidence*). {27.3.7.2} Climate change will exacerbate current and future risks to health, given the region's population growth rates and vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, pollution, and food production in poor regions (*medium confidence*).

In many CA and SA countries, a first step toward adaptation to future climate changes is to reduce the vulnerability to present climate. Long-term planning and the related human and financial resource needs may be seen as conflicting with the present social deficit in the welfare of the CA and SA population. Various examples demonstrate possible synergies between development, adaptation, and mitigation planning, which can help local communities and governments to allocate efficiently available resources in the design of strategies to reduce vulnerability. However, the generalization of such actions at a continental scale requires that both the CA and SA citizens and governments address the challenge of building a new governance model, where imperative development needs, vulnerability reduction, and adaptation strategies to climate stresses will be truly intertwined. {27.3.4, 27.4-5}

27.1. Introduction

27.1.1. The Central and South America Region

The Central America (CA) and South America (SA) region harbors unique ecosystems and has the highest biodiversity on the planet and a variety of eco-climatic gradients. Unfortunately, this natural wealth is threatened by advancing agricultural frontiers resulting from a rapidly growing agricultural and cattle production (Grau and Aide, 2008). The region experienced a steady economic growth, accelerated urbanization, and important demographic changes in the last decade; poverty and inequality are decreasing continuously, but at a low pace (ECLAC, 2011c). Adaptive capacity is improving in part thanks to poverty alleviation and development initiatives (McGray et al., 2007).

The region has multiple stressors on natural and human systems derived in part from significant land use changes and exacerbated by climate variability/climate change. Climate variability at various time scales has been affecting social and natural systems, and extremes in particular have affected large regions. In Central and South America, 613 climatological and hydro-meteorological extreme events occurred in the period 2000–2013, resulting in 13,883 fatalities, 53.8 million people affected, and economic losses of US$52.3 billion (www.emdat.be). Land is facing increasing pressure from competing uses such as cattle ranching, food production, and bioenergy.

The region is regarded as playing a key role in the future world economy because countries such as Brazil, Chile, Colombia, and Panama, among others, are rapidly developing and becoming economically important in the world scenario. The region is bound to be exposed to the pressure related to increasing land use and industrialization. Therefore, it is expected to have to deal with increasing emission potentials. Thus, science-based decision making is thought to be an important tool to control innovation and development of the countries in the region.

Two other important contrasting features characterize the region: having the biggest tropical forest of the planet on the one side, and possessing the largest potential for agricultural expansion and development during the next decades on the other. This is the case because the large countries of SA, especially, would have a major role in food and bioenergy production in the future, as long as policies toward adaptation to global climate change will be strategically designed. The region is already one of the top producers and user of bioenergy and this experience will serve as an example to other developing regions as well as developed regions.

27.1.2. Summary of the Fourth Assessment Report and IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation Findings

27.1.2.1. Fourth Assessment Report Findings

According to the Working Group II contribution to the Fourth Assessment Report (WGII AR4), Chapter 13 (Latin America), during the last decades of the 20th century, unusual extreme weather events have been severely affecting the Latin America (LA) region, contributing greatly to the strengthening of the vulnerability of human systems to natural disasters. In addition, increases in precipitation were observed in southeastern South America (SESA), northwest Peru, and Ecuador; while decreases were registered in southern Chile, southwest Argentina, southern Peru, and western CA since 1960. Mean warming was near 0.1°C per decade. The rate of sea level rise (SLR) has accelerated over the last 20 years, reaching 2 to 3 mm yr^{-1}. The glacier-retreat trend has intensified, reaching critical conditions in the Andean countries. Rates of deforestation have been continuously increasing, mainly due to agricultural expansion, and land degradation has been intensified for the entire region.

Mean warming for LA at the end of 21st century could reach 1°C to 4°C (SRES B2) or 2°C to 6°C (SRES A2) (*medium confidence*; WGII AR4 Chapter 13, p. 583). Rainfall anomalies (positive or negative) will be larger for the tropical part of LA. The frequency and intensity of weather and climate extremes is *likely* to increase (*medium confidence*).

Future impacts include: "significant species extinctions, mainly in tropical LA" (*high confidence*); "replacement of tropical forest by savannas, and semi-arid vegetation by arid vegetation" (*medium confidence*); "increases in the number of people experiencing water stress" (*medium confidence*); "probable reductions in rice yields and possible increases of soy yield in SESA" (WGII AR4 Chapter 13, p. 583); and "increases in crop pests and diseases" (*medium confidence*; WGII AR4 Chapter 13, p. 607)—with "some coastal areas affected by sea level rise, weather and climatic variability and extremes" (*high confidence*; WGII AR4 Chapter 13, p. 584).

Some countries have made efforts to adapt to climate change and variability, for example, through the conservation of key ecosystems (e.g., biological corridors in Mesoamerica, Amazonia, and Atlantic forest; compensation for ecosystem services in Costa Rica), the use of early warning systems and climate forecast (e.g., fisheries in eastern Pacific, subsistence agriculture in northeast Brazil), and the implementation of disease surveillance systems (e.g., Colombia) (WGII AR4 Chapter 13, p. 591). However, several constraints such as the lack of basic information, observation, and monitoring systems; the lack of capacity-building and appropriate political, institutional, and technological frameworks; low income; and settlements in vulnerable areas outweigh the effectiveness of these efforts.

27.1.2.2. IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation Findings

As reported in Section 3.4 of the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; IPCC, 2012b), a changing climate leads to changes in the frequency, intensity, spatial extent, or duration of weather and climate extremes, and can result in unprecedented extremes. Levels of confidence in historical changes depend on the availability of high-quality and homogeneous data and relevant model projections. This has been a major problem in CA and SA, where a lack of long-term homogeneous and continuous climate and hydrological records and of complete studies on trends has not allowed for an identification of trends in extremes, particularly in CA.

Recent observational studies and projections from global and regional models suggest changes in extremes. With *medium confidence*, increases in warm days and decreases in cold days, as well as increases on warm nights and decreases in cold nights, have been identified in CA, northern SA, northeast Brazil (NEB), SESA, and the west coast of SA. In CA, there is *low confidence* that any observed long-term increase in tropical cyclone activity is robust, after accounting for past changes in observing capabilities. In other regions, such as Amazonia (insufficient evidence), inconsistencies among studies and detected trends result in *low confidence* of observed rainfall trends. Although it is *likely* that there has been an anthropogenic influence on extreme temperature in the region, there is *low confidence* in attribution of changes in tropical cyclone activity to anthropogenic influences.

Projections for the end of the 21st century for differing emissions scenarios (SRES A2 and A1B) show that for all CA and SA, models project substantial warming in temperature extremes. It is *likely* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century on the global scale. With *medium confidence*, it is *very likely* that the length, frequency, and/or intensity of heat waves will experience a large increase over most of SA, with a weaker tendency toward increasing in SESA. With *low confidence*, the models also project an increase of the proportion of total rainfall from heavy falls for SESA and the west coast of SA, while for Amazonia and the rest of SA and CA there are not consistent signals of change. In some regions, there is *low confidence* in projections of changes in fluvial floods. Confidence is low owing to limited evidence and because the causes of regional changes are complex. There is *medium confidence* that droughts will intensify along the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration in Amazonia and NEB.

The character and severity of the impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. These are influenced by a wide range of factors, including anthropogenic climate change, climate variability, and socioeconomic development.

Table 27-1 | Regional observed changes in temperature, precipitation, and climate extremes in various sectors of Central America (CA) and South America (SA). Additional information on changes in observed extremes can be found in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Seneviratne et al., 2012) and the IPCC WGI AR5, Sections 2.4–2.6. (CDDs = consecutive dry days; NAMS = North American Monsoon System; PDSI = Palmer Drought Severity Index; SAMS = South American Monsoon System; SD = standard deviation.)

Region	Variable	Reference	Period	Observed changes
Central America and northern South America	Precipitation in NAMS	Englehart and Douglas (2006)	1943–2002	+0.94 mm day^{-1} over 58 years
	Rainfall onset in NAMS	Grantz et al. (2007)	1948–2004	–10 to –20 days over 57 years
	Summertime precipitation in NAMS	Anderson et al. (2010)	1931–2000	+17.6 mm per century
	Rainfall extremes (P95) in NAMS	Cavazos et al. (2008)	1961–1998	+1.3% per decade
	Cold days and nights in CA and northern SA	Donat et al. (2013)	1951–2010	Cold days: –1 day per decade. Cold nights: –2 days per decade
	Warm days and nights in northern SA	Donat et al. (2013)	1951–2010	Warm days: +2 to +4 days per decade. Warm nights: +1 to +3 days per decade
	Heavy precipitation (R10) in northern SA	Donat et al. (2013)	1951–2010	+1 to +2 days per decade
	CDDs in northern SA	Donat et al. (2013)	1951–2010	–2 days per decade
West coast of South America	Sea surface temperature and air temperatures off coast of Peru and Chile (15°S–35°S)	Falvey and Garreaud (2009); Gutiérrez et al. (2011a,b); Kosaka and Xie (2013)	1960–2010	–0.25°C per decade, –0.7°C over 11 years for 2002–2012
	Temperature, precipitation, cloud cover, and number of rainy days since the mid-1970s off the coast of Chile (18°S–30°S)	Schulz et al. (2012)	1920–2009	–1°C over 40 years, –1.6 mm over 40 years, –2 oktas over 40 years, and –0.3 day over 40 years
	Wet days until 1970, increase after that, reduction in the precipitation rate in southern Chile (37°S–43°S)	Quintana and Aceituno (2012)	1900–2007	–0.34% until 1970 and +0.37% after that, –0.12%
	Cold days and nights on all SA coast	Donat et al. (2013)	1951–2010	Cold days: –1 day per decade. Cold nights: –2 days per decade
	Warm nights on all SA coast, warm days in the northern coast of SA, warm days off the coast of Chile	Donat et al. (2013)	1951–2010	Warm nights: –1 day per decade. Warm days: +3 days per decade. Warm days: –1 day per decade
	Warm nights on the coast of Chile	Dufek et al. (2008)	1961–1990	+5% to +9% over 31 years
	Dryness as estimated by the PDSI for most of the west coast of SA (Chile, Ecuador, northern Chile)	Dai (2011)	1950–2008	–2 to –4 over 50 years
	Heavy precipitation (R95) in northern and central Chile	Dufek et al. (2008)	1961–1990	–45 to –105 mm over 31 years
	Temperature and extreme precipitation in southern Chile	Vicuña et al. (2013)	1976–2008	Increase in annual maximum temperature from +0.5°C to +1.1°C per decade; change in number of days with intense rainfall events from –2.7 to +4.2 days per decade.

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Table 27-1 (continued)

Region	Variable	Reference	Period	Observed changes
Southeastern South America	Mean annual air temperature in southern Brazil	Sansigolo and Kayano (2010)	1913–2006	+0.5°C to +0.6°C per decade
	Frequency of cold days and nights, warm days in Argentina and Uruguay	Rusticucci and Renom (2008)	1935–2002	–1.2% per decade, –1% per decade, +0.2% per decade
	Highest annual maximum temperature, lowest annual minimum air temperature in Argentina and Uruguay	Rusticucci and Tencer (2008)	1956–2003	+0.8°C over 47 years, +0.6°C over 47 years
	Warm nights in Argentina and Uruguay and southern Brazil	Rusticucci (2012)	1960–2009	+10–20% over 41 years
	Warm nights in most of the region	Dufek et al. (2008)	1961–1990	+7% to +9% over 31 years
	Cold nights in most of the region	Dufek et al. (2008)	1961–1990	–5% to –9% over 31 years
	Warm days and nights in most of the region	Donat et al. (2013)	1951–2010	Warm nights: +3 days per decade. Warm days: +4 days per decade
	Cold days and nights in most of the region	Donat et al. (2013)	1951–2010	Cold nights: –3 days per decade. Cold days: –3 days per decade
	CDDs in the La Plata Basin countries (Argentina, Bolivia, and Paraguay) and decrease of CDDs in SA south of 30°S	Dufek et al. (2008)	1961–1990	+15 to +21 days over 31 years, –21 to –27 days over 31 years
	Number of dry months during the warm season (October–March) in the Pampas region between 25°S and 40°S	Barrucand et al. (2007)	1904–2000	From 2–3 months in 1904–1920 to 1–2 months in 1980–2000
	Moister conditions as estimated by the PDSI in most of southeastern SA	Dai (2011)	1950–2008	0–4 PDSI over 50 years
	Rainfall trends in the Paraná River Basin	Dai et al. (2009)	1948–2008	+1.5 mm day^{-1} over 50 years
	Number of days with precipitation above 10 mm (R10) in most of the region	Donat et al. (2013)	1951–2010	+2 days per decade
	Heavy precipitation (R95) in most of the region	Donat et al. (2013)	1951–1910	+1% per decade and –4 days per decade
	Heavy precipitation (R95) in most of the region	Dufek et al. (2008)	1961–1990	+45 to +135 mm over 31 years
	Heavy precipitation (R95) in the state of São Paulo	Dufek and Ambrizzi (2008)	1950–1999	+50 to +75 mm over 40 years
	CDDs in the state of São Paulo	Dufek and Ambrizzi (2008)	1950–1990	–25 to –50 days over 40 years
	Lightning activity varies significantly with change in temperature in the state of São Paulo	Pinto and Pinto (2008); Pinto et al. (2013)	1951–2006	+40% per 1°C for daily and monthly time scales and approximately +30% per 1°C for decadal time scale
	Number of days with rainfall above 20 mm in the city of São Paulo	Silva Dias et al. (2012); Marengo et al. (2013)	2005–2011	+5 to +8 days over 11 years
	Excess rainfall events duration after 1950	Krepper and Zucarelli (2010)	1901–2003	+21 months over 53 years
	Dry events and events of extreme dryness from 1972 to 1996	Vargas et al. (2011)	1972–1996	–29 days over 24 years
	Number of dry days in Argentina	Rivera et al. (2013)	1960–2005	–2 to –4 days per decade
	Extreme daily rainfall in La Plata Basin	Penalba and Robledo (2010)	1950–2000	+33% to +60% increase in spring, summer, and autumn, –10% to –25% decrease in winter
	Frequency of heavy rainfall in Argentina, southern Brazil, and Uruguay	Re and Barros (2009)	1959–2002	+50 to +150 mm over 43 years
	Annual precipitation in the La Plata Basin	Doyle and Barros (2011); Doyle et al. (2012)	1960–2005	+5 mm $year^{-1}$

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27.2. Major Recent Changes and Projections in the Region

27.2.1. Climatic Stressors

27.2.1.1. Climate Trends, Long-Term Changes in Variability, and Extremes

In CA and SA, decadal variability and changes in extremes have been affecting large sectors of the population, especially those more vulnerable and exposed to climate hazards. Observed changes in some regions have been attributed to natural climate variability, while in others they have been attributed to land use change (e.g., increased urbanization), meaning that land use change is a result of anthropogenic drivers. Table 27-1 summarizes the observed trends in the region's climate.

Since around 1950, in CA and the North American Monsoon System (NAMS), rainfall has been starting increasingly later and has become more irregular in space and time, while rainfall has been increasing and the intensity of rainfall has been increasing during the onset season (see references in Table 27-1). Arias et al. (2012) relate those changes to decadal rainfall variations in NAMS.

The west coast of SA experienced a prominent but localized coastal cooling of about 1°C during the past 30 to 50 years extending from central Peru down to central Chile. This occurs in connection with an increased upwelling of coastal waters favored by the more intense trade winds (Falvey and Garreaud, 2009; Narayan et al., 2010; Gutiérrez et al., 2011a,b; Schulz et al., 2012; Kosaka and Xie, 2013). In the extremely arid northern coast of Chile, rainfall, temperature, and cloudiness show strong interannual and decadal variability, and since the mid-1970s,

Table 27-1 (continued)

Region	Variable	Reference	Period	Observed changes
Andes	Mean maximum temperature along the Andes, and increase in the number of frost days	Marengo et al. (2011b)	1921–2010	+0.10°C to +0.12°C per decade in 1921–2010, and +0.23–0.24°C per decade during 1976–2010; +8 days per decade during 1996–2002
	Air temperature and changes in precipitation in northern Andes (Colombia, Ecuador)	Villacís (2008)	1961–1990	+0.1°C to +0.22°C per decade, –4% to +4% per decade
	Temperature and precipitation in northern and central Andes of Peru	SENAMHI (2005, 2007, 2009a,c,d)	1963–2006	+0.2°C to +0.45°C per decade, –20% to –30% over 40 years
	Temperature and precipitation in the southern Andes of Peru	SENAMHI (2007, 2009a,b,c,d); Marengo et al. (2011b)	1964–2006	+0.2°C to +0.6°C per decade, –11 to +2 mm per decade
	Air temperature and rainfall over Argentinean and Chilean Andes and Patagonia	Masiokas et al. (2008); Falvey and Garreaud (2009)	1950–1990	+0.2°C to +0.45°C per decade, –10% to –12% per decade
	Number of days with rainfall above 10 mm (R10)	Donat et al. (2013)	1950–2010	–3 days per decade
	Dryness in the Andes between 35.65°S and 39.9°S using the PDSI	Christie et al. (2011)	1950–2003	–7 PDSI over 53 years
	Rainfall decrease in the Mantaro Valley, central Andes of Peru	SENAMHI (2009c)	1970–2005	–44 mm per decade
	Air temperature in Colombian Andes	Poveda and Pineda (2009)	1959–2007	+1°C over 20 years
Amazon region	Decadal variability of rainfall in northern and southern Amazonia	Marengo et al. (2009b); Satyamurty et al. (2010)	1920–2008	–3 SDs over 30 years in northern Amazonia and +4 SDs over 30 years in southern Amazonia since the mid-1970s
	Rainfall in all the region	Espinoza et al. (2009a,b)	1975–2003	–0.32% over 28 years
	Onset of the rainy season in southern Amazonia	Butt et al. (2011); Marengo et al. (2011b)	1950–2010	–1 month since 1976–2010
	Precipitation in the SAMS core region	Wang et al. (2012)	1979–2008	+2 mm day^{-1} per decade
	Onset becomes steadily earlier from 1948 to early 1970s, demise dates have remained later, and SAMS duration was longer after 1972	Carvalho et al. (2011)	1948–2008	SAMS from 170 days (1948–1972) to 195 days (1972–1982)
	Spatially varying trends of heavy precipitation (R95), increase in many areas and insufficient evidence in others	Marengo et al. (2009b)	1961–1990	+100 mm over 31 years in western and extreme eastern Amazonia
	Spatially varying trends in dry spells (CDDs), increase in many areas and decrease in others	Marengo et al. (2009b, 2010)	1961–1990	+15 mm over 31 years in western Amazonia, –20 mm in southern Amazonia
	Rainfall in most of Amazonia and in western Amazonia	Dai et al. (2009); Dai (2011)	1948–2008	+1 mm day^{-1} over 50 years, –1.5 mm day^{-1} over 50 years
	Dryness as estimated by the PDSI in southern Amazonia and moister conditions in western Amazonia	Dai (2011)	1950–2008	–2 to –4 over 50 years, +2 to +4 over 50 years
	Seasonal mean convection and cloudiness	Arias et al. (2011)	1984–2007	+30 W m^{-2} over 23 years, –8% over 23 years
	Onset of rainy season in southern Amazonia due to land use change	Butt et al. (2011)	1970–2010	–0.6 days over 30 years
	Precipitation in the region	Gloor et al. (2013)	1990–2010	–20 mm over 21 years
Northeastern Brazil	Rainfall trends in interior northeastern Brazil and in northern northeastern Brazil	Dai et al. (2009); Dai (2011)	1948–2008	–0.3 mm day^{-1} over 50 years, +1.5 mm day^{-1} over 50 years
	Heavy precipitation (R95) in some areas, and in southern northeastern Brazil	Silva and Azevedo (2008)	1970–2006	–2 mm over 24 years to +6 mm over 24 years
	CDDs in most of southern northeastern Brazil	Silva and Azevedo (2008)	1970–2006	–0.99 day over 24 years
	Total annual precipitation in northern northeastern Brazil	Santos and Brito (2007)	1970–2006	+1 to +4 mm year^{-1} over 24 years
	Spatially varying trends in heavy precipitation (R95) in northern northeastern Brazil	Santos and Brito (2007)	1970–2006	–0.1 to +5 mm year^{-1} over 24 years
	Spatially varying trends in heavy precipitation (R95) and CDDs in northern northeastern Brazil	Santos et al. (2009)	1935–2006	–0.4 to +2.5 mm year^{-1} over 69 years, –1.5 to +1.5 days year^{-1} over 69 years
	Dryness in southern northeastern Brazil as estimated by the PDSI, and northern northeastern Brazil	Dai (2011)	1950–2008	–2 to –4 over 50 years, 0 to +1 over 50 years

the minimum daily temperature, cloudiness, and precipitation have decreased. In central Chile, a negative precipitation trend was observed over the period 1935–1976, and an increase after 1976, while further south, the negative trend in rainfall that prevailed since the 1950s has intensified by the end of the 20th century (Quintana and Aceituno, 2012). To the east of the Andes, NEB exhibits large interannual rainfall variability, with a slight decrease since the 1970s (Marengo et al. 2013a). Droughts in this region (e.g., 1983, 1987, 1998) have been associated with El Niño and/or a warmer Tropical North Atlantic Ocean. However, not all El Niño years result in drought in NEB, as the 2012–2013 drought occurred during La Niña (Marengo et al., 2013a).

In the La Plata Basin in SESA, various studies have documented interannual and decadal scale circulation changes that have led to decreases in the

Box 27-1 | Extreme Events, Climate Change Perceptions, and Adaptive Capacity in Central America

Central America (CA) has traditionally been characterized as a region with high exposure to geo-climatic hazards derived from its location and topography and with high vulnerability of its human settlements (ECLAC, 2010c). It has also been identified as the most responsive tropical region to climate change (Giorgi, 2006). Evidence for this has been accumulating particularly in the last 30 years, with a steady increase in extreme events including storms, floods, and droughts. In the period 2000–2009, 39 hurricanes occurred in the Caribbean basin compared to 15 and 9 in the 1980s and 1990s, respectively (UNEP and ECLAC, 2010). The impacts of these events on the population and the economy of the region have been tremendous: the economic loss derived from 11 recent hydrometereological events evaluated amounted to US$13.64 billion and the number of people impacted peaked with Hurricane Mitch in 1998, with more than 600,000 persons affected (ECLAC, 2010c). A high percentage of the population in CA live on or near highly unstable steep terrain with sandy, volcanic soils prone to mudslides, which are the main cause of casualties and destruction (Restrepo and Alvarez, 2006).

The increased climatic variability in the past decade certainly changed the perception of people in the region with respect to climate change. In a survey to small farmers in 2003, Tucker et al. (2010) found that only 25% of respondents included climate events as a major concern. A subsequent survey in 2007 (Eakin et al., 2013) found that more than 50% of respondents cited drought conditions and torrential rains as their greatest concern. Interestingly, there was no consensus on the direction in climate change pattern: The majority of households in Honduras reported an increase in the frequency of droughts but in Costa Rica and Guatemala a decrease or no trend at all was reported. A similar discrepancy in answers was reported with the issue of increased rainfall. But there was general agreement in all countries that rainfall patterns were more variable, resulting in higher difficulty in recognizing the start of the rainy season.

The high levels of risk to disasters in CA are the result of high exposure to hazards and the high vulnerability of the population and its livelihoods derived from elevated levels of poverty and social exclusion (Programa Estado de la Nación-Región, 2011). Disaster management in the region has focused on improving early warning systems and emergency response for specific extreme events (Saldaña-Zorrilla, 2008) but little attention has been paid to strengthening existing social capital in the form of local organizations and cooperatives. These associations can be central in increasing adaptive capacity through increased access to financial instruments and strategic information on global markets and climate (Eakin et al., 2011). There is a need to increase the communication of the knowledge from local communities involved in processes of autonomous adaptation to policymakers responsible for strengthening the adaptive capacities in CA (Castellanos et al., 2013).

frequency of cold nights in austral summer, as well as to increases in warm nights and minimum temperatures during the last 40 years. Simultaneously, a reduction in the number of dry months in the warm season is found since the mid-1970s, while heavy rain frequency is increasing in SESA (references in Table 27-1). In SESA, increases in precipitation are responsible for changes in soil moisture (Collini et al., 2008; Saulo et al., 2010), and although feedback mechanisms are present at all scales, the effect on atmospheric circulation is detected at large scales. Moreover, land use change studies in the Brazilian southern Amazonia for the last decades showed that the impact on the hydrological response is time lagged at larger scales (Rodriguez, D.A. et al., 2010).

In the central Andes, in the Mantaro Valley (Peru), precipitation shows a strong negative trend, while warming is also detected (SENAMHI, 2007). In the southern Andes of Peru air temperatures have increased during 1964–2006, but no clear signal on precipitation changes has been detected (Marengo et al., 2009a). In the northern Andes (Colombia, Ecuador), changes in temperature and rainfall in 1961–1990 have been identified by Villacís (2008). In the Patagonia region, Masiokas et al. (2008) have identified an increase of temperature together with precipitation reductions during 1912–2002. Vuille et al. (2008a) found that climate in the tropical Andes has changed significantly over the past 50 to 60 years. Temperature in the Andes has increased by approximately 0.1°C per decade, with only 2 of the last 20 years being below the 1961–1990 average. Precipitation has slightly increased in the second half of the 20th century in the inner tropics and decreased in the outer tropics. The general pattern of moistening in the inner tropics and drying in the subtropical Andes is dynamically consistent with observed changes in the large-scale circulation, suggesting a strengthening of the tropical atmospheric circulation. Moreover, a positive significant trend in mean temperature of 0.09°C per decade during 1965–2007 has been detected over the Peruvian Andes by Lavado et al. (2012).

For the Amazon basin, Marengo (2004) and Satyamurty et al. (2010) concluded that no systematic unidirectional long-term trends toward drier or wetter conditions in both the northern and southern Amazon have been identified since the 1920s. Rainfall fluctuations are more characterized by interannual scales linked to El Niño-Southern Oscillation (ENSO) or decadal variability. Analyzing a narrower time period, Espinoza et al. (2009a,b) found that mean rainfall in the Amazon basin for 1964–2003 has decreased, with stronger amplitude after 1982, especially in the Peruvian western Amazonia (Lavado et al., 2012), consistent with reductions in convection and cloudiness in the same region (Arias et al., 2011). Recent studies by Donat et al. (2013) suggest that heavy rains are increasing in frequency in Amazonia. Regarding seasonal extremes in the Amazon region, two major droughts and three floods have affected the region from 2005 to 2012, although these events have been related to natural climate variability rather than to deforestation (Marengo et al., 2008, 2012, 2013a; Espinoza et al., 2011, 2012, 2013; Lewis et al., 2011; Satyamurty et al., 2013).

On the impacts of land use changes on changes in the climate and hydrology of Amazonia, Zhang et al. (2009) suggest that biomass-burning aerosols can work against the seasonal monsoon circulation transition, and thus reinforce the dry season rainfall pattern for southern Amazonia,

Table 27-2 | Regional projected changes in temperature, precipitation, and climate extremes in different sectors of Central America (CA) and South America (SA). Various studies used A2 and B2 scenarios from Coupled Model Intercomparison Project Phase 3 (CMIP3) and various Representative Concentration Pathway (RCP) scenarios for CMIP5, and different time slices from 2010 to 2100. To make results comparable, the CMIP3 and CMIP5 at the time slice ending in 2100 are included. Additional information on changes in projected extremes can be found in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; see IPCC, 2012), and in IPCC WGI AR5 Sections 9.5, 9.6, 14.2, and 14.7. (CDDs = consecutive dry days.)

Region	Variable	Reference	Models and scenarios	Projected changes
Central America and northern South America	Leaf Area Index, evapotranspiration by 2070–2099 in CA	Imbach et al. (2012)	23 CMIP3 models, A2	Evapotranspiration: +20%; Leaf Area Index: –20% + 0.94 mm/day/58 years
	Air temperature by 2075 and 2100 in CA	Aguilar et al. (2009)	9 CMIP3 models, A2	+2.2°C by 2075; +3.3°C by 2100
	Rainfall in CA and Venezuela, air temperature in the region	Kitoh et al. (2011); Hall et al. (2013)	20 km MRI-AGCM3.1S model, A1B	Rainfall decrease/increase of about –10%/+10% by 2079. Temperature increases of about +2.5°C to +3.5°C by 2079
	Precipitation and evaporation in most of the region. Soil moisture in most land areas in all seasons	Nakaegawa et al. (2013b)	20 km MRI-AGCM3.1S model, A1B	Precipitation decrease of about –5 mm day^{-1}, evaporation increase of about +3 to +5 mm day^{-1}; soil moisture to decrease by –5 mm day^{-1}
	Rainfall in Nicaragua, Honduras, northern Colombia, and northern Venezuela; rainfall in Costa Rica and Panama. Temperature in all regions by 2071–2100	Campbell et al. (2011)	PRECIS forced with HadAM3, A2	Rainfall: –25% to –50%, and +25% to +50%; temperature: +3°C to +6°C
	Precipitation and temperature in northern SA, decrease in interior Venezuela, temperature increases by 2071–2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Increases by +30% to +50%; reductions by –10% to –20%; temperature: +4°C to +5°C
	Precipitation and temperature by 2100 in CA	Karmalkar et al. (2011)	PRECIS forced with HadAM3, A2	Precipitation: –24% to –48%; temperature: +4°C to +5°C
	Warm nights, CDDs, and heavy precipitation in Venezuela by 2100	Marengo et al. (2009a, 2010)	PRECIS forced with HadAM3, A2	Increase of +12% to +18%, +15 to +25 days, and reduction of 75 to 105 days
	Air temperature and precipitation in CA by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +3°C to +5°C; reduction of –10% to –30%
	CDDs and heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Increase of +5 days, increase of +2% to +8%
	Rainfall over Panama by 2099	Fábrega et al. (2013)	20 km MRI-AGCM3.1S model, A1B	Increase of +5%
West coast of South America	Precipitation, runoff, and temperature at the Limari river basin in semi-arid Chile by 2100	Vicuña et al. (2011)	PRECIS forced with HadAM3, A2	Precipitation: –15% to –25%; runoff: –6% to –27%; temperature: +3°C to +4°C
	Air temperature and surface winds in west coast of SA (Chile) by 2100	Garreaud and Falvey (2009)	15 CMIP3 models, PRECIS forced with HadAM3, A2	Temperature: +1°C; coastal winds: +1.5 m s^{-1}
	Precipitation in the bands 5°N–10°S, 25°S–30°S, 10°S–25°S, and 30°S–50°S; temperature increase by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Increases of 30–40%; increases of 3°C to 5°C
	Warm nights, CDDs, and heavy precipitation in 5°N–5°S by 2100	Marengo et al. (2009a, 2010)	PRECIS forced with HadAM3, A2	Increase of +3% to +18%, reduction of –5 to –8 days, increase of +75 to +105 days
	Air temperature, increase in precipitation between 0° and 10°S, and between 20°S and 40°S by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +2°C to +3°C; increase of 10%, reduction of –10% to –30%
	CDDs between 5°N and 10°S and south of 30°S; heavy precipitation between 5°S and 20°S and south of 20°S by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Increase of 10 days and between +2% and +10%
	Precipitation between 15°S and 35°S and south of 40°S; temperature by 2100	Nuñez et al. (2009)	MM5 forced with HadAM3, A2	Precipitation: –2 mm day^{-1}; +2 mm day^{-1}; temperature: +2.5°C
	Precipitation in Panama and Venezuela by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5–MPI OM model, A1B	Precipitation: –1 to –3 mm day^{-1}

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Table 27-2 (continued)

Region	Variable	Reference	Models and scenarios	Projected changes
Southeastern South America	Precipitation and runoff, and air temperature by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Precipitation: +20% to +30%; runoff: +10% to +20%; air temperature: +2.5°C to +3.5°C
	Precipitation and temperature in the La Plata basin by 2050	Cabré et al. (2010)	MM5 forced with HadAM3, A2	Precipitation: +0.5 to 1.5 mm day^{-1}; temperature: +1.5°C to 2.5°C
	Warm nights, CDDs, and heavy precipitation by 2100	Menendez and Carril (2010)	7 CMIP3 models, A1B	Warm nights: +10% to +30%; CDDs: +1 to +5 days; heavy precipitation: +3% to +9%
	Precipitation during summer and spring, and in fall and winter by 2100	Seth et al. (2010)	9 CMIP3 models, A2	Precipitation: +0.4 to +0.6 mm day^{-1}, –0.02 to –0.04 mm day^{-1}
	Warm nights, CDDs, and heavy precipitation by 2100	Marengo et al. (2009a, 2010)	PRECIS forced with HadAM3, A2	Increase of +6% to +12%, +5 to +20 days, +75 to +105 days
	Air temperature and rainfall by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +2°C to +4°C, increase of +20% to +30%
	CDDs and heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Increase of +5% to +10% and of +2% to +8%
	Precipitation in north central Argentina, decrease in southern Brazil, increase of air temperature by 2100	Nuñez et al. (2009)	MM5 forced with HadAM3, A2	Increase of +0.5 to +1 mm day^{-1}, reduction of –0.5 mm day^{-1}, increase of +3°C to +4.5°C
	Drought frequency, intensity, and duration in SA south of 20°S for 2011–2040 relative to 1979–2008	Penalba and Rivera (2013)	15 CMIP5 models, RCP4.5 and 8.5	Frequency increase of 10–20%, increase in severity of 5–15%, and reduction in duration of 10–30%
	Precipitation, heavy precipitation, reduction of CDDs in the eastern part of the region, increase in the western part of the region by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increase of +2 mm day^{-1}, of +5 to +15 mm, reduction of –10 days and increase of +5 days
	Precipitation in southeastern SA by 2100	Sörensson et al. (2010)	9 CMIP3 models, A1B	Increase of +0.3 to +0.5 mm day^{-1}
Andes	Precipitation and temperature, increase by 2100 in the Altiplano	Minvielle and Garreaud (2011)	11 CMP3 models, A2	Precipitation: –10% to –30%; temperature: >3°C
	Precipitation at 5°N–5°S and 30°S–45°S, at 5°S–25°S; temperature by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Increase of +10% to +30%, decrease of –20% to –30%, increase of +3.5°C to +4.5°C
	Warm nights, heavy precipitation, and CDDs south of 15°S by 2100	Marengo et al. (2009a)	PRECIS forced with HadAM3, A2	Increase of +3% to +18%, reduction of –10 to –20 days, and reduction of –75 to –105 days
	Air temperature, rainfall between 0° and 10°S, and reduction between 10°S and 40°S	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +3°C to +4°C, increase of 10%, and reduction of –10%
	CDDs and increase of heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of –5 days, increase of +2 to +4% south of 20°S
	Precipitation, heavy precipitation, and CDDs by 2070–2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increases of +1 to +3 mm day^{-1}, +5 mm and of +5 to +10 days
	Summer precipitation and surface air temperature in the Altiplano region by 2099	Minvielle and Garreaud (2011)	9 CMIP3 models, A2	Reduction in precipitation between –10% and –30%, and temperature increase of +3°C
	Temperature and rainfall in lowland Bolivia in 2070–2099	Seiler et al. (2013)	5 CMIP3 models (A1B) and 5 CMIP5 models (RCP4.5, 8.5)	Increase of 2.5°C to 5°C, reduction of 9% annual precipitation
	Precipitation in the dry season, temperature, and evapotranspiration 2079–2098	Guimberteau et al. (2013)	CMIP3 models, A1B	–1.1 mm; +2°C; +7%

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while Wang et al. (2011) suggests the importance of deforestation and vegetation dynamics on decadal variability of rainfall in the region. Costa and Pires (2010) have suggested a possible decrease in precipitation due to soybean expansion in Amazonia, mainly as a consequence of its very high albedo. In the South American Monsoon System (SAMS) region, positive trends in rainfall extremes have been identified in the last 30 years, with a pattern of increasing frequency and intensity of heavy rainfall events, and earlier onsets and late demise of the rainy season (see Table 27-1).

27.2.1.2. Climate Projections

Since the AR4, substantial additional regional analysis has been carried out using the Coupled Model Intercomparison Project Phase 3 (CMIP3) model ensemble. In addition, projections from CMIP5 models and new experiences using regional models (downscaling) have allowed for a better description of future changes in climate and extremes in CA and SA. Using CMIP3 and CMIP5 models, Giorgi (2006), Diffenbaugh et al. (2008), Xu et al. (2009), Diffenbaugh and Giorgi (2012), and Jones and Carvalho (2013) have identified areas of CA/western North America and the Amazon as persistent regional climate change hotspots throughout the 21st century of the Representative Concentration Pathway (RCP)8.5 and RCP4.5. Table 27-2 summarizes projected climatic changes derived from global and regional models for the region, indicating the projected change, models, emission scenarios, time spans, and references.

In CA and Northern Venezuela, projections from CMIP3 models and from downscaling experiments suggest precipitation reductions and warming together with an increase in evaporation, and reductions in

Table 27-2 (continued)

Region	Variable	Reference	Models and scenarios	Projected changes
Amazon region	Rainfall in central and eastern Amazonia and in western Amazonia; air temperature in all regions by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Precipitation: –20% to –30%, +20% to +30%; temperature: +5°C to +7°C
	Intensity of the South Atlantic Convergence Zone and in rainfall in the South American monsoon region, 2081–2100	Bombardi and Carvalho (2009)	10 CMIP3 models, A1B	Precipitation: –100 to –200 mm over 20 years
	Precipitation in western Amazonia during summer and in winter in Amazonia by 2100	Mendes and Marengo (2010)	5 CMIP3 models, A2 and ANN	+1.6% in summer and –1.5% in winter
	Number of South American Low Level Jet (SALLJ) events east of the Andes, and the moisture transport from Amazonia to the La Plata basin by 2090	Soares and Marengo (2009)	PRECIS forced with HadAM3, A2	+50% SALLJ events during summer, increase in moisture transport by 50%
	Precipitation in the South American monsoon during summer and spring, and during fall and winter by 2100	Seth et al. (2010)	9 CMIP3 models, A2	Increase of +0.15 to +0.4 mm/day, reductions of –0.10 to –0.26 mm/day
	Warm nights, CDDs in eastern Amazonia; heavy precipitation in western Amazonia and in eastern Amazonia by 2100	Marengo et al. (2009a)	PRECIS forced with HadAM3, A2	Increase of +12% to +15%, of 25–30 days in eastern Amazonia, increase in western Amazonia of 75–105 days, and reduction of –15 to –75 days in eastern Amazonia
	Increase in air temperature; rainfall increase in western Amazonia and decrease in eastern Amazonia by 2100	Giorgi and Diffenbaugh (2008)	CMIP3 models, A1B	Increase of +4°C to +6°C, increase of +10%, and decrease between –10% and –30%
	Reduction of CDDs and increase in heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of –5 to –10 days, increase of +2% to +8%
	Onset and late demise of the rainy season in South American Monsoon System (SAMS) by 2040–2050 relative to 1951–1980	Jones and Carvalho (2013)	10 CMIP5 models, RCP8.5	Onset 14 days earlier than present, demise 17 days later than present
	Precipitation in SAMS during the monsoon wet season in 2071–2100 relative to 1951–1980	Jones and Carvalho (2013)	10 CMIP5 models, RCP8.5	Increase of 300 mm during the wet season
	Precipitation in western Amazonia, heavy precipitation in northern Amazonia and in southern Amazonia, CDDs in western Amazonia and increase by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increase of +1 to +3 mm day^{-1}, reduction of –1 to –3 mm, increase of +5 to +10 mm, decrease of –5 to –10 days, increase of +20 to +30 days
Northeastern Brazil	Rainfall and temperature in the entire region by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Precipitation: –20% to +20%; temperature: +3°C to +4°C
	Warm nights, CDDs, heavy precipitation by 2100	Marengo et al. (2009a)	PRECIS forced with HadAM3, A2	Increase of +18% to +24%, of +25 to +30 days, and –15 to –75 days
	Air temperature and precipitation by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +2°C to +4°C, reduction of –10% to –30%
	CDDs and heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of –5% to –10%, increase of +2% to +6%
	Precipitation, heavy precipitation, and CDDs by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increase of +1 to +2 mm day^{-1}, increase of +5 to +10 mm, and increase of +10 to +30 days

soil moisture for most of the land during all seasons by the end of the 21st century (see references in Table 27-2). However, the spread of projections is high for future precipitation.

Analyses from global and regional models in tropical and subtropical SA show common patterns of projected climate in some sectors of the continent. Projections from CMIP3 regional and high-resolution global models show by the end of the 21st century, for the A2 emission scenario, a consistent pattern of increase of precipitation in SESA, northwest of Peru and Ecuador, and western Amazonia, while decreases are projected for northern SA, eastern Amazonia, central eastern Brazil, NEB, the Altiplano, and southern Chile (Table 27-2). For some regions, projections show mixed results in rainfall projections for Amazonia and the SAMS region, suggesting high uncertainties on the projections (Table 27-2).

As for extremes, CMIP3 models and downscaling experiments show increases in dry spells are projected for eastern Amazonia and NEB, while rainfall extremes are projected to increase in SESA, in western Amazonia, northwest Peru, and Ecuador, while over southern Amazonia, NEB, and eastern Amazonia, the maximum number of consecutive dry days tends to augment, suggesting a longer dry season. Increases in warm nights throughout SA are also projected by the end of the 21st century (see references in Table 27-2). Shiogama et al. (2011) suggest that, although the CMIP3 ensemble mean assessment suggested wetting across most of SA, the observational constraints indicate a higher probability of drying in the eastern Amazon basin.

The CMIP5 models project an even larger expansion of the monsoon regions in NAMS in future scenarios (Jones and Carvalho, 2013; Kitoh et al., 2013). A comparison from eight models from CMIP3 and CMIP5 identifies some improvements in the new generation models. For example, CMIP5 inter-model variability of temperature in summer was lower over northeastern Argentina, Paraguay, and northern Brazil, in the last decades of the 21st century, as compared to CMIP3. Although

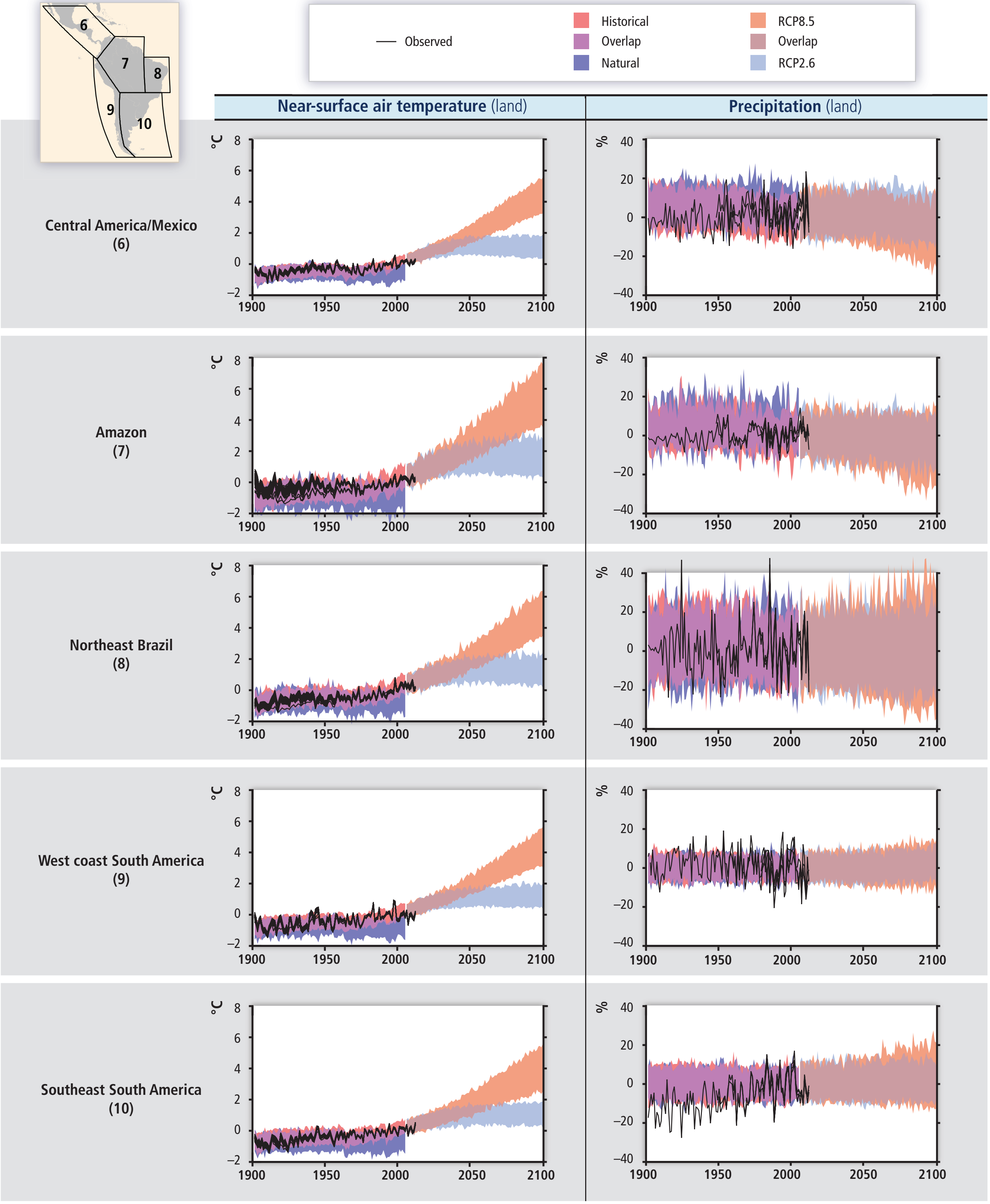


Figure 27-1 | Observed and simulated variations in past and projected future annual average temperature over the Central and South American regions defined in IPCC (2012a). Black lines show various estimates from observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the Representative Concentration Pathway (RCP)2.6 emissions scenario (63), and RCP8.5 (63). Data are anomalies from the 1986–2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Table SM21-5.

no major differences were observed in both precipitation data sets, CMIP5 inter-model variability was lower over northern and eastern Brazil in the summer by 2100 (Blázquez and Nuñez, 2013; Jones and Carvalho, 2013).

The projections from the CMIP5 models at regional level for CA and SA (using the same regions from SREX) are shown in Figure 27-1, and update some of these previous projections based on SRES A2 and B2 emission scenarios from CMIP3. Figure 27-1 shows that in relation to the baseline period 1986–2005, for CA and northern SA–Amazonia, temperatures are projected to increase by approximately 0.6°C and 2°C for the RCP2.6 scenario, and by 3.6°C and 5.2°C for the RCP8.5 scenario. For the rest of SA, increases by about 0.6°C to 2°C are projected for the RCP4.5 and by about 2.2°C to 7°C for the RCP8.5 scenario. The observed records show increases of temperature from 1900 to 1986 by about 1°C. For precipitation, while for CA and northern SA–Amazonia precipitation is projected to vary between +10 and –25% (with a large spread among models). For NEB, there is a spread among models between +30 and –30%, making it hard to identify any projected rainfall change. This spread is much lower in the western coast of SA and SESA, where the spread is between +20 and –10% (Chapter 21; Box 21-3).

CMIP5-derived RCP8.5 projections for the late 21st century, as depicted in Figure 27-2, follow: CA – mean annual warming of 2.5°C and rainfall reduction of 10%, and reduction in summertime precipitation; SA – mean warming of 4°C, with rainfall reduction up to 15% in tropical SA east of the Andes, and an increase of about 15 to 20% in SESA and in other regions of the continent. Changes shown for the mid-21st century are small. Both Figures 27-1 and 27-2 illustrate that there is some degree of uncertainty on climate change projections for regions, particularly for rainfall in CA and tropical SA.

27.2.2. Non-Climatic Stressors

27.2.2.1. Trends and Projections in Land Use and Land Use Change

Land use change is a key driver of environmental degradation for the region that exacerbates the negative impacts from climate change (Sampaio et al., 2007; Lopez-Rodriguez and Blanco-Libreros, 2008). The high levels of deforestation observed in most of the countries in the region have been widely discussed in the literature as a deliberate development strategy based on the expansion of agriculture to satisfy the growing world demand for food, energy, and minerals (Benhin, 2006; Grau and Aide, 2008; Müller et al., 2008). Land is facing increasing pressure from competing uses, among them cattle ranching, food, and bioenergy production. The enhanced competition for land increases the

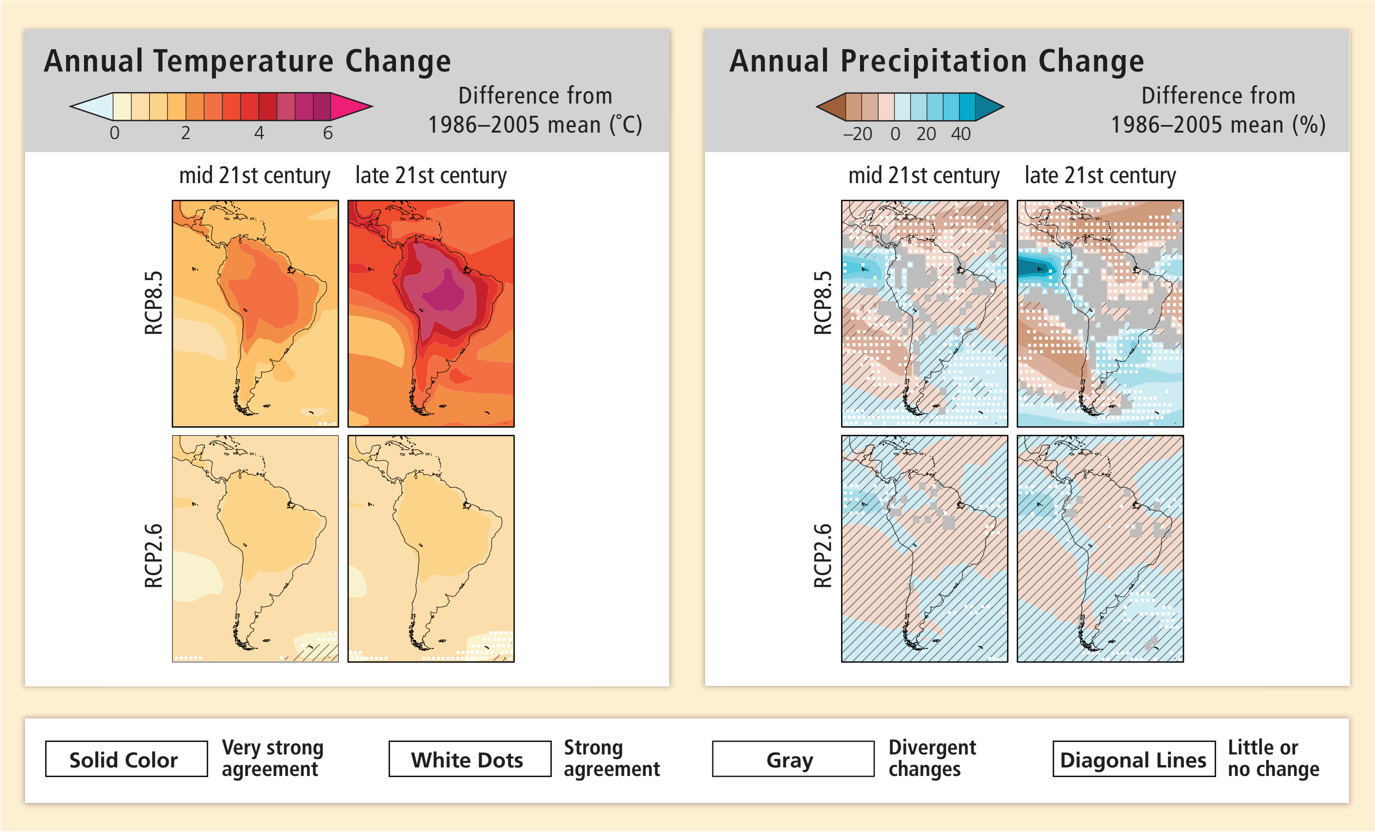


Figure 27-2 | Projected changes in annual average temperature and precipitation. CMIP5 multi-model mean projections of annual average temperature changes (left panel) and average percent changes in annual mean precipitation (right panel) for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC] risk of land use changes, which may lead to negative environmental and socioeconomic impacts. Agricultural expansion has relied in many cases on government subsidies, which have often resulted in lower land productivity and more land speculation (Bulte et al., 2007; Roebeling and Hendrix, 2010). Some of the most affected areas due to the expansion of the agricultural frontier are fragile ecosystems such as the edges of the Amazon forest in Brazil, Colombia, Ecuador, and Peru, and tropical Andes including the Paramo, where activities such as deforestation, agriculture, cattle ranching, and gold mining are causing severe environmental degradation (ECLAC, 2010d), and the reduction of environmental services provided by these ecosystems.

Deforestation rates for the region remain high in spite of a reducing trend in the last decade (Ramankutty et al., 2007; Fearnside, 2008). Brazil is by far the country with the highest area of forest loss in the world according to the latest Food and Agriculture Organization (FAO) statistics (2010): 21,940 km² yr⁻¹, equivalent to 39% of world deforestation for the period 2005–2010. Bolivia, Venezuela, and Argentina follow in deforested area (Figure 27-3), with 5.5, 5.2, and 4.3% of the total world deforestation, respectively. The countries of CA and SA lost a total of 38,300 km² of forest per year in that period (69% of the total world deforestation; FAO, 2010). These numbers are limited by the fact that many countries do not have comparable information through time, particularly for recent years. Aide et al. (2013) completed a wall-to-wall analysis for the region for the period 2001–2010, analyzing not only deforestation but also reforestation, and reported very different results than FAO (2010) for some countries where reforestation seems to be higher than deforestation, particularly in Honduras, El Salvador, Panama, Colombia, and Venezuela. For Colombia and Venezuela, these results are contradictory with country analyses that align better with the FAO data (Rodríguez, J.P. et al., 2010; Armenteras et al., 2013).

Deforestation in the Amazon forest has received much international attention in the last decades, both because of its high rates and its rich biodiversity. Brazilian Legal Amazon is now one of the best-monitored ecosystems in terms of deforestation since 1988 (INPE, 2011). Deforestation for this region peaked in 2004 and has steadily declined since then to a lowest value of 4656 km² yr⁻¹ for the year 2012 (see Figure 27-4). Such reduction results from a series of integrated policies to control illegal deforestation, particularly enforcing protected areas, which now shelter 54% of the remaining forests of the Brazilian Amazon (Soares-Filho et al., 2010). Deforestation in Brazil is now highest in the Cerrado (drier ecosystem south of Amazon), with an average value of 14,179 km² yr⁻¹ for the period 2002–2008 (FAO, 2009).

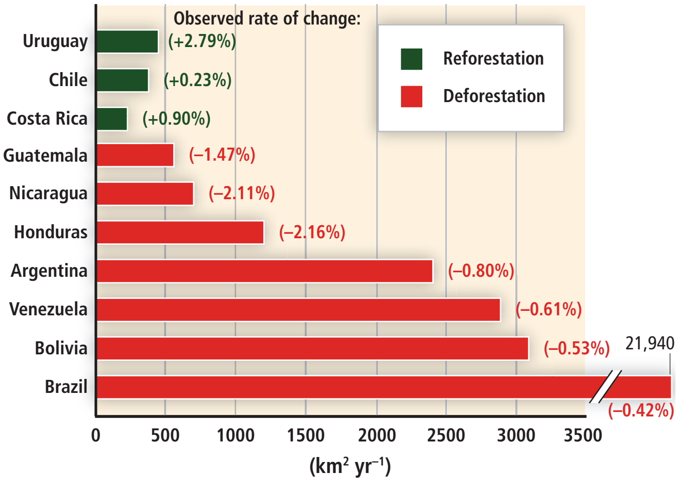


Figure 27-3 | Forest cover change per year for selected countries in Central and South America (2005–2010). Notice three countries listed with a positive change in forest cover (based on data from FAO, 2010).

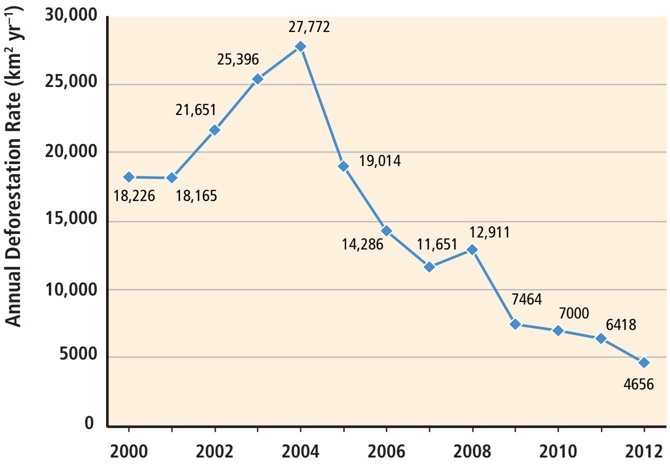


Figure 27-4 | Deforestation rates in Brazilian Amazonia (km² yr⁻¹) based on measurements by the PRODES project (INPE, 2011).

The area of forest loss in CA is considerably less than in SA, owing to smaller country sizes (Carr et al., 2009), but when relative deforestation rates are considered, Honduras and Nicaragua show the highest values for CA and SA (FAO, 2010). At the same time, CA includes some countries where forest cover shows a small recovery trend in the last years: Costa Rica, El Salvador, Panama, and possibly Honduras, where data are conflicting in the literature (FAO, 2010; Aide et al., 2013). This forest transition is the result of (1) economies less dependent on agriculture, and more on industry and services (Wright and Samaniego, 2008); (2) processes of international migration with the associated remittances (Hecht and Saatchi, 2007); and (3) a stronger emphasis on the recognition of environmental services of forest ecosystems (Kaimowitz, 2008). The same positive trend is observed in some SA countries (Figure 27-3). However, a substantial amount of forest is gained through (single-crop) plantations, most noticeably in Chile (Aguayo et al., 2009), which has a much lower ecological value than the depleted natural forests (Echeverría et al., 2006; Izquierdo et al., 2008).

Land degradation is also an important process compromising extensive areas of CA and SA very rapidly. According to data from the Global Land Degradation Assessment and Improvement (GLADA) project of the Global Environmental Facility (GEF), additional degraded areas reached 16.4% of the entire territory of Paraguay, 15.3% of Peru, and 14.2% of Ecuador for the period 1982–2002. In CA, Guatemala shows the highest proportion of degraded land, currently at 58.9% of the country's territory, followed by Honduras (38.4%) and Costa Rica (29.5%); only El Salvador shows a reversal of the land degradation process, probably due to eased land exploitation following intensive international migratory processes (ECLAC, 2010d).

Deforestation and land degradation are attributed mainly to increased extensive and intensive agriculture. Two activities have traditionally dominated the agricultural expansion: soy production (only in SA) and beef. But, more recently, biomass for biofuel production has become as important (Nepstad and Stickler, 2008) with some regions also affected by oil and mining extractions. Deforestation by small farmers, coming mainly from families who migrate in search for land, is relatively low: extensive cattle production is the predominant land use in deforested areas of tropical and subtropical Latin America (Wassenaar et al., 2007). Cattle is the only land use variable correlated with deforestation in Colombia (Armenteras et al., 2013), and in the Brazilian Amazon the peak of deforestation in 2004 (Figure 27-4) was primarily the result of increased cattle ranching (Nepstad et al., 2006). Mechanized farming, agro-industrial production, and cattle ranching are the major land use change drivers in eastern Bolivia but subsistence agriculture by indigenous colonists is also important (Killeen et al., 2008).

In recent years, soybean croplands have expanded continuously in SA, becoming increasingly more important in the agricultural production of the region. Soybean-planted area in Amazonian states (mainly Mato Grosso) in Brazil expanded 12.1% per year during the 1990s, and 16.8% per year from 2000 to 2005 (Costa et al., 2007). This landscape-scale conversion from forest to soy and other large-scale agriculture can alter substantially the water balance for large areas of the region, resulting in important feedbacks to the local climate (Hayhoe et al., 2011; Loarie et al., 2011; see Section 27.3.4.1).

Soybean and beef production have also impacted other ecosystems next to the Amazon, such as the Cerrado (Brazil) and the Chaco dry forests (Bolivia, Paraguay, Argentina, and Brazil). Gasparri et al. (2008) estimated carbon emissions from deforestation in northern Argentina, and concluded that deforestation in the Chaco forest has accelerated in the past decade from agricultural expansion and is now the most important source of carbon emissions for that region. In northwest Argentina (Tucumán and Salta provinces), 14,000 km^2 of dry forest were cleared from 1972 to 2007 as a result of technological improvements and increasing rainfall (Gasparri and Grau, 2009). Deforestation continued during the 1980s and 1990s, resulting in cropland area covering up to 63% of the region by 2005 (Viglizzo et al., 2011). In central Argentina (northern Córdoba province), cultivated lands have increased from 3 to 30% (between 1969 and 1999); and the forest cover has decreased from 52.5 to 8.2%. This change has also been attributed to the synergistic effect of climatic, socioeconomic, and technological factors (Zak et al., 2008). Losses in the Atlantic forest are estimated in 29% of the original area in 1960, and in 28% of the Yunga forest area, mainly due to cattle ranching migration from the Pampas and Espinal (Viglizzo et al., 2011).

Palm oil is a significant biofuel crop also linked to recent deforestation in tropical CA and SA. Its magnitude is still small compared with deforestation related to soybean and cattle ranching, but is considerable for specific countries and expected to increase due to increasing demands for biofuels (Fitzherbert et al., 2008). The main producers of palm oil in the region are Colombia and Ecuador, followed by Costa Rica, Honduras, Guatemala, and Brazil; Brazil has the largest potential for expansion, as nearly half of the Amazonia is suitable for oil palm cultivation (Butler and Laurance, 2009). Palm oil production is also growing in the Amazonian region of Peru, where 72% of new plantations have expanded into forested areas, representing 1.3% of the total deforestation for that country for the years 2000–2010 (Gutiérrez-Vélez et al., 2011).

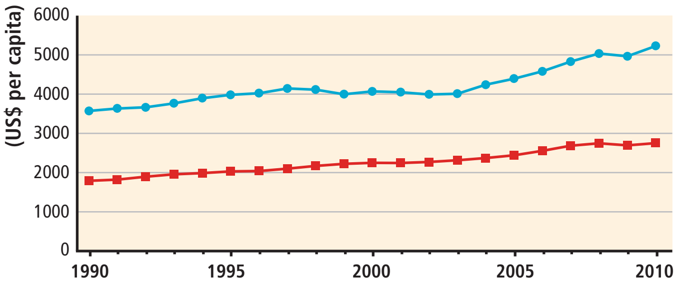
However, forests are not the only important ecosystems threatened in the region. An assessment of threatened ecosystems in SA by Jarvis et al. (2010) concluded that grasslands, savannahs, and shrublands are more threatened than forests, mainly from excessively frequent fires (>1 yr^{-1}) and grazing pressure. An estimation of burned land in LA by Chuvieco et al. (2008) also concluded that herbaceous areas presented the highest occurrence of fires. In the Río de la Plata region (central-east Argentina, southern Brazil, and Uruguay), grasslands decreased from 67.4 to 61.4% between 1985 and 2004. This reduction was associated with an increase in annual crops, mainly soybean, sunflower, wheat, and maize (Baldi and Paruelo, 2008).

Even with technological changes that might result in agricultural intensification, the expansion of pastures and croplands is expected to continue in the coming years (Wassenaar et al., 2007; Kaimowitz and Angelsen, 2008), particularly from an increasing global demand for food and biofuels (Gregg and Smith, 2010) with the consequent increase in commodity prices. This agricultural expansion will be mainly in LA and sub-Saharan Africa as these regions hold two-thirds of the global land with potential to expand cultivation (Nepstad and Stickler, 2008). It is important to consider the policy and legal needs to keep this process of large-scale change under control as much as possible; Takasaki (2007) showed that policies to eliminate land price distortions and promote technological transfers to poor colonists could reduce deforestation. It is also important to consider the role of indigenous groups; there is a growing acknowledgment that recognizing the land ownership and authority of indigenous groups can help central governments to better manage many of the natural areas remaining in the region (Oltremari and Jackson, 2006; Larson, 2010). The impact of indigenous groups on land use change can vary: de Oliveira et al. (2007) found that only 9% of the deforestation in the Peruvian Amazon between 1999 and 2005 happened in indigenous territories, but Killeen et al. (2008) found that Andean indigenous colonists in Bolivia were responsible for the largest land cover changes in the period 2001–2004. Indigenous groups are important stakeholders in many territories in the region and their well-being should be considered when designing responses to pressures on the land by a globalized economy (Gray et al., 2008; Killeen et al., 2008).

27.2.2.2. Trends and Projections in Socioeconomic Conditions

Development in the region has traditionally displayed four characteristics: low growth rates, high volatility, structural heterogeneity, and very unequal income distribution (ECLAC, 2008; Bárcena, 2010). This combination of factors has generated high and persistent poverty levels (45% for CA and 30% for SA for year 2010), with the rate of poverty being generally higher in rural than urban areas (ECLAC, 2009b). SA has based its economic growth in natural resource exploitation (mining, energy, agricultural), which involves direct and intensive use of land and water, and in energy-intensive and, in many cases, highly polluting natural resource-based manufactures. In turn, CA has exploited its proximity to the North American market and its relatively low labor costs (ECLAC, 2010e). The region shows a marked structural heterogeneity, where modern production structures coexist with large segments of the population with low productivity and income levels (ECLAC, 2010g). The gross domestic product (GDP) per capita in SA is twice that of CA; in addition, in the latter, poverty is 50% higher (see Figure 27-5).

(a) GDP per capita



(b) % poverty

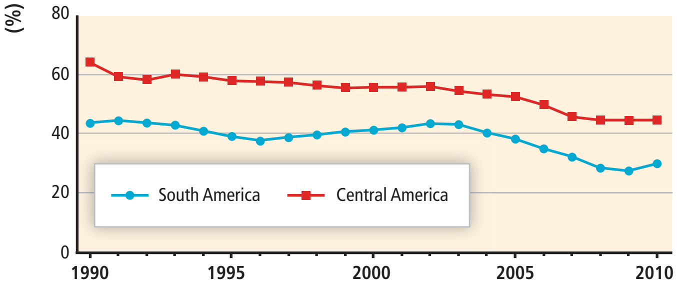


Figure 27-5 | Evolution of GDP per capita and poverty (income below US$2 per day) from 1990–2010: Central and South America (US$ per inhabitant at 2005 prices and percentages) (ECLAC, 2011c; 2012a).

The 2008 financial crisis reached CA and SA through exports and credits, remittances, and worsening expectations by consumers and producers (Bárcena, 2010; Kacef and López-Monti, 2010). This resulted in the sudden stop of six consecutive years of robust growth and improving social indicators (ECLAC, 2010e), which contributed to higher poverty in 2009 after 6 years where poverty had declined by 11%. Poverty rates fell from 44 to 33% of the total population from 2003 to 2008 (Figure 27-5), leaving 150 million people in this situation while extreme poverty diminished from 19.4 to 12.9% (which represents slightly more than 70 million people) (ECLAC, 2009b).

In the second half of 2009, industrial production and exports began to recover and yielded a stronger economic performance (GDP growth of 6.4% in SA and 3.9% in CA in 2010; ECLAC, 2012b). SA benefited the most because of the larger size of their domestic markets and the greater diversification of export markets. Conversely, slower growth was observed in CA, with more open economies and a less diversified portfolio of trading partners and a greater emphasis on manufacturing trade (ECLAC, 2010g).

The region is expected to continue to grow in the short term, albeit at a pace that is closer to potential GDP growth, helped by internal demand as the middle class becomes stronger and as credit becomes more available. In SA, this could be boosted by external demand from the Asian economies as they continue to grow at a rapid pace. The macroeconomic challenge is to act counter cyclically, creating conditions for productive development that is not based solely on commodity exports (ECLAC, 2010f).

In spite of its economic growth, CA and SA still display high and persistent inequality: most countries have Gini coefficients between 0.5 and 0.6, whereas the equivalent figures in a group of 24 developed countries vary between under 0.25 and around 0.4. The average per capita income of the richest 10% of households is approximately 17 times that of the poorest 40% of households (ECLAC, 2010g). Nevertheless, during the first decade of the century, prior to the financial crisis, the region has shown a slight but clear trend toward a more equitable distribution of income and a stronger middle class population, resulting in a higher demand for goods (ECLAC, 2010g,h, 2011b). Latin American countries also reported gains in terms of human development, although these gains have slowed down slightly over recent years. In comparative terms, as measured by the Human Development Index (HDI), the performance of countries varied greatly in 2007 (from Chile with 0.878 and Argentina with 0.866 to Guatemala with 0.704 and Nicaragua with 0.699), although those with lower levels of HDI showed notably higher improvements than countries with the highest HDI (UNDP, 2010).

Associated with inequality are disparities in access to water, sanitation, and adequate housing for the most vulnerable groups—for example, indigenous peoples, Afro-descendants, children, and women living in poverty—and in their exposure to the effects of climate change. The strong heterogeneity of subnational territorial entities in the region takes the form of high spatial concentration and persistent disparities in the territorial distribution of wealth (ECLAC, 2010g,h, 2011b).

The region faces significant challenges in terms of environmental sustainability and adaptability to a changing climate (ECLAC, 2010h), resulting from the specific characteristics of its population and economy already discussed and aggravated with a significant deficit in infrastructure development. CA and SA countries have made progress in incorporating environmental protection into decision-making processes, particularly in terms of environmental institutions and legislation, but there are still difficulties to effectively incorporate environmental issues into relevant public policies (ECLAC, 2010h). Although climate change imposes new challenges, it also provides an opportunity to shift development and economic growth patterns toward a more environmentally friendly course.

27.3. Impacts, Vulnerabilities, and Adaptation Practices

27.3.1. Freshwater Resources

CA and SA are regions with high average but unevenly distributed water resources availability (Magrin et al., 2007a). The main user of water is agriculture, followed by the region's 580 million inhabitants (including the Caribbean), of which 86% had access to water supply by 2006 (ECLAC, 2010b). According to the International Energy Agency (IEA), the region meets 60% of its electricity demand through hydropower generation, which contrasts with the 20% average contribution of other regions (see Table 27-6 and case study in Section 27.6.1).

27.3.1.1. Observed and Projected Impacts and Vulnerabilities

In CA and SA there is much evidence of changing hydrologic related conditions. The most robust trend for major rivers is found in the sub-basins of the La Plata River basin (*high confidence,* based on *robust* *evidence*, *high agreement*). This basin, second only to the Amazon in size, shows a positive trend in streamflow in the second half of the 20th century at different sites (Pasquini and Depetris, 2007; Krepper et al., 2008; Saurral et al., 2008; Amsler and Drago, 2009; Conway and Mahé, 2009; Dai et al., 2009; Krepper and Zucarelli, 2010; Dai, 2011; Doyle and Barros, 2011). An increase in precipitation and a reduction in evapotranspiration from land use changes have been associated with the trend in streamflows (Saurral et al., 2008; Doyle and Barros, 2011), with the former being more important in the southern sub-basins and the latter in the northern ones (Doyle and Barros, 2011; see Section 27.2.1). Increasing trends in streamflows have also been found in the Patos Lagoon in southern Brazil (Marques, 2012) and Laguna Mar Chiquita (a closed lake), and in the Santa Fe Province, both in Argentina, with ecological and erosive consequences (Pasquini et al., 2006; Rodrigues Capítulo et al., 2010; Troin et al., 2010; Venencio and García, 2011; Bucher and Curto, 2012).

Table 27-3 | Observed trends related to Andean cryosphere. (LIA = Little Ice Age; w.e. = water equivalent.)

(a) Andean tropical glacier trends.

Country	Documented massifs	Latitude	Significant changes recorded		References
			Variable code number[a]	Description of trend [period of observed trend]	
Venezuela	Cordillera de Mérida	10°N	1	+300 to +500 m [between LIA maximum and today]	Morris et al. (2006); Polissar et al. (2006)
			5	Accelerated melting [since 1972]. Risk of disappearing completely, as equilibrium line altitude is close to the highest peak (Pico Bolívar, 4979 m)	
Colombia	Parque Los Nevados	4°50′N	3	LIA maximum between 1600 and 1850	Ceballos et al. (2006); Ruiz et al. (2008); Poveda and Pineda (2009); IDEAM (2012); Rabatel et al. (2013)
	Sierra Nevada del Cocuy	6°30′N	3	Many small/low elevation glaciers (<5000 meters above sea level) have disappeared.	
	Sierra Nevada de Santa Marta	10°40′N	3	–60 to –84% [1850–2000]; –50% [last 50 years]; –10 to –50% [past 15 years]; retreat 3.0 km^2 year^{-1} [since 2000]	
Ecuador	Antisana	0°28′S	1	+300 m [between the middle of the 18th century (LIA maximum) and the last decades of the 20th century]; about +200 m [20th century]	Francou et al. (2007); Vuille et al. (2008); Jomelli et al. (2009); Cáceres (2010); Rabatel et al. (2013)
	Chimborazo and Carihuayrazo	1°S	3	About –45% [1976–2006]. Glaciers below 5300 m in process of extinction	
Peru	Cordillera Blanca	9°S	1	About +100 m [between LIA maximum and beginning of the 20th century]; +150 m [20th century]	Raup et al. (2007); Jomelli et al. (2009); Mark et al. (2010); UGHR (2010); Bury et al. (2011); Baraer et al. (2012); Rabatel et al. (2013)
			3	–12 to –17% [18th century]; –17 to –20% [19th century]; –20 to –35% [1960s–2000s]	
			4	–8 m decade^{-1} [since 1970] (Yanamarey glacier)	
			8	+1.6% (±1.1) (watersheds with >20% glacier area)	
			8	Seven out of nine watersheds decreasing dry-season discharge	
	Coropuna volcano	15°33′S	3	–26% [1962–2000]	Racoviteanu et al. (2007)
	Cordillera Vilcanota	13°55′S	3	10 times faster [in 1991–2005 compared to 1963–2005]	Thompson et al. (2006, 2011)
			3, 5	About –30% area and about –45% volume [since 1985]	Salzmann et al. (2013)
Bolivia	Cordillera Real and Cordillera Quimsa Cruz	16°S	1	+300 m [between LIA maximum and late 20th century]; +180 to +200 m [20th century]	Rabatel et al. (2006, 2008); Francou et al. (2007); Vuille et al. (2008); Soruco et al. (2009); Gilbert et al. (2010); Jomelli et al. (2011); Rabatel et al. (2013)
			3	–48% [1976–2006] in the Cordillera Real; Chacaltaya vanished [in 2010].	
			5	Zongo glacier has lost a mean of 0.4 m (w.e.) year^{-1} [in the 1991–2011 period]; glaciers in the Cordillera Real lost 43% of their volume [1963–2006; maximum rate of loss in 1976–2006].	
			2	+1.1°C ± 0.2°C [over the 20th century] at about 6340 meters above sea level	
	Caquella rock glacier (South Bolivian Altiplano)	21°30′S	7	Evidence of recent degradation	Francou et al. (1999)

(b) Extratropical Andean cryosphere (glaciers, snowpack, runoff effects) trends.

Region	Documented massifs/sites	Latitude	Significant changes recorded		References
			Variable code number[a]	Value of trend [period of observed trend]	
Chile, Argentina, Bolivia, and Argentinean Patagonia		South of 15°S	6	No significant trend	Foster et al. (2009)
Desert Andes (17°S–31°S)	Huasco basin glaciers	29°S	5	–0.84 m (w.e.) year^{-1} [2003/2004–2007/2008]	Nicholson et al. (2009); Gascoin et al. (2011); Rabatel et al. (2011)

Continued next page →

Table 27-3(b) (continued)

Region	Documented massifs/sites	Latitude	Significant changes recorded		References
			Variable code number[a]	Value of trend [period of observed trend]	
Central Andes (31°S–36°S)	Piloto/Las Cuevas	32°S	5	−10.50 m (w.e.) [last 24 years]	Leiva et al. (2007)
	Aconcagua basin glaciers	33°S	3	−20% [last 48 years]	Pellicciotti et al. (2007); Bown et al. (2008)
			3	−14% [1955–2006]	
			8	Significant decrease in Aconcagua basin streamflow	
	Central Andes glaciers	33°S–36°S	3	−3% [since 1955]	Le Quesne et al. (2009)
			4	−50 to −9 m year^{-1} [during 20th century]	
			5	−0.76 to −0.56 m (w.e.) year^{-1} [during 20th century]	
	Central Andes		1	+122 ± 8 m (winter) and +200 ± 6 m (summer) [1975–2001]	Carrasco et al. (2005)
	Snowpack	30°S–37°S	6	Positive, though nonsignificant, linear trend [1951–2005]	Masiokas et al. (2006); Vich et al. (2007); Vicuña et al. (2013)
			8	Mendoza River streamflow: possible link to rising temperatures and snowpack/glacier effects. Not conclusive; increase in high and low flows possibly associated with increase in temperature and effects on snowpack	
	Morenas Coloradas rock glacier	32°S–33°S	7	Significant change in active layer possibly associated with warming processes	Trombotto and Borzotta (2009)
	Cryosphere in the Andes of Santiago	33.5°S	5	Expansion of thermokarst depressions	Bodin et al. (2010)
	Basins	28°S–47°S	8	Non-significant increase in February runoff; possible increase of glacier melt [1950–2007]	Casassa et al. (2009)
		30°S–40°S	8	Significant negative timing trend (centroid timing date shifting toward earlier in the year) for 23 out of the 40 analyzed series	Cortés et al. (2011)
Patagonian Andes (36°S–55°S)	Basins	28°S–47°S	8	Not significant increase in February runoff trends that might suggest an increase of glacier melt in the Andes [1950–2007]	Casassa et al. (2009)
	Northwest Patagonia	38°S–45°S	4	Recession of six glaciers based on aerial photograph analysis	Masiokas et al. (2008)
	Proglacial lakes	40°S–50°S	8	Summertime negative trend on lakes indicating that melt water is decreasing	Pasquini et al. (2008)
	Casa Pangue glacier	41°S	5	−2.3 ± 0.6 m (w.e.) year^{-1} [1961–1998]	Bown and Rivera (2007)
			4	−3.6 ± 0.6 m year^{-1} [1981–1998]	
	Manso Glacier	41°S	8	Reduction in discharge associated with reduction in melt and precipitation	Pasquini et al. (2013)
	Patagonian Ice Field	47°S–51°S	5	−1.6 m (w.e.) year^{-1} or −27.9 ± 11 km^3 (w.e.) year^{-1} [2002–2006]	Chen et al. (2007)
	Northern Patagonian Ice Field	47°S	8	Glacial lake outburst flood possible response to retreat of Calafate glacier [20th century]	Harrison et al. (2006)
	Southern Patagonian Ice Field	48°S–51°S	4	Larger retreating rates observed on the west side coinciding with lower elevations of equilibrium line altitudes	Barcaza et al. (2009)
	Northern Patagonian, Southern Patagonian, and Cordillera Darwin ice fields	47°S–51°S, 54°S	4	5.7 to 12.2 km [1945–2005]	Lopez et al. (2010)
	Gran Campo Nevado	53°S	4	−2.8% of glacier length per decade [1942–2002]	Schneider et al. (2007)
			3	−2.4% per decade [1942–2002]	
	Cordón Martial glaciers	54°S	5	Slow retreat from late LIA. Acceleration started 60 years ago.	Sterlin and Iturraspe (2007)

[a] Variable coding: (1) Increase in equilibrium line altitude; (2) atmospheric warming revealed by englacial temperature measured at high elevation; (3) area reduction; (4) frontal retreat; (5) volume reduction; (6) snow cover; (7) rock glaciers; (8) runoff change.

There is no clear long-term trend for the Amazon River. Espinoza et al. (2009a, 2011) showed that the 1974–2004 apparent stability in mean discharge at the main stem of the Amazon in Obidos is explained by opposing regional features of Andean rivers (e.g., increasing trends during the high-water period in Peruvian and Colombian Amazons and decreasing trend during the low-water period in Peruvian and Bolivian Amazons (Lavado et al., 2012). In recent years extremely low levels were experienced during the droughts of 2005 and 2010, while record high levels were detected during the 2009 and 2012 floods (Section 27.2.1).

Major Colombian rivers draining to the Caribbean Sea (Magdalena and Cauca) exhibit decreasing trends along their main channels (Carmona and Poveda, 2011), while significant trends are absent for all other major large rivers in NEB and northern SA (Dai et al., 2009). Dai (2011) showed a drying trend in CA rivers.

A rapid retreat and melting of the tropical Andes glaciers of Venezuela, Colombia, Ecuador, Peru, and Bolivia has been further reported following the IPCC AR4, through use of diverse techniques (*high confidence*, based

Table 27-4 | Synthesis of projected climate change impacts on hydrological variables in Central American and South American basins and major glaciers.

Region	Basins studied	Variable code number[a]	Projected change	Period	General circulation model (greenhouse gas scenario)	References
Río de La Plata Basin and Southeastern South America	Paraná River	1	+4.9% (not robust)	2081–2100	CMIP3 models (A1B)	Nohara et al. (2006)
			+10 to +20%	2100	Eta-HadCM3 (A1B)	Marengo et al. (2011a)
			+18.4% (significant)	2075–2100	CMIP3 models (A1B)	Nakaegawa et al. (2013a)
	Rio Grande	1	+20 to –20%	Different periods	7 CMIP3 models	Gosling et al. (2011); Nóbrega et al. (2011); Todd et al. (2011)
	Itaipu Power Plant (on the Paraná River)	1	Left bank: –5 to –15%; right bank: +30%	2010–2040	CCCMA–CGCM2 (A2)	Rivarola et al. (2011)
			0 to –30%	2070–2100		
	Concórdia River	1	–40%	2070–2100	HadRM3P (A2, B2)	Perazzoli et al. (2013)
	Carcarañá River	2	Increase	2010–2030	HadCM3 (A2)	Venencio and García (2011)
		3	Slight reduction			
Amazon Basin	Peruvian Amazon basins	1	Increase in some basins; reduction in others	Three time slices	BCM2, CSMK3 and MIHR (A1B, B1)	Lavado et al. (2011)
	Basins in region of Alto Beni, Bolivia	1	Increase and reduction	2070–2100	CMIP3 models (A1B)	Fry et al. (2012)
		3	Always reduction			
		5	Increase in water stress			
	Paute and Tomebamba Rivers	1	Increase in some scenarios; reduction in others	2070–2100	CMIP3 models (A1B)	Buytaert et al. (2011)
	Amazon River	1	+5.4% (not robust)	2081–2100	CMIP3 models (A1B)	Nohara et al. (2006)
			+6%	2000–2100	ECBilt–CLIO–VECODE (A2)	Aerts et al. (2006)
			+3.7% (significant)	2075–2100	CMIP3 models (A1B)	Nakaegawa et al. (2013a)
			At Óbidos Station: no change in high flow; reduction in low flow	2046–2065/ 2079–2098	8 AR4 GCMs (B1, A1B, and A2)	Guimberteau et al. (2013)
	Amazon and Orinoco Rivers	1	–20%	2050s	HadCM3 (A2)	Palmer et al.(2008)
	Basins in Brazil	1	Consistent decrease	2050s	HadCM3 and CMIP3 models (A1B)	Arnell and Gosling (2013)
Tropical Andes	Colombian glaciers	4	Disappearance by 2020s	Linear extrapolation		Poveda and Pineda (2009)
	Cordillera Blanca glacierized basins	1	Increase for next 20–50 years, reduction afterwards	2005–2020	Temperature output only (B2)	Chevallier et al. (2011)
		4	Area –38 to –60%. Increased seasonality	2050	Not specified (A1, A2, B1, B2)	Juen et al. (2007)
			Area –49 to –75%. Increased seasonality	2080		
			Increased seasonality	2030	16 CMIP3 models (A1B, B1)	Condom et al. (2012)
	Basins providing water to cities of Bogotá, Quito, Lima, and La Paz	5	Inner tropics: only small change; increase in precipitation and increase in evapotranspiration	2010–2039 and 2040–2069	19 CMIP3 models (A1B, A2)	Buytaert and De Bièvre (2012)
			Outer tropics: severe reductions; decrease in precipitation and increase in evapotranspiration			
Central Andes	Limarí River	1	–20 to –40%	2070–2100	HadCM3 (A2, B2)	Vicuña et al. (2011)
			–20%	2010–2040	15 CMIP3 models (A1B, B2, B1)	Vicuña et al. (2012)
			–30 to –40%; change in seasonality	2070–2100		
	Maipo River	1	–30%	Three 30-year periods	HadCM3 (A2, B2)	ECLAC (2009a); Melo et al. (2010); Meza et al. (2012)
		5	Unmet demand up to 50%	2070–2090		
	Mataquito River	1	Reduction in average and low flows Increase in high flows	Three 30-year periods	CMIP3 (A2, B1) and CMIP5 (RCP4.5 and 8.5) models	Demaria et al. (2013)
	Maule and Laja Rivers	1	–30%	Three 30-year periods	HadCM3 (A2, B2)	ECLAC (2009a); McPhee et al. (2010)
	Bío Bío River	1	–81 to +7%	2070–2100	8 GCMs (6 SRES)	Stehr et al. (2010)
	Limay River	1	–10 to –20%	2080s	HadCM2 (NS)	Seoane and López (2007)

Continued next page →

Table 27-4 (continued)

Region	Basins studied	Variable code number[a]	Projected change	Period	General circulation model (greenhouse gas scenario)	References
Northeastern Brazil	Basins in the Brazilian states of Ceará and Piauí	1	No significant change up to 2025. After 2025: strong reduction with ECHAM4; slight increase with HadCM2.	2000–2100	HadCM2, ECHAM4 (NS)	Krol et al. (2006); Krol and Bronstert (2007)
	Paracatu River	1	+31 to +131%	2000–2100	HadCM3 (A2)	De Mello et al. (2008)
			No significant change	2000–2100	HadCM3 (B2)	
	Jaguaribe River	2	Demand: +33 to +44%	2040	HadCM3 (A2, B2)	Gondim et al. (2008, 2012)
			Irrigation water needs: +8 to +9%	2025–2055	HadCM3 (B2)	
	Parnaíba River	1	–80%	2050s	HadCM3 (A2)	Palmer et al. (2008)
	Mimoso River	1	Dry scenario: –25 to –75%	2010–2039, 2040–2069, and 2070–2099	CSMK3 and HadCM3 (A2, B1)	Montenegro and Ragab (2010)
			Wet scenario: +40 to +140%			
		3	No change			
	Tapacurá River	1	B1: –4.89%, –14.28%, –20.58%	Three 30-year periods	CSMK3 and MPEH5 (A2, B1)	Montenegro and Ragab (2012)
			A2: +25.25%, +39.48%, +21.95%			
	Benguê Catchment	1	–15% reservoir yield	Sensitivity scenario in 2100 selected from Third and Fourth Assessment Report general circulation models with good skill. +15% potential evapostranspiration, –10% precipitation		Krol et al. (2011)
	Aquifers in northeastern Brazil	3	Reduction	2040–2070	HadCM3, ECHAM4 (A2,B2)	Hirata and Conicelli (2012)
Northern South America	Essequibo River	1	–50%	2050s	HadCM3 (A2)	Palmer et al. (2008)
	Magdalena River	1	Non-significant changes in near future. End of 21st century changes in seasonality.	2015–2035 and 2075–2099	CMIP3 multi-model ensemble (A1B)	Nakaegawa and Vergara (2010)
	Sinú River	1	–2 to –35%	2010–2039	CCSRNIES, CSIROMK2B, CGCM2, HadCM3 (A2)	Ospina-Noreña et al. (2009a,b)
Central America	Lempa River	1	–13%	2070–2100	CMIP3 models (B1)	Maurer et al. (2009)
			–24%	2070–2100	CMIP3 models (A2)	
	Río Grande de Matagalpa	1	–70%	2050s	HadCM3 (A2)	Palmer et al. (2008)
	Basins in Mesoamerica	1	Decrease across the region	2070–2100	CMIP3 (A2, A1B, B1)	Imbach et al. (2012)
			Consistent decrease	2050s	HadCM3 and CMIP3 models (A1B)	Arnell and Gosling (2013)
			Consistent reduction in northern CA	2050–2099	30 GCMs (A1B)	Hidalgo et al. (2013)
	Basins in Panama	1	Basins discharging into the Pacific: +35 to +40%	2075–2099	MRI-AGCM3.1 (A1B)	Fábrega et al. (2013)
			Basins in the Bocas del Toro region: –50%			

[a] Variable coding: (1) Runoff/discharge; (2) demand; (3) recharge; (4) glacier change; (5) unmet demand/water availability.

on *robust evidence*, *high agreement*). Rabatel et al. (2013) provides a synthesis of these studies (specific papers are presented in Table 27-3a). Tropical glaciers' retreat has accelerated in the second half of the 20th century (area loss between 20 and 50%), especially since the late 1970s in association with increasing temperature in the same period (Bradley et al., 2009). In early stages of glacier retreat, associated streamflow tends to increase due to an acceleration of glacier melt, but after a peak in streamflow as the glacierized water reservoir gradually empties, runoff tends to decrease, as evidenced in the Cordillera Blanca of Peru (Chevallier et al., 2011; Baraer et al., 2012), where seven out of nine river basins have probably crossed a critical threshold, exhibiting a decreasing dry-season discharge (Baraer et al., 2012). Likewise, glaciers and ice fields in the extratropical Andes located in central-south Chile and Argentina face significant reductions (see review in Masiokas et al. (2009) and details in Table 27-3b), with their effect being compounded by changes in snowpack extent, thus magnifying changes in hydrograph seasonality by reducing flows in dry seasons and increasing them in wet seasons (Pizarro et al., 2013; Vicuña et al., 2013). Central-south Chile and Argentina also face significant reductions in precipitation as shown in Section 27.2.1, contributing to runoff reductions in the last decades of the 20th century (Seoane and López, 2007; Rubio-Álvarez and McPhee, 2010; Urrutia et al., 2011; Vicuña et al., 2013), corroborated with long-term trends found through dendrochronology (Lara et al., 2007; Urrutia et al., 2011). Trends in precipitation and runoff are less evident in the central-north region in Chile (Fiebig-Wittmaack et al., 2012; Souvignet et al., 2012).

As presented in Table 27-4, the assessment of future climate scenarios implications in hydrologic related conditions shows a large range of uncertainty across the spectrum of climate models (mostly using CMIP3 simulations with the exception of Demaria et al. (2013)) and scenarios considered. Nohara et al. (2006) studied climate change impacts on 24 of the main rivers in the world considering a large number of General Circulation Models (GCMs), and found no robust change for the Paraná

(La Plata Basin) and Amazon Rivers. Nevertheless, in both cases the average change showed a positive value consistent, at least with observations for the La Plata Basin. In a more recent work Nakaegawa et al. (2013a) showed a statistically significant increase for both basins in a study that replicated that of Nohara et al. (2006) but with a different hydrologic model. Focusing in extreme flows Guimberteau et al. (2013) show that by the middle of the century no change is found in high flow on the main stem of the Amazon River but there is a systematic reduction in low-flow streamflow. In contrast, the northwestern part of the Amazon River shows a consistent increase in high flow and inundated area (Guimberteau et al., 2013; Langerwisch et al., 2013). On top of such climatic uncertainty, future streamflows and water availability projections are confounded by the potential effects of land use changes (Moore et al., 2007; Coe et al., 2009; Georgescu et al., 2013).

The CA region shows a consistent future runoff reduction. Maurer et al. (2009) studied climate change projections for the Lempa River basin, one of the largest basins in CA, covering portions of Guatemala, Honduras, and El Salvador. They showed that future climate projections (increase in evaporation and reduction in precipitation) imply a reduction of 20% in inflows to major reservoirs in this system (see Table 27-4). Imbach et al. (2012) found similar results using a modeling approach that also considered potential changes in vegetation. These effects could have large hydropower generation implications as discussed in the case study in Section 27.6.1.

The evolution of tropical Andes glaciers associated future climate scenarios has been studied using trend (e.g., Poveda and Pineda, 2009), regression (e.g., Juen et al., 2007; Chevallier et al., 2011), and explicit modeling (e.g., Condom et al., 2012) analysis. These studies indicate that glaciers will continue their retreat (Vuille et al., 2008a) and even disappear as glacier equilibrium line altitude rises, with larger hydrological effects during the dry season (Kaser et al., 2010; Gascoin et al., 2011). This is expected to happen during the next 20 to 50 years (Juen et al., 2007; Chevallier et al., 2011; see Table 27-4). After that period water availability during the dry months is expected to diminish. A projection by Baraer et al. (2012) for the Santa River in the Peruvian Andes finds that once the glaciers are completely melt, annual discharge would decrease by 2 to 30%, depending on the watershed. Glacier retreat can exacerbate current water resources-related vulnerability (Bradley et al., 2006; Casassa et al., 2007; Vuille et al., 2008b; Mulligan et al., 2010), diminishing the mountains' water regulation capacity, making the supply of water for diverse purposes, as well as for ecosystems integrity, more expensive and less reliable (Buytaert et al., 2011). Impacts on economic activities associated with conceptual scenarios of glacier melt reduction have been monetized (Vergara et al., 2007), representing about US$100 million in the case of water supply for Quito, and between US$212 million and US$1.5 billion in the case of the Peruvian electricity sector due to losses of hydropower generation (see the case study in Section 27.6.1). Andean communities will face an important increase in their vulnerability, as documented by Mark et al. (2010), Pérez et al. (2010), and Buytaert and De Bièvre (2012).

In central Chile, Vicuña et al. (2011) project changes in the seasonality of streamflows of the upper snowmelt-driven watersheds of the Limarí River, associated with temperature increases and reductions in water availability owing to a reduction (increase) in precipitation (evapotranspiration). Similar conclusions are derived across the Andes on the Limay River in Argentina by Seoane and López (2007). Under these conditions, semi-arid highly populated basins (e.g., Santiago, Chile) and with extensive agriculture irrigation and hydropower demands are expected to increase their current vulnerability (*high confidence*; ECLAC, 2009a; Souvignet et al., 2010; Fiebig-Wittmaack et al., 2012; Vicuña et al., 2012; see Table 27-4). Projected changes in the cryosphere conditions of the Andes could affect the occurrence of extreme events, such as extreme low and high flows (Demaria et al., 2013), Glacial Lake Outburst Floods (GLOF) occurring in the ice fields of Patagonia (Dussaillant et al., 2010; Marín et al., 2013), volcanic collapse and debris flow associated with accelerated glacial melting in the tropical Andes (Carey, 2005; Carey et al., 2012b; Fraser, 2012), and with volcanoes in southern Chile and Argentina (Tormey, 2010), as well as scenarios of water quality pollution by exposure to contaminants as a result of glaciers' retreat (Fortner et al., 2011).

Another semi-arid region that has been studied thoroughly is northeast Brazil (Hastenrath, 2012). de Mello et al. (2008), Gondim et al. (2008), Souza et al. (2010), and Montenegro and Ragab (2010) have shown that future climate change scenarios would decrease water availability for agriculture irrigation owing to reductions in precipitation and increases in evapotranspiration (*medium confidence*). Krol and Bronstert (2007) and Krol et al. (2006) presented an integrated modeling study that linked projected impacts on water availability for agriculture with economic impacts that could potentially drive full-scale migrations in the NEB region.

27.3.1.2. Adaptation Practices

At an institutional level, a series of policies have been developed to reduce vulnerability to climate variability as faced today in different regions and settings. In 1997, Brazil instituted the National Water Resources Policy and created the National Water Resources Management System under the shared responsibility between the states and the federal government. Key to this new regulation has been the promotion of decentralization and social participation through the creation of National Council of Water Resources and their counterparts in the states, the States Water Resources Councils. The challenges and opportunities dealing with water resources management in Brazil in the face of climate variability and climate change have been well studied (Abers, 2007; Kumler and Lemos, 2008; Medema et al., 2008; Engle et al., 2011; Lorz et al., 2012). Other countries in the region are following similar approaches. In the last years, there have been constitutional and legal reforms toward more efficient and effective water resources management and coordination among relevant actors in Honduras, Nicaragua, Ecuador, Peru, Uruguay, Bolivia, and Mexico; although in many cases, these innovations have not been completely implemented (Hantke-Domas, 2011). Institutional and governance improvements are required to ensure an effective implementation of these adaptation measures (e.g., Halsnæs and Verhagen, 2007; Engle and Lemos, 2010; Lemos et al., 2010; Zagonari, 2010; Pittock, 2011; Kirchhoff et al. 2013).

With regard to region-specific freshwater resources issues it is important to consider adaptation to reduce vulnerabilities in the communities along the tropical Andes and the semi-arid basins in Chile-Argentina, NEB, and the northern CA basins. Different issues have been addressed in

Frequently Asked Questions

FAQ 27.1 | What is the impact of glacier retreat on natural and human systems in the tropical Andes?

The retreat of glaciers in the tropical Andes mountains, with some fluctuations, started after the Little Ice Age (16th to 19th centuries), but the rate of retreat (area reduction between 20 and 50%) has accelerated since the late 1970s. The changes in runoff from glacial retreat into the basins fed by such runoff vary depending on the size and phase of glacier retreat. In an early phase, runoff tends to increase as a result of accelerated melting, but after a peak, as the glacierized water reservoir gradually empties, runoff tends to decrease. This reduction in runoff is more evident during dry months, when glacier melt is the major contribution to runoff (*high confidence*).

A reduction in runoff could endanger high Andean wetlands (bofedales) and intensify conflicts between different water users among the highly vulnerable populations in high-elevation Andean tropical basins. Glacier retreat has also been associated with disasters such as glacial lake outburst floods that are a continuous threat in the region. Glacier retreat could also impact activities in high mountainous ecosystems such as alpine tourism, mountaineering, and adventure tourism (*high confidence*).

assessment of adaptation strategies for tropical Andean communities such as the role of governance and institutions (Young and Lipton, 2006; Lynch, 2012), technology (Carey et al., 2012a), and the dynamics of multiple stressors (McDowell and Hess, 2012; Bury et al., 2013). Semi-arid regions are characterized by pronounced climatic variability and often by water scarcity and related social stress (Krol and Bronstert, 2007; Scott et al., 2012, 2013). Adaptation tools to face the threats of climate change for the most vulnerable communities in the Chilean semi-arid region are discussed by Young et al. (2010) and Debels et al. (2009). In CA, Benegas et al. (2009), Manuel-Navarrete et al. (2007), and Aguilar et al. (2009) provide different frameworks to understand vulnerability and adaptation strategies to climate change and variability in urban and rural contexts, although no specific adaptation strategies are suggested. The particular experience in NEB provides other examples of adaptation strategies to manage actual climate variability. Broad et al. (2007) and Sankarasubramanian et al. (2009) studied the potential benefits of streamflow forecast as a way to reduce the impacts of climate change and climate variability on water distribution under stress conditions. An historical review and analysis of drought management in this region are provided by Campos and Carvalho (2008). de Souza Filho and Brown (2009) studied different water distribution policy scenarios, finding that the best option depended on the degree of water scarcity. The study by Nelson and Finan (2009) provides a critical perspective of drought-related policies, arguing that they constitute an example of maladaptation as they do not try to solve the causes of vulnerability and instead undermine resilience. Tompkins et al. (2008) are also critical of risk reduction practices in this region because they have fallen short of addressing the fundamental causes of vulnerability needed for efficient longer term drought management. Other types of adaptation options that stem from studies on arid and semi-arid regions are related to (1) increase in water supply from groundwater pumping (Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010; Burte et al., 2011; Nadal et al., 2013), fog interception practices (Holder, 2006; Klemm et al., 2012), and reservoirs and irrigation infrastructure (Fry et al., 2010; Vicuña et al., 2010, 2012); and (2) improvements in water demand management associated with increased irrigation efficiency and practices (Geerts et al., 2010; Montenegro and Ragab, 2010; van Oel et al., 2010; Bell et al., 2011; Jara-Rojas et al., 2012) and changes toward less water-intensive crops (Montenegro and Ragab, 2010).

Finally, flood management practices also provide a suite of options to deal with actual and future vulnerabilities related to hydrologic extremes, such as the management of ENSO-related events in Peru via participatory (Warner and Oré, 2006) or risk reduction approaches (Khalil et al., 2007), the role of land use management (Bathurst et al., 2010, 2011; Coe et al., 2011), and flood hazard assessment (Mosquera-Machado and Ahmad, 2006) (*medium confidence*).

27.3.2. Terrestrial and Inland Water Systems

27.3.2.1. Observed and Projected Impacts and Vulnerabilities

CA and SA house the largest biological diversity and several of the world's megadiverse countries (Mittermeier et al., 1997; Guevara and Laborde, 2008). However, land use change has led to the existence of six biodiversity hotspots, that is, places with a great species diversity that show high habitat loss and also high levels of species endemism: Mesoamerica, Chocó-Darien-Western Ecuador, Tropical Andes, Central Chile, Brazilian Atlantic forest, and Brazilian Cerrado (Mittermeier et al., 2005). Thus, conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss in the region (Ayoo, 2008). Tropical deforestation is the second largest driver of anthropogenic climate change on the planet, adding up to 17 to 20% of total greenhouse gas (GHG) emissions during the 1990s (Gullison et al., 2007; Strassburg et al., 2010). In parallel, the region still has large extensions of wilderness areas for which the Amazon is the most outstanding example. Nevertheless, some of these areas are precisely the new frontier of economic expansion. For instance, between 1996 and 2005, Brazil deforested about 19,500 $km^2 yr^{-1}$, which represented 2 to 5% of global annual carbon dioxide (CO_2) emissions (Nepstad et al., 2009). Between 2005 and 2009, deforestation in the Brazilian Amazon dropped by 36%, which is partly related to the network of protected areas that now covers around 45.6% of the biome in Brazil (Soares-Filho et al., 2010). Using the LandSHIFT modeling framework for land use change and the IMPACT projections of crop/livestock production, Lapola et al. (2011) projected that zero deforestation in the Brazilian Amazon forest by 2020 (and of the Cerrado by 2025) would require either a reduction of 26 to 40% in livestock production until 2050 or a doubling of average livestock density from 0.74 to 1.46 head per hectare. Thus, climate change may imply reduction of yields and entail further deforestation.

Local deforestation rates or rising GHGs globally drive changes in the regional SA that during this century might lead the Amazon rainforest into crossing a critical threshold at which a relatively small perturbation can qualitatively alter the state or development of a system (Cox et al., 2000; Salazar et al., 2007; Sampaio et al., 2007; Lenton et al., 2008; Nobre and Borma, 2009). Various models are projecting a risk of reduced rainfall and higher temperatures and water stress, which may lead to an abrupt and irreversible replacement of Amazon forests by savanna-like vegetation, under a high emission scenario (A2), from 2050–2060 to 2100 (Betts et al., 2004, 2008; Cox et al., 2004; Salazar et al., 2007; Sampaio et al., 2007; Malhi et al., 2008, 2009; Sitch et al., 2008; Nobre and Borma, 2009; Marengo et al., 2011c). The possible "savannization" or "die-back" of the Amazon region would potentially have large-scale impacts on climate, biodiversity, and people in the region. The possibility of this die-back scenario occurring, however, is still an open issue and the uncertainties are still very high (Rammig et al., 2010; Shiogama et al., 2011).

Plant species are rapidly declining in CA, SA, Central and West Africa, and Southeast Asia (Bradshaw et al., 2009). Risk estimates of plant species extinction in the Amazon, which do not take into account possible climate change impacts, range from 5 to 9% by 2050 with a habitat reduction of 12 to 24% (Feeley and Silman, 2009) to 33% by 2030 (Hubbell et al., 2008). The highest percentage of rapidly declining amphibian species occurs in CA and SA. Brazil is among the countries with most threatened bird and mammal species (Bradshaw et al., 2009).

A similar scenario is found in inland water systems. Among components of aquatic biodiversity, fish are the best-known organisms (Abell et al., 2008), with Brazil accounting for the richest icthyofauna of the planet (Nogueira et al., 2010). For instance, the 540 Brazilian small microbasins host 819 fish species with restrict distribution. However, 29% of these microbasins have historically lost more than 70% of their natural vegetation cover and only 26% show a significant overlap with protected areas or indigenous reserves. Moreover, 40% of the microbasins overlap with hydrodams (see Section 27.6.1 and Chapter 3) or have few protected areas and high rates of habitat loss (Nogueira et al., 2010).

The faster and more severe the rate of climate change, the more severe the biological consequences such as species decline (Brook et al., 2008). Vertebrate fauna in North and South America is projected to suffer species losses until 2100 of at least 10%, as forecasted in more than 80% of the climate projections based on a low-emissions scenario (Lawler et al., 2009). Vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains for emission scenarios varying from low B1 to mid-high A2 (Lawler et al., 2009). Elevational specialists, that is, a small proportion of species with small geographic ranges restricted to high mountains, are most frequent in the Americas (e.g., Andes and Sierra Madre) and might be particularly vulnerable to global warming because of their small geographic ranges and high energetic and area requirements, particularly birds and mammals (Laurance et al., 2011). In Brazil, projections for Atlantic forest birds (Anciães and Peterson, 2006), endemic bird species (Marini et al., 2009), and plant species (by 2055, scenarios HHGSDX50 and HHGGAX50; Siqueira and Peterson, 2003) of the Cerrado indicate that distribution will dislocate toward the south and southeast, precisely where fragmentation and habitat loss are worse. Global climate change is also predicted to increase negative impacts worldwide, including SA, on freshwater fisheries due to alterations in physiology and life histories of fish (Ficke et al., 2007).

In addition to climate change impacts at the individual species level, biotic interactions will be affected. Modifications in phenology, structure of ecological networks, predator-prey interactions, and non-trophic interactions among organisms have been forecasted (Brooker et al., 2008; Walther, 2010). The outcome of non-trophic interactions among plants is expected to shift along with variation in climatic parameters, with more facilitative interactions in more stressful environments, and more competitive interactions in more benign environments (Brooker et al., 2008; Anthelme et al., 2012). These effects are expected to have a strong influence of community and ecosystem (re-)organization given the key engineering role played by plants on the functioning of ecosystems (Callaway, 2007). High Andean ecosystems, especially those within the tropics, are expected to face exceptionally strong warming effects during the 21st century because of their uncommonly high altitude (Bradley et al., 2006). At the same time they provide a series of crucial ecosystem services for millions of people (Buytaert et al., 2011). For these reasons shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in this region.

Although in the region biodiversity conservation is largely confined to protected areas, with the magnitude of climatic changes projected for the century, it is expected that many species and vegetational types will lose representativeness inside such protected areas (Heller and Zavaleta, 2009).

27.3.2.2. Adaptation Practices

The subset of practices that are multi-sectoral, multi-scale, and based on the premise that ecosystem services reduce the vulnerability of society to climate change are known as Ecosystem-based Adaptation (EbA; Vignola et al., 2009; see Glossary and Box CC-EA). Schemes such as the payment for environmental services (PES) and community management fit the concept of EbA that begins to spread in CA and SA (Vignola et al., 2009). The principle behind these schemes is the valuation of ecosystem services that should reflect both the economic and cultural benefits derived from the human-ecosystem interaction and the capacity of ecosystems to secure the flow of these benefits in the future (Abson and Termansen, 2011).

Because PES schemes have developed more commonly in CA and SA than in other parts of the world (Balvanera et al., 2012), this topic will be covered as a case study (see Section 27.6.2).

Ecological restoration, conservation in protected areas, and community management can all be important tools for adaptation. A meta-analysis of 89 studies by Benayas et al. (2009) (with a time scale of restoration varying from <5 to 300 years), including many in SA, showed that ecological restoration enhances the provision of biodiversity and environmental services by 44 and 25%, respectively, as compared to degraded systems. Moreover, ecological restoration increases the potential for carbon sequestration and promotes community organization, economic activities, and livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon et al., 2011; Rodrigues et al., 2011). In that sense, Locatelli et al. (2011) revised several ecosystem conservation and restoration initiatives in CA and SA that simultaneously help mitigate and adapt to climate change. Chazdon et al. (2009) also highlight the potential of restoration efforts to build ecological corridors (see Harvey et al., 2008, for an example in Central America).

The effective management of natural protected areas and the creation of new protected areas within national protected area systems and community management of natural areas are also efficient tools to adapt to climate change and to reconcile biodiversity conservation with socioeconomic development (e.g., Bolivian Andes: Hoffmann et al., 2011; Panama: Oestreicher et al., 2009). Porter-Bolland et al. (2012) compared protected areas with areas under community management in different parts of the tropical world, including CA and SA, and found that protected areas have higher deforestation rates than areas with community management. Similarly, Nelson and Chomitz (2011) found for the region that (1) protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and (2) in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas. This contrasts with the findings of Miteva et al. (2012), who found protected areas more efficient in constraining deforestation than other schemes. Other good examples of adaptive community management in the continent include community forest concessions (e.g., Guatemala: Radachowsky et al., 2012), multiple-use management of forests (Guariguata et al., 2012; see also examples in Brazil: Klimas et al., 2012, Soriano et al., 2012, and Bolivia: Cronkleton et al., 2012); and local communities where research and monitoring protocols are in place to pay the communities for collecting primary scientific data (Luzar et al., 2011).

27.3.3. Coastal Systems and Low-Lying Areas

27.3.3.1. Observed and Projected Impacts and Vulnerabilities

Climate change is altering coastal and marine ecosystems (Hoegh-Guldberg and Bruno, 2010). Coral reefs (Chapter 5; Box CC-CR), seagrass beds, mangroves, rocky reefs and shelves, and seamounts have few to no areas left in the world that remain unaffected by human influence (Halpern et al., 2008). Anthropogenic drivers associated with climate change decreased ocean productivity, altered food web dynamics, reduced the abundance of habitat-forming species, shifted species distributions, and led to a greater incidence of disease (Hoegh-Guldberg and Bruno, 2010). Coastal and marine impacts and vulnerability are often associated with collateral effects of climate change such as SLR, ocean warming, and ocean acidification (Box CC-OA). Overfishing, habitat pollution and destruction, and the invasion of species also negatively impact biodiversity and the delivery of ecosystem services (Guarderas et al., 2008; Halpern et al., 2008). Such negative impacts lead to losses that pose significant challenges and costs for societies, particularly in developing countries (Hoegh-Guldberg and Bruno, 2010). For instance, the Ocean Health Index (Halpern et al., 2012), which measures how healthy the coupling of the human-ocean system is for every coastal country (including parameters related to climate change), indicates that CA countries rank among the lowest values. For SA, Suriname stands out with one of the highest scores.

Coastal states of LA and the Caribbean have a human population of more than 610 million, three-fourths of whom live within 200 km of the coast (Guarderas et al., 2008). For instance, studying seven countries in the region (El Salvador, Nicaragua, Costa Rica, Panama, Colombia, Venezuela, Ecuador), Lacambra and Zahedi (2011) found that more than 30% of the population lives in coastal areas directly exposed to climatic events. Large coastal populations are related to the significant transformation marine ecosystems have been undergoing in the region. Fish stocks, places for recreation and tourism, and controls of pests and pathogens are all under pressure (Guarderas et al., 2008; Mora, 2008). Moreover, SLR varied from 2 to 7 mm yr^{-1} between 1950 and 2008 in CA and SA. The Western equatorial border, influenced by the ENSO phenomenon, shows a lower variation (of about 1 mm yr^{-1}) and a range of variation under El Niño events of the same order of magnitude that sustained past changes (Losada et al., 2013). The distribution of population is a crucial factor for inundation impact, with coastal areas being non-homogeneously impacted. A scenario of 1 m SLR would affect some coastal populations in Brazil and the Caribbean islands (see Figure 27-6; ECLAC, 2011a).

27.3.3.1.1. Coastal impacts

Based on trends observed and projections, Figure 27-6 shows how potential impacts may be distributed in the region. (a) *Flooding*: Since flooding probability increases with increasing sea level, one may expect a higher probability of flooding in locations showing >40% of change over the last 60 years in the 100-years total sea level (excluding hurricanes). The figure also identifies urban areas where the highest increase in flooding level has been obtained. (b) *Beach erosion*: It increases with potential sediment transport, thus locations where changes in potential sediment transport have increased over a certain threshold have a higher probability to be eroded. (c) *Sea ports and reliability of coastal structures*: The figure shows locations where, in the case of having a protection structure in place, there is a reduction in the reliability of the structures owing to the increase in the design wave height estimates (ECLAC, 2011a).

27.3.3.1.2. Coastal dynamics

Information on coastal dynamics is based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information, and satellite information. Advanced statistical techniques have been used for obtaining trends including uncertainties (Izaguirre et al., 2013; Losada et al., 2013).

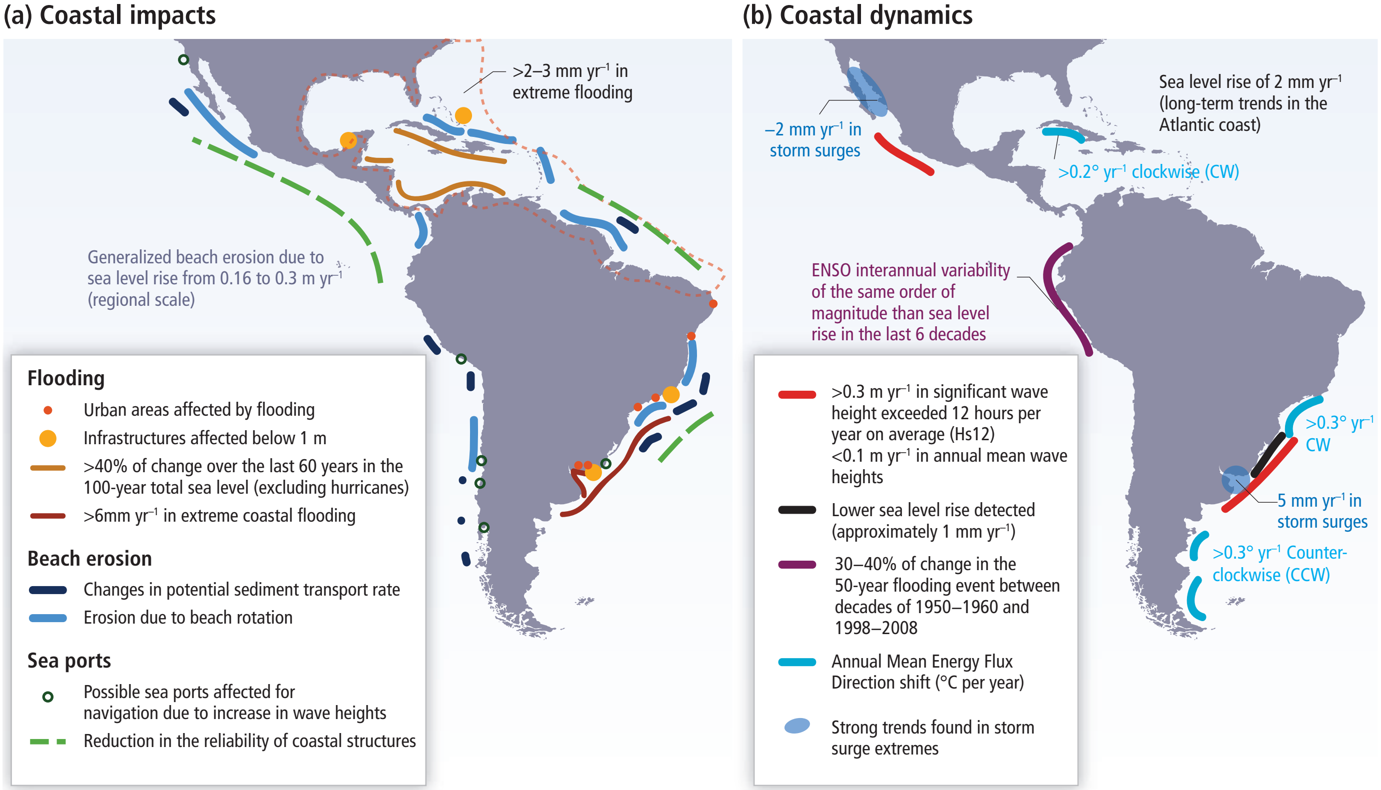


Figure 27-6 | Current and predicted coastal impacts (a) and coastal dynamics (b) in response to climate change. (a) Coastal impacts: Based on trends observed and projections, the figure shows how potential impacts may be distributed in the region (ECLAC, 2011a). ***Flooding***: Since flooding probability increases with increasing sea level, one may expect a higher probability of flooding in locations showing >40% of change over the last 60 years in 100-year total sea level (excluding hurricanes). The figure also identifies urban areas where the highest increase in flooding level has been obtained. ***Beach erosion***: Increases with potential sediment transport, and thus locations where changes in potential sediment transport have increased over a certain threshold have a higher probability of being eroded. ***Sea ports and reliability of coastal structures***: Shows locations where, in the case of having a protection structure in place, there is a reduction in the reliability of the structures due to the increase in the design wave height estimates. (b) Coastal dynamics: Information based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information, and satellite information. Advanced statistical techniques have been used for obtaining trends including uncertainties (Izaguirre et al., 2013; Losada et al., 2013).

The greatest flooding levels (hurricanes not considered) in the region are found in Rio de La Plata area, which combine a 5 mm yr^{-1} change in storm surge with SLR changes in extreme flooding levels (ECLAC, 2011a; Losada et al., 2013). Extreme flooding events may become more frequent because return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected, while at the same time beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast (ECLAC, 2011a).

The majority of the literature concerning climate change impacts for coastal and marine ecosystems considers coral reefs (see also Chapter 5; Box CC-CR), mangroves, and fisheries. Coral reefs are particularly sensitive to climate-induced changes in the physical environment (Baker et al., 2008) to an extent that one-third of the more than 700 species of reef-building corals worldwide are already threatened with extinction (Carpenter et al., 2008). Coral bleaching and mortality are often associated with ocean warming and acidification (Baker et al., 2008). If extreme sea surface temperatures were to continue, the projections using SRES scenarios (A1FI, 3°C sensitivity, and A1B with 2°C and 4.5°C sensitivity) indicate that it is possible that the Mesoamerican coral reef will collapse by mid-century (between 2050 and 2070), causing major economic losses (Vergara, 2009). Extreme high sea surface temperatures have been increasingly documented in the western Caribbean near the coast of CA and have resulted in frequent bleaching events (1993, 1998, 2005, and again in 2010) of the Mesoamerican coral reef, located along the coasts of Belize, Honduras, and Guatemala (Eakin et al., 2010). Reef and also mangrove ecosystems are estimated to contribute greatly to goods and services in economic terms. In Belize, for example, this amount is approximately US$395 to US$559 million annually, primarily through marine-based tourism, fisheries, and coastal protection (Cooper et al., 2008). In the Eastern Tropical Pacific, seascape trace abundance of cement and elevated nutrients in upwelled waters are factors that help explain high bioerosion rates of local coral reefs (Manzello et al., 2008). In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years (Francini-Filho et al., 2008). This estimate is based on coral disease prevalence and progression rate, along with growth rate of *Mussismilia braziliensis*—a major reef-building coral species that is endemic in Brazil. These authors also pointed out that coral diseases intensified between 2005 and 2007 based on qualitative observations since the 1980s and regular monitoring since 2001. They have also predicted that the studied coral species will be nearly extinct in less than a century if the current rate of mortality due to disease is not reversed.

Mangroves are largely affected by anthropogenic activities whether or not they are climate driven. All mangrove forests, along with important ecosystem goods and services, could be lost in the next 100 years if the present rate of loss continues (1 to 2% a year; Duke et al., 2007). Moreover, estimates are that climate change may lead to a maximum global loss of 10 to 15% of mangrove forest by 2100 (Alongi, 2008). In CA and SA, some of the main drivers of loss are deforestation and land conversion, agriculture, and shrimp ponds (Polidoro et al., 2010). The Atlantic and Pacific coasts of CA are some of the most endangered on the planet with regard to mangroves, as approximately 40% of present species are threatened with extinction (Polidoro et al., 2010). Approximately 75% of the global mangrove extension is concentrated in 15 countries, among which Brazil is included (Giri et al., 2011). The rate of survival of original mangroves lies between 12.8 and 47.6% in the Tumaco Bay (Colombia), resulting in ecosystem collapse, fisheries reduction, and impacts on livelihoods (Lampis, 2010). Gratiot et al. (2008) project for the current decade an increase of mean high water levels of 6 cm followed by 90 m shoreline retreat, implying flooding of thousands of hectares of mangrove forest along the coast of French Guiana.

Peru and Colombia are two of the eight most vulnerable countries to climate change impacts on fisheries, owing to the combined effect of observed and projected warming, to species and productivity shifts in upwelling systems, to the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities (Allison et al., 2009). Fisheries production systems are already pressured by overfishing, habitat loss, pollution, invasive species, water abstraction, and damming (Allison et al., 2009). In Brazil, a decadal rate of 0.16 trophic level decline (as measured by the Marine Trophic Index, which refers to the mean trophic level of the catch) has been detected through most of the northeastern coast, between 1978 and 2000, which is one of the highest rates documented in the world (Freire and Pauly, 2010).

Despite the focus in the literature on corals, mangroves, and fisheries, there is evidence that other benthic marine invertebrates that provide key services to reef systems, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change (Przeslawski et al., 2008). The same applies for seagrasses, for which a worldwide decline has accelerated from a median of 0.9% yr^{-1} before 1940 to 7% yr^{-1} since 1990, which is comparable to rates reported for mangroves, coral reefs, and tropical rainforests, and place seagrass meadows among the most threatened ecosystems on earth (Waycott et al., 2009).

A major challenge of particular relevance at local and global scales will be to understand how these physical changes will impact the biological environment of the ocean (e.g., Gutiérrez et al., 2011b), as the Humboldt Current system—flowing along the west coast of SA—is the most productive upwelling system of the world in terms of fish productivity.

27.3.3.2. Adaptation Practices

Designing marine protected areas (MPAs) that are resilient to climate change is a key adaptation strategy in coastal and marine environments (McLeod et al., 2009). By 2007, LA and the Caribbean (which includes CA and SA countries) had more than 700 MPAs established covering around 1.5% of the coastal and shelf waters, most of which allow varying levels of extractive activities (Guarderas et al., 2008). This protected area cover, however, is insufficient to preserve important habitats or connectivity among populations at large biogeographic scales (Guarderas et al., 2008).

Nevertheless, examples of adaptation in CA and SA are predominantly related to MPAs. In Brazil, a protected area type known as “Marine Extractive Reserves” currently benefits 60,000 small-scale fishermen along the coast (de Moura et al., 2009). Examples of fisheries’ co-management, a form of a participatory process involving local fishermen communities, government, academia, and non-governmental organizations, are reported to favor a balance between conservation of marine fisheries, coral reefs, and mangroves on the one hand (Francini-Filho and de Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations on the other (de Moura et al., 2009; Hastings, 2011).

Significant financial and human resources are expended annually in the marine reserves to support reef management efforts. These actions, including the creation of marine reserves to protect from overfishing, improvement of watershed management, and protection or replanting of

Frequently Asked Questions

FAQ 27.2 | Can payment for ecosystem services be used as an effective way to help local communities adapt to climate change?

Ecosystems provide a wide range of basic services, such as providing breathable air, drinkable water, and moderating flood risk (*very high confidence*). Assigning values to these services and designing conservation agreements based on these (broadly known as payment for ecosystem services, or PES) can be an effective way to help local communities adapt to climate change. It can simultaneously help protect natural areas and improve livelihoods and human well-being (*medium confidence*). However, during design and planning, a number of factors need to be taken into consideration at the local level to avoid potentially negative results. Problems can arise if (1) the plan sets poor definitions about whether the program should focus just on actions to be taken or the end result of those actions, (2) many perceive the initiative as commoditization of nature and its intangible values, (3) the action is inefficient to reduce poverty, (4) difficulties emerge in building trust between various stakeholders involved in agreements, and (5) there are eventual gender or land tenure issues.

coastal mangroves, are proven tools to improve ecosystem functioning. In Mesoamerican reefs Carilli et al. (2009) found out that such actions may also actually increase the thermal tolerance of corals to bleaching stress and thus the associated likelihood of surviving future warming.

In relation to mangroves, in addition to marine protected areas that include mangroves and functionally linked ecosystems, Gilman et al. (2008) list a number of other relevant adaptation practices: coastal planning to facilitate mangrove migration with SLR, management of activities within the catchment that affect long-term trends in the mangrove sediment elevation, better management of non-climate stressors, and the rehabilitation of degraded areas. However, such types of practices are not frequent in the region.

On the other hand, the implementation of adaptation strategies to SLR or to address coastal erosion is more commonly seen in many countries in the region (Lacambra and Zahedi, 2011). For instance, redirecting new settlements to better-protected locations and to promote investments in appropriate infrastructure shall be required in the low elevation coastal zones (LECZ) of the region, particularly in lower income countries with limited resources, which are especially vulnerable. The same applies to countries with high shares of land (e.g., Brazil ranking 7th worldwide of the total land area in the LECZ) and/or population (e.g., Guyana and Suriname ranking 2nd and 5th by the share of population in the LECZ, having respectively 76 and 55% of their populations in such areas) (McGranahan et al., 2007). Adaptation will demand effective and enforceable regulations and economic incentives, all of which require political will as well as financial and human capital (McGranahan et al., 2007). Adaptive practices addressing river flooding are also being made available as in the study of Casco et al. (2011) for the low Paraná River in Argentina (see also Chapters 5 and 6 for coastal and marine adaptation).

27.3.4. Food Production Systems and Food Security

27.3.4.1. Observed and Projected Impacts and Vulnerabilities

Increases in the global demand for food and biofuels promoted a sharp increase in agricultural production in SA and CA, associated mainly with the expansion of planted areas (see Chapter 7), and this trend is predicted to continue in the future (see Section 27.2.2.1). Ecosystems are being and will be affected in isolation and synergistically by climate variability/change and land use changes, which are comparable drivers of environmental change (see Sections 27.2.2.1, 27.3.2.1). By the end of the 21st century (13 GCMs, under SRES A1B and B1) SA could lose between 1 and 21% of its arable land due to climate change and population growth (Zhang and Cai, 2011).

Optimal land management could combine efficient agricultural and biofuels production with ecosystem preservation under climate change. However, current practices are leading to a deterioration of ecosystems throughout the continent (see Section 27.3.2). In southern Brazilian Amazonia water yields (mean daily discharge (mm d^{-1})) were near four times higher in soy than in forested watersheds, and showed greater seasonal variability (Hayhoe et al., 2011). In the Argentinean Pampas current land use changes disrupt water and biogeochemical cycles and may result in soil salinization, altered carbon and nitrogen storage, surface runoff, and stream acidification (Nosetto et al., 2008; Berthrong et al., 2009; Farley et al., 2009). In central Argentina flood extension was associated with the dynamics of groundwater level, which has been influenced by precipitation and land use change (Viglizzo et al., 2009).

27.3.4.1.1. Observed impacts

The SESA region has shown significant increases in precipitation and wetter soil conditions during the 20th century (Giorgi, 2002; see Table 27-1) that benefited summer crops and pastures productivity, and contributed to the expansion of agricultural areas (Barros, 2008a; Hoyos et al., 2012). Wetter conditions observed during 1970–2000 (in relation to 1930–1960) led to increases in maize and soybean yields (9 to 58%) in Argentina, Uruguay, and southern Brazil (Magrin et al., 2007b). Even if rainfall projections estimate increases of about 25% in SESA for 2100, agricultural systems could be threatened if climate reverts to a drier situation due to inter-decadal variability. This could put at risk the viability of continuous agriculture in marginal regions of Argentina's Pampas (Podestá et al., 2009). During the 1930s and 1940s, dry and windy conditions together with deforestation, overgrazing, overcropping, and non-suitable tillage produced severe dust storms, cattle mortality, crop failure, and rural migration (Viglizzo and Frank, 2006).

At the global scale (see Chapter 7), warming since 1981 has reduced wheat, maize, and barley productivity, although the impacts were small compared with the technological yield gains over the same period (Lobell and Field, 2007). In central Argentina, simulated potential wheat yield—without considering technological improvements—has been decreasing at increasing rates since 1930 (1930–2000: –28 kg ha^{-1} yr^{-1}; 1970–2000: –53 kg ha^{-1} yr^{-1}) in response to increases in minimum temperature during October–November (1930–2000: +0.4°C per decade; 1970–2000: +0.6°C per decade) (Magrin et al., 2009). The observed changes in the growing season temperature and precipitation between 1980 and 2008 have slowed the positive yield trends due to improved genetics in Brazilian wheat, maize, and soy, as well as Paraguayan soy. In contrast, rice in Brazil and soybean in Argentina have benefited from precipitation and temperature trends (Lobell et al., 2011). In Argentina, increases in soybean yield may be associated with weather types that favor the entry of cold air from the south, reducing thermal stress during flowering and pod set, and weather types that increase the probability of dry days at harvest (Bettolli et al., 2009).

27.3.4.1.2. Projected impacts

Assessment of future climate scenarios implications to food production and food security (see Table 27-5) shows a large range of uncertainty across the spectrum of climate models and scenarios. One of the uncertainties is related to the effect of CO_2 on plant physiology. Many crops (such as soybean, common bean, maize, and sugarcane) can probably respond with an increasing productivity as a result of higher growth rates and better water use efficiency. However, food quality could decrease as a result of higher sugar contents in grain and fruits, and decreases in the protein content in cereals and legumes (DaMatta et al., 2010). Uncertainties associated with climate and crop models, as well as with the uncertainty in human behavior, potentially lead to large error bars on any long-term prediction of food output. However, the trends presented here represent the current available information.

In SESA, some crops could be benefitted until mid-21st century if CO$_2$ effects are considered (see Table 27-5), although interannual and decadal climate variability could provoke important damages. In Uruguay and Argentina, productivity could increase or remain almost stable until the 2030s–2050s depending on the SRES scenario (ECLAC, 2010c). Warmer and wetter conditions may benefit crops toward the southern and western zone of the Pampas (Magrin et al., 2007c; ECLAC, 2010c). In south Brazil, irrigated rice yield (Walter et al., 2010) and bean productivity (Costa et al., 2009) are expected to increase. If technological improvement is considered, the productivity of common bean and maize could increase

Table 27-5 | Impacts on agriculture.

Country/region		Activity	Time slice	Special report on Emissions Scenarios (SRES)	CO$_2$	Changes	Source
Southeastern South America	Uruguay	Annual crops	2030/2050/2070/2100	A2		+185/–194/–284/–508	ECLAC (2010a)[1]
			2030/2050	B2		+92/+169	
		Livestock	2030/2050/2070/2100	A2		+174/–80/–160/–287	
			2030/2050	B2		+136/+182	
		Forestry	2030/2050/2070/2100	A2		+15/+39/+52/+19	
			2030/2050/2070	B2		+6/+13/+18	
	Paraguay	Cassava	2020/2050/2080	A2		+16/+22/+22	ECLAC (2010a)
		Wheat	2020/2050/2080	A2		+4/–9/–13	
				B2		–1/+1/–5	
		Maize	2020/2050/2080	A2		+3/+3/+8	
				B2		+3/+1/+6	
		Soybean	2020/2050/2080	A2		0/–10/–15	
				B2		0/–15/–2	
		Bean	2020/2050/2080	A2		–1/+10/+16	
	Argentina	Maize	2080	A2/B2	N	–24/–15	ECLAC (2010a)
				A2/B2	Y	+1/0	
		Soybean	2080	A2/B2	N	–25/–14	
				A2/B2	Y	+14/+19	
		Wheat	2080	A2/B2	N	–16/–11	
				A2/B2	Y	+3/+3	
		Soybean	2020/2050/2080	A2	Y	+24/+42/+48	Travasso et al. (2008)
				B2	Y	+14/+30/+33	
		Maize	2020/2050/2080	A2	Y	+8/+11/+16	
				B2	Y	+5/+5/+9	
	Brazil	Rice		2CO$_2$/0ºC	Y	+60	Walter et al. (2010)
				2CO$_2$/+5ºC	Y	+30	
		Bean	2050/2080	A2	N	Up to –30%	Costa et al. (2009)[2]
			2020/2050/2080	A2+CO$_2$	Y	Up to: +30/+30/+45	
				A2+CO$_2$+T	Y	Up to: +45/+75/+90	
		Maize	2050/2080	A2	N	Up to –30%	
				A2+CO$_2$	Y	Near to –15%	
			2020/2050/2080	A2+CO$_2$+T	Y	Up to: +40/+60/+90	
		Arabica coffee		+0 to +1ºC		+1.5%	Zullo et al. (2011)[3]
				+1 to +2ºC		+15.9%	
				+2 to +3ºC		+28.6%	
				+3 to +4ºC		–12.9%	
State of São Paulo, Brazil		Sugarcane	2040	Pessimistic		+6%	Marin et al. (2009)
				Optimistic		+2%	

Continued next page →

between 40 and 90% (Costa et al., 2009). Sugarcane production could benefit, as warming could allow the expansion of planted areas toward the south, where low temperatures are a limiting factor (Pinto et al., 2008). Increases in crop productivity could reach 6% in São Paulo state toward 2040 (Marin et al., 2009). In Paraguay the yields of soybean, maize, and wheat could have slight variations (–1.4 to +3.5%) until 2020 (ECLAC, 2010a).

In Chile and western Argentina, yields could be reduced by water limitation. In central Chile (30°S to 42°S) temperature increases, reduction in chilling hours, and water shortages may reduce productivity of winter crops, fruits, vines, and radiata pine. Conversely, rising temperatures, more moderate frosts, and more abundant water will *very likely* benefit all species toward the south (ECLAC, 2010a; Meza and da Silva, 2009). In northern Patagonia (Argentina) fruit and vegetable growing could be negatively affected because of a reduction in rainfall and in average flows in the Neuquén River basin. In the north of the Mendoza basin (Argentina) increases in water demand, due to population growth, may compromise the availability of subterranean water for irrigation, pushing up irrigation costs and forcing many producers out of farming toward 2030. Also, water quality could be reduced by the worsening of existing salinization processes (ECLAC, 2010a).

In CA, NEB, and parts of the Andean region (Table 27-5) climate change could affect crop yields, local economies, and food security. It is *very likely* that growing season temperatures in parts of tropical SA, east of the Andes, and CA exceed the extreme seasonal temperatures documented from 1900 to 2006 at the end of this century (23 GCMs), affecting regional agricultural productivity and human welfare (Battisti and Naylor, 2009). For NEB, declining crop yields in subsistence crops such as beans,

Table 27-5 (continued)

Country/region	Activity	Time slice	Special report on Emissions Scenarios (SRES)	CO$_2$	Changes	Source
Northeastern Brazil	Cassava	2020–2040		N	0 to –10	Lobell et al. (2008)
	Maize	2020–2040		N	0 to –10	
	Rice	2020–2040		N	–1 to –10	
	Wheat	2020–2040		N	–1 to –14	
	Maize				–20 to –30	Margulis et al. (2010)
	Bean				–20 to –30	
	Rice				–20 to –30	
	Cowpea bean		+1.5°C		–26%	Silva et al. (2010)[3]
			+3.0°C		–44%	
			+5.0°C		–63%	
Central America	Maize	2030/2050/2070/2100	A2		0/0/–10/–30	ECLAC (2010a)
	Bean	2030/2050/2070/2100	A2		–4/–19/–29/–87	
	Rice	2030/2050/2070/2100	A2		+3/–3/–14/–63	
	Rice	2020–2040		N	0 to –10	Lobell et al. (2008)
	Wheat	2020–2040		N	–1 to –9	
Panamá	Maize	2020/2050/2080	A2	Y	–0.5/+2.4/+4.5	Ruane et al. (2011)
			B1	Y	–0.1/–0.8/+1.5	
Andean Region	Wheat	2020–2040		N	–14 to +2	Lobell et al. (2008)
	Barley	2020–2040		N	0 to –13	
	Potato	2020–2040		N	0 to –5	
	Maize	2020–2040		N	0 to –5	
Colombia	All main crops	2050	17 GCMs (A2)		80% of crops impacted in more than 60% of current cultivated areas	Ramirez et al. (2012)
Chile (34.6° to 38.5°S)	Maize	2050	A1FI	Y	–5% to –10%	Meza and Silva (2009)
	Wheat	2050	A1FI	Y	–10% to –20%	

Notes:
Changes are expressed as differences in relative yield (%), except for [1] and [3].

N: Without considering CO$_2$ biological effects.
Y: Considering CO$_2$ biological effects.
2CO$_2$: Considering double CO$_2$ concentration (780 ppm CO$_2$).
T: Considering technological improvement (genetic changes).

[1] Gross value of production (millions of US$).
[2] Huge spatial variability; values are approximated.
[3] Changes in the percentage of areas with low climate risk.

corn, and cassava are projected (Lobell et al., 2008; Margulis et al., 2010). In addition, increases in temperature could reduce the areas currently favorable to cowpea bean (Silva et al., 2010). The highest warming foreseen for 2100 (5.8°C, under SRES A2 scenario) could make the coffee crop unfeasible in Minas Gerais and São Paulo (southeast Brazil) if no adaptation action is accomplished. Thus, the coffee crop may have to be transferred to southern regions where temperatures are lower and the frost risk will be reduced (Camargo, 2010). With +3ºC, Arabica coffee is expected to expand in the extreme south of Brazil, the Uruguayan border, and northern Argentina (Zullo Jr. et al., 2011). Brazilian potato production could be restricted to a few months in currently warm areas, which today allow potato production year-round (Lopes et al., 2011). Large losses of suitable environments for the "Pequi" tree (*Caryocar brasiliense*, an economically important Cerrado fruit tree) are projected by 2050, affecting mainly the poorest communities in central Brazil (Nabout et al., 2011). In the Amazon region soybean yields would be reduced by 44% in the worst scenario (Hadley Centre climate prediction model 3 (HadCM3) and no CO_2 fertilization) by 2050 (Lapola et al., 2011). By 2050, according to 17 GCMs under SRES A2 scenario, 80% of crops will be impacted in more than 60% of current areas of cultivation in Colombia, with severe impacts in perennial and exportable crops (Ramirez-Villegas et al., 2012).

Teixeira et al. (2013) identified hotspots for heat stress toward 2071–2100 under the A1B scenario and suggest that rice in southeast Brazil, maize in CA and SA, and soybean in central Brazil will be the crops and zones most affected by increases in temperature.

In CA, changes projected in climate could severely affect the poorest population and especially their food security, increasing the current rate of chronic malnutrition. Currently, Guatemala is the most food insecure country by percentage of the population (30.4%) and the problem has been increasing in recent years (FAO, WFP, and IFAD, 2012). The impact of climate variability and change is a great challenge in the region. As an example, the recent rust problem on the coffee sector of 2012–2013 has affected nearly 600,000 ha (55% of the total area) (ICO, 2013) and will reduce employment by 30 to 40% for the harvest 2013–2014 (FEWS NET, 2013). At least 1.4 million people in Guatemala, El Salvador, Honduras, and Nicaragua depend on the coffee sector, which is very susceptible to climate variations. In Panamá, the large interannual climate variability will continue to be the dominant influence on seasonal maize yield into the coming decades (Ruane et al., 2013). In the future, warming conditions combined with more variable rainfall are expected to reduce maize, bean, and rice productivity (ECLAC, 2010c); rice and wheat yields could decrease up to 10% by 2030 (Lobell et al., 2008; *medium confidence*). In CA, nearly 90% of agricultural production destined for internal consumption is composed by maize (70%), bean (25%), and rice (6%) (ECLAC, 2011d).

Climate change may also alter the current scenario of plant diseases and their management, having effects on productivity (Ghini et al., 2011). In Argentina, years with severe infection of late cycle diseases in soybean could increase; severe outbreaks of the Mal de Rio Cuarto virus in maize (natural vectors: *Delphacodes kuscheli* and *Delphacodes hayward*) could be more frequent; and wheat head fusariosis will increase slightly in the south of the Pampas region by the end of the century (ECLAC, 2010a). In Brazil favorable areas for soybean and coffee rusts will move toward the south, particularly for the hottest scenario of 2080 (Alves et al., 2011). Potato late blight (*Phytophtora infestans*) severity is expected to increase in Peru (Giraldo et al., 2010).

The choice of livestock species could change in the future. For example, by 2060, under a hot and dry scenario, beef and dairy cattle, pig, and chicken production choice could decrease between 0.9 and 3.2%, while sheep election could increase by 7% mainly in the Andean countries (Seo et al., 2010). Future climate could strongly affect milk production and feed intake in dairy cattle in Brazil, where substantial modifications in areas suitable for livestock, mainly in the Pernambuco region, are expected (da Silva et al., 2009). Warming and drying conditions in Nicaragua could reduce milk production, mainly among farmers who are already seriously affected under average dry season conditions (Lentes et al., 2010).

Climate change impact on regional welfare will depend not only on changes in yield, but also in international trade. According to Hertel et al. (2010), by 2030, global cereal price could change between increases of 32% (low-productivity scenario) or decreases of 16% (optimistic yield scenario). A rise in prices could benefit net exporting countries such as Brazil, where gains from terms of trade shifts could outweigh the losses due to climate change. Despite experiencing significant negative yield shocks, some countries tend to gain from higher commodity prices. However, most poor household are food purchasers and rising commodity prices tend to have a negative effect on poverty (von Braun, 2007). According to Chapter 7, increases in prices during 2007–2009 led to rising poverty in Nicaragua.

27.3.4.2. Adaptation Practices

Genetic advances and suitable soil and technological management may induce an increase in some crops' yield despite unfavorable future climate conditions. In Argentina, genetic techniques, specific scientific knowledge, and land use planning are viewed as promising sources of adaptation (Urcola et al., 2010). Adjustments in sowing dates and fertilization rates could reduce negative impacts or increase yields in maize and wheat crops in Argentina and Chile (Magrin et al., 2009; Meza and da Silva, 2009; Travasso et al., 2009b). Furthermore, in central Chile and southern Pampas in Argentina warmer climates could allow performing two crops per season, increasing productivity per unit land (Monzon et al., 2007; Meza et al., 2008). In Brazil, adaptation strategies for coffee crops include planting at high densities, vegetated soil, accurate irrigation and breeding programs, and shading management system (arborization) (Camargo, 2010). Shading is also used in Costa Rica and Colombia. In south Brazil, a good option for irrigated rice could be to plant early cultivars (Walter et al., 2010).

Water management is another option for needed better preparedness regarding water scarcity (see Section 27.3.1). In Chile, the adoption of water conservation practices depends on social capital, farm size, and land use; and the adoption of technologies that require investment depend on the access to credit and irrigation water subsidies (Jara-Rojas et al., 2012). Deficit irrigation could be an effective measure for water savings in dry areas such as the Bolivian Altiplano (quinoa), central Brazil (tomatoes), and northern Argentina (cotton) (Geerts and Raes, 2009). In rainfed crops adaptive strategies might need to look at the harvest, storage, temporal transfer, and efficient use of rainfall water. In addition, some agronomic practices such as fallowing, crop sequences, groundwater management, no-till operations, cover crops, and fertilization could improve the adaptation to water scarcity (Quiroga and Gaggioli, 2011).

One approach to adapting to future climate change is by assisting people to cope with current climate variability (Baethgen, 2010), for which the use of climatic forecasts in agricultural planning presents a measure. Increased access and improvement of climate forecast information enhances the ability of farmers in the Brazilian Amazon to cope with El Niño impacts (Moran et al., 2006). The Southern Oscillation Index for maize and the South Atlantic Sea Surface Temperature for soybean and sunflower were the best indicators of annual crop yield variability in Argentina (Travasso et al., 2009a). Another possibility to cope with extreme events consists in transferring weather-related risks by using different types of rural insurance (Baethgen, 2010). Index insurance is one mechanism that has been recently introduced to overcome obstacles to traditional agricultural and disaster insurance markets (see Chapter 15). For the support of such parametric agricultural insurance, a Central American climate database was recently established (SICA, 2013).

Local and indigenous knowledge has the potential to bring solutions even in the face of rapidly changing climatic conditions (Folke et al., 2002; Altieri and Koohafkan, 2008), although migration, climate change, and market integration are reducing indigenous capacity for dealing with weather and climate risk (Pérez et al., 2010; Valdivia et al., 2010). Crop diversification is used in the Peruvian Andes to suppress pest outbreaks and dampen pathogen transmission (Lin, 2011). In Honduras, Nicaragua, and Guatemala traditional practices have proven more resilient to erosion and runoff and have helped retain more topsoil and moisture (Holt-Gimenez, 2002). In El Salvador, if local sustainability efforts continue, the future climate vulnerability index could only slightly increase by 2015 (Aguilar et al., 2009). Studies with Indigenous farmers in highland Bolivia and Peru indicate that constraints on access to key resources must be addressed for reducing vulnerability over time (McDowell and Hess, 2012; Sietz et al., 2012). In Guatemala and Honduras adaptive response between coffees farmers is mainly related to land availability, while participation in organized groups and access to information contribute to adaptive decision making (Tucker et al., 2010). Otherwise, adaptation may include an orientation toward non-farming activities to sustain their livelihoods and be able to meet their food requirements (Sietz, 2011). In NEB increasing vulnerability related to degradation of natural resources (due to overuse of soil and water) encouraged farmers toward off-farm activities; however, they could not improve their well-being (Sietz et al., 2006, 2011). Migration is another strategy in ecosystems and regions at high risk of climate hazards (see Section 27.3.1.1). During 1970–2000 LA and the Caribbean has had a great rate of net migration per population in the dryland zones (de Sherbinin et al., 2012). In CA nearly 25% of the surveyed households reported some type of migration during the coffee crisis (Tucker et al., 2010). Some migrations—for example, Guatemala, 1960s–1990s; El Salvador, 1950s–1980s; NEB, 1960s–present—have provoked conflict in receiving areas (Reuveny, 2007).

Shifting in agricultural zoning has been an autonomous adaptation observed in SA. In Argentina., for example, increases in precipitation promoted the expansion of the agricultural frontier to the west and north of the traditional agricultural area, resulting in environmental damage that could be aggravated in the future (República Argentina, 2007; Barros, 2008b). Adjustment of production practices—like those of farmers in the semi-arid zones of mountain regions of Bolivia, which began as they noticed strong changes in the climate since the 1980s, including upward migration of crops, selection of more resistant varieties, and water capturing—presents a further adaptation measure (PNCC, 2007).

Organic systems could enhance adaptive capacity as a result of the application of traditional skills and farmers' knowledge, soil fertility-building techniques, and a high degree of diversity (ITC, 2007). As mentioned previously, crop diversity, local knowledge, soil conservation, and economic diversity are all documented strategies for managing risk in CA and SA. A controversial but important issue in relation to adaptation is the use of genetically modified plants to produce food, with biotech crops being a strategy to cope with the needed food productivity increase considering the global population trend (see Chapter 7). Brazil and Argentina are the second and third fastest growing biotech crop producers in the world after the USA (Marshall, 2012). However, this option is problematic for the small farms (Mercer et al., 2012), which are least favorable toward GMO (Soleri et al., 2008). According to Eakin and Wehbe (2009) some practices could be an adaptive option for specific farm enterprises, but may have maladaptive implications at regional scales, and over time become maladaptive for individual enterprises.

27.3.5. Human Settlements, Industry, and Infrastructure

According to the World Bank database (World Bank, 2012) CA and SA are the geographic regions with the second highest urban population (79%), behind North America (82%) and well above the world average (50%). Therefore this section focuses on assessing the literature on climate change impacts and vulnerability of urban human settlements. The information provided should be complemented with other sections of the chapter (see Sections 27.2.2.2, 27.3.1, 27.3.3, 27.3.7).

27.3.5.1. Observed and Projected Impacts and Vulnerabilities

Urban human settlements suffer from many of the vulnerabilities and impacts already presented in several sections of this chapter. The provision of critical resources and services as already discussed in the chapter—water, health, and energy—and of adequate infrastructure and housing remain determinants of urban vulnerability that are enhanced by climate change (Smolka and Larangeira, 2008; Winchester, 2008; Roberts, 2009; Romero-Lankao et al., 2012c, 2013b).

Water resource management (see Section 27.3.1) is a major concern for many cities that need to provide both drinking water and sanitation (Henríquez Ruiz, 2009). More than 20% of the population in the region are concentrated in the largest city in each country (World Bank, 2012), hence water availability for human consumption in the region's megacities (e.g., São Paulo, Santiago, Lima, Buenos Aires) is of great concern. In this context, reduction in glacier and snowmelt related runoff in the

Box 27-2 | Vulnerability of South American Megacities to Climate Change: The Case of the Metropolitan Region of São Paulo

Research in the Metropolitan Region of São Paulo (MRSP), between 2009 and 2011, represents a comprehensive and interdisciplinary project on the impacts of climate variability and change, and vulnerability of Brazilian megacities. Studies derived from this project (Nobre et al., 2011; Marengo et al., 2013b) identify the impacts of climate extremes on the occurrence of natural disasters and human health. These impacts are linked to a projected increase of 38% in the extension of the urban area of the MRSP by 2030, accompanied by a projected increase in rainfall extremes. These may induce an intensification of urban flash floods and landslides, affecting large populated areas already vulnerable to climate extremes and variability. The urbanization process in the MRSP has been affecting the local climate, and the intensification of the heat island effect to a certain degree may be responsible for the 2°C warming detected in the city during the last 50 years (Nobre et al., 2011). This warming has been further accompanied by an increase in heavy precipitation as well as more frequent warm nights (Silva Dias et al., 2012; Marengo et al., 2013b). By 2100, climate projections based on data from 1933–2010 show an expected warming between 2°C and 3°C in the MRSP, together with a possible doubling of the number of days with heavy precipitation in comparison to the present (Silva Dias et al., 2012; Marengo et al., 2013b).

With the projected changes in climate and in the extension of the MRSP (Marengo et al., 2013b) more than 20% of the total area of the city could be potentially affected by natural disasters. More frequent floods may increase the risk of leptospirosis, which, together with increasing air pollution and worsening environmental conditions that trigger the risk of respiratory diseases, would leave the population of the MRSP more vulnerable. Potential adaptation measures include a set of strategies that need to be developed by the MRSP and its institutions to face these environmental changes. These include improved building controls to avoid construction in risk areas, investment in public transportation, protection of the urban basins, and the creation of forest corridors in the collecting basins and slope regions. The lessons learned suggest that the knowledge on the observed and projected environmental changes, as well as on the vulnerability of populations living in risk areas, is of great importance for defining adaptation policies that in turn constitute a first step toward building resilient cities that in turn improve urban quality of life in Brazil.

Andes poses important adaptation challenges for many cities, for example, the metropolitan areas of Lima, La Paz/El Alto, and Santiago de Chile (Bradley et al., 2006; Hegglin and Huggel, 2008; Melo et al., 2010). Flooding is also a preoccupation in several cities. In São Paulo for example, according to Marengo et al. (2009b, 2013b) the number of days with rainfall above 50 mm were almost zero during the 1950s and now they occur between two and five times per year (2000–2010). The increase in precipitation is one of the expected risks affecting the city of São Paulo as presented in Box 27-2. Increases in flood events during 1980–2000 have been observed also in the Buenos Aires province and Metropolitan Area (Andrade and Scarpati, 2007; Barros et al., 2008; Hegglin and Huggel, 2008; Nabel et al., 2008). There are also the combined effects of climate change impacts, human settlements' features, and other stresses, such as more intense pollution events (Moreno, 2006; Nobre, 2011; Nobre et al., 2011; Romero-Lankao et al., 2013b) and more intense hydrological cycles from urban heat island effects. In terms of these combined effects, peri-urban areas and irregular settlements pose particular challenges to urban governance and risk management given their scale, lack of infrastructure, and socioeconomic fragility (Romero-Lankao et al., 2012a).

Changes in prevailing urban climates have led to changing patterns of disease vectors, and water-borne disease issues linked to water availability and subsequent quality (see Section 27.3.7). The influence of climate change on particulate matter and other local contaminants is another concern (Moreno, 2006; Romero-Lankao et al., 2013b). It is important to highlight the relationship between water and health, given the problems of water stress and intense precipitation events affecting many urban centers. Both relate to changing disease risks, as well as wider problems of event-related mortalities and morbidity, and infrastructure and property damage. These risks are compounded for low-income groups in settlements with little or no service provision, for example, waste collection, piped drinking water, and sanitation (ECLAC, 2008). Existing cases of flooding, air pollution, and heat waves reveal that not only low-income groups are at risk, but also that wealthier sectors are not spared. Factors such as high-density settlement (Barros et al., 2008) and the characteristics of some hazards explain this—for example, poor and wealthy alike are at risk from air pollution and temperature in Santiago de Chile and Bogotá (Romero-Lankao et al., 2012b, 2013b).

There are also other climate change risks in terms of economic activity location and impacts on urban manufacturing and service workers (e.g., thermal stress; Hsiang, 2010) and the forms of urban expansion or sprawl into areas where ecosystem services may be compromised and risks enhanced (e.g., floodplains). Both processes are also related to rising motorization rates that facilitate suburban development and new regional agglomerations that bring pressure to bear on land uses that favor infiltration, surface cooling, and biodiversity; the number of light vehicles in LA and the Caribbean is expected to double between 2000 and 2030, and be three times the 2000 figure by 2050 (Samaniego, 2009).

While urban populations face diverse social, political, economic, and environmental risks in daily life, climate change adds a new dimension to these risk settings (Pielke, Jr. et al., 2003; Roberts, 2009; Romero-Lankao and Qin, 2011). Because urban development remains fragile in many cases, with weak planning responses, climate change can compound existing challenges. The probabilities and magnitudes of these events in each urban center will differ significantly according to socioeconomic, institutional, and physical contexts.

27.3.5.2. Adaptation Practices

The direct and indirect effects of climate change such as flooding, heat islands, and food insecurity present cities with a set of challenges and opportunities for mainstreaming flood management, warning systems, and other adaptation responses with sustainability goals (Bradley et al., 2006; Hegglin and Huggel, 2008; Hardoy and Pandiella, 2009; Romero-Lankao, 2010, 2012a; Romero-Lankao et al., 2013a).

Urban populations, economic activities, and authorities have a long experience of responding to climate-related hazards, particularly through disaster risk management, for example, Tucuman and San Martin, Argentina (Plaza and Pasculi, 2007; Sayago et al., 2010), and land use and economic development planning to a limited extent (Barton, 2009). Climate policies can build on these. Local administrations participate in the International Council for Local Environmental Initiatives (ICLEI), Cities Climate Leadership Group (C40), Inter-American Development Bank (IDB), Emerging and Sustainable Cities Initiative (ESCI) (IDB, 2013), and other networks, demonstrating their engagement in the generation of more climate-resilient cities. In smaller settlements, there is less capacity for adequate responses, for example, climate change and vulnerability information (Hardoy and Romero-Lankao, 2011). Policies, plans, and programs are required to reduce social vulnerability, and identify and reduce potential economic effects of climate on the local economy. Rio de Janeiro, for example, with its coastline property and high dependence on tourists (and their perceptions of risk), cannot ignore these climate-related hazards (Gasper et al., 2011).

Poverty and vulnerability, as interlinked elements of the adaptation challenge in CA and SA, remain pivotal to understanding how urban climate policies can be streamlined with broader development issues and not solely the capacity to respond to climate change (Hardoy and Pandiella, 2009; Winchester and Szalachman, 2009; Hardoy and Romero-Lankao, 2011). These broader links include addressing the determinants of vulnerability (e.g., access to education, health care, and infrastructure, and to emergency response systems (Romero-Lankao, 2007a; Romero-Lankao and Qin, 2011)). Among these response options, a focus on social assets has been highlighted by Rubin and Rossing (2012), rather than a purely physical asset focus.

Much urbanization involves in-migrating or already resident, low-income groups and their location in risk-prone zones (da Costa Fereira et al., 2011). The need to consider land use arrangements, particularly urban growth on risk-prone zones, as part of climate change adaptation highlights the role of green areas that mitigate the heat island effect and reduce risks from landslides and flooding (Rodríguez Laredo, 2011; Krellenberg et al., 2013).

In the case of governance frameworks, there is clear evidence that incorporation of climate change considerations into wider city planning is still a challenge, as are more inter-sectoral and participative processes that have been linked to more effective policies (Barton, 2009, 2013; de Oliveira, 2009; Romero-Lankao et al., 2013a). Several metropolitan adaptation plans have been generated over the last 5 years, for example, Bogotá, Buenos Aires, Esmeraldas, Quito, and São Paulo, although for the most part they have been restricted to the largest conglomerations and are often included as an addition to mitigation plans (Romero-Lankao, 2007b; Carmin et al., 2009; Romero-Lankao et al., 2012b, 2013a; Luque et al., 2013).

27.3.6. Renewable Energy

27.3.6.1. Observed and Projected Impacts and Vulnerabilities

Table 27-6 shows the relevance of renewable energy in the LA energy matrix as compared to the world for 2009 according to IEA statistics (IEA, 2012). Hydropower is the most representative source of renewable energy and therefore analyzed separately (see the case study in Section 27.6.1.). Geothermal energy is not discussed, as it is assumed that there is no impact of climate change on the effectiveness of this energy type (Arvizu et al., 2011).

Hydro, wind energy, and biofuel production might be sensitive to climate change in Brazil (de Lucena et al., 2009). With the vital role that renewable energy plays in mitigating the effects of climate change, being by far the most important sources of non-hydro renewable energy in SA and CA, this sensitivity demands the implementation of renewable energy projects that will increase knowledge on the crops providing bioenergy.

For historical reasons, CA and SA developed sugarcane as bioenergy feedstock. Brazil accounts for the most intensive renewable energy production as bioethanol, which is used by the majority of the cars in the country (Goldemberg, 2008) whereas biodiesel comprises 5% of all diesel nationwide. With the continent's long latitudinal length, the expected impacts of climate change on plants will be complex owing to a wide variety of climate conditions, so that different crops would have to be used in different regions. In Brazil, most of the biodiesel comes from soybeans, but there are promising new sources such as palm oil (de Lucena et al., 2009). The development of palm oil as well as soybean are important factors that induce land use change, with a potential to influence stability of forests and biodiversity in certain key regions in SA, such as the Amazon (Section 27.2.2.1).

Biofuels can help CA and SA to decrease emissions from energy production and use. However, renewable energy might imply potential problems such as those related to positive net emissions of GHGs, threats to biodiversity, an increase in food prices, and competition for

Table 27-6 | Comparison of consumption of different energy sources in Latin America and the world (in thousand tonnes of oil equivalent on a net calorific value basis).

Energy resource		**Latin America**						**World**					
		TFC (non-electricity)		**TFC (via electricity generation)**		**TFC (total)**		**TFC (non-electricity)**		**TFC (via electricity generation)**		**TFC (total)**	
Fossil	Coal and peat	9008	3%	1398	2%	10,406	3%	831,897	12%	581,248	40%	1,413,145	17%
	Oil	189,313	55%	8685	13%	197,998	48%	3,462,133	52%	73,552	5%	3,535,685	44%
	Natural gas	59,440	17%	9423	14%	68,863	17%	1,265,862	19%	307,956	21%	1,573,818	19%
Nuclear		0	0%	1449	2%	1449	0%	0	0%	193,075	13%	193,075	2%
Renewable	Biofuels and waste	82,997	24%	2179	3%	85,176	21%	1,080,039	16%	20,630	1%	1,100,669	14%
	Hydropower	0	0%	45,920	66%	45,920	11%	0	0%	238,313	17%	238,313	3%
	Geothermal, solar, wind, other renewable	408	0%	364	1%	772	0%	18,265	0%	26,592	2%	44,857	1%
Total		341,166	100%	69,418	100%	410,584	100%	6,658,196	100%	1,441,366	100%	8,099,562	100%

TFC = Total final consumption.

Source: IEA (2012).

water resources (Section 27.2.3), some of which can be reverted or attenuated (Koh and Ghazoul, 2008). For example, the sugarcane agro-industry in Brazil combusts bagasse to produce electricity, providing power for the bioethanol industry and increasing sustainability. The excess heat energy is then used to generate bioelectricity, thus allowing the biorefinery to be self-sufficient in energy utilization (Amorim et al., 2011; Dias et al., 2012). In 2005–2006 the production of bioelectricity was estimated to be 9.2 kWh per tonne of sugarcane (Macedo et al., 2008). Most bioenergy feedstocks at present in production in CA and SA are grasses. In the case of sugarcane, the responses to the elevation of CO_2 concentration up to 720 ppmv have been shown to be positive in terms of biomass production and principally regarding water use efficiency (de Souza et al., 2008).

The production of energy from renewable sources such as hydro- and wind power is greatly dependent on climatic conditions and therefore may be impacted in the future by climate change. de Lucena et al. (2010a) suggest an increasing energy vulnerability of the poorest regions of Brazil to climate change together with a possible negative influence on biofuels production and electricity generation, mainly biodiesel and hydropower respectively.

Expansion of biofuel crops in Brazil might cause both direct and indirect land use changes (e.g., biofuel crops replacing rangelands, which previously replaced forests) with the direct land use changes, according to simulation performed by Lapola et al. (2010) of the effects for 2020. The same study shows that sugarcane ethanol and biodiesel derived from soybean each contribute, with about one-half of the indirect deforestation projected for 2020 (121,970 km^2) (Lapola et al., 2010). Thus, indirect land use changes, especially those causing the rangeland frontier to move further into the Amazonian forests, might potentially offset carbon savings from biofuel production.

The increase in global ethanol demand is leading to the development of new hydrolytic processes capable of converting cellulose into ethanol (dos Santos et al., 2011). The expected increase in the hydrolysis technologies is *very likely* to balance the requirement of land for biomass crops. Thus, the development of these technologies has a strong potential to diminish social (e.g., negative health effects due the burning process, poor labor conditions) and environmental impacts (e.g., loss of biodiversity, water and land uses) whereas it can improve the economic potential of sugarcane. One adaptation measure will be to increase the productivity of bioenergy crops due to planting in high productivity environments with highly developed technologies, in order to use less land. As one of the main centers of biotech agriculture application in the world (Gruskin, 2012), the region has a great potential to achieve this goal.

As the effects previously reported on crops growing in SESA might prevail (see Section 27.3.4.1), that is, that an increase in productivity may happen due to increasing precipitation, future uncertainty will have to be dealt with by preparing adapted varieties of soybean in order to maintain food and biodiesel production, mainly in Argentina, as it is one of the main producers of biodiesel from soybean in the world (Chum et al., 2011).

Other renewable energy sources—such as wind power generation—may also be vulnerable, raising the need for further research. According to de Lucena et al. (2009, 2010b), the projections of changes in wind power in Brazil may favor the use of this kind of energy in the future.

27.3.6.2. Adaptation Practices

Renewable energy will become increasingly more important over time, as this is closely related to the emissions of GHGs (Fischedick et al., 2011). Thus, renewable energy could have an important role as adaptation means to provide sustainable energy for development in the region (see also Section 27.6.1). However, the production of renewable energy requires large available areas for agriculture, which is the case of

Argentina, Bolivia, Brazil, Chile, Colombia, Peru, and Venezuela, which together represent 90% of the total area of CA and SA. However, for small countries it might not be possible to use bioenergy. Instead, they could benefit in the future from other types of renewable energy, such as geothermal, eolic, photovoltaic, and so forth, depending on policies and investment in different technologies. This is important because economic development is thought to be strongly correlated with an increase in energy use (Smil, 2000), which is itself associated with an increase in emissions (Sathaye et al., 2011).

LA is second to Africa in terms of technical potential for bioenergy production from rainfed lignocellulosic feedstocks on unprotected grassland and woodlands (Chum et al., 2011). Among the most important adaptation measures regarding renewable energy are (1) management of land use change ; and (2) development of policies for financing and management of science and technology for all types of renewable energy in the region.

If carefully managed, biofuel crops can be used as a means to regenerate biodiversity as proposed by Buckeridge et al. (2012), highlighting that the technology for tropical forest regeneration has become available and that forests could share land with biofuel crops (such as sugarcane) taking advantage of forests' mitigating potential. A possible adaptation measure could be to expand the use of reforestation technology to other countries in CA and SA.

One of the main adaptation issues is related to food versus fuel (Valentine et al., 2012). This is important because an increase in bioenergy feedstocks might threaten primary food production in a scenario expected to feed future populations with an increase of 70% in production (Gruskin, 2012; Valentine et al., 2012). This is particularly important in the region, as it has one of the highest percentages of arable land available for food production in the world (Nellemann et al., 2009). As CA and SA develop new strategies to produce more renewable energy there might be a pressure for more acreage to produce bioenergy. Because climate change will affect bioenergy and food crops at the same time, their effects, as well as the adaptation measures related to agriculture, will be similar. The main risks identified by Arvizu et al. (2011) are (1) business as usual, (2) unreconciled growth, and (3) environment and food versus fuel. Thus, the most important adaptation measures will be the ones related to the control of economic growth, environmental management, and agriculture production. The choice for lignocellulosic feedstocks (e.g., sugarcane second-generation technologies) will be an important mitigation/adaptation measure because these feedstocks do not compete with food (Arvizu et al., 2011). In the case of sugarcane, for instance, an increase of approximately 40% in the production of bioethanol is expected as a result of the implantation of second-generation technologies coupled with the first-generation ones already existent in Brazil (Dias et al., 2012; de Souza et al., 2013).

Biodiesel production has the lowest costs in LA (Chum et al., 2011) owing to the high production of soybean in Brazil and Argentina. The use of biodiesel to complement oil-derived diesel is a productive choice for adaptation measures regarding this bioenergy source. Also, the cost of ethanol, mainly derived from sugarcane, is the lowest in CA, SA, and LA (Chum et al., 2011) and as an adaptation measure, such costs, as well as the one of biodiesel, should be lowered even more by improving technologies related to agricultural and industrial production of both. Indeed, it has been reported that in LA the use of agricultural budgets by governments for investment in public goods induces faster growth, decreasing poverty and environmental degradation (López and Galinato, 2007).The pressure of soy expansion due to biodiesel demand can lead to land use change and consequently to economic teleconnections, as suggested by Nepstad et al. (2006). These teleconnections may link Amazon deforestation derived from soy expansion to economic growth in some developing countries because of changes in the demand of soy. These effects may possibly mean a decrease in jobs related to small to big farms in agriculture in Argentina (Tomei and Upham, 2009) on the one hand, and deforestation in the Amazon due to the advance of soybean cropping in the region on the other (Nepstad and Stickler, 2008).

27.3.7. Human Health

27.3.7.1. Observed and Projected Impacts and Vulnerabilities

Changes in weather extremes and climatic patterns are affecting human health (*high confidence*), by increasing morbidity, mortality, and disabilities, and through the emergence of diseases in previously non-endemic regions (*high confidence*; Winchester and Szalachman, 2009; Rodríguez-Morales, 2011). Heat waves and cold spells have increased urban mortality rates (McMichael et al., 2006; Bell et al., 2008; Hardoy and Pandiella, 2009; Muggeo and Hajat, 2009; Hajat et al., 2010). Outbreaks of vector- and water-borne diseases were triggered in CA by Hurricane Mitch in 1998 (Costello et al., 2009; Rodríguez-Morales et al., 2010), while the 2010–2012 Colombian floods caused hundreds of deaths and displaced thousands of people (Hoyos et al., 2012).

The number of cases of malaria have increased in Colombia during the last 5 decades alongside air temperatures (Poveda et al., 2011; Arevalo-Herrera et al., 2012), but also in urban and rural Amazonian regions undergoing large environmental changes (Gil et al., 2007; Tada et al., 2007; Cabral et al., 2010; da Silva-Nunes et al., 2012). Malaria transmission has reached 2300 m in the Bolivian Andes, and vectors are found at higher altitudes from Venezuela to Bolivia (Benítez and Rodríguez-Morales, 2004; Lardeux et al., 2007; Pinault and Hunter, 2011).

Although the incidence of malaria has decreased in Argentina, its vector density has increased in the northwest along with climate variables (Dantur Juri et al., 2010, 2011). El Niño drives malaria outbreaks in Colombia (Mantilla et al., 2009; Poveda et al., 2011), amidst other factors (Rodríguez-Morales et al., 2006; Osorio et al., 2007; Restrepo-Pineda et al., 2008). Linkages between ENSO and malaria are also reported in Ecuador and Peru (Anyamba et al., 2006; Kelly-Hope and Thomson, 2010), French Guiana (Hanf et al., 2011), Amazonia (Olson et al., 2009), and Venezuela (Moreno et al., 2007).

Unlike malaria, dengue fever and its hemorrhagic variant are mostly urban diseases whose vector is affected by climate conditions. Their incidence have risen in tropical America in the last 25 years, causing annual economic losses of US$2.1+ (1 to 4) billion (Torres and Castro, 2007; Tapia-Conyer et al., 2009; Shepard et al., 2011). Environmental and climatic variability affect their incidence in CA (Fuller et al., 2009; Rodríguez-Morales et al., 2010; Mena et al., 2011), in Colombia

(Arboleda et al., 2009), and in French Guiana alongside malaria (Carme et al., 2009; Gharbi et al., 2011). In Venezuela, dengue fever increases during La Niña (Rodríguez-Morales and Herrera-Martinez, 2009; Herrera-Martinez and Rodríguez-Morales, 2010). Weather and climate variability are also associated with dengue fever in southern SA (Honório et al., 2009; Costa et al., 2010; de Carvalho-Leandro et al., 2010; Degallier et al., 2010; Lowe et al., 2011), involving also demographic and geographic factors in Argentina (Carbajo et al., 2012). In Rio de Janeiro a 1°C increase in monthly minimum temperature led to a 45% increase of dengue fever in the next month, and 10 mm increase in rainfall to a 6% increase (Gomes et al., 2012). Despite large vaccination campaigns, the risk of yellow fever outbreaks has increased mostly in tropical America's densely populated poor urban settings (Gardner and Ryman, 2010), alongside climate conditions (Jentes et al., 2011).

Schistosomiasis is endemic in rural areas of Suriname, Venezuela, the Andean highlands, and rural and peripheral urbanized regions of Brazil (Barbosa et al., 2010; Kelly-Hope and Thomson, 2010; Igreja, 2011). It is *highly likely* that schistosomiasis will increase in a warmer climate (Mangal et al., 2008; Mas-Coma et al., 2009; Lopes et al., 2010). Vegetation indices are associated with human fascioliasis in the Andes (Fuentes, 2004).

Hantaviruses have been recently reported throughout the region (Jonsson et al., 2010; MacNeil et al., 2011), and El Niño and climate change augment their prevalence (Dearing and Dizney, 2010). Variation in hantavirus reservoirs in Patagonia is strongly dependent on climate and environmental conditions (Andreo et al., 2012; Carbajo et al., 2009). In Venezuela, rotavirus is more frequent and more severe in cities with minimal seasonality (Kane et al., 2004). The peak of rotavirus in Guatemala occurs in the dry season, causing 60% of total diarrhea cases (Cortes et al., 2012).

In spite of its rapid decline, climate-sensitive Chagas disease is still a major public health issue (Tourre et al., 2008; Moncayo and Silveira, 2009; Abad-Franch et al., 2009; Araújo et al., 2009; Gottdenker et al., 2011). Climate also affects the most prevalent mycosis (Barrozo et al., 2009), and ENSO is associated with outbreaks of bartonellosis in Peru (Payne and Fitchett, 2010).

The high incidence of cutaneous leishmaniasis in Bolivia is exacerbated during La Niña (Gomez et al., 2006; García et al., 2009). Cutaneous leishmaniasis is affected in Costa Rica by temperature, forest cover, and ENSO (Chaves et al., 2008), and in Colombia by land cover, altitude, climatic variables, and El Niño (Cárdenas et al., 2006, 2007, 2008; Valderrama-Ardila et al., 2010), and decreases during La Niña in Venezuela (Cabaniel et al., 2005). Cutaneous leishmaniasis in Suriname peaks during the March dry season (35%; van der Meide et al., 2008), and in French Guiana is intensified after the October-December dry season (Rotureau et al., 2007). The incidence of visceral leishmaniasis has increased in Brazil (highest in LA) in association with El Niño and deforestation (Ready, 2008; Cascio et al., 2011; Sortino-Rachou et al., 2011), as in Argentina, Paraguay, and Uruguay (Bern et al., 2008; Dupnik et al., 2011; Salomón et al., 2011; Fernández et al., 2012). Visceral leishmaniasis transmission in Venezuela is associated with rainfall seasonality (Feliciangeli et al., 2006; Rodríguez-Morales et al., 2007). The incidence of skin cancer in Chile has increased in recent years, concomitantly with climate and geographic variables (Salinas et al., 2006).

Onchocerciasis (river blindness) vector exhibits seasonal biting rates (Botto et al., 2005; Rodríguez-Pérez et al., 2011), and leptospirosis is prevalent in CA's warm-humid tropical regions (Valverde et al., 2008). Other climate-driven infectious diseases are ascariasis and gram-positive cocci in Venezuela (Benítez et al., 2004; Rodríguez-Morales et al., 2010) and Carrion's disease in Peru (Huarcaya et al., 2004).

Seawater temperature affects the abundance of cholera bacteria (Koelle, 2009; Jutla et al., 2010; Marcheggiani et al., 2010; Hofstra, 2011), which explains the outbreaks during El Niño in Peru, Ecuador, Colombia, and Venezuela (Cerda Lorca et al., 2008; Martínez-Urtaza et al., 2008; Salazar-Lindo et al., 2008; Holmner et al., 2010; Gavilán and Martínez-Urtaza, 2011; Murugaiah, 2011).

The worsening of air quality and higher temperatures in urban settings are increasing chronic respiratory and cardiovascular diseases, and morbidity from asthma and rhinitis (Grass and Cane, 2008; Martins and Andrade, 2008; Gurjar et al., 2010; Jasinski et al., 2011; Rodriguez et al., 2011), but also atherosclerosis, pregnancy-related outcomes, cancer, cognitive deficit, otitis, and diabetes (Olmo et al., 2011). Dehydration

Frequently Asked Questions

FAQ 27.3 | Are there emerging and reemerging human diseases as a consequence of climate variability and change in the region?

Human health impacts have been exacerbated by variations and changes in climate extremes. Climate-related diseases have appeared in previously non-endemic regions (e.g., malaria in the Andes, dengue in CA and southern SA) (*high confidence*). Climate variability and air pollution have also contributed to increase the incidence of respiratory and cardiovascular, vector- and water-borne and chronic kidney diseases, hantaviruses and rotaviruses, pregnancy-related outcomes, and psychological trauma (*very high confidence*). Health vulnerabilities vary with geography, age, gender, ethnicity, and socioeconomic status, and are rising in large cities. Without adaptation measures (e.g., extending basic public health services), climate change will exacerbate future health risks, owing to population growth rates and existing vulnerabilities in health, water, sanitation and waste collection systems, nutrition, pollution, and food production in poor regions (*medium confidence*).

from heat waves increases hospitalizations for chronic kidney diseases (Kjellstrom et al., 2010), affecting construction, sugarcane, and cotton workers in CA (Crowe et al., 2009, 2010; Kjellstrom and Crowe, 2011; Peraza et al., 2012).

Extreme weather/climate events affect mental health in Brazil (depression, psychological distress, anxiety, mania, and bipolar disorder), in particular in drought-prone areas of NEB (Coêlho et al., 2004; Volpe et al., 2010). Extreme weather, meager crop yields, and low GDP are also associated with increased violence (McMichael et al., 2006).

Multiple factors increase the region's vulnerability to climate change: precarious health systems; malnutrition; inadequate water and sanitation services; poor waste collection and treatment systems; air, soil, and water pollution; lack of social participation; and inadequate governance (Luber and Prudent, 2009; Rodríguez-Morales, 2011; Sverdlik, 2011). Human health vulnerabilities in the region depend on geography, age (Perera, 2008; Martiello and Giacchi, 2010; Åstrom et al., 2011; Graham et al., 2011), gender (de Oliveira et al., 2011), race, ethnicity, and socioeconomic status (Diez Roux et al., 2007; Martiello and Giacchi, 2010). Neglected tropical diseases in LA cause 1.5 to 5.0 million disability-adjusted life years (DALYs) (Hotez et al., 2008).

Vulnerability of megacities (see Section 27.3.5) is aggravated by access to clean water, rapid spread of diseases (Borsdorf and Coy, 2009), and migration from rural areas forced by disasters (Campbell-Lendrum and Corvalán, 2007; Borsdorf and Coy, 2009; Hardoy and Pandiella, 2009). Human health vulnerabilities have been assessed in Brazil through composite indicators involving epidemiological variables, downscaled climate scenarios, and socioeconomic projections (Confalonieri et al., 2009; Barata et al., 2011; Barbieri and Confalonieri, 2011). The Andes and CA are among the regions of highest predicted losses (1 to 27%) in labor productivity from future climate scenarios (Kjellstrom et al., 2009).

27.3.7.2. Adaptation Strategies and Practices

Adaptation efforts in the region (Blashki et al., 2007; Costello et al., 2011) are hampered by lack of political commitment, gaps in scientific knowledge, and institutional weaknesses (Keim, 2008; Lesnikowski et al., 2011; Olmo et al., 2011; see Section 27.4.3). Research priorities and current strategies must be reviewed (Halsnæs and Verhagen, 2007; Romero and Boelaert, 2010; Karanja et al., 2011), and preventive/responsive systems must be put in place (Bell, 2011) to foster adaptive capacity (Campbell-Lendrum and Bertollini, 2010; Huang et al., 2011). Colombia established a pilot adaptation program to cope with changes in malaria transmission and exposure (Poveda et al., 2011). The city of São Paulo has implemented local pollution control measures, with the co-benefit of reducing GHG emissions (de Oliveira, 2009; Nath and Behera, 2011).

Human well-being indices must be explicitly stated as adaptation policies in LA (e.g., Millennium Development Goals; Franco-Paredes et al., 2007; Halsnæs and Verhagen, 2007; Mitra and Rodriguez-Fernandez, 2010). South–south cooperation and multidisciplinary research are required to design relevant adaptation and mitigation strategies (Tirado et al., 2010; Team and Manderson, 2011).

27.4. Adaptation Opportunities, Constraints, and Limits

27.4.1. Adaptation Needs and Gaps

During the last few years, the study of adaptation to climate change has progressively switched from an impact-focused approach (mainly climate-driven) to include a vulnerability-focused vision (Boulanger et al., 2011). As a consequence, the development and implementation of systemic adaptation strategies, involving institutional, social, ecosystem, environmental, financial, and capacity components (see Chapter 14) to cope with present climate extreme events is a key step toward climate change adaptation, especially in SA and CA countries. Although different frameworks and definitions of vulnerability exist, a general tendency aims at studying vulnerability to climate change, especially in SA and CA, focusing on the following aspects: urban vulnerability (e.g., Hardoy and Pandiella, 2009; Heinrichs and Krellenberg, 2011), rural community (McSweeney and Coomes, 2011; Ravera et al., 2011), rural farmer vulnerability (Oft, 2010), and sectoral vulnerability (see Section 27.3). The approach used can be holistic or systemic (Ison, 2010; Carey et al., 2012b), where climate drivers are actually few with respect to all other drivers related to human and environment interactions including physical, economic, political, and social context, as well as local characteristics such as occupations, resource uses, accessibility to water, and so forth (Manuel-Navarrete et al., 2007; Young et al., 2010).

In developing and emergent countries, there exists a general consensus that the adaptive capacity is low, strengthened by the fact that poverty is the key determinant of vulnerability in LA (to climate-related natural hazards; see Rubin and Rossing, 2012) and thus a limit to resilience (Pettengell, 2010) leading to a "low human development trap" (UNDP, 2007). However, Magnan (2009, p. 1) suggests that this analysis is biased by a "relative immaturity of the science of adaptation to explain what are the processes and the determinants of adaptive capacity." Increasing research efforts on the study of adaptation is therefore of great importance to improve understanding of the actual societal, economical, community, and individual drivers defining the adaptive capacity. Especially, a major focus on traditions and their transmission (Young and Lipton, 2006) may actually indicate potential adaption potentials in remote and economically poor regions of SA and CA. Such a potential does not dismiss the fact that the nature of future challenges may actually not be compared to past climate variability (e.g., glacier retreat in the Andes).

Coping with new situations may require new approaches such as a multi-level risk governance (Corfee-Morlot et al., 2011; Young and Lipton, 2006) associated with decentralization in decision making and responsibility. Although the multi-level risk governance and the local participatory approach are interesting frameworks for strengthening adaptation capacity, perception of local and national needs is diverging, challenging the implementation of adaptation strategies in CA/SA (Salzmann et al., 2009). At present, despite an important improvement during the last few years, there still exists a certain lack of awareness of environmental changes and their implications for livelihoods and businesses (Young et al., 2010). Moreover, considering the limited financial resources of some states in CA and SA, long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the population. This situation weakens the importance of adaptation planning to climate change in the political agenda (Carey et al., 2012b), and therefore requires international involvement as one facilitating factor in natural hazard management and climate change adaptation, with respect to sovereignty according to international conventions including the United Nations Framework Convention on Climate Change (UNFCCC). In addition, as pointed out by McGray et al. (2007), development, adaptation, and mitigation are not separate issues. Development and adaptation strategies especially should be tackled together in developing countries such as SA and CA, focusing on strategies to reduce vulnerability. The poor level of adaptation of present-day climate in SA and CA countries is characterized by the fact that responses to disasters are mainly reactive rather than preventive. Some early warning systems are being implemented, but the capacity of responding to a warning is often limited, particularly among poor populations. Finally, actions combining public communication (and education), public decision-maker capacity-building, and a synergetic development-adaptation funding will be key to sustain the adaptation process that CA and SA require to face future climate change challenges.

27.4.2. Practical Experiences of Autonomous and Planned Adaptation, Including Lessons Learned

Adaptation processes in many cases have been initiated a few years ago, and there is still a lack of literature to evaluate their efficiency in reducing vulnerability and building resilience of the society against climate change. However, experiences of effective adaptation and maladaptation are slowly being documented (see also Section 27.4.3); some lessons have already been learned from these first experiences (see Section 27.3); and tools, such as the Index of Usefulness of Practices for Adaptation (IUPA) to evaluate adaptation practices, have been developed for the region (Debels et al., 2009). Evidenced by these practical experiences, there is a wide range of options to foster adaptation and thus adaptive capacity in CA and SA. In CA and SA, many societal issues are strongly connected to development goals and are often considered a priority in comparison to adaptation efforts to climate change. However, according to the 135 case studies analyzed by McGray et al. (2007), 21 of which were in CA and SA, the synergy between development and adaptation actions makes it possible to ensure a sustainable result of the development projects.

Vulnerability and disaster risk reduction may not always lead to long-term adaptive capacity (Tompkins et al., 2008; Nelson and Finan, 2009), except when structural reforms based on good governance (Tompkins et al., 2008) and negotiations (de Souza Filho and Brown, 2009) are implemented. While multi-level governance can help to create resilience and reduce vulnerability (Roncoli, 2006; Young and Lipton, 2006; Corfee-Morlot et al., 2011), capacity-building (Eakin and Lemos, 2006), good governance, and enforcement (Lemos et al., 2010; Pittock, 2011) are key components.

Autonomous adaptation experience is mainly realized at local levels (individual or communitarian) with examples found, for instance, for rural communities in Honduras (McSweeney and Coomes, 2011), Indigenous communities in Bolivia (Valdivia et al., 2010), and coffee agroforestry systems in Brazil (de Souza et al., 2012). However, such adaptation processes do not always respond specifically to climate forcing. For instance, the agricultural sector adapts rapidly to economic stressors, although, despite a clear perception of climate risks, it may last longer before responding to climate changes (Tucker et al., 2010). In certain regions or communities, such as Anchioreta in Brazil (Schlindwein et al., 2011), adaptation is part of a permanent process and is actually tackled through a clear objective of vulnerability reduction, maintaining and diversifying a large set of natural varieties of corn, allowing the farmers to diversify their planting. Another kind of autonomous adaptation is the southward displacement of agriculture activities (e.g., wine, coffee) through the purchase of lands, which will become favorable for such agriculture activities in a warmer climate. In Argentina, the increase of precipitation observed during the last 30 years contributed to a westward displacement of the annual crop frontier.

However, local adaptation to climate and non-climate drivers may undermine long-term resilience of socio-ecological systems when local, short-term strategies designed to deal with specific threats or challenges do not integrate a more holistic and long-term vision of the system at threat (Adger et al., 2011). Thus, policy should identify the sources of and conditions for local resilience and strengthen their capacities to adapt and learn (Borsdorf and Coy, 2009; Adger et al., 2011; Eakin et al., 2011), as well as to integrate new adapted tools (Oft, 2010). This sets the question of convergence between the local-scale/short-term and broad-scale/long-term visions in terms of perceptions of risks, needs to adapt, and appropriate policies to be implemented (Eakin and Wehbe, 2009; Salzmann et al., 2009). Even if funding for adaptation is available, the overarching problem is the lack of capacity and/or willingness to address the risks, especially those threatening lower income groups (Satterthwaite, 2011a). Adaptation to climate change cannot eliminate the extreme weather risks, and thus efforts should focus on disaster preparedness and post-disaster response (Sverdlik, 2011). Migration is the last resort for rural communities facing water stress problems in CA and SA (Acosta-Michlik et al., 2008).

In natural hazard management contributing to climate change adaptation, specific cases such as the one in Lake 513 in Peru (Carey et al., 2012b) clearly allowed identification of facilitating factors for a successful adaptation process (technical capacity, disaster events with visible hazards, institutional support, committed individuals, and international involvement) as well as impediments (divergent risk perceptions, imposed government policies, institutional instability, knowledge disparities, and invisible hazards). In certain cases, forward-looking learning (anticipatory process), as a contrast to learning by shock (reactive process), has been found as a key element for adaptation and resilience (Tschakert and Dietrich, 2010) and should be promoted as a tool for capacity-building at all levels (stakeholders, local and national governments). Its combination with role-playing game and agent-based models (Rebaudo et al., 2011) can strengthen and accelerate the learning process.

Planned adaptation policies promoted by governments have been strengthened by participation in international networks, where experience and knowledge can be exchanged. As an example, the C40 Cities-Climate Leadership Group or ICLEI include Bogotá (Colombia), Buenos Aires (Argentina), Caracas (Venezuela), Curitiba, Rio de Janeiro, and São Paulo (Brazil), Lima (Peru), and Santiago de Chile (Chile). Most of these cities have come up with related action and strategy plans (e.g., Action Plan

Buenos Aires 2030, Plan of Caracas 2020, or the Metropolitan Strategy to CCA of Lima) (C40 Cities, 2011).

At a regional policy level, an example of intergovernmental initiatives in SA and CA is the Ibero-American Programme on Adaptation to Climate Change (PIACC), developed by the Ibero-American Network of Climate Change Offices (RIOCC) (Keller et al., 2011b). For CA specifically, the Central American Commission for Environment and Development (CCAD) brings together the environmental ministries of the Central American Integration System (Sistema de la Integración Centroamericana (SICA)) that released its climate change strategy in 2010 (CCAD and SICA, 2010; Keller et al., 2011a).

These initiatives demonstrate that there has been a growing awareness of CA and SA governments on the need to integrate climate change and future climate risks in their policies. To date, in total, 18 regional Non-Annex countries, including Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Guyana, Panama, Paraguay, Peru, Suriname, Uruguay, and Venezuela, have already published their first and/or second National Communication to the UNFCCC (see UNFCCC, 2012), making it possible to measure the country's emissions and to assess its present and future vulnerability.

27.4.3. Observed and Expected Barriers to Adaptation

Adaptation is a dynamic process, which to be efficient requires a permanent evolution and even transformation of the vulnerable system. Such a transformation process can be affected by several constraints, including constraints affecting the context of adaptation as well as the implementation of policies and measures (see Section 16.3.2).

Major constraints related to the capacity and resources needed to support the implementation of adaptation policies and processes include: access to (Lemos et al., 2010) and exchange of knowledge (e.g., adaptive capacity can be enhanced by linking indigenous and scientific knowledge; Valdivia, 2010); access to and quality of natural resources (López-Marrero, 2010); access to financial resources, especially for poor households (Satterthwaite, 2011b; Hickey and Weis, 2012; Rubin and Rossing, 2012), as well as for institutions (Pereira et al., 2009); access to technological resources (López-Marrero, 2010) and technical assistance (Guariguata, 2009; Eakin et al., 2011), as well as the fostering of public-private technology transfer (La Rovere et al., 2009; Ramirez-Villegas et al., 2012) and promotion of technical skills (Hickey and Weis, 2012); and social asset-based formation at the local level (Rubin and Rossing, 2012).

In terms of framing adaptation, as a constraint to affect the adaptation context, it is usually considered that a major barrier to adaptation is the perception of risks, and many studies focused on such an issue (e.g., Schlindwein et al., 2011). New studies (Adger et al., 2009) identified social limits to possible adaptation to climate change in relation with issues of values and ethics, risk, knowledge, and culture, even though such limits can evolve in time. Indeed, while being a necessary condition, perception may not be the main driver for initiating an adaptation process. As pointed out by Tucker et al. (2010) with a specific focus on CA, exogenous factors (economic, land tenure, cost, etc.) may actually strongly constrain the decision-making process involved in a possible adaptation process. In that sense, efficient governance and management are key components in the use of climate and non-climate information in the decision-making and adaptation process. As a consequence, it is difficult to describe adaptation without defining at which level it is thought. Indeed, though much effort is invested in national and regional policy initiatives, most of the final adaptation efforts will be local. National and international (transborder) governance is key to build adaptive capacity (Engle and Lemos, 2010) and therefore to strengthen (or weaken) local adaptation through efficient policies and delivery of resources. At a smaller scale (Agrawal, 2008), local institutions can strongly contribute to vulnerability reduction and adaptation. However, at all levels, the efficiency in national and local adaptation activities strongly depend on the capacity-building and information transmission to decision makers (Eakin and Lemos, 2006).

27.5 Interactions between Adaptation and Mitigation

Synergies between adaptation and mitigation strategies on the local level can be reached as a result of self-organization of communities in cooperatives (see, e.g., "The SouthSouthNorth Capacity Building Module on Poverty Reduction" (SSN Capacity Building Team, 2006), which manages recycling or renewable energy production, leading to an increase in energy availability, thus production capacity, and therefore new financial resources). Moreover, Venema and Cisse (2004) also support the development of decentralized renewable energy solutions for the growth of renewable energy in CA and SA (see also Section 27.3.6) next to a large infrastructure project (see their case studies for Argentina and Brazil).

In spite of their smaller size (individual or communitarian), these solutions offer adaptation and mitigation benefits. On one hand, fossil-based energy consumption is reduced, while energy availability is increased. On the other hand, reduction of energy precariousness is key in any development strategy. Thus, it allows local community and individuals to grow socially and economically, and therefore to reduce vulnerability, avoiding the poverty trap (UNDP, 2007), and to initiate an adaptation process based on non-fossil fuel energy sources. Such initiatives also depend on local and organizational leaderships (UN-HABITAT, 2011).

Such integrated strategies of income generation as adaptation measures as well as production of renewable energy are also identified for vulnerable, small farmers diversifying their crops toward crops for vegetable oil and biodiesel production in Brazil. Barriers identified concern capacity-building and logistical requirements, making policy tools, credit mechanism, and organization into cooperatives, and fostering necessary research (La Rovere et al., 2009). Other promising interactions of mitigation and adaptation are identified, for example, for the management of Brazilian tropical natural and planted forest (Guariguata, 2009).

At national and regional scales, CA and SA countries will require the allocation of human and financial resources to adapt to climate change. While resources are limited, too large an economic dependence of these countries to fossil fuels will reduce their adaptive capacity. The reduction in energy consumption and the integration of renewable energies in their energetic matrix is therefore a key issue for all these countries to sustain their development and growth and therefore increase their adaptive capacity (see also Section 27.3.6).

Reforestation and avoided deforestation are important practices that contribute to both mitigation and adaptation efforts in the region as in other parts of the world. Maintaining forest cover can provide a suite of environmental services including local climate regulation, water regulation, and reduced soil erosion—all of which can reduce the vulnerability of communities to variable climate (see Section 27.3.2.2; Vignola et al., 2009).

27.6. Case Studies

27.6.1. Hydropower

Hydropower is the main source of renewable energy in CA and SA (see Section 27.3.6). The region is second only to Asia in terms of hydropower energy generation in the world, displaying a 20% share of total annual generation and an average regional capacity factor of greater than 50% (SRREN Table 5-1; IPCC, 2011). As a result, the region has by far the largest proportion of electricity generated through hydropower facilities (Table 27-6). The hydropower proportion of total electricity production is greater than 40% in the region, and in some cases is near or close to 80%, as in the case of Brazil, Colombia, and Costa Rica (IEA, 2012). Although there is debate, especially in tropical environments, about GHG emissions from hydropower reservoirs (Fearnside and Pueyo, 2012), this form of electricity generation is often seen as a major contributor to mitigating GHG emissions worldwide (see IPCC, 2011; Kumar et al., 2011). But, on the other hand, hydropower is a climate-related sector, thus making it prone to the potential effects of changing climate conditions (see Section 27.3.1.1). In this regard the CA and SA region constitutes a unique example to study these relations between climate change mitigation and adaptation in relation to hydropower generation.

Diverse studies have analyzed the potential impacts of climate change on hydropower generation (Table 27-4). Maurer et al. (2009) studied future conditions for the Lempa River (El Salvador, Honduras, and Guatemala), showing a potential reduction in hydropower capacity of 33 to 53% by 2070–2099. A similar loss is expected for the Sinú-Caribe basin in Colombia where, despite a general projection of increased precipitation, losses due to evaporation enhancement reduce inflows to hydroelectric systems, thus reducing electricity generation up to 35% (Ospina Noreña et al., 2009a). Further studies (Ospina Noreña et al., 2011a,b) have estimated vulnerability indices for the hydropower sector in the same basin, and identified reservoir operation strategies to reduce this vulnerability. Overall reductions in hydropower generation capacity are also expected in Chile for the main hydropower generation river basins (Maule, Laja, and Biobio (ECLAC, 2009a; McPhee et al., 2010; Stehr et al., 2010)), and also in the Argentinean Limay River basin (Seoane and López, 2007). Ecuador, on the other hand, faces an increase in generation capacity associated with an increment in precipitation on its largest hydroelectric generator, the Paute River basin (Buytaert et al., 2010). Brazil, although being the country with the largest installed hydroelectric capacity in the region, still has unused generation capacity in sub-basins of the Amazon River (Soito and Freitas, 2011). However, future climate conditions plus environmental concerns pose an important challenge for the expansion of the system (Freitas and Soito, 2009; Andrade et al., 2012; Finer and Jenkins, 2012). According to de Lucena et al. (2009), hydropower systems in southern Brazil (most significantly the Parana River system) could face a slight increase in energy production under an A2 scenario. However, the rest of the country's hydropower system, especially those in NEB, could face a reduction in power generation, thus reducing the reliability of the whole system (de Lucena et al., 2009).

An obvious implication of the mentioned impacts is the need to replace the energy lost through alternative (see Section 27.3.6.2) or traditional sources. Adaptation measures have been studied for Brazil (de Lucena et al., 2010a), with results implying an increase in natural gas and sugarcane bagasse electricity generation on the order of 300 TWh, increase in operation costs on the order of US$7 billion annually, and US$50 billion in terms of investment costs by 2035. In Chile, the study by ECLAC (2009a) assumed that the loss in hydropower generation, on the order of 18 TWh for the 2011–2040 period (a little over 10% of actual total hydropower generation capacity) would be compensated by the least operating cost source available, coal-fired power plant, implying an increase of 2 MT CO_2-eq of total GHG emissions (emissions for the electricity sector in Chile totaled 25 MT CO_2-eq in 2009). Ospina Noreña (2011a,b) studied some adaptation options, such as changes in water use efficiency or demand growth that could mitigate the expected impacts on hydropower systems in the Colombian Sinú-Caribe River basin. Changes in seasonality and total availability could also increase complexities in the management of multiple-use dedicated basins in Peru (Juen et al., 2007; Condom et al., 2012), Chile (ECLAC, 2009a), and Argentina (Seoane and López, 2007), that could affect the relationship between different water users within a basin. It is worth noting that those regions that are projected to face an increase in streamflow and associated generation capacity, such as Ecuador or Costa Rica, also share difficulties in managing deforestation, erosion, and sedimentation which limits the useful life of reservoirs (see Section 27.3.1.1). In these cases it is important to consider these effects in future infrastructure operation (Ferreira and Teegavarapu, 2012) and planning, and also to enhance the ongoing process of recognizing the value of the relation between ecosystem services and hydropower system operations (Leguía et al., 2008) (see more on PES in Sections 27.3.2.2, 27.6.2).

27.6.2. Payment for Ecosystem Services

Payment for ecosystem services (PES) is commonly described as a set of transparent schemes for securing a well-defined ecosystem service (or a land use capable to secure that service) through conditional payments or compensations to voluntary providers (Engel et al., 2008; Tacconi, 2012). Van Noordwijk et al. (2012) provides a broader definition to PES by arguing that it encompasses three complementary approaches: (1) the one above, that is, commodification of predefined ecosystem services so that prices can be negotiated between buyers and sellers; plus (2) compensation for opportunities forgone voluntarily or by command and control decisions; and (3) coinvestment in environmental stewardships. Therefore, the terms *conservation agreements*, *conservation incentives*, and *community conservation* are often used as synonyms or as something

Table 27-7 | Cases of government-funded physiological-ecological simulation (PES) schemes in Central America and South America.

Countries	Level	Start	Name	Benefits	References
Brazil	Sub-national (Amazonas state)	2007	Bolsa Floresta	By 2008, 2700 traditional and indigenous families already benefitted: financial compensation and health assistance in exchange for zero deforestation in primary forests.	Viana (2008)
Costa Rica	National	1997	Fondo Nacional de Financiamiento Forestal	PES is a strong incentive for reforestation and, for agroforestry ecosystems alone, more than 7000 contracts have been set since 2003 and nearly 2 million trees planted.	Montagnini and Finney (2011)
Ecuador	National	2008	Socio-Bosque	By 2010, the program already included more than half a million hectares of natural ecosystems protected and has more than 60,000 beneficiaries.	De Koning et al. (2011)
Guatemala	National	1997	Programa de Incentivos Forestales	By 2009, the program included 4174 beneficiaries, who planted 94,151 hectares of forest. In addition, 155,790 hectares of natural forest were under protection with monetary incentives.	INE (2011)

different or broader than PES (Milne and Niesten, 2009; Cranford and Mourato, 2011). For simplicity, we refer to PES in its broadest sense (van Noordwijk et al., 2012).

Services subjected to such types of agreements often include regulation of freshwater flows, carbon storage, provision of habitat for biodiversity, and scenic beauty (de Koning et al., 2011; Montagnini and Finney, 2011). Because the ecosystems that provide the services are mostly privately owned, policies often aim at supporting landowners to maintain the provision of services over time (Kemkes et al., 2010). Irrespective of the debate as to whether payments or compensations should be designed to focus on actions or results (Gibbons et al., 2011), experiences in Colombia, Costa Rica, and Nicaragua show that PES can finance conservation, ecosystem restoration, and better land use practices (Montagnini and Finney, 2011; see also Table 27-5). However, based on examples from Ecuador and Guatemala, Southgate et al. (2010) argue that uniformity of payment for beneficiaries can be inefficient if recipients accept less compensation in return for conservation measures, or if recipients that promote greater environmental gains receive only the prevailing payment. Other setbacks to PES schemes might include cases where there is a perception of commoditization of nature and its intangible values (e.g., Bolivia, Cuba, Ecuador, and Venezuela); other cases where mechanisms are inefficient to reduce poverty; and slowness to build trust between buyers and sellers, as well as gender and land tenure issues that might arise (Asquith et al., 2008; Peterson et al., 2010; Balvanera et al., 2012; van Noordwijk et al., 2012). Table 27-7 lists select examples of PES schemes in Latin America, with a more complete and detailed list given in Balvanera et al. (2012).

The PES concept (or "fishing agreements") also applies to coastal and marine areas, although only a few cases have been reported. Begossi (2011) argues that this is due to three factors: origin (the mechanism was originally designed for forests), monitoring (marine resources such as fish are more difficult to monitor than terrestrial resources), and definition of resource boundaries in offshore water. One example of a compensation mechanism in the region is the so-called *defeso*, in Brazil. It consists of a period (reproductive season) when fishing is forbidden by the government and fishermen receive a financial compensation. It applies to shrimp, lobster, and both marine and freshwater fisheries (Begossi et al., 2011).

27.7. Data and Research Gaps

The scarcity of and difficulty in obtaining high-resolution, high quality, and continuous climate, oceanic, and hydrological data, together with availability of only very few complete regional studies, pose challenges for the region to address changes in climate variability and the identification of trends in extremes, in particular for CA. This situation hampers studies on frequency and variability of extremes, as well as impacts and vulnerability analyses of the present and future climates, and the development of vulnerability assessments and adaptation actions.

Related to observed impacts in most sectors, there is an imbalance in information availability among countries. While more studies have been performed for Brazil, southern SA, and SESA region, much less are available for CA and for some regions of tropical SA. An additional problem is poor dissemination of results in peer-reviewed publications because most information is available only as grey literature. There is a need for studies focused on current impacts and vulnerabilities across sectors throughout CA and SA, with emphasis on extremes to improve risk management assessments.

The complex interactions between climate and non-climate drivers make the assessment of impacts and projections difficult, as is the case for water availability and streamflows owing to current and potential deforestation, overfishing and pollution regarding the impacts on fisheries, or impacts on hydroenergy production. The lack of interdisciplinary integrated studies limits our understanding of the complex interactions between natural and socioeconomic systems. In addition, accelerating deforestation and land use changes, as well as changes in economic conditions, impose a continuous need for updated and available data sets that feed basic and applied studies.

To address the global challenge of food security and food quality, both important issues in CA and SA, investment in scientific agricultural knowledge needs to be reinforced, mainly with regard to the integration of agriculture with organic production, and the integration of food and bioenergy production. It is necessary to consider ethical aspects when the competition for food and bioenergy production is analyzed to identify which activity is most important at a given location and time and whether bioenergy production would affect food security for a particular population.

SLR and coastal erosion are also relevant issues; the lack of comparable measurements of SLR in CA and SA make the present and future integrated assessment of the impacts of SLR in the region difficult. Of local and global importance will be improving our understanding of the physical oceanic processes, in particular of the Humboldt Current system flowing along the west coast of SA, which is one of the most productive systems worldwide.

More information and research about the impacts of climate variability and change on human health is needed. One problem is the difficulty in accessing health data that are not always archived and ready to be used in integrated studies. Another need refers to building the necessary critical mass of transdisciplinary scientists to tackle the climate change-human health problems in the region. The prevailing gaps in scientific knowledge hamper the implementation of adaptation strategies, thus demanding a review of research priorities toward better disease control. With the aim of further studying the health impacts of climate change and identifying resilience, mitigation, and adaptation strategies, South-South cooperation and multidisciplinary research are considered to be relevant priorities.

In spite of the uncertainty that stems from global and regional climatic projections, the region needs to act in preparation for a possible increase in climate variability and in extremes. It is necessary to undertake research activities leading to public policies to assist societies in coping with current climate variability, such as, for example, risk assessment and risk management. Another important aspect since AR4 is the improvement of climate modeling and the generation of high-resolution climate scenarios, which in countries in CA and SA resulted in the first integrated regional studies on impacts and vulnerability assessments of climate change focusing on sectors such as agriculture, energy, and human health.

Research on adaptation and the scientific understanding of the various processes and determinants of adaptive capacity is also mandatory for the region, with particular emphasis on increasing adaptation capacity involving the traditional knowledge of ancestral cultures and how this knowledge is transmitted. Linking indigenous knowledge with scientific knowledge is important. The concept of "mother earth" (madre tierra in Spanish) as a living system has been mentioned in recent years, as a key sacred entity on the view of indigenous nations and as a system that may be affected and also resilient to climate change. Although some adaptation processes have been initiated in recent years dealing with this and other indigenous knowledge, there is only very limited scientific literature discussing these subjects so far.

The research agenda needs to address vulnerability and foster adaptation in the region, encompassing an inclusion of the regions' researchers and focusing also on governance structures and action-oriented research that addresses resource distribution inequities.

Regional and international partnerships, and research networks and programs, have allowed linking those programs with local strategies for adaptation and mitigation, also providing opportunities to address research gaps and exchange among researchers. Examples are the European Union funded projects CLARIS LPB (La Plata Basin) in SESA, and AMAZALERT in Amazonia. Other important initiatives come from the Interamerican Institute for Global Change Research (IAI), World Health Organization (WHO), Global Environment Facility (GEF), Inter-American Development Bank (IDB), Economic Commission for Latin America and the Caribbean (ECLAC, CEPAL), La Red, and BirdLife International, among others. The same holds for local international networks such as the International Council for Local Environmental Initiatives (ICLEI) or C40, of which CA and SA cities form part. The weADAPT initiative is a good example on how CA and SA practitioners, researchers, and policy makers can have access to credible, high-quality information and to share experiences and lessons learned in other regions of the world.

27.8. Conclusions

CA and SA harbor unique ecosystems and maximum biodiversity, with a variety of eco-climatic gradients rapidly changing from development initiatives. Agricultural and beef production as well as bioenergy crops are on the rise, mostly by expanding agricultural frontiers. Poverty and inequality are decreasing, but at a slow pace. Socioeconomic development shows a high level of heterogeneity and a very unequal income distribution, resulting in high vulnerability to climatic conditions. There is still a high and persistent level of poverty in most countries (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade.

The IPCC AR4 and SREX reports contain ample evidence of increase in extreme climate events in CA and SA. During 2000–2013, 613 weather and climate extreme events led to 13,883 fatalities and 53.8 million people affected, with estimated losses of US$52.3 billion. During 2000–2009, 39 hurricanes occurred in the CA-Caribbean basin compared to 15 and 9 in the decade of 1980 and 1990, respectively. In SESA, more frequent and intense rainfall extremes have favored an increase in the occurrence of flash floods and landslides. In Amazonia extreme droughts were reported in 2005 and 2010, and record floods were observed in 2009 and 2012. In 2012–2013 an extreme drought affected NEB.

While warming occurred in most of CA and SA, cooling was detected off the coast of southern Peru and Chile. There is growing evidence that Andean glaciers (both tropical and extratropical) are retreating in response to warming trends. Increases in precipitation were registered in SESA, CA, and the NAMS regions, while decreases were observed in southern Chile, and a slight decrease in NEB after the middle 1970s. In CA a gradual delay of the beginning of the rainfall season has been observed. SLR varied from 2 to 7 mm yr^{-1} between 1950 and 2008 in CA and SA, which is a reason for concern because a large proportion of the population of the region lives by the coast.

Land use and land cover change are key drivers of regional environmental change in SA and CA. Natural ecosystems are affected by climate variability/change and land use change. Deforestation, land degradation, and biodiversity loss are attributed mainly to increased extensive agriculture for traditional export activities and bioenergy crops. Agricultural expansion has affected fragile ecosystems, causing severe environmental degradation and reducing the environmental services provided by these ecosystems. Deforestation has intensified the process of land degradation, increasing the vulnerability of communities exposed to floods, landslides, and droughts. Plant species are rapidly declining in CA and SA, with a high percentage of rapidly declining amphibian species. However, the region has still large extensions of natural vegetation cover, with the Amazon being the main example. Ecosystem-based adaptation practices, such as the establishment of protected areas and their effective management, conservation agreements, community management of natural areas, and payment for ecosystem services are increasingly more common across the region.

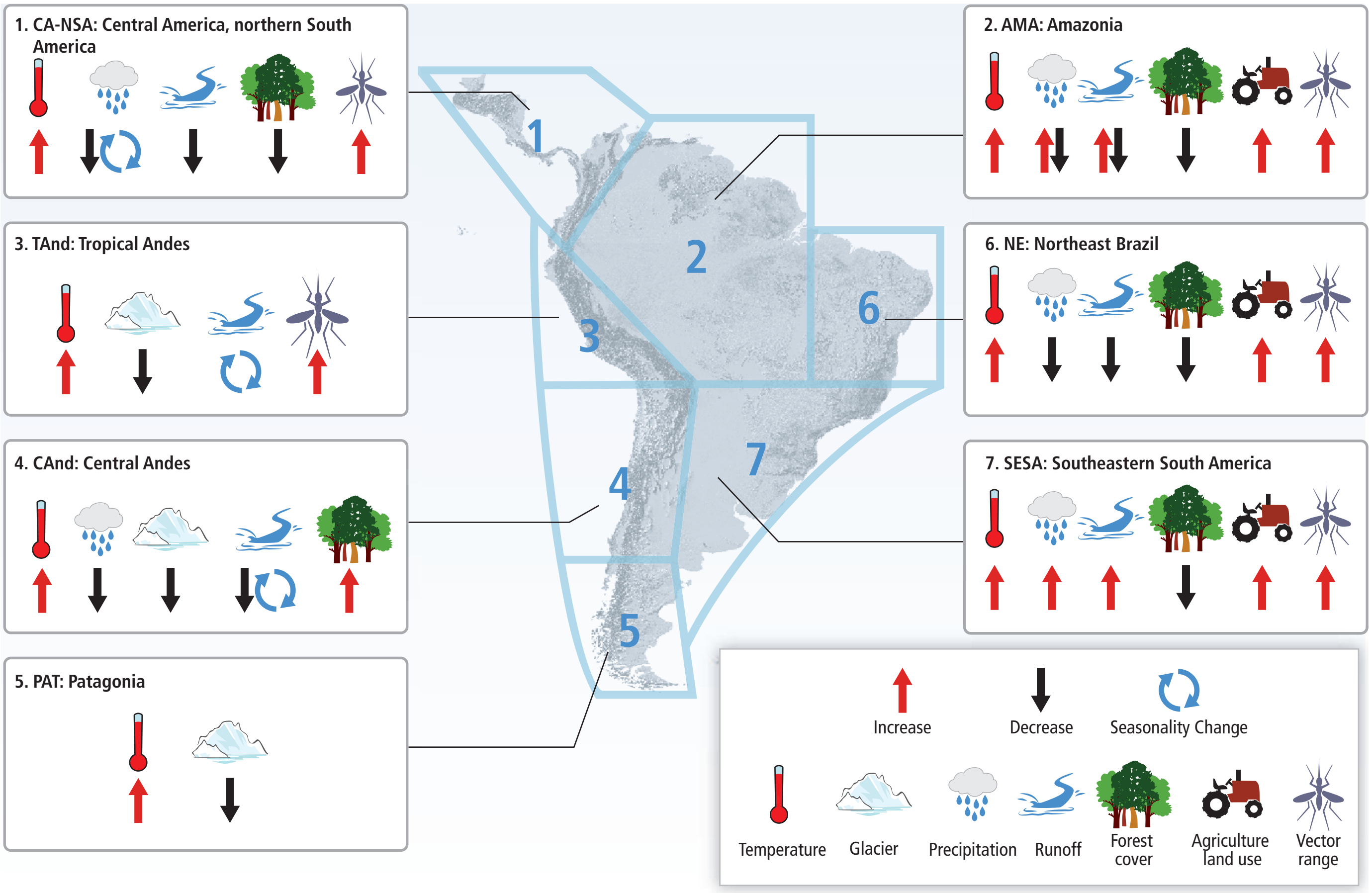


Figure 27-7 | Summary of observed changes in climate and other environmental factors in representative regions of Central and South America. The boundaries of the regions in the map are conceptual (neither geographic nor political precision). Information and references to changes provided are presented in different sections of the chapter.

Figure 27-7 summarizes of some of the main observed trends in global environmental change drivers across different representative regions of CA and SA. Changes in climate and non-climate drivers have to be compounded with other socioeconomic related trends, such as the rapid urbanization experienced in the region.

Some observed impacts on human and natural systems can be directly or indirectly attributed to human influences (see also Figure 27-8):

- Changes in river flow variability in the Amazon River during the last 2 decades, robust positive trends in streamflow in sub-basins of the La Plata River basin, and increased dryness for most of the river basins in west coast of South America during the last 50 years
- Reduction in tropical glaciers and ice fields in extratropical and tropical Andes over the second half of the 20th century that can be attributed to an increase in temperature
- Coastal erosion, bleaching of coral reefs in the coast of CA, and reduction in fisheries stock
- Increase in agricultural yield in SESA, and shift in agricultural zoning (significant expansion of agricultural areas, mainly in climatically marginal regions)
- Increase in frequency and extension of dengue fever, yellow fever, and malaria.

However, for some impacts the number of concluding studies is still insufficient, leading to low levels of confidence for attribution to human influences.

By the end of the century, the CMIP5-derived projections for RCP8.5 yielded: CA – mean annual warming of 2.5°C (range: 1.5°C to 5.0°C), mean rainfall reduction of 10% (range: –25% to +10%), and reduction in summertime precipitation; SA – mean warming of 4°C (range: 2.0°C to 5.0°C), with rainfall reduction up to 15% in tropical SA east of the Andes, and an increase of about 15 to 20% in SESA and in other regions of the continent, and increases in warm days and nights *very likely* to occur in most of SA; SESA – increases in heavy precipitation, and increases in dry spell in northeastern SA. However, there is some degree of uncertainty in climate change projections for regions, particularly for rainfall in CA and tropical SA.

Current vulnerability in terms of water supply in the semi-arid zones and the tropical Andes is expected to increase even further due to climate change. This would be exacerbated by the expected glacier retreat, precipitation reduction, and increased evapotranspiration demands as expected in the semi-arid regions of CA and SA. These scenarios would affect water supply for large cities, small communities, food production, and hydropower generation. There is a need for reassessing current practices to reduce the mismatch between water supply and demand to reduce future vulnerability, and to implement constitutional and legal reforms toward more efficient and effective water resources management.

SLR due to climate change and human activities on coastal and marine ecosystems pose threats to fish stocks, corals, mangroves, recreation

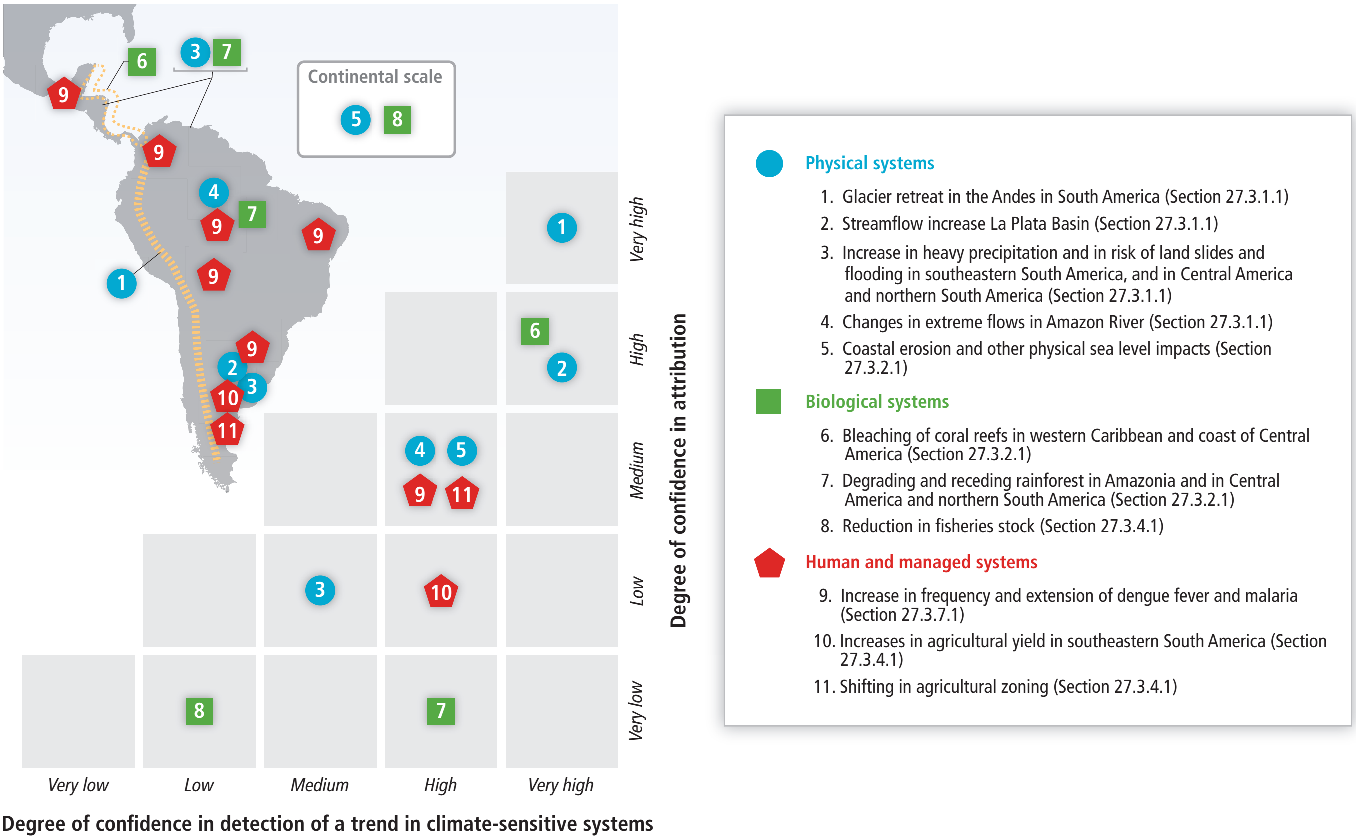


Figure 27-8 | Observed impacts of climate variations and attribution of causes to climate change in Central and South America.

and tourism, and diseases control in CA and SA. Coral reefs, mangroves, fisheries, and other benthic marine invertebrates that provide key ecosystem services, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change. It is possible that the Mesoamerican coral reef will collapse by mid-century (between 2050 and 2070), causing major economic and environmental losses. In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years. In the Rio de La Plata area extreme flooding events may become more frequent because return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected. Beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast.

Urban populations in CA and SA face diverse social, political, economic, and environmental risks in daily life, and climate change will add a new dimension to these risks. Because urban development remains fragile in many cases, with weak planning responses, climate change can compound existing challenges, for example, water supply in cities from glacier, snowmelt, and paramos related runoff in the Andes (Lima, La Paz/El Alto, Santiago de Chile, Bogotá), flooding in several cities such as São Paulo and Buenos Aires, and health-related challenges in many cities of the region.

Climate change will affect individual species and biotic interactions. Vertebrate fauna will suffer major species losses especially in high-altitude areas; elevational specialists might be particularly vulnerable because of their small geographic ranges and high energetic requirements. Freshwater fisheries can suffer alterations in physiology and life histories. In addition, modifications in phenology, structure of ecological networks, predator-prey interactions, and non-trophic interactions among organisms will affect biotic interactions. Shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in High Andean ecosystems. Although in the region biodiversity conservation is largely confined to protected areas, it is expected that many species and vegetational types will lose representativeness inside such protected areas.

Changes in food production and food security are expected to have great spatial variability, with a wide range of uncertainty mainly related to climate and crop models. In SESA average productivity could be sustained or increased until the mid-century, although interannual and decadal climate variability is *likely* to impose important damages. In other regions such as NEB, CA, and some Andean countries agricultural productivity could decrease in the short term, threatening the food security of the poorest population. The expansion of pastures and croplands is expected to continue in the coming years, particularly from an increasing global demand for food and biofuels. The great challenge for CA and SA will be to increase the food and bioenergy production and at the same time sustain the environmental quality in a scenario of climate change.

Renewable energy provides great potential for adaptation and mitigation. Hydropower is currently the main source of renewable energy in CA and SA, followed by biofuels. SESA is one of the main sources of production of the feedstocks for biofuel production, mainly with sugarcane and soybean, and future climate conditions may lead to an increase in productivity and production. Advances in second-generation biofuels will be important as a measure of adaptation, as they have the potential to increase biofuel productivity. In spite of the large amount of arable land available, the expansion of biofuels might have some direct and indirect land use change effects, producing teleconnections that could lead to deforestation of native tropical forests and loss of employment in some countries. This might also affect food security.

Changes in weather and climatic patterns are negatively affecting human health in CA and SA, by increasing morbidity, mortality, and disabilities, and through the emergence of diseases in previously non-endemic regions. Multiple factors increase the region's vulnerability to climate change: precarious health systems; malnutrition; inadequate water and sanitation services; population growth; poor waste collection and treatment systems; air, soil, and water pollution; food in poor regions; lack of social participation; and inadequate governance. Vulnerabilities vary with geography, age, gender, race, ethnicity, and socioeconomic status, and are rising in large cities. Climate change and variability may exacerbate current and future risks to health.

Climate change will bring modifications to environmental conditions in space and time, and the frequency and intensity of weather and climate processes. In many CA and SA countries, a first step toward adaptation to climate change is to reduce the vulnerability to present climate, taking into account future potential impacts, particularly of weather and climate extremes. Long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the CA and SA population. Such conditions weaken the importance of adaptation planning to climate change on the political agenda. Currently, there are few experiences on synergies between development, adaptation, and mitigation planning, which can help local communities and governments to allocate available resources in the design of strategies to reduce vulnerability and develop adaptation measures. Facing a new climate system and, in particular, the exacerbation of extreme events, will call for new ways to manage human and natural systems for achieving sustainable development.

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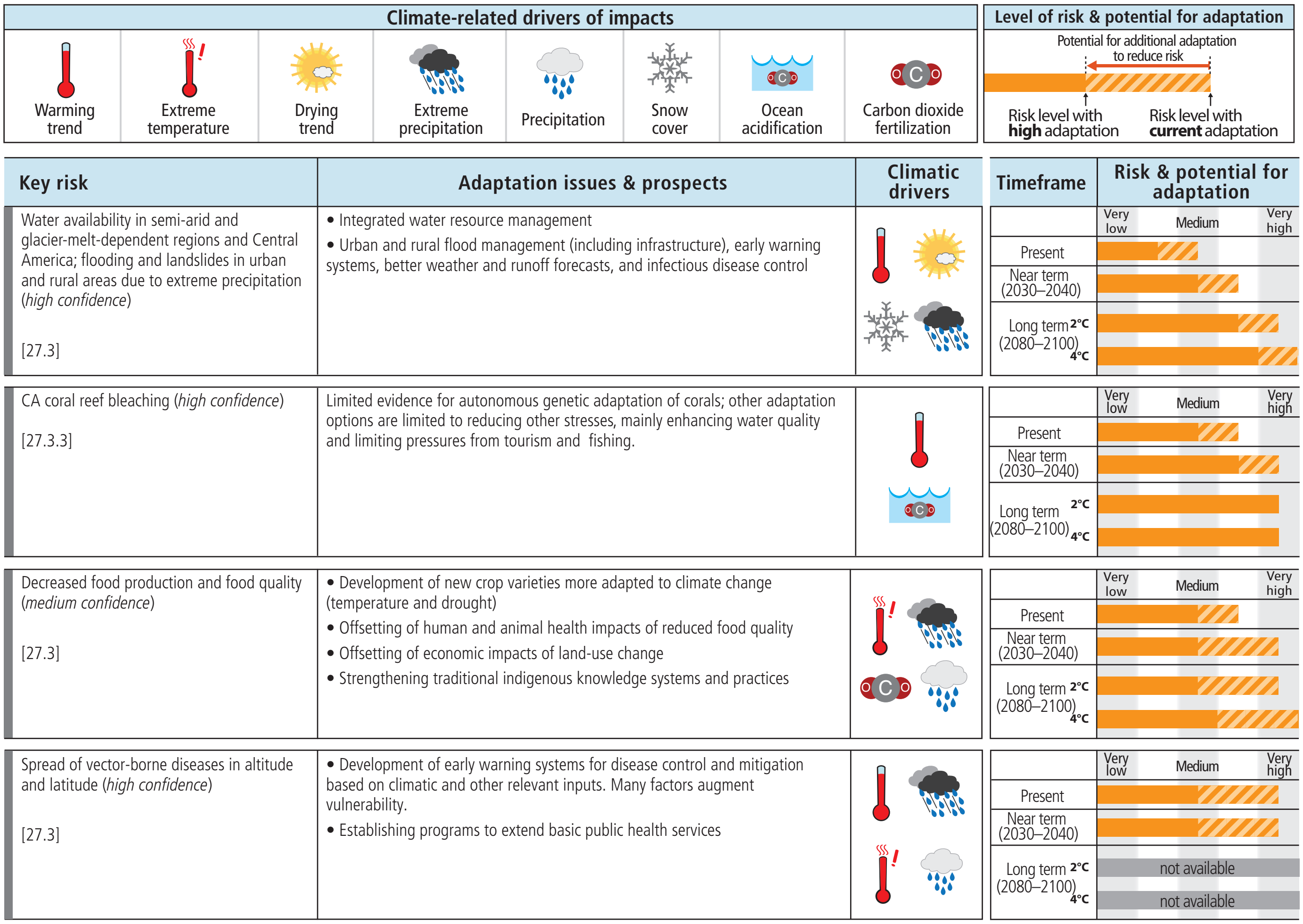
Table 27-8 | Key risks from climate change and the potential for risk reduction through mitigation and adaptation.



Climate-related drivers of impacts							
🌡 Warming trend	🌡! Extreme temperature	☀ Drying trend	⛈ Extreme precipitation	🌧 Precipitation	❄ Snow cover	🌊 Ocean acidification	OCO Carbon dioxide fertilization

Level of risk & potential for adaptation

Potential for additional adaptation to reduce risk

Risk level with **high** adaptation

Risk level with **current** adaptation

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Water availability in semi-arid and glacier-melt-dependent regions and Central America; flooding and landslides in urban and rural areas due to extreme precipitation (*high confidence*) [27.3]	• Integrated water resource management • Urban and rural flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control	🌡 ☀ ❄ ⛈		Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	
			4°C	
CA coral reef bleaching (*high confidence*) [27.3.3]	Limited evidence for autonomous genetic adaptation of corals; other adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing.	🌡 🌊		Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	
			4°C	
Decreased food production and food quality (*medium confidence*) [27.3]	• Development of new crop varieties more adapted to climate change (temperature and drought) • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land-use change • Strengthening traditional indigenous knowledge systems and practices	🌡! ⛈ OCO 🌧		Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	
			4°C	
Spread of vector-borne diseases in altitude and latitude (*high confidence*) [27.3]	• Development of early warning systems for disease control and mitigation based on climatic and other relevant inputs. Many factors augment vulnerability. • Establishing programs to extend basic public health services	🌡 ⛈ 🌡! 🌧		Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	not available
			4°C	not available

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28

Polar Regions

Coordinating Lead Authors:
Joan Nymand Larsen (Iceland), Oleg A. Anisimov (Russian Federation)

Lead Authors:
Andrew Constable (Australia), Anne B. Hollowed (USA), Nancy Maynard (USA), Pål Prestrud (Norway), Terry D. Prowse (Canada), John M.R. Stone (Canada)

Contributing Authors:
Terry V. Callaghan (UK), Mark Carey (USA), Peter Convey (UK), Andrew Derocher (Canada), Bruce C. Forbes (Finland), Peter T. Fretwell (UK), Solveig Glomsrød (Norway), Dominic Hodgson (UK), Eileen Hofmann (USA), Grete K. Hovelsrud (Norway), Gita L. Ljubicic (Canada), Harald Loeng (Norway), Eugene Murphy (UK), Steve Nicol (Australia), Anders Oskal (Norway), James D. Reist (Canada), Phil Trathan (UK), Barbara Weinecke (Australia), Fred Wrona (Canada)

Review Editors:
Maria Ananicheva (Russian Federation), F. Stuart Chapin III (USA)

Volunteer Chapter Scientist:
Vasiliy Kokorev (Russian Federation)

This chapter should be cited as:

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Executive Summary

Additional and stronger scientific evidence has accumulated since the AR4 that reinforces key findings made in the Fourth Assessment Report (AR4).

The impacts of climate change, and the adaptations to it, exhibit strong spatial heterogeneity in the polar regions because of the high diversity of social systems, biophysical regions, and associated drivers of change (*high confidence*). {28.2.2} For example, the tree line has moved northward and upward in many, but not all, Arctic areas (*high confidence*) and significant increases in tall shrubs and grasses have been observed in many places (*very high confidence*). {28.2.3.1.2}

Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the polar regions (*medium confidence*). The response rate and the spatial extent of the shifts will differ by species based on their vulnerability to change and their life history. {28.2.2, 28.3.2} Loss of sea ice in summer and increased ocean temperatures are expected to impact secondary pelagic production in some regions of the Arctic Ocean, with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). These changes are expected to alter the species composition of zooplankton in some regions, with associated impacts on some fish and shellfish populations (*medium confidence*). {28.2.2.1} Also, changes in sea ice and the physical environment to the west of the Antarctic Peninsula are altering phytoplankton stocks and productivity, and krill (*high confidence*). {28.2.2.2}

Climate change is impacting terrestrial and freshwater ecosystems in some areas of Antarctica and the Arctic. This is due to ecological effects resulting from reductions in the duration and extent of ice and snow cover and enhanced permafrost thaw (*very high confidence*), and through changes in the precipitation-evaporation balance (*medium confidence*). {28.2.1, 28.2.3}

The primary concern for polar bears over the foreseeable future is the recent and projected loss of annual sea ice cover, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent. {28.2.2.1.2, 28.3.2.2.2}

Rising temperatures, leading to the further thawing of permafrost, and changing precipitation patterns have the potential to affect infrastructure and related services in the Arctic (*high confidence*). {28.3.4.3} Particular concerns are associated with damage to residential buildings resulting from thawing permafrost, including Arctic cities; small, rural settlements; and storage facilities for hazardous materials. {28.2.4-5}

In addition, there is new scientific evidence that has emerged since the AR4.

The physical, biological, and socioeconomic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by drivers other than climate change but also demography, culture, and economic development. Climate change has compounded some of the existing vulnerabilities caused by these other factors (*high confidence*). {28.2.4-5, 28.4} For example, food security for many Indigenous and rural residents in the Arctic is being impacted by climate change, and in combination with globalization and resource development food insecurity is projected to increase in the future (*high confidence*). {28.2.4}

The rapid rate at which climate is changing in the polar regions will impact natural and social systems (*high confidence*) and may exceed the rate at which some of their components can successfully adapt (*low* to *medium confidence*). {28.2.4, 28.4} The decline of Arctic sea ice in summer is occurring at a rate that exceeds most of the earlier generation model projections (*high confidence*), and evidence of similarly rapid rates of change is emerging in some regions of Antarctica. {WGI AR5 Chapters 4, 5, 9} In the future, trends in polar regions of populations of marine mammals, fish, and birds will be a complex response to multiple stressors and indirect effects (*high confidence*). {28.3.2} Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea level rise, and increased weather intensity are forcing relocation of some Indigenous communities in Alaska (*high confidence*). {28.2.4.2, 28.2.5, 28.3.4}

Shifts in the timing and magnitude of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival of dependent species (*medium confidence*). If the timing of primary and secondary production is no longer matched to the timing of spawning or egg release, survival could be impacted, with cascading implications to higher trophic levels. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). {28.2.2, 28.3.2} Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species, the majority likely to arrive through direct human assistance (*high confidence*).

Ocean acidification has the potential to inhibit embryo development and shell formation of some zooplankton and krill in the polar regions, with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Embryos of Antarctic krill have been shown to be vulnerable to increased concentrations of carbon dioxide (CO_2) in the water (*high confidence*). As well, there is increasing evidence that pelagic molluscs (pteropods) are vulnerable to ocean acidification (*medium confidence*). {28.2.2, 28.3.2}

There is increased evidence that climate change will have large effects on Arctic communities, especially where narrowly based economies leave a smaller range of adaptive choices. {28.2.6.1, 28.4} Some commercial activities will become more profitable while others will face decline. Increased economic opportunities are expected with increased navigability in the Arctic Ocean and the expansion of some land- and freshwater-based transportation networks. {28.2.6.1.3, 28.3.4.3} The informal, subsistence-based economy will be impacted (*high confidence*). There is *high confidence* that changing sea ice conditions may result in more difficult access for hunting marine mammals. {28.2.6.1.6} Although Arctic residents have a history of adapting to change, the complex interlinkages among societal, economic, and political factors and climatic stresses represent unprecedented challenges for northern communities, particularly if the rate of change will be faster than the social systems can adapt (*high confidence*). {28.2.5, 28.4}

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase—especially for many Indigenous peoples (*high confidence*). {28.2.4} These impacts are expected to vary among the diverse settlements, which range from small, remote, predominantly Indigenous communities to large cities and industrial settlements (*high confidence*), especially those in highly vulnerable locations along ocean and river shorelines. {28.2.4}

28.1. Introduction

Several recent climate impact assessments on polar regions have been undertaken, including the synthesis report on Snow, Water, Ice and Permafrost in the Arctic (AMAP, 2011a), the State of the Arctic Coast 2010 (2011) reports, the Antarctic Climate and the Environment (Turner et al., 2009, 2013), Arctic Resilience Interim Report 2013 (2013), and the findings of the International Polar Year (IPY; Krupnick et al., 2011). These reports draw a consistent pattern of climate-driven environmental, societal, and economic changes in the polar regions in recent decades. In this chapter, we use the scientific literature, including these reports, to consolidate the assessment of the impacts of climate change on polar regions from 2007, advance new scientific evidence of impacts, and identify key gaps in knowledge on current and future impacts. Previous IPCC reports define the Arctic as the area within the Arctic Circle (66°N), and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58°S (IPCC, 2007). For the purpose of this report we use the conventional IPCC definitions as a basis, while incorporating a degree of flexibility when describing the polar regions in relation to particular subjects.

Changes in the physical and chemical environments of the polar regions are detailed in the WGI contribution to the AR5. There is evidence that Arctic land surface temperatures have warmed substantially since the mid-20th century, and the future rate of warming is expected to exceed the global rate. Sea ice extent at the summer minimum has decreased significantly in recent decades, and the Arctic Ocean is projected to become nearly ice free in summer within this century. The duration of snow cover extent and snow depth are decreasing in North America while increasing in Eurasia. Since the late 1970s, permafrost temperatures have increased between 0.5°C and 2°C. In the Southern Hemisphere, the strongest rates of atmospheric warming are occurring in the western Antarctic Peninsula (WAP, between 0.2°C and 0.3°C per decade) and the islands of the Scotia Arc, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration. Warming, although less than WAP, has also occurred in the continental margins near the Bellingshausen Sea, Prydz Bay, and the Ross Sea, with areas of cooling in between. Land regions have experienced glacial recession and changes in the ice and permafrost habitats in the coastal margins. The Southern Ocean continues to warm, with increased freshening at the surface due to precipitation leading to increased stratification. In both polar regions, as a result of acidification, surface waters will become seasonally corrosive to aragonite within decades, with some regions being affected sooner than others (see Box CC-OA; WGI AR5 Chapter 6). Observations and models indicate that the carbon cycle of the Arctic and Southern Oceans will be impacted by climate change and increased carbon dioxide (CO_2).

28.2. Observed Changes and Vulnerability under Multiple Stressors

28.2.1. Hydrology and Freshwater Ecosystems

28.2.1.1. Arctic

Arctic rivers and lakes continue to show pronounced changes to their hydrology and ecology. Previously noted increases in Eurasian Arctic

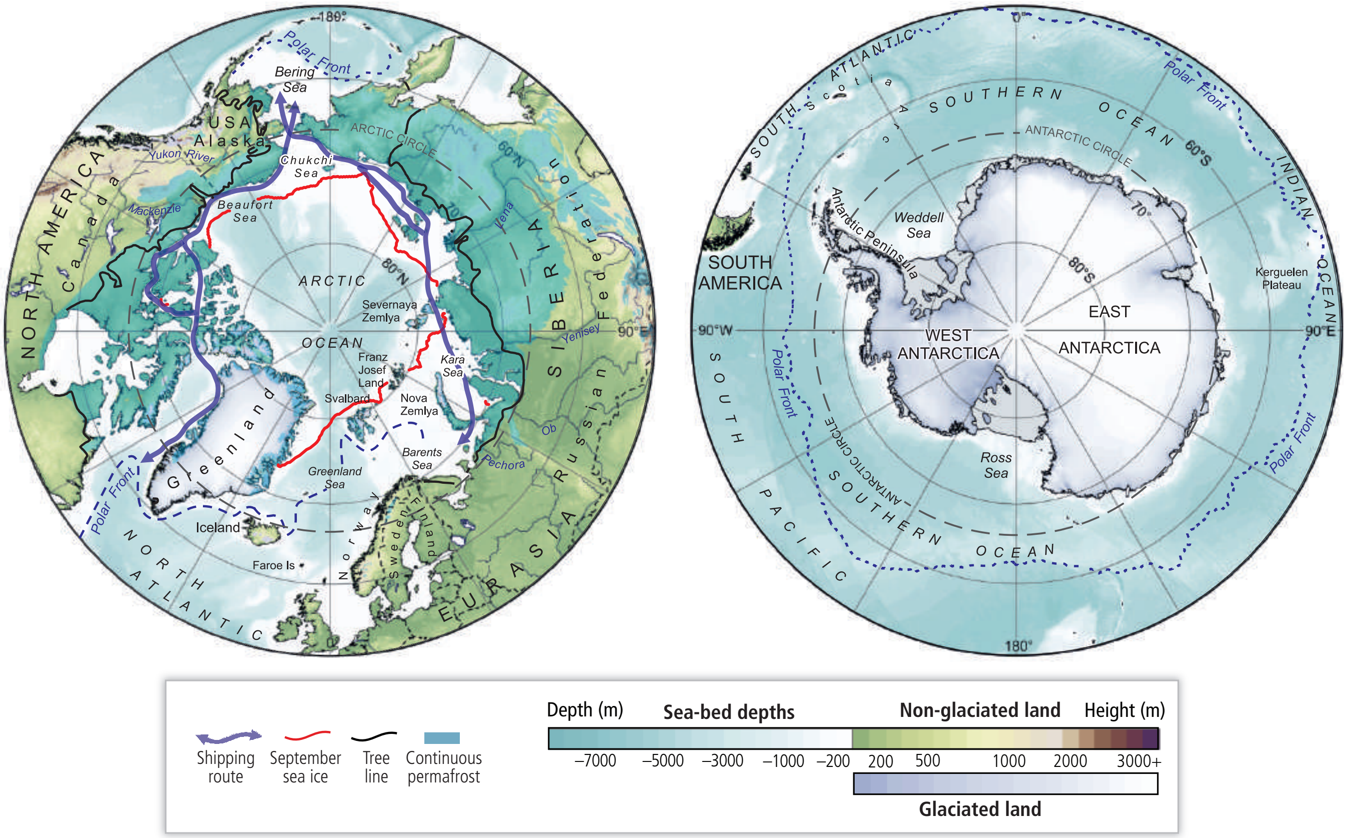


Figure 28-1| Location maps of the north and south polar regions (courtesy of P. Fretwell, British Antarctic Survey).

river flow (1936–1999; Peterson et al., 2002) could not, for a similar period (1951–2000), be attributed with certainty to precipitation changes (Milliman et al., 2008) but has been, including more recent extreme increases (2007), attributed to enhanced poleward atmospheric moisture transport (Zhang et al., 2013). By contrast, decreased flow in high-latitude Canadian rivers (1964–2000; average –10%) does match that for precipitation (Déry and Wood, 2005). Recent data (1977–2007) for 19 circumpolar rivers also indicate an area-weighted average increase of +9.8% (–17.1 to 47.0%; Overeem and Syvitski, 2010) accompanied by shifts in flow timing, with May snowmelt increasing (avg. 66%) but flow in the subsequent month of peak discharge decreasing (~7%). Across the Russian Arctic, dates of spring maximum discharge have also started to occur earlier, particularly in the most recent (1960–2001) period analyzed (average –5 days; range for four regions +0.2 to –7.1 days), but no consistent trend exists for magnitude (average –1%; range +21 to –24%; Shiklomanov et al., 2007). Earlier timing was most pronounced in eastern, colder continental climates, where increases in air temperature have been identified as the dominant control (Tan et al., 2011).

Increases have also occurred in winter low flows for many Eurasian and North American rivers (primarily in the late 20th century; Smith et al., 2007; Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009; Ye et al., 2009), the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm et al., 2010). Most such studies suggest permafrost thaw (WGI AR5 Chapter 4) has increased winter flow, whereas others suggest increases in net winter precipitation minus evapotranspiration (Rawlins et al., 2009a,b; Landerer et al., 2010). Insufficient precipitation stations preclude deciphering the relative importance of these factors (WGI AR5 Section 2.5.1).

The surface-water temperatures of large water bodies has warmed (1985–2009; Schneider and Hook, 2010), particularly for mid- and high latitudes of the Northern Hemisphere, with spatial patterns generally matching those for air temperature. Where water bodies warmed more rapidly than air temperature, decreasing ice cover was suggested as enhancing radiative warming. Paleolimnological evidence indicates that the highest primary productivity was associated with warm, ice-free summer conditions and the lowest with periods of perennial ice (Melles et al., 2007). Increasing water temperatures affect planktonic and benthic biomass and lead to changes in species composition (Christoffersen et al., 2008; Heino et al., 2009, Jansson et al., 2010). Reduced ice cover with higher air temperatures and evaporation are responsible for the late-20th to early-21st century desiccation of some Arctic ponds (Smol and Douglas, 2007).

Changes have occurred in the size and number of permafrost lakes over the last half-century (Hinkel et al., 2007; Marsh et al., 2009), but their patterns and rates of change are not consistent because of differing thawing states, variations in warming, and effects of human activities (Hinket et al., 2007; Prowse and Brown, 2010a). Thawing permafrost affects the biogeochemistry of water entering lakes and rivers (Frey and McClelland, 2009; Kokelj et al., 2009) and their ecological structure and function (Lantz and Kokelj, 2008; Thompson et al., 2008; Mesquita et al., 2010), such as enhancing eutrophication by a shift from pelagic to benthic-dominated production (Thompson et al., 2012).

The aquatic ecosystem health and biodiversity of northern deltas is dependent on combined changes in the elevation of spring river ice-jam floods and sea level (Lesack and Marsh, 2007, 2010). Diminishing ice shelves (last half-century) have also caused a decline in the number of freshwater epishelf lakes that develop behind them (Veillette et al., 2008; Vincent et al., 2009). Although such biophysical dependencies have been established, temporal trends in such river-delta and epishelf lake impacts and their linkages to changing climate remain to be quantified precisely.

An interplay of freshwater-marine conditions also affects the timing, growth, run size, and distribution of several Arctic freshwater and anadromous fish. Key examples include the timing of marine exit of Yukon River Chinook salmon (*Oncorhynchus tshawytscha*; 1961–2009) varied with air and sea temperatures and sea ice cover (Mundy and Evenson, 2011); the growth of young-of-year Arctic cisco (*Coregonus autumnalis*; 1978–2004) varied in response to lagged sea ice concentration and Mackenzie River discharge, also indicating that decreased sea ice concentration and increased river discharge enhanced marine primary production, leading to more favorable foraging conditions (von Biela et al., 2011); and factors that influence the water level and freshening of rivers, as well as the strength, duration, and directions of prevailing coastal winds, affect survival of anadromous fishes during coastal migration and their subsequent run size (Fechhelm et al., 2007).

28.2.1.2. Antarctic

Biota of Antarctic freshwater systems (lakes, ponds, short streams, and seasonally wetted areas) are dominated by benthic microbial communities of cyanobacteria and green algae in a simple food web. Mosses occur in some continental lakes with higher plants absent. Planktonic ecosystems are typically depauperate and include small algae, bacteria, and colorless flagellates, with few metazoans and no fish (Quesada and Velázquez, 2012). Recent compilations of single-year data sets have reinforced previous conclusions on the changing freshwater habitats in Antarctica (Verleyen et al., 2012). In regions where the climate has warmed, the physical impacts on aquatic ecosystems include loss of ice and perennial snow cover, increasing periods of seasonal open water, increased water column temperatures, and changes in water column stratification. In some areas, a negative water balance has occurred as a result of increased temperature and changes in wind strength driving enhanced evaporation and sublimation and leading to increased salinity in lakes in recent decades (Hodgson et al., 2006a). In other areas, especially glacial forelands, increased temperatures have led to greater volumes of seasonal meltwater in streams and lakes together with increased nutrient fluxes (*high confidence*). In both cases, the balance between precipitation and evaporation can have detectable effects on lake ecosystems (*medium confidence*) through changes in water body volume and lake chemistry (Lyons et al., 2006; Quesada et al., 2006). Non-dilute lakes with a low lake depth to surface area ratio are most susceptible to interannual and inter-decadal variability in the water balance, as measured by changes in specific conductance (*high confidence*; Verleyen et al., 2012). Warming in the northwestern Antarctic Peninsula region has resulted in permafrost degradation in the last approximately 50 years, impacting surface geomorphology and hydrology (Bockheim et al., 2013) with the potential to increase soil biomass.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

28.2.2.1.1. Marine plankton, fish, and other invertebrates

WGI documented the expected physical and chemical changes that will occur in Arctic marine ecosystems (WGI AR5 Chapters 4, 6, 11). Naturally occurring interannual, decadal, and multi-decadal variations in climate will continue to influence the Arctic Ocean and its neighboring high-latitude seas (Chapter 5). In recent years (2007–2012), ocean conditions in the Bering Sea have been cold (Stabeno et al., 2012a), while the Barents Sea has been warm (Lind and Ingvaldsen, 2012).

In this section, we build on previous reviews of observed species responses to climate (Wassman et al., 2011) to summarize the current evidence of the impact of physical and chemical changes in marine systems on the phenology, spatial distribution, and production of Arctic marine species. For each type of response, the implications for phytoplankton, zooplankton, fish, and shellfish are discussed. The implications of these changes on marine ecosystem structure and function will be the result of the synergistic effects of all three types of biological responses.

Phenological response

The timing of spring phytoplankton blooms is a function of seasonal light, hydrographic conditions, and the timing of sea ice breakup (Wassman, 2011). In addition to the open water phytoplankton bloom, potentially large ice algal blooms can form under the sea ice (Arrigo, 2012). During the period 1997–2009, a trend toward earlier phytoplankton blooms was detected in approximately 11% of the area of the Arctic Ocean (Kahru et al., 2011). This advanced timing of annual phytoplankton blooms coincided with decreased sea ice concentration in early summer. Brown and Arrigo (2013) studied the timing and intensity of spring blooms in the Bering Sea from 1997 to 2010 and found that in northern regions sea ice consistently retreated in late spring and was associated with ice-edge blooms, whereas in the southern regions the timing of sea ice retreat varied, with ice-edge blooms associated with late ice retreat, and open water blooms associated with early ice retreat. Given the short time series and limited studies, there is *medium confidence* that climate variability and change has altered the timing and the duration of phytoplankton production.

The life cycles of calanoid copepods in the Arctic Ocean and Barents Sea are timed to utilize ice algal and phytoplankton blooms (Falk-Petersen et al., 2009; Søreide et al., 2010; Darnis et al., 2012). Based on a synthesis of existing data, Hunt, Jr. et al. (2011) hypothesized that, in the southeastern Bering Sea, ocean conditions and the timing of sea ice retreat influences the species composition of dominant zooplankton, with lipid-rich copepods being more abundant in cold years.

There is ample evidence that the timing of spawning and hatching of some fish and shellfish is aligned to match larval emergence with seasonal increases in prey availability (Gjosaeter et al., 2009; Vikebø et al., 2010; Bouchard and Fortier, 2011; Drinkwater et al., 2011). These regional phenological adjustments to local conditions occurred over many generations (Ormseth and Norcross, 2009; Geffen et al., 2011; Kristiansen et al., 2011). There is *medium* to *high confidence* that climate-induced disruptions in this synchrony can result in increased larval or juvenile mortality or changes in the condition factor of fish and shellfish species in the Arctic marine ecosystems.

Observed spatial shifts

Spatial heterogeneity in primary production has been observed (Lee et al., 2010; Grebmeier, 2012). Simulation modeling studies show that spatial differences in the abundance of four species of copepod can be explained by regional differences in the duration of the growing season and temperature (Ji et al., 2012). Retrospective studies based on surveys from 1952 to 2005 in the Barents Sea revealed that changes in the species composition, abundance, and distribution of euphausiids were related to climate-related changes in oceanographic conditions (Zhukova et al., 2009).

Retrospective analysis of observed shifts in the spatial distribution of fish and shellfish species along latitudinal and depth gradients showed observed spatial shifts were consistent with expected responses of species to climate change (Simpson et al., 2011; Poloczanska et al., 2013; see also Box CC-MB). Retrospective studies from the Bering Sea, Barents Sea, and the northeast Atlantic Ocean and Icelandic waters showed that fish shift their spatial distribution in response to climate variability (i.e., interannual, decadal, or multi-decadal changes in ocean temperature; Mueter and Litzow, 2008; Sundby and Nakken, 2008; Hátún et al., 2009; Valdimarsson et al., 2012; Kotwicki and Lauth, 2013). There are limits to the movement potential of some species. Vulnerability assessments indicate that the movement of some sub-Arctic fish and shellfish species into the Arctic Ocean may be impeded by the presence of water temperatures on the shelves that fall below their thermal tolerances (Hollowed et al., 2013; Hunt, Jr. et al., 2013). Coupled biophysical models have reproduced the observed spatial dynamics of some the species in the Bering and Barents Seas, and are being used to explain the role of climate variability and change on the distribution and abundance of some species (Huse and Ellingsen, 2008; Parada et al., 2010). In summary, there is *medium* to *high confidence* based on observations and modeling that some fish and shellfish have shifted their distribution in response to climate impacts on the spatial distribution and volume of suitable habitat.

Observed variations in production

Seasonal patterns in light, sea ice cover, freshwater input, stratification, and nutrient exchange act in concert to produce temporal cycles of ice algal and phytoplankton production in Arctic marine ecosystems (Perrette et al., 2011; Wassmann, 2011; Tremblay et al., 2012). Satellite observations and model estimates for the period 1988–2007 showed that phytoplankton productivity increased in the Arctic Ocean in response to a downward trend in the extent of summer sea ice (Zhang et al., 2010). Satellite data provided evidence of a 20% increase in annual net primary production in the Arctic Ocean between 1998 and 2009 in response to extended ice-free periods (Arrigo and van Dijken, 2011). Regional trends in primary production will differ in response to the amount of open water area in summer (Arrigo and van Dijken, 2011). Other studies showed gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad et al., 2011). A recent 5-year study (2004–2008) in the Canada Basin showed that smaller phytoplankton densities were higher than larger phytoplankton densities in years when sea surface temperatures (SSTs) were warmer, the water column was more stratified, and nutrients were more depleted during the Arctic summer (Li et al., 2009; Morán et al., 2010). Additional observations will help to resolve observed differences between *in situ* and satellite-derived estimates of primary production (Matrai et al., 2013). In conclusion, based on recent observations and modeling, there is *medium* to *high confidence* that primary production has increased in the Arctic Ocean in response to changes in climate and its impact on the duration and areal extent of ice-free periods in summer.

Regional differences in zooplankton production have been observed. During a period of ocean warming (1984–2010), Dalpadado et al. (2012) observed an increase in the biomass of lipid-rich euphausiids in the Barents Sea and relatively stable levels of biomass and production of *Calanus finmarchicus*. In the Bering Sea, observations over the most recent decade in the southeast Bering Sea showed *C. marshallae* were more abundant in cold than in warm years (Coyle et al., 2011).

There is strong evidence that climate variability impacts the year-class strength of Arctic marine fish and shellfish through its influence on predation risk; the quality, quantity, and availability of prey; and reproductive success (Mueter et al., 2007; Bakun 2010; Drinkwater et al., 2010). Regional differences in the species responses to climate change will be a function of the exposure of the species to changing environmental conditions, the sensitivity of the species to these changes (Beaugrand and Kirby, 2010), and the abilities of species to adapt to changing conditions (Pörtner and Peck, 2010; Donelson et al., 2011). There is *high confidence* that shifts in ocean conditions have impacted the abundance of fish and shellfish in Arctic regions. Observed trends in the abundance of commercial fish and shellfish may also be influenced by historical patterns of exploitation (Vert-pre et al., 2013).

28.2.2.1.2. Marine mammals, polar bears, and seabirds

Studies on responses of Arctic and subarctic marine mammals to climate change are limited and vary according to insight into their habitat requirements and trophic relationships (Laidre et al., 2008). Many Arctic and sub-Arctic marine mammals are highly specialized, have long life spans, and are poorly adapted to rapid environmental change (Moore and Huntington, 2008), and changes may be delayed until significant sea ice loss has occurred (Freitas et al., 2008; Laidre et al., 2008).

Climate change effects on Arctic and sub-Arctic marine mammal species will vary by life history, distribution, and habitat specificity (*high confidence*). Climate change will improve conditions for a few species, have minor negative effects for others, and some will suffer major negative effects (Laidre et al., 2008; Ragen et al., 2008). Climate change resilience will vary and some ice-obligate species should survive in regions with sufficient ice and some may adapt to ice-free conditions (Moore and Huntington, 2008). Less ice-dependent species may be more adaptable but an increase in seasonally migrant species could increase competition (Moore and Huntington, 2008).

Climate change vulnerability was associated with feeding specialization, ice dependence, and ice reliance for prey access and predator avoidance (Laidre et al., 2008). There is *medium agreement* on which species' life histories are most vulnerable. Hooded seals (*Cystophora cristata*) and narwhal (*Monodon monoceros*) were identified as most at risk and ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*) as least sensitive (Laidre et al., 2008). Kovacs et al. (2010) shared concern for hooded seals and narwhal but had concerns for ringed seals and bearded seals. Narwhal may have limited ability to respond to habitat alteration (Williams et al., 2011). Species that spend only part of the year in the Arctic (e.g., gray whale (*Eschrichtius robustus*), killer whale (*Orcinus orca*)) may benefit from reduced ice (Laidre et al., 2008; Moore, 2008; Higdon and Ferguson, 2009; Matthews et al., 2011; Ferguson et al., 2012). Killer whale expansion into the Arctic could cause a trophic cascade (Higdon and Ferguson, 2009), although there is *limited evidence* at this time.

There is *limited evidence* although *medium agreement* that generalists and pelagic feeding species may benefit from increased marine productivity from reduced ice while benthic feeding species near continental shelf habitats may do poorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary or habitat specialists will do poorly with reduced ice. Reduction of summer/autumn ice was the primary extrinsic factor affecting Pacific walrus (*Odobenus rosmarus*), with predictions of distribution changes, reduced calf recruitment, and longer term predictions of high extinction probability (Cooper et al., 2006; MacCracken, 2012). Summer ice retreat may make migration to such habitats energetically unprofitable for ringed seals (Freitas et al., 2008). Ice loss threatens Baltic ringed seals (Kovacs and Lydersen, 2008). In Hudson Bay, earlier spring break-up and changes in snow cover over lairs have reduced ringed seal recruitment (Ferguson et al., 2005). Changes in snowfall over the 21st century were projected to reduce ringed seal habitat for lairs by 70% (Hezel et al., 2012). Similarly, harp seal (*Pagophilus groenlandicus*) breeding habitat was affected by changing ice conditions that could reduce pup survival (Bajzak et al., 2011). Although there is *limited evidence*, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, shipping, and development; Burek et al., 2008).

Empirical studies provide direct insight into the mechanisms of climate change impact on polar bears (*Ursus maritimus*) but modeling allows predictive capacity (Amstrup et al., 2010; Hunter et al., 2010; Durner et al., 2011; Castro de la Guardia et al., 2013).

Polar bears are highly specialized and use annual ice over the continental shelves as their preferred habitat (Durner et al., 2009; Miller et al., 2012). The recent and projected loss of annual ice over continental shelves, decreased ice duration, decreased ice thickness, and habitat fragmentation are causing reduced food intake, increased energy expenditure, and increased fasting in polar bears (*high confidence*; Stirling and Parkinson, 2006; Regehr et al., 2007; Durner et al., 2009; Amstrup et al., 2010; Hunter et al., 2010; Derocher et al., 2011; Rode et al., 2012; Sahanatien and Derocher, 2012; Castro de la Guardia et al., 2013).

Subpopulation response varies geographically. Only 2 of the 19 subpopulations—Western Hudson Bay (Regehr et al., 2007) and the southern Beaufort Sea (Regehr et al., 2010; Rode et al., 2010a)—have data series adequate for clear identification of abundance effects related to climate change. Many other subpopulations show characteristics associated with decline but some remain stable. Declining ice is causing lower body condition, reduced individual growth rates, lower fasting endurance, lower reproductive rates, and lower survival (*high confidence*; Regehr et al., 2007, 2010; Rode et al., 2010a, 2012; Molnar et al., 2011). Condition is a precursor to demographic change (*very high confidence*; Hunter et al., 2010; Regehr et al., 2010; Rode et al., 2010a; Robinson et al., 2011). The decline in the subpopulation in Western Hudson Bay by 21% between 1987 and 2004 was related to climate change (*medium confidence*; Regehr et al., 2007). Replacement of multi-year ice by annual ice could increase polar bear habitat (*low confidence*; Derocher et al., 2004). Increasing the distance to multi-year ice and terrestrial refugia at maximal melt may result in drowning, cub mortality, and increased energetic costs (Monnett and Gleason, 2006; Durner et al., 2011; Pagano et al., 2012). There is *robust evidence* of changes in sea ice conditions changing polar bear distribution including den areas (*high confidence*; Fischbach et al., 2007; Schliebe et al., 2008; Gleason and Rode, 2009; Towns et al., 2010; Derocher et al., 2011). The number of human-bear interactions is projected to increase with warming (*high confidence*; Stirling and Parkinson, 2006; Towns et al., 2009).

Use of terrestrial resources by polar bears was suggested as adaptive (Dyck et al., 2007, 2008; Dyck and Romberg, 2007; Armstrong et al., 2008; Dyck and Kebreab, 2009; Rockwell and Gormezano, 2009; Smith et al., 2010). Polar bears cannot adapt to terrestrial foods (Stirling et al., 2008b; Amstrup et al., 2009; Rode et al., 2010b; Slater et al., 2010), and will most likely not be able to adapt to climate change and reduced sea ice extent (*very high confidence*). Changing ice conditions are linked to cannibalism (Amstrup et al., 2006), altered feeding (Cherry et al., 2009), unusual hunting behavior (Stirling et al., 2008a), and diet change (Iverson et al., 2006; Thiemann et al., 2008) (*medium confidence*).

Upwelling or subsurface convergence areas found in frontal zones and eddies, and the marginal ice zone, are associated with high marine productivity important to Arctic seabirds (e.g., Irons et al., 2008). Long-term or permanent shifts in convergence areas and the marginal ice-edge zone induced by climate change may cause mismatch between the timing of breeding and the peak in food availability, and thus potentially have strong negative impacts on seabird populations (*medium confidence*; Gaston et al., 2005, 2009; Moline et al., 2008; Grémillet and Boulinier, 2009).

The contrasting results from the relatively few studies of impacts of climate change on Arctic seabirds demonstrate that future impacts will be highly variable between species and between populations of the same species (*medium confidence*). Retreating sea ice and increasing SSTs have favored some species and disadvantaged others (Gaston et al., 2005; Byrd et al., 2008; Irons et al., 2008; Karnovsky et al., 2010; Fredriksen et al., 2013). Some species of seabirds respond to a wide range of sea surface temperatures via plasticity of their foraging behavior, allowing them to maintain their fitness levels (Grémillet et al., 2012). Phenological changes and changes in productivity of some breeding colonies have been observed (Byrd et al., 2008; Gaston and Woo, 2008; Moe et al., 2009). Negative trends in population size, observed over the last few decades for several species of widespread Arctic seabirds, may be related to over-harvesting and pollution as well as climate change effects (Gaston, 2011). For those species whose distribution is limited by sea ice and cold water, polar warming could be beneficial (Mehlum, 2012).

A major ecosystem shift in the northern Bering Sea starting in the mid-1990s caused by increased temperatures and reduced sea ice cover had a negative impact on benthic prey for diving birds, and these populations have declined in the area (Grebmeier et al., 2006). More recently, the Bering Sea has turned colder again.

28.2.2.2. Antarctica

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry, and vertical mixing (Massom and Stammerjohn, 2010; Boyd et al., 2012; Murphy et al., 2012a). Moreover, there is large-scale regional variability in habitats (Grant et al., 2006) and their responses to climate change. Antarctic krill, *Euphausia superba* (hereafter, krill), is the dominant consumer, eating diatoms, and, in turn, is the main prey of fish, squid, marine mammals, and seabirds. Krill is dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean (Rogers et al., 2012). In the East Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the Antarctic Circumpolar Current (Nicol et al., 2000a,b) while to the north copepods and myctophid fish are most important (Rogers et al., 2012). Further west, where the Weddell Sea exerts an influence, krill are found as far north as the Sub-Antarctic Circumpolar Current Front (Jarvis et al., 2010). Where sea ice dominates for most of the year, ice-obligate species (e.g., *Euphausia crystallorophias* and *Peluragramma antarcticum*) are most important (Smith et al., 2007).

Few studies were available in AR4 to document and validate the changes in these systems resulting from climate change. Those studies reported increasing abundance of benthic sponges and their predators, declining populations of krill, Adélie and emperor penguins, and Weddell seals, and a possible increase in salps, noting some regional differences in these trends. The importance of climate processes in generating these changes could not be distinguished from the indirect consequences of the recovery of whale and seal populations from past over-exploitation (Trathan and Reid, 2009; Murphy et al., 2012a,b).

28.2.2.2.1. Marine plankton, krill, fish, and other invertebrates

Distributions of phytoplankton and zooplankton have moved south with the frontal systems (Hinz et al., 2012; Mackey et al., 2012), including range expansion into the Southern Ocean from the north by the coccolithophorid *Emiliania huxleyi* (Cubillos et al., 2007) and the red-tide dinoflagellate *Noctiluca scintillans* (McLeod et al., 2012) (*medium confidence*). There is insufficient evidence to determine whether other range shifts are occurring.

Collapsing ice shelves are altering the dynamics of benthic assemblages by exposing areas previously covered by ice shelves, allowing increased primary production and establishment of new assemblages (e.g., collapse of the Larson A/B ice shelves) (*medium confidence*; Peck et al., 2009; Gutt et al., 2011). More icebergs are grounding, causing changes in local oceanography and declining productivity that consequently affects productivity of benthic assemblages (*low confidence*; Thrush and Cummings, 2011). Iceberg scour on shallow banks is also increasing, disrupting resident benthic assemblages (*medium confidence*; Barnes and Souster, 2011; Gutt et al., 2011).

Primary production is changing regionally in response to changes in sea ice, glacial melt, and oceanographic features (*medium confidence*; Arrigo et al., 2008; Boyd et al., 2012). Off the west Antarctic Peninsula, phytoplankton stocks and productivity have decreased north of 63°S, but increased south of 63°S (*high confidence*; Montes-Hugo et al., 2009; Chapter 6). This study (based on time series of satellite-derived and measured chlorophyll concentrations) also indicated a change from diatom-dominated assemblages to ones dominated by smaller phytoplankton (Montes-Hugo et al., 2009). The reduced productivity in the north may be tempered by increased inputs of iron through changes to ocean processes in the region (*low confidence*; Dinniman et al., 2012).

Since the 1980s, Antarctic krill densities have declined in the Scotia Sea (Atkinson et al., 2004), in parallel with regional declines in the extent and duration of winter sea ice (Flores et al., 2012). Uncertainty remains over changes in the krill population because this decline was observed using net samples and is not reflected in acoustic abundance time series (Nicol and Brierley, 2010); the observed changes in krill density may have been partly a result of changes in distribution (Murphy et al., 2007). Nevertheless, given its dependence on sea ice (Nicol et al., 2008), the krill population may already have changed and will be subject to further alterations (*high confidence*).

The response of krill populations is probably a complex response to multiple stressors. Decreases in recruitment of post-larval krill across the Scotia Sea have been linked to declines in sea ice extent in the Antarctic Peninsula region (*medium confidence*; Wiedenmann et al., 2009) but these declines may have been offset by increased growth arising from increased water temperature in that area (Wiedenmann et al., 2008). However, near South Georgia krill productivity may have declined as a result of the increased metabolic costs of increasing temperatures (*low confidence*; Hill et al., 2013). The combined effects of changing sea ice, temperature, and food have not been investigated.

28.2.2.2.2. Marine mammals and seabirds

In general, many Southern Ocean seals and seabirds exhibit strong relationships to a variety of climate indices, and many of these relationships are negative to warmer conditions (*low confidence*; Trathan et al., 2007; Barbraud et al., 2012; Forcada et al., 2012). Regional variations in climate change impacts on habitats and food will result in a mix of direct and indirect effects on these species. For example, Adélie penguin colonies are declining in recent decades throughout the Antarctic Peninsula while the reduction in chinstrap penguins is more regional (Lynch et al., 2012) and related to reductions in krill availability (Lima and Estay, 2013). In contrast, gentoo penguins are increasing in that region and expanding south (*high confidence*; Lynch et al., 2012). This may be explained by the reduced sea ice habitats and krill availability in the north, resulting in a southward shift of krill predators, particularly those dependent on sea ice (Forcada et al., 2012) and the replacement of these predators in the north by species that do not depend on sea ice, such as gentoo penguins and elephant seals (*low confidence*; Costa et al., 2010; Trivelpiece et al., 2011; Ducklow et al., 2012; Murphy et al., 2013). A contrasting situation is in the Ross Sea, where Adélie penguin populations have increased (Smith, Jr. et al., 2012). The mechanisms driving these changes are currently under review and may be more than simply sea ice (Lynch et al., 2012; Melbourne-Thomas et al., 2013). For example, too much or too little sea ice may have negative effects on the demography of Adélie and emperor penguins (see Barbraud et al., 2012, for review). Also, increased snow precipitation that accumulates in breeding colonies can decrease survival of chicks of Adélie penguins when accompanied by reduced food supply (Chapman et al., 2011).

Changes elsewhere are less well known. Some emperor penguin colonies have decreased in recent decades (*low confidence*; Barbraud et al., 2008; Jenouvrier et al., 2009), and one breeding site has been recorded as having been vacated (Trathan et al., 2011). However, there is insufficient evidence to make a global assessment of their current trend. In the sub-Antarctic of the Indian sector, reductions in seal and seabird populations may indicate a region-wide shift to a system with lower productivity (*low confidence*; Weimerskirch et al., 2003; Jenouvrier et al., 2005a,b) but commercial fishing activities may also play a role.

Where frontal systems are shifting south, productive foraging areas also move to higher latitudes. In the Indian sector, this is thought to be causing declines in king penguin colonies on sub-Antarctic islands (*low confidence*; Péron et al., 2010), while the shift in wind patterns may be causing changes to the demography of albatross (*low confidence*; Weimerskirch et al., 2012).

As identified in the WGII AR4, some species' populations may suffer as a result of fisheries while others are recovering from past over-exploitation, either of which may confound interpretation of the response of these species and their food webs to climate change. The recovery of Antarctic fur seals on some sub-Antarctic islands has been well documented, and their populations may now be competing with krill-eating macaroni penguins (Trathan et al., 2012). More recently, there has been confirmation that populations of some Antarctic whales are recovering, such as humpbacks (Nicol et al., 2008; Zerbini et al., 2010), suggesting that food is currently not limiting. In contrast, a number of albatross and petrel populations are declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall et al., 2012).

28.2.3. Terrestrial Ecosystems

28.2.3.1. Arctic

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 130,000 years), mainly driven by natural climate change. Significant altitudinal and latitudinal advances and retreats in tree line have been common, animal species have gone extinct, and animal populations have fluctuated significantly throughout this period (e.g., Lorenzen et al., 2011; Salonen et al., 2011; Mamet and Kershaw, 2012).

28.2.3.1.1. Phenology

Phenological responses attributable to warming are apparent in most Arctic terrestrial ecosystems (*medium confidence*). They vary from earlier onset and later end of season in western Arctic Russia (Zeng et al., 2013), to little overall trend in plant phenology in the Swedish sub-Arctic (Callaghan et al., 2010), to dramatic earlier onset of phenophases in Greenland (Høye et al., 2007; Post et al., 2009a; Callaghan et al., 2011a; see Figure 28-2).

28.2.3.1.2. Vegetation

The latest assessment of changes in Normalized Difference Vegetation Index (NDVI), a proxy for plant productivity, from satellite observations between 1982 and 2012 shows that about a third of the Pan-Arctic has substantially greened, less than 4% browned, and more than 57% did not change significantly (Xu et al., 2013; Figure 28-3). The greatest increases reported in recent years were in the North American high Arctic, along the Beaufort Sea and the east European Arctic (Zhang et al., 2008; Pouliot et al., 2009; Bhatt et al., 2010; Forbes et al., 2010; Walker et al., 2011; Epstein et al., 2012; Macias-Fauria et al., 2012; Xu et al., 2013).

The positive trends in NDVI are associated with increases in the summer warmth index (sum of the monthly mean temperatures above freezing expressed as degrees Celsius per month) that have increased on average by 5°C per month for the Arctic as a whole (Xu et al., 2013). However, the even greater 10°C to 12°C per month increase for the land adjacent to the Chukchi and Bering Seas (Figure 28-3) was associated with decreases in NDVI. On the Yamal Peninsula in Russia the pattern of NDVI is partly due to surface disturbance, such as landslide activity (Walker et al., 2009). Small rodent cycles reduce NDVI in sub-Arctic Sweden, by decreasing biomass and changing plant species composition (Olofsson et al., 2012). The changing NDVI signal should therefore generally be interpreted with care.

In common with tree line trees and herbs, the abundance and biomass of deciduous shrubs and graminoids (grasses and grass-like plants) have

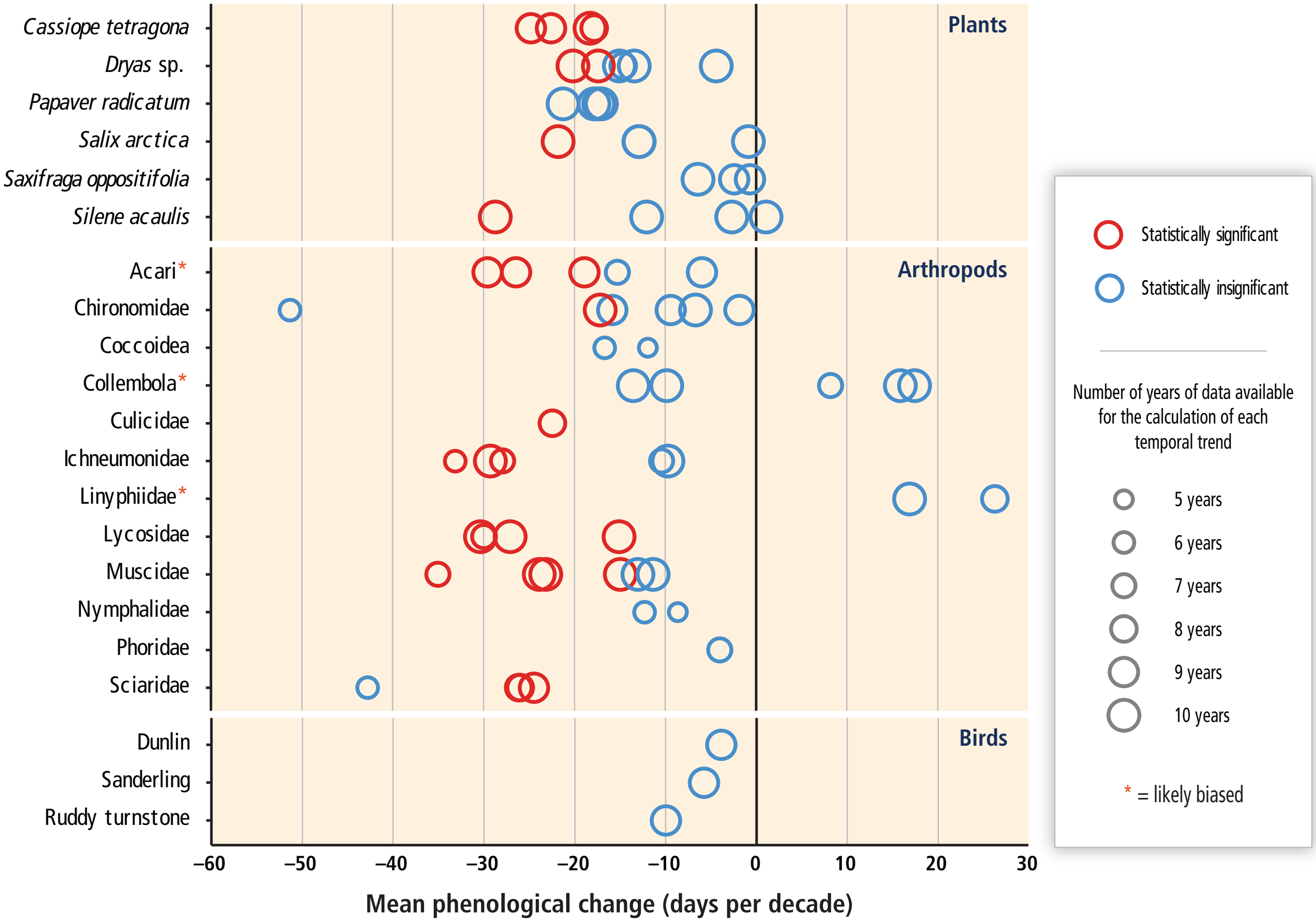


Figure 28-2 | Temporal change in onset of flowering (plants), median date of emergence (arthropods), and clutch initiation dates (birds) estimated from weekly sampling in permanents plots (plants and arthropods) and near-daily surveys through the breeding period in a 19 km^2 census area (birds) during 1996–2005 in high-Arctic Greenland. Trends based on 5 to 10 years of observations are red circles when statistically significant and otherwise blue. Trends in arthropod taxa marked by asterisks (*) are likely to be biased (Høye et al., 2007).

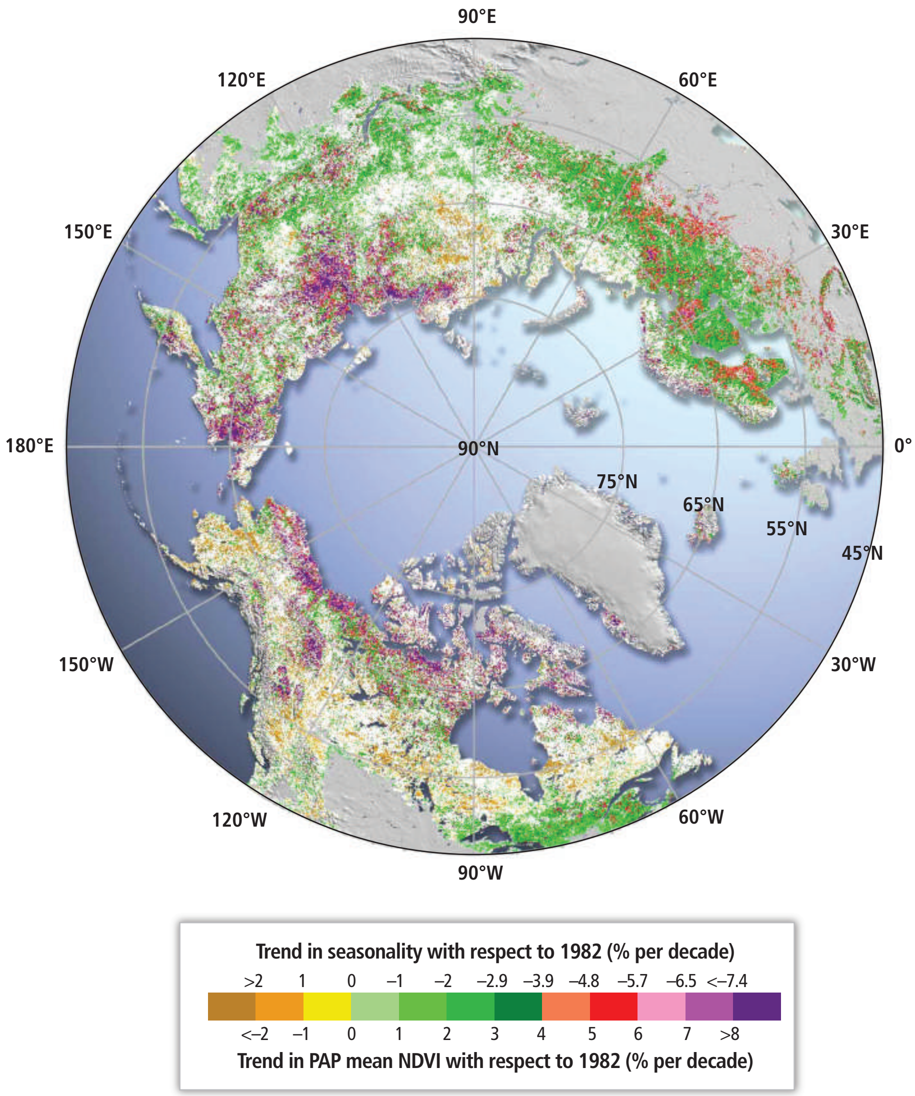


Figure 28-3 | Significant changes ($p < 0.01$) in photosynthetically active period (PAP) Normalized Difference Vegetation Index (NDVI) between 1982 and 2012 (Xu et al., 2013).

increased substantially in certain parts of the Arctic tundra in recent years, but remained stable or decreased in others (*very high confidence*). Attribution for the increases and decreases in deciduous shrubs and graminoids is heterogeneous, with drivers varying among different regions (*very likely*), including Arctic warming, differences in herbivory, industrial development, legacies from past land use, and changes in moisture (Post and Pedersen, 2008; Forbes et al., 2009, 2010; Kitti et al., 2009; Olofsson et al., 2009; Callaghan et al., 2011b, 2013; Kumpula et al., 2011, 2012; Myers-Smith et al., 2011; Elmendorf et al., 2012b; Gamon et al., 2013).

Shrubs have generally expanded their ranges and/or growth over the last 20 years (Danby and Hik, 2007; Hudson and Henry, 2009; Forbes et al., 2010; Hallinger et al., 2010; Callaghan et al., 2011b; Hedenås et al., 2011; Hill and Henry, 2011; Myers-Smith et al., 2011a,b; Rundqvist et al., 2011; Elmendorf et al., 2012a,b; Macias-Fauria et al., 2012), and have varied from dramatic, that is, 200% area increase in study plots (Rundqvist et al., 2011) in sub-Arctic Sweden, to early invasion of a fell field community on west Greenland by low shrubs (Callaghan et al., 2011a).

A synthesis (61 sites; Elmendorf et al., 2012a) of experimental warming studies of up to 20 years duration in tundra sites worldwide showed, overall, increased growth of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness. Elmendorf et al. (2012a) point out that the groups that increased most in abundance under simulated warming were graminoids in cold regions and primarily shrubs in warm regions of the tundra. However, strong heterogeneity in responses to the experimental warming suggested that other factors could moderate the effects of climate warming significantly, such as herbivory, differences in soil nutrients and pH, precipitation, winter temperatures and snow cover, and species composition and density.

Snow bed habitats have decreased in sub-Arctic Sweden (Björk and Molau, 2007; Hedenås et al., 2011). In other plant communities, changes have been less dramatic, ranging from small increases in species richness in the south west Yukon of the Canadian sub-Arctic (Danby et al., 2011), through subtle changes in plant community composition in west and southeast Greenland (Callaghan et al., 2011a; Daniëls and De Molenaar, 2011) to 70-year stability of a plant community on Svalbard (Prach et al., 2010).

The responses to Arctic warming of lichen and bryophyte (mosses) diversity have been heterogeneous, varying from consistent negative effects to significant increases in recent years (Hudson and Henry, 2009; Tømmervik et al., 2009, 2012). Forbes and Kumpula (2009) recorded long-term and widespread lichen degradation in northern Finland attributed more to trampling of dry lichens by reindeer in summer than to winter consumption as forage.

Palaeorecords of vegetation change indicate that the northern tree line should extend upward and northward during current climate warming (Callaghan et al., 2005) because tree line is related to summer warmth (e.g., Harsch et al., 2009). Although the tree line has moved northward and upward in many Arctic areas, it has not shown a general circumpolar expansion in recent decades (*high confidence*).

Model projections that suggest a displacement of between 11 and 50% of tundra by forest by 2100 (see references in Callaghan et al., 2005) and shifts upslope by 2 to 6 m yr^{-1} (Moen et al., 2004) and northwards by 7.4 to 20 km yr^{-1} (Kaplan and New, 2006) might be overestimating rate of tree line advance by a factor of up to 2000 (Van Bogaert et al., 2011). The fastest upslope shifts of tree lines recorded during 20th century warming are 1 to 2 m yr^{-1} (Shiyatov et al., 2007; Kullman and Öberg, 2009) whereas the fastest so-far recorded northward-migrating tree line replaces tundra by taiga at a rate of 3 to 10 m yr^{-1} (Kharuk et al., 2006). In some areas, the location of the tree line has not changed or has changed very slowly (Payette, 2007; MacDonald et al., 2008). A global study by Harsch et al. (2009) showed that only 52% of 166 global tree line sites studied had advanced over the past 100 years. In many cases the tree line has even retreated (Cherosov et al., 2010). At the small scale, the tree line has shown increase, decrease, and stability in neighboring locations (Lloyd et al., 2011; Van Bogaert et al., 2011).

Evidence for densification of the forest at the sub-Arctic tree line is robust and consistent within Fennoscandia (Tømmervik et al., 2009; Hedenås et al., 2011; Rundqvist et al., 2011) and Canada (Danby and Hik, 2007). Dendroecological studies indicate enhanced conifer recruitment during the 20th century in the northern Siberian taiga (Briffa et al., 2008). Some of the changes are dramatic, such as an increase in area of mountain birch in study plots in northern Sweden by 600% between 1977/1998 and 2009/2010 (Rundqvist et al., 2011) and a doubling of tree biomass in Finnmarksvidda in northern Norway since 1957 (Tømmervik et al., 2009). However, model projections of displacement of deciduous forest by evergreen forest (Wolf et al., 2008; Wramneby et al., 2010) have not so far been validated.

Where the mountain birch tree line has increased in elevation and shrub (e.g., willow, dwarf birch) abundance has increased, the response can be an interaction between climate warming, herbivory pressure, and earlier land use (Olofsson et al., 2009; Hofgaard et al., 2010; Van Bogaert et al., 2011). In Fennoscandia and Greenland, heavy grazing by large herbivores may significantly check deciduous low erect shrub (e.g., dwarf shrub and willow) growth (Post et al., 2008; Kitti et al., 2009; Olofsson et al., 2009).

Less moisture from snow and more rain now favors broadleaf trees over conifers and mosses in some areas (Juday, 2009) while moisture deficits are reducing the growth of some northern forests (Goetz et al., 2005; Verbyla, 2008; Yarie, 2008) and making them more susceptible to insect pest outbreaks (see references in Callaghan et al., 2011c). Death of trees through drought stress or insect pest activity will increase the probability of fire, which will have positive feedbacks (increase warming) on the climate (Mack et al., 2011).

28.2.3.1.3. Changes in animal populations

The documented collapse or dampening of population cycles of voles and lemmings over the last 20 to 30 years in parts of Fennoscandia and Greenland (Schmidt et al., 2012) can be attributed with *high confidence* to climate change (Ims et al., 2007, 2011; Gilg et al., 2009; Kausrud et al., 2009). A shortening of the snow season and more thaw and/or rain events during the winter will have an effect on the subnivean space, which provides thermal insulation, access to food, and protection from predators (Berg et al., 2008; Kausrud et al., 2009; Johansson et al., 2011). However, the causes of the changes in the lemming and vole cycles are still being debated as factors other than climate change may also be of importance (Brommer et al., 2010; Krebs, 2011).

Climate-mediated range expansion both in altitude and latitude of insect pests, and increased survival due to higher winter temperatures, has been documented for bark beetles in North America (Robertson et al., 2009) and for geometrid moths in Fennoscandia (Jepsen et al., 2008, 2011; Callaghan et al., 2010), causing more extensive forest damage than before. Outbreaks of insect pests such as geometrid moths can even reduce the strengths of CO_2 sinks in some areas (Heliasz et al., 2011).

The decline in wild reindeer and caribou (both *Rangifer tarandus*) populations in some regions of about 30% over the last 10 to 15 years has been linked both to climate warming and anthropogenic landscape changes (Post et al., 2009a; Vors and Boyce, 2009; Russell and Gunn, 2010). Even though most of the Arctic has warmed, the decline in the populations has not been uniform. Some of the North American large, wild herds have, for example, declined by 75 to 90%, while other wild herds and semi-domestic herds in Fennoscandia and Russia have been stable or even increased (Forbes et al., 2009; Gunn et al., 2009; Vors and Boyce, 2009; Forbes, 2010; Joly et al., 2011; Kumpula et al., 2012).

The expected and partially observed increased primary productivity of Arctic tundra may potentially increase the supply of food for Arctic ungulates. However, the overall quality of forage may decline during warming, for example, if the nitrogen content of key fodder species for ungulates were to drop during warming (Turunen et al., 2009; Heggberget et al., 2010), while lichen biomass, an important winter fodder for reindeer, is decreasing over parts of the Arctic region. Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes and their impacts on ungulate populations (van Der Wal et al., 2007; Turunen et al., 2009).

More frequent rain-on-snow icing events and thicker snowpacks caused by warmer winters and increased precipitation may restrict access to vegetation and may have profound negative influences on the population dynamics of Arctic ungulates (Berg et al., 2008; Forchhammer et al., 2008; Miller and Barry, 2009; Stien et al., 2010, 2012; Hansen et al., 2011). Such events have caused heavy mortality in some semi-domestic reindeer herds and musk oxen in recent years (Grenfell and Putkonen, 2008; Forbes, 2009; Bartsch et al., 2010), and have also been shown to synchronize the dynamics of a resident vertebrate community (small mammals, reindeer, and Arctic fox) in Svalbard (Hansen et al., 2013). In contrast, Tyler et al. (2008) and Tyler (2010) suggested that generally warmer winters enhance the abundance of reindeer populations.

It has been suggested that warming-induced trophic mismatches between forage availability and quality and timing of calving have a role in the decline of circumpolar reindeer and caribou populations (Post and Forchhammer, 2008; Post et al., 2009a,b), although such trophic mismatch has been disputed (Griffith et al., 2010).

Adjustment via phenotypic plasticity instead of adaptation by natural selection is expected to dominate vertebrate responses to rapid Arctic climate change, and many such adjustments have already been documented (Gilg et al., 2012).

28.2.3.1.4. Long-term trends and event-driven changes

Long-term climate change impacts on vegetation and animal populations are accelerated when tipping points are triggered by events such as extreme weather, fire, insect pest, and disease outbreaks. The impacts of winter thaw events on ecosystems are now well documented (e.g., Bokhorst et al., 2011) but studies of the severe impacts of tundra fires on vegetation and biospheric feedbacks are recent (Mack et al., 2011). Results from experimental winter thaws were validated by a natural event in northern Norway and Sweden in 2007 that reduced NDVI by almost 30% over at least 1400 km^2 (Bokhorst et al., 2009). Studies on relationships between climate change and plant disease are rare, but Olofsson et al. (2011) showed that increased snow accumulation led to a higher incidence of fungal growth on sub-Arctic vegetation.

28.2.3.2. Antarctica

Antarctic terrestrial ecosystems occur in 15 biologically distinct areas (Terauds et al., 2012), with those in the maritime and sub-Antarctic islands experiencing the warmest temperatures, reduced extreme seasonality and greatest biodiversity (Convey, 2006). In the cooler conditions on the continent, species must be capable of exploiting the short periods where temperature and moisture availability are above physiological and biochemical thresholds. In many areas, there is no visible vegetation, with life being limited, at the extreme, to endolithic (within rock) communities of algae, cyanobacteria, fungi, bacteria, and lichens (Convey, 2006).

Few robust studies are available of biological responses to observed climatic changes in natural Antarctic terrestrial ecosystems. The rapid population expansion and local-scale colonization by two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in maritime Antarctica (Parnikoza et al., 2009) remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. Radiocarbon dating of moss peat deposits has shown that growth rates and microbial productivity have risen rapidly on the Antarctic Peninsula since the 1960s, consistent with temperature changes, and are unprecedented in the last 150 years (Royles et al., 2013). In east Antarctica, moss growth rates over the last 50 years have been linked to changes in wind speed and temperature and their influence on water availability (Clarke et al., 2012). A contributing factor is that air temperatures have increased past the critical temperature at which successful sexual reproduction (seed set) can now take place, changing the dominant mode of reproduction and increasing the potential distance for dispersal (*low confidence*; Convey, 2011). Similar changes in the local distribution and development of typical cryptogamic vegetation of this region have been reported (Convey, 2011), including the rapid colonization of ice-free ground made available through glacial retreat and reduction in extent of previously permanent snow cover (Olech and Chwedorzewska, 2011). As these vegetation changes create new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonize them (*low confidence*).

28.2.4. Health and Well-being of Arctic Residents

The warming Arctic and major changes in the cryosphere are significantly impacting the health and well-being of Arctic residents and projected to increase, especially for many Indigenous peoples. Although impacts are expected to vary among the diverse settlements that range from small, remote, predominantly Indigenous to large cities and industrial settlements, this section focuses more on health impacts of climate change on Indigenous, isolated, and rural populations because they are especially vulnerable to climate change owing to a strong dependence on the environment for food, culture, and way of life; their political and economic marginalization; existing social, health, and poverty disparities; as well as their frequent close proximity to exposed locations along ocean, lake, or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen et al., 2010; Cochran et al., 2013).

28.2.4.1. Direct Impacts of a Changing Climate on the Health of Arctic Residents

Direct impacts of climate changes on the health of Arctic residents include extreme weather events, rapidly changing weather conditions, and increasingly unsafe hunting conditions (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts) (*high confidence*; Revich, 2008; AMAP, 2009; IPCC, 2012). Intense precipitation events and rapid snowmelt are expected to impact the magnitude and frequency of slumping and active layer detachment, resulting in rock falls, debris flow, and avalanches (Kokelj et al., 2009; Ford et al., 2010). Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration, and/or rapid onset of extreme weather events, storms, and inundation by large storm surges, which, in turn, may create risks to safe travel or subsistence activities, loss of access to critical supplies and services to rural or isolated communities (e.g., food, telecommunications, fuel), and risk of being trapped outside one's own community (*high confidence*; Laidre et al., 2008; Parkinson, 2009; Brubaker et al., 2011b,c). Changing river and sea ice conditions affect the safety of travel for

Indigenous populations especially, and inhibit access to critical hunting, herding, and fishing areas (Andrachuk and Pearce, 2010; Derksen et al., 2012; Huntington and Watson, 2012).

Cold exposure has been shown to increase the frequency of certain injuries (e.g., hypothermia, frostbite), accidents, and diseases (respiratory, circulatory, cardiovascular, musculoskeletal) (Revich and Shaposhmikov, 2010). Studies in northern Russia have indicated an association between low temperatures and social stress and cases of cardiomyopathy (Revich and Shaposhnikov, 2010). It is expected that winter warming in the Arctic will reduce winter mortality rates, primarily through a reduction in respiratory and cardiovascular deaths (Shaposhnikov et al., 2010). Researchers project that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, studies are showing respiratory and cardiac stress associated with extreme warm summer days and that rising temperatures are accompanied by increased air pollution and mortality, especially in Russian cities with large pollution sources (Revich, 2008; Revich and Shaposhnikov, 2012).

28.2.4.2. Indirect Impacts of Climate Change on the Health of Arctic Residents

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion) (*high confidence*; Maynard and Conway, 2007; Parkinson and Evengård, 2009; Brubaker et al., 2011a; see also Chapter 11).

In addition to the climate change impacts and processes are the complicated impacts from contaminants such as persistent organic pollutants (POPs), radioactivity, and heavy metals (e.g., mercury), which create additional and/or synergistic impacts on the overall health and well-being of all Arctic communities (Armitage et al., 2011; UNEP and AMAP, 2011; Teran et al., 2012). Ambient temperature variability and temperature gradients directly affect the volatilization, remobilization, and transport pathways of mercury and POPs in the atmosphere, ocean currents, sea ice, and rivers. Transport pathways, inter-compartmental distribution, and bioaccumulation and transformation of environmental contaminants such as POPs, mercury, and radionuclides in the Arctic may consequently be affected by climate change (*high confidence*; AMAP 2011b; Ma et al., 2011; UNEP and AMAP 2011; Teng et al., 2012). Ma et al. (2011) and Hung et al. (2010) demonstrated that POPs are already being remobilized into the air from sinks in the Arctic region as a result of decreasing sea ice and increasing temperatures.

Contaminants and human health in the Arctic are tightly linked to the climate and Arctic ecosystems by factors such as contaminant cycling and climate (increased transport to and from the Arctic), and the related increased risks of transmission to residents through subsistence life ways (Maynard, 2006; AMAP, 2010; Armitage et al., 2011; UNEP and AMAP, 2011; Teran et al., 2012). The consumption of traditional foods by Indigenous peoples places these populations at the top of the Arctic food chain and through biomagnification, therefore, they may receive some of the highest exposures in the world to certain contaminants (Armitage et al., 2011; UNEP and AMAP, 2011). Contaminants such as POPs are known for their adverse neurological and medical effects on humans, particularly the developing fetus, children, women of reproductive age, and the elderly; thus it is important to include contaminants as a significant part of any climate impact assessment (UNEP and AMAP, 2011).

Radioactivity in the Arctic is also a concern because there are many potential and existing radionuclide sources in some parts of the Arctic, and contamination can remain for long periods of time in soils and some vegetation, creating potentially high exposures for people (AMAP, 2010). Climate changes can mobilize radionuclides throughout the Arctic environment, and also potentially impact infrastructure associated with nuclear activities by changes in permafrost, precipitation, erosion, and extreme weather events (AMAP, 2010).

Warming temperatures are enabling increased overwintering survival and distribution of new insects that sting and bite as well as many bird, animal, and insect species that can serve as disease vectors and, in turn, causing an increase in human exposure to new and emerging infectious diseases (Parkinson et al., 2008; Epstein and Ferber, 2011). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia and Canada (Ogden et al., 2010; Tokarevich et al., 2011) and Sweden (Lindgren and Gustafson, 2001) and *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean (Hughes-Hanks et al., 2005). It is also expected that temperature increases will increase the incidence of zoonotic diseases as relocations of animal populations occur (Revich et al., 2012; Hueffler et al., 2013).

Harmful algal blooms (HABs), whose biotoxins can be a serious health hazard to humans or animals (paralysis, death), are increasing globally and expected to increase in the Arctic, and HABs are influenced directly by climate change-related factors such as temperature, winds, currents, nutrients, and runoff (Portier et al., 2010; Epstein and Ferber, 2011; Walsh et al., 2011; see also Chapters 6, 11). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, caused by *Vibrio parahaemolyticus*, in Alaskan oysters (McLaughlin et al., 2005). In addition, warmer temperatures raise the possibility of anthrax exposure in Siberia from permafrost thawing of historic cattle burial grounds (Revich and Podolnaya, 2011).

The impacts of climate change on food security and basic nutrition are critical to human health because subsistence foods from the local environment provide Arctic residents, especially Indigenous peoples, with unique cultural and economic benefits necessary to well-being and contribute a significant proportion of daily requirements of nutrition, vitamins, and essential elements to the diet (Ford, 2009; Ford and Berrang-Ford, 2009). However, climate change is already an important threat because of the decrease in predictability of weather patterns, low water levels and streams, timing of snow, and ice extent and stability, impacting the opportunities for successful hunting, gathering, fishing, and access to food sources and increasing the probability of accidents (*high confidence*; Ford and Furgal, 2009; Ford et al., 2010). In recent years, populations of marine and land mammals, fish, and water fowl are also being reduced or displaced, thus reducing the traditional food supply (Gearheard et al., 2006; West and Hovelsrud, 2010; Lynn et al., 2013).

Traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by warming temperatures, thus further reducing food available to the community (Brubaker et al., 2011b,c). For example, food contamination caused by thawing of permafrost "ice cellars" is occurring and increasingly wet conditions make it harder to dry food for storage (Hovelsrud et al., 2011). Indigenous people increasingly have to abandon their semi-nomadic lifestyles, limiting their overall flexibility to access traditional foods from more distant locations (www.arctichealthyukon.ca). These reductions in the availability of traditional foods plus general globalization pressures are forcing Indigenous communities to increasingly depend on expensive, non-traditional, and often less healthy Western foods, increasing the rates of modern diseases associated with processed food and its packaging, such as cardiovascular diseases, diabetes, dental caries, and obesity (Armitage et al., 2011; Berrang-Ford et al., 2011; Brubaker et al., 2011b,c).

Climate change is beginning to threaten community and public health infrastructure, often in communities with no central water supply and treatment sources. This is especially serious in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada) through increased river and coastal flooding and erosion, increased drought, and thawing of permafrost, resulting in loss of reservoirs, damage to landfill sites, or sewage contamination (GAO, 2009; Bronen, 2011). Saltwater intrusion and bacterial contamination may also be threatening community water supplies (Parkinson et al., 2008; Virginia and Yalowitz, 2012). Quantities of water available for drinking, basic hygiene, and cooking are becoming limited owing to damaged infrastructure, drought, and changes in hydrology (Virginia and Yalowitz, 2012). Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure spreads sewage in villages with no municipal water supply. This can result in higher rates of hospitalization for pneumonia, influenza, skin infections, and respiratory viral infections (Parkinson and Evengård, 2009; Virginia and Yalowitz, 2012). Compounding these impacts in rural areas as well as cities are respiratory and other illnesses caused by air-borne pollutants (e.g., contaminants, microbes, dust, mold, pollen, smoke) (Revich, 2008; Rylander and Schilling, 2011; Revich and Shaposhnikov, 2012).

It is now well documented that the many climate-related impacts on Arctic communities are causing significant psychological and mental distress and anxiety among residents (Levintova, 2010; Portier et al., 2010; Coyle and Susteren, 2012; see also Chapter 11). For example, changes in the physical environment (e.g., through thawing permafrost and erosion) that may lead to forced or voluntary relocation of residents out of their villages or loss of traditional subsistence species are causing mental health impacts among Indigenous and other vulnerable, isolated populations (Curtis et al., 2005; Albrecht et al., 2007; Coyle and Susteren, 2012; Maldonado et al, 2013). Special concern has been expressed by many communities about the unusually high and increasing numbers of suicides in the Arctic, especially among Indigenous youth, and efforts are underway to try to develop a thorough assessment as well as establish effective intervention efforts (Albrecht et al., 2007; Portier et al., 2010; USARC, 2010).

28.2.5. Indigenous Peoples and Traditional Knowledge

Indigenous populations in the Arctic—the original Native inhabitants of the region—are considered especially vulnerable to climate change because of their close relationship with the environment and its natural resources for physical, social, and cultural well-being (Nuttall et al., 2005; Parkinson, 2009; Cochran et al., 2013). Although there are wide differences in the estimates, including variations in definitions of the Arctic region, Arctic Indigenous peoples are estimated to number between 400,000 and 1.3 million (Bogoyavlensky and Siggner, 2004; Galloway-McLean, 2010). According to 2010 census data, there are approximately 68,000 Indigenous people living in the Russian Arctic. These Arctic residents depend heavily on the region's terrestrial, marine, and freshwater renewable resources, including fish, mammals, birds, and plants; however, the ability of Indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by the unprecedented rate of climate change (*high confidence*; Nakashima et al., 2012; Cochran et al., 2013). In habitats across the Arctic, climate changes are affecting these livelihoods through decreased sea ice thickness and extent, less predictable weather, severe storms, sea level rise, changing seasonal melt/freeze-up of rivers and lakes, changes in snow type and timing, increasing shrub growth, permafrost thaw, and storm-related erosion, which, in turn, are causing such severe loss of land in some regions that a number of Alaskan coastal villages are having to relocate entire communities (Oskal, 2008; Forbes and Stammler, 2009; Mahoney et al., 2009; Bartsch et al., 2010; Weatherhead et al., 2010; ,Bronen, 2011; Brubaker et al., 2011b,c; Eira et al., 2012; Huntington and Watson, 2012; McNeeley, 2012; Maldonado et al., 2013). In addressing these climate impacts, Indigenous communities must at the same time consider multiple other stressors such as resource development (oil and gas, mining); pollution; changes in land use policies; changing forms of governance; and the prevalence in many Indigenous communities of poverty, marginalization, and resulting health disparities (Abryutina, 2009; Forbes et al., 2009; Reinert et al., 2009; Magga et al., 2011; Vuojala-Magga et al., 2011; Nakashima et al., 2012; Mathiesen et al., 2013).

Traditional knowledge is the historical knowledge of Indigenous peoples accumulated over many generations and it is increasingly emerging as an important knowledge base for more comprehensively addressing the impacts of environmental and other changes as well as development of appropriate adaptation strategies for Indigenous communities (WGII AR4 Chapter 15; Oskal, 2008; Reinert et al., 2008; Wildcat, 2009; Magga et al., 2011; Vuojala-Magga et al., 2011; Nakashima et al., 2012; Vogesser et al, 2013). For example, Saami reindeer herders have specialized knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter, and spring reindeer rangelands (Roturier and Roue, 2009; Eira et al., 2012; Vikhamar-Schuler et al., 2013) and traditional governance systems for relating to natural environments (Sara, 2013). Increasingly, traditional knowledge is being combined with Western scientific knowledge to develop more sustainable adaptation strategies for all communities in the changing climate.

For example, at Clyde River, Nunavut, Canada, Inuit experts and scientists both note that wind speed has increased in recent years and that wind direction changes more often over shorter periods (within a day) than it did during the past few decades (Gearheard et al., 2010; Overland et al., 2012). In Norway, Sámi reindeer herders and scientists are both observing direct and indirect impacts to reindeer husbandry such as changes in snow and ice cover, forage availability, and timing of river freeze-thaw patterns from increasing temperatures (Eira et al., 2012). On the Yamal Peninsula in western Siberia, detailed Nenets observations and recollections of iced-over autumn and winter pastures due to rain-on-snow events have proven suitable for calibrating the satellite-based microwave sensor SeaWinds (Bartsch et al., 2010) and NASA's AMSR-E sensor.

28.2.6. Economic Sectors

28.2.6.1. Arctic

28.2.6.1.1. Agriculture and forestry

Climate change presents benefits and costs for forestry and agriculture (Aaheim et al., 2009; Hovelsrud et al., 2011). In Iceland, for example, tree limits are found at higher altitudes than before, and productivity of many plants has increased (Björnsson et al., 2011). Grain production in Iceland has increased in the last 2 decades, and work on soil conservation and forestry has benefited from warming (Sigurdsson et al., 2007; Björnsson et al., 2011), but also the number of new insect pests on trees and shrubs has increased in the past 20 years. A strong relationship between rate of new insect pest colonization and outbreak intensity in forests exists with changes in annual temperature during the past century (Halldórsson et al., 2013). Climate change impacts on species change and fire frequency have potential impact on commercial forest harvesting activity. Vulnerability of forestry to changes that affect road conditions and thus accessibility during thawing periods has been found in Sweden (Keskitalo, 2008). A case study on Greenland found challenges for plant diseases in potatoes and grass fields, with pathogens and pests present in agricultural cropping systems, for example, black scurf (*Rhizoctonia*) and common scab (*Streptomyces* scabies) (Neergaard et al., 2009).

28.2.6.1.2. Open and freshwater fisheries

Current commercial fisheries are sharply divided between regions of high-yield and value (e.g., commercial fisheries in the southern Bering Sea, Baffin Bay, the east and west Greenland Seas, the Iceland Shelf Sea, the deep Norwegian/Greenland Sea, and the Barents Sea) and subsistence fisheries in the coastal regions of the Arctic Ocean. The relative absence of commercial fishing activity in the Arctic Ocean results from a combination of fisheries policy, the abundance of the resource, the lack of infrastructure for capturing and processing fish, and the difficulties in accessing fishing grounds, especially during winter. In most regions, fisheries management strategies have been developed to build sustainable fisheries and rebuild overfished stocks (Froese and Proelß, 2010; Livingston et al., 2011). Recently observed changes in the spatial distribution and abundance of mackerel (*Scomber scombrus*) has challenged existing international agreements for shared resources in the North Atlantic (Arnason, 2012; Astthorsson et al., 2012). Although loss of sea ice in summer is allowing greater access to fisheries resources in the Arctic Ocean, some nations have prohibited commercial fishing within their exclusive economic zones until there is sufficient understanding of stock status to ensure that proposed fisheries would be managed sustainably (Stram and Evans, 2009; Wilson and Ormseth, 2009).

Several Arctic coastal sea-run fishes are targeted for subsistence and commercial use in the Arctic. Commercial transactions from fishing are typically for local markets; however, the socioeconomic and cultural importance of these fishes to Indigenous peoples far outweighs their monetary value. Reist et al. (2006) and Fechhelm et al. (2007) found that climate-related factors that influenced the water level and freshening of rivers were related to run size of Arctic cisco (*Coregonus autumnalis*). Similarly, a recent study based on Chinook salmon (*Oncorhynchus tshawytscha*) run timing for the period 1961–2009 showed that success in the fishery was dependent on the timing of the marine exit, which was tightly coupled to environmental conditions that were linked to climate (Mundy and Evenson, 2011).

28.2.6.1.3. Marine transportation

Observations and climate models indicate that in the period between 1979–1988 and 1998–2007 the number of days with ice-free conditions (less than 15% ice concentration) increased by 22 days along the Northern Sea Route (NSR) in the Russian Arctic, and by 19 days in the Northwest Passage (NWP) in the Canadian Arctic, while the average duration of the navigation season in the period 1980–1999 was 45 and 35 days, respectively (Mokhow and Khon, 2008). Increased shipping associated with the opening of the NSR will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific. The future status of marine, terrestrial, and freshwater biota may be negatively affected as a result of substantial coastal infrastructure to facilitate offshore developments (Meschtyb et al., 2005). Also, the frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season for fish and marine mammals, which is the late spring/summer, when these resources can be found throughout the NSR area (Østreng, 2006).

28.2.6.1.4. Infrastructure

Much of the physical infrastructure in the Arctic relies on and is adapted to local sea ice conditions, permafrost, and snow (Huntington et al., 2007; Sundby and Nakken, 2008; Sherman et al., 2009; West and Hovelsrud, 2010; Forbes, 2011). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower poses major economic costs and risks, which are more closely linked to the design of the structure than with thawing permafrost. Current engineering practices are designed to help minimize the impacts (Prowse et al., 2009). Much of the infrastructure has been built with weather conditions in mind, but remains vulnerable and inadequate to respond to environmental emergencies, natural disasters, and non-environmental accidents (NRTEE, 2009). Northern safety, security, and environmental integrity are much dependent on transportation infrastructure. Ice as a provisioning system provides a transportation corridor and a platform for a range of activities and access to food sources in the Arctic (Eicken et al., 2009).

In northern Canada climate warming presents an additional challenge for northern development and infrastructure design. While the impacts of climate change become increasingly significant over the longer time scales, in the short term of greater significance will be the impacts associated with ground disturbance and construction (Smith and Risebrough, 2010).

Climate change impacts have increased the demand for improved communication infrastructure and related services and community infrastructure for the safety and confidence in drinking water (NRTEE, 2009). The access, treatment, and distribution of drinking water is generally dependent on a stable platform of permafrost for pond or lake retention. Several communities have reported the need for more frequent water-quality testing of both municipal systems and untreated water sources to ensure its suitability for drinking (Furgal, 2008).

28.2.6.1.5. Resource exploration

The Arctic has large reserves of minerals (Lindholt, 2006; Harsem et al., 2011; Peters et al., 2011) and potentially large reserves of undiscovered sources of raw minerals and oil and gas. Predicted new access to offshore energy resources is hypothesized to be a significant share of the global supply of oil and gas (Gautier et al., 2009; Berkman, 2010). The socioeconomic impacts of oil and gas exploration activity may be positive or negative (Duhaime et al., 2004; Huntington et al., 2007; Forbes, 2008; Forbes et al., 2009; Kumpula et al., 2011; Harsem et al., 2011).

Climatic warming is accelerating access to northern lands for development (Forbes et al., 2009). Yamal in Western Siberia has approximately 90% of Russia's gas reserves, but at the same time represents the largest area of reindeer herding in the world (Jernsletten and Klokov, 2002; Stammler, 2005; Forbes and Kumpula, 2009). Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to loss of "available room for adaptation" for reindeer husbandry (Nuttall et al., 2005; Oskal, 2008; Forbes et al., 2009). Sharp increases in future oil and gas and other resource development in the Russian north and other Arctic regions are anticipated—along with associated infrastructure, pollution, and other development byproducts—which will reduce the availability of pasturelands for reindeer and use by Indigenous communities (Derome and Lukina, 2011; Degteva and Nellermann, 2013).

28.2.6.1.6. Informal, subsistence-based economy

Hunting, gathering, herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Nuttall et al., 2005; Poppel and Kruse, 2009; Crate et al., 2010; Larsen and Huskey, 2010). In the early 1990s—initially in western Canada, and later elsewhere—Indigenous communities started reporting climate change impacts (Berkes and Armitage, 2010). According to some herders, whalers, and walrus hunters, non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes and Stammler, 2009; Forbes et al., 2009; Ignatowski and Rosales, 2013).

The Inuit and Saami have expressed strong concern about the effects of climate warming on their livelihoods (Forbes and Stammler, 2009; Magga et al., 2011). For the Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn; earlier melt-out and faster sea ice retreat in spring; and thinner, less predictable ice in general (Krupnik and Jolly, 2002; Cochran et al., 2013). Diminished sea ice translates into more difficult access for hunting marine mammals, and greater risk for the long-term viability of subsistence species such as polar bear populations (*high confidence*; Laidre et al., 2008). Most Inuit communities depend to some extent on marine mammals for nutritional and cultural reasons, and many benefit economically from polar bear and narwhal hunting. A reduction in these resources represents a potentially significant economic loss (Hovelsrud et al., 2008). Among Fennoscandian Saami, the economic viability of reindeer herding is threatened by competition with other land users coupled with strict agricultural norms (Forbes, 2006; Magga et al., 2011). Reindeer herders are concerned that more extreme weather may exacerbate this situation (Oskal, 2008).

Climate change is affecting reindeer herding communities through greater variability in snow melt/freeze, ice, weather, winds, temperatures, and precipitation, which, in turn are affecting snow quality and quantity—the most critical environmental variables for reindeer sustainability (Bartsch et al., 2010; Magga et al., 2011; Eira et al., 2012). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow that then block the animals' access to their forage and subsequent starvation (Bartsch, 2010; Maynard et al., 2011; Eira et al., 2012).

28.2.6.2. Antarctica and the Southern Ocean

Economic activities in the Antarctic have been limited to fishing and tourism (IPCC, 2007). Ship-based tourism is a significant industry in Antarctica but does not involve permanent shore-based infrastructure. Over recent decades, the number of tourists landing in Antarctica has risen from 7322 in 1996/1997 to 32,637 in 2007/2008 (IAATO, 2012). Visits generally coincide with the times when wildlife are breeding and are often restricted because of the presence of fast ice, sea ice, or icebergs. They are expected to continue to increase, with an increasing chance of terrestrial alien species being introduced from tourism and other vectors as ice-free areas increase from climate change (Chown et al., 2012). Scientific activity by a number of nations is also taking place and has the potential to impact upon local ecologies. Mineral resource activity is prohibited south of 60°S under the Protocol on Environmental Protection to the Antarctic Treaty.

Fisheries in Antarctica, primarily through fisheries for Antarctic krill, could amount to approximately 6% of existing global marine capture fisheries (Nicol et al., 2012). The pattern of the krill fishery has been affected by changes in the sea ice extent around the Antarctic Peninsula, where the fishery has been taking advantage of the ice-free conditions and taking more of its catch during winter in that region (*high confidence*; Kawaguchi et al., 2009). Ecosystem-based management of krill fisheries by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has yet to include procedures to account for climate change impacts, although the need to do so has been identified (Trathan and Agnew, 2010; Constable, 2011).

28.3. Key Projected Impacts and Vulnerabilities

28.3.1. Hydrology and Freshwater Ecosystems

28.3.1.1. Arctic

Accompanying projected increases in high-latitude river flow (Section 3.4.5; WGI AR5 Section 12.4.5.4) are earlier spring runoff (Pohl et al., 2007; Dankers and Middelkoop, 2008; Hay and McCabe, 2010), greater spring snowmelt (Adam et al., 2009), and increases in spring sediment fluxes (Lewis and Lamoureux, 2010). Enhanced permafrost thaw (WGI AR5 Section 12.4.6.2) will continue to affect the dynamics of thermokarst lakes and related ecological effects (Section 28.2.1.1). Thawing permafrost and changes in the hydrological regime of the Arctic rivers, particularly those traversing regions affected by industrial developments, will increase the contaminant flow (Nikanorov et al., 2007). Loss of glacier ice masses will alter runoff hydrographs; sediment loads; water chemistry; thermal regimes; and related channel stability, habitat, and biodiversity (Milner et al., 2009; Moore et al., 2009). Although snow, freshwater ice, and permafrost affect the morphology of arctic alluvial channels, their future combined effects remain unclear (McNamara and Kane, 2009). For small permafrost streams, however, longer projected periods of flowing water will modify nutrient and organic matter processing (Greenwald et al., 2008; Zarnetske et al., 2008) but long-term negative impacts of increased sediment load on biological productivity could outweigh any positive effects from increased nutrient loading (Bowden et al., 2008).

Changes to river-ice flooding are also projected to occur as a result of changes in (1) hydraulic gradients for near-coastal locations because of sea level rise, (2) streamwise air-temperature gradients, and (3) the timing and magnitude of spring snowmelt (Prowse et al., 2011). Synergistic/antagonistic effects among these factors, however, require detailed site-specific analyses for accurate projections of future conditions (Beltaos and Prowse, 2009). Reduced (increased) ice-jam flooding will have positive (negative) benefits for river-side northern communities/infrastructure but could also alter delta-riparian (Lesack and Marsh, 2010) and coastal marine (Emmerton et al., 2008) ecosystems. The quality of river water entering the marine environment will also be affected by the reduction or loss of stamukhi lakes that process river inputs (Dumas et al., 2006; Galand et al., 2008).

Future changes to lake ice regimes will include delayed freeze-up, advanced break-up, thinner ice and changes in cover composition (especially white ice in areas of enhanced winter precipitation), increased water temperature, and earlier and longer-lasting summer stratification (Dibike et al., 2011), all of which will affect a range of aquatic processes, including secondary productivity (Borgstrøm and Museth, 2005; Prowse et al., 2007; Prowse and Brown, 2010b). Patterns of species richness and diversity are also projected to change with alterations to ice duration—increased open-water periods favoring the development of new trophic levels, colonization of new aquatic species assemblages (Vincent et al., 2009), greater atmosphere-water gas exchange, and a decrease in winter kill of resident fish with cascading effects on lower trophic levels (Balayla et al., 2010). The loss of ice, however, can also decrease key habitat availability and quality (Vincent et al., 2008). Geochemical responses of Arctic lakes will also be altered. As observed for thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production (Metje and Frenzel, 2007; Laurion et al., 2010). Because temperature sensitivity has a stronger control over methane production than oxidation (Duc et al., 2010), elevated water temperatures will enhance methanogenesis, causing increased methane release from sediments. The net balance of these two processes operating under a broad range of future changing environmental factors, however, remains to be quantified (Walter et al., 2007a,b, 2008; Laurion et al., 2010).

As well as methane, increased water temperatures are projected to lead to reduced organic carbon (OC) burial. Projections, based on a range of six climate warming scenarios (IPCC, 2007), indicate that there will be a 4 to 27% decrease (0.9 to 6.4 TgC yr^{-1}) in OC burial across lakes of the northern boreal zone by the end of the 21st century as compared to rates for the approximately last half-century (Gudasz et al., 2010). Although these estimates assume that future OC delivery will be similar to present-day conditions, even with enhanced supply from thawing permafrost, higher water temperatures will increase OC mineralization and thereby lower burial efficiency. The amount of burial also depends on lake depth and mixing regimes. For non-thermally stratified shallow lakes, there will be a greater opportunity for water-sediment mixing, and hence greater carbon recycling back into the water column. By contrast, for lakes that become increasingly thermally stratified, carbon sinking below the thermocline will tend not to return to the surface until an increasing later fall turnover, thereby decreasing the probability of sediment-stored carbon being returned to the water column (Flanagan et al., 2006).

Changes in ice cover, thermal regimes, and stratification patterns will also affect the fate of contaminants in northern lakes. Higher water temperatures can enhance the methylation of mercury and modify food web and energy pathways, such as through enhanced algal scavenging (a major food web entry pathway for mercury), resulting in increased mercury bioavailability to higher trophic levels (Outridge et al., 2007; Carrie et al., 2010).

28.3.1.2. Antarctica

This assessment reinforces conclusions of AR4. Increased temperatures will impact aquatic ecosystems in Antarctica (*high confidence*), but the exact nature of these impacts will vary regionally. The most vulnerable freshwater systems are in the northern Antarctic Peninsula and maritime Antarctic islands, where a small increase in temperature can have widespread ecosystem impacts because the average temperature is within a few degrees of the melting point (*high confidence*; Quesada and Velázquez, 2012). Potential impacts are expected to range from immediate catastrophic impacts such as loss of bounding ice masses causing drainage of freshwater and epishelf lakes (Smith et al., 2006; Hodgson, 2011), to more gradual impacts on changes in the amount and duration of catchment ice and snow cover; accelerated glacier melting; declining volumes of precipitation falling as snow; permafrost; and active layer and hydrological changes, such as water retention times (*medium confidence*; e.g., Vieira et al., 2010; Quesada and Velázquez, 2012; Bockheim et al., 2013).

Changes in the thickness and duration of seasonal ice cover, longer melt seasons, and larger volumes of water flowing into the lakes are expected in the future (*medium confidence*; Lyons et al., 2006) but the ecological effects will vary between lakes, depending on their depth to surface area ratio, with insufficient evidence to fully assess future changes in these systems. Longer ice-free seasons may cause physical conditions to be more favorable for primary production (Hodgson and Smol, 2008) but very high irradiances experienced during summer in some systems can substantially inhibit algal blooms under ice-free conditions (Tanabe et al., 2007), which would favor the growth of benthic cyanobacteria species (Hodgson et al., 2005). In other lakes, increases in meltwater supply may increase suspended solids and reduce light penetration and may offset the increases in the underwater light regime predicted as a result of extended ice-free periods (Quesada et al., 2006).

Under a warming climate an increase in microbial biomass is expected because of the increased water supply from glacial melt and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved OC delivery to lakes (Velázquez et al., 2013). This organic supply will promote growth and reproduction in the benthos and plankton and imbalances in population dynamics (Quesada and Velázquez, 2013). Nutrient enrichment of some freshwater habitats in the vicinity of fur seal colonies will increase because of expanding fur seal populations (*high confidence*; Quayle et al., 2013).

Away from glacial forelands, increasing aridity will occur in the long term in some areas of the continent (Hodgson et al., 2006b) and on sub-Antarctic islands (*medium confidence*; Smith, Jr. et al., 2012). Closed basin lakes can dry up completely causing local extinctions or retreat into cryptic or resistant life-cycle stages, as experienced in Arctic lakes (Smol and Douglas, 2007b). Other effects include desiccation of moss banks due to increased evaporation and sublimation rates (*medium confidence*; Wasley et al., 2006). Studies have also shown that warming of once cold freshwater habitats in Antarctica will allow the sub- and maritime Antarctic species to re-invade and establish self-maintaining populations on the Antarctic continent, particularly where human vectors are involved (*medium confidence*; Barnes et al., 2006; Hodgson et al., 2006b). For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman et al., 2010), with a possibility that surface Antarctic lakes contain endemic species that are relics of Gondwana (cf. Convey and Stevens, 2007) and that would become extinct should they be lost from these lakes as a result of climate change.

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Ocean Acidification in the Arctic and Antarctic

The effects of ocean acidification on polar marine food webs can have considerable implications (*medium confidence*). For example, if some regions in the Arctic become understaturated with respect to aragonite (the primary structural component of the shells of some marine calcifiers such as molluscs and urchins), the growth and survial of these organisms will be impacted (WGI AR5 Figure 6.28; Chierici and Fransson, 2009; Fabry et al., 2009; Yamamoto-Kawai et al., 2009). In laboratory experiments, Arctic pteropods (*Limacina helicina*, a small planktonic mollusc) held under conditions consistent with projected ocean warming and acidification in the Arctic Ocean in early spring were able to extend their shells in corrosive waters but dissolution marks were observed (Comeau et al., 2010, 2012). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on *Limacina helicina* and other vulnerable species (Orr et al., 2009). At the current time there are insufficient data to fully assess the ecosystem consequences of acidification on pteropods because it is unclear whether other species, with a similar nutritive value, will replace pteropods.

In the Southern Ocean, foraminifera have thinner shells than in the Holocene and there is evidence for shell thickness to be related to atmospheric CO_2, supporting the hypothesis that ocean acidification will affect this abundant protozoan in this region (Moy et al., 2009). Similarly, shells are thinner from sediment traps in aragonite undersaturated water (below the aragonite saturation horizon (ASH)) compared to those captured above the ASH in sub-Antarctic waters, but there is no time series of data related to change in the ASH (Roberts et al., 2011). Shell dissolution has been observed in surface waters in the Atlantic sector as a result of both upwelling and atmospheric changes in CO_2 (*medium confidence*; Bednarsek et al., 2012). Other impacts of acidification on Southern Ocean organisms are currently uncertain, but short-term negative impacts need to be considered together with an organism's capacity to adapt in the longer term (Watson et al., 2012).

Only a few studies have been conducted on commercially exploited polar species on ocean acidification. Antarctic krill embryonic development (Kawaguchi et al., 2011) and post-larval krill metabolic physiology (Saba et al., 2012) may be impeded by elevated CO_2 concentrations, which may negatively impact the reproductive success of krill more generally under emission scenarios used in Coupled Model Intercomparison Project Phase 5 (CMIP5) (*medium confidence*; Kawaguchi et al., 2013). Long et al. (2013) examined the effects of acidification on red king crab (*Paralithodes camtschaticus*) and found animals exposed to reduced pH exhibited increased hatch duration, decreased egg yolk, increased larval size, and decreased larval survival. In contrast, Hurst et al. (2012) conducted laboratory experiments at levels of elevated CO_2 predicted to be present in the Gulf of Alaska and Bering Sea in the next century and found that juvenile walleye pollock (*Gadus chalcogrammus*) exhibited a general resiliency of growth energetics to the direct effects of CO_2 changes.

28.3.2.2. Arctic

28.3.2.2.1. Marine plankton, fish, and other invertebrates

Phenological response

Projected changes in the timing, spatial distribution, and intensity of spring blooms may result in mismatches with the timing of the emergence of Arctic grazers (Søreide et al., 2010). Based on past experience, some species will adapt to local conditions by shifting key life cycle events (hatch date, maturity schedule, and reproductive timing) or diet to accommodate differences in the regional timing and availability of prey and environmental conditions (Ormseth and Norcross, 2007; Sundby and Nakken, 2008; Vikebø et al., 2010; Darnis et al., 2012). For example, loss of sea ice cover in spring is expected to change fish behavior in ice-bound areas (Mundy and Evenson, 2011). It is uncertain whether endemic animals will be able to alter key phenologies fast enough to keep pace with the projected rates of change in the Arctic Ocean.

Projected spatial shifts

Simulation studies revealed that a 2-week longer growing season and a 2°C increase in temperature would not be sufficient to allow expatriate species (*Calanus finmarchicus* or *C. marshallae*) to invade the Arctic Ocean (Ji et al., 2012). Ellingsen et al. (2008) projected future zooplankton distribution and abundance in the Barents Sea for the period 1995–2059 using a regional climate model that was forced with climate model output based on the *Special Report on Emission Scenarios* (SRES) B2 scenario. They projected that by 2059, Atlantic origin zooplankton will increase and Arctic origin zooplankton will decrease in the Barents Sea.

The literature is mixed with respect to the potential for future movement of fish and shellfish into the Arctic Ocean. Modeling studies project that marine fish stocks potentially will shift their distributions into the Arctic Ocean, resulting in an increase in biodiversity in the region (Cheung et al., 2009, 2011; see also Box CC-MB). However, other studies show the persistence of cold seawater temperatures on the shelf regions of the Arctic Ocean and northern Bering Sea will restrict or retard movement of several sub-Arctic fish and shellfish species into the Arctic Ocean (Sigler et al., 2011; Stabeno et al., 2012b; Hunt, Jr. et al., 2013). In waters off the coasts of Europe there is a potential for increased fish production because of the combined effects of intrusion of Atlantic water over the relatively broader shelf regions and advective corridors for larval drift and range expansion of spawners. Huse and Ellingsen (2008) forced a spatially explicit coupled biophysical model for the Barents Sea with future climate scenarios to project the implications of climate change on the spawning distribution of capelin (*Mallotus villosus*). Projections show that the spawning distribution of capelin will shift to the east and new spawning grounds will be colonized. A key factor governing this expansion will be the availability of pelagic prey. In the southeast Bering Sea, there is evidence that planktivorous species such as walleye pollock will shift their distribution in response to shifts in ocean temperature (Kotwicki and Lauth, 2013). In summary, the spatial distribution of some fish and shellfish in the Barents and southeast Bering Seas will shift in response to climate change (*high confidence*).

Projected impacts on production

In the deep basins of the Arctic Ocean the number of ice-free days in summer are expected to result in longer productive seasons (*high confidence*; Slagstad et al., 2011). Ellingsen et al. (2008) projected that annual primary production would increase by 2059 in the Barents Sea. Tremblay et al. (2012) hypothesized that longer ice-free periods in summer in the Arctic Ocean could provide for more opportunities for episodic nutrient pulses that would enhance secondary production through the growing season. However, in the Arctic Ocean, these changes in primary production may be offset later in the year by increased zooplankton grazing (Olli et al., 2007) or nutrient depletion due to stronger stratification and shifts in the mixed layer depth (Wassmann, 2011; Tremblay et al., 2012). Therefore, there is *medium confidence* that annual phytoplankton production will increase in the central Arctic Ocean.

In the few cases where future abundance of fish has been projected using climate change scenarios, species exhibited different trends related to their vulnerability. Forward extrapolation of observed responses suggests that increased summer sea surface temperatures in the Bering and Barents Seas will cause a decrease in the abundance of energy-rich copepods and euphausiids (Coyle et al., 2011; Slagstad et al., 2011). This change in prey quality is expected to lower survival of walleye pollock in the eastern Bering Sea by 2050 (Mueter et al., 2011). Climate-enhanced stock projection models showed time trends in cross-shelf transport of juvenile northern rock sole (*Lepidopsetta polyxystra*) to nursery areas will not be substantially altered by climate change (Wilderbuer et al., 2012).

28.3.2.2.2. Marine mammals, polar bears, and seabirds

The effects of the projected reduction in sea ice extent in this century (Wang and Overland, 2009) on Arctic marine mammals and seabirds will vary spatially and temporally (Laidre et al., 2008). Many ice-associated marine mammals and seabirds will be affected by ice loss, with altered species distributions, migration patterns, behavior, interspecific interactions, demography, population changes, and vulnerability to extinction but there is *limited evidence* of changes for most species (*high confidence*).

The polar bear population of the southern Beaufort Sea is projected to decline by 99% by 2100, with a probability estimated at 0.80 to 0.94 under A1B (Hunter et al., 2010). The northern Beaufort Sea population is stable although decline is predicted with warming (Stirling et al., 2011). Projected extirpation of approximately two-thirds of the world's polar bears was predicted for mid-century under A1B (Amstrup et al., 2008). Aspects of this study were criticized (Armstrong et al., 2008) but refuted (Amstrup et al., 2009). The two-thirds decline is consistent with other studies and has *robust evidence* with *medium agreement*. Projected extinction of polar bears is *unlikely*. There is *very high confidence* of subpopulation extirpation.

It is *likely* that the high Arctic seabird species partly or completely dependent on the sympagic ecosystem or the cold Arctic waters close to the ice edge will be negatively impacted if the projected changes in these physical parameters occur (*medium confidence*). A general increase in sea surface temperatures, retreat of the ice cover, and earlier break up of fast ice may improve the environmental conditions and food abundance for seabird species that have their range in the southern part of the Arctic or south of the Arctic (*medium confidence*). A poleward expansion of the range of these species is expected during a continued warming (*medium confidence*).

Several factors other than climate influence seabird population dynamics (Regular et al., 2010), and projections of changes with a continued Arctic warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA, 2005). At present, the resolution of Atmosphere-Ocean General Circulation Models are not detailed enough to project spatial changes in mesoscale oceanographic features such as frontal zones and eddies of importance to Arctic seabirds.

28.3.2.3. Antarctica and the Southern Ocean

Continued rising temperatures in the Southern Ocean will result in increased metabolic costs in many ectothermic pelagic species, southward movement of temperate species, and contraction of the range of polar species (*medium confidence*). Southward movement of ocean fronts and associated biota that are prey of sub-Antarctic island-based predators will result in energetic inefficiencies for some of those predators (*low confidence*; Péron et al., 2012; Weimerskirch et al., 2012).

For Antarctic krill, insufficient evidence is available to predict what will happen to circumpolar productivity because of regional variability of the effects of climate change on the different factors (positive and negative) that affect krill, directly and indirectly. For example, increased metabolic and growth rates from warming may be countered by a reduced food supply and the effects of ocean acidification (Sections 28.2.2.2, 28.3.2.1). Also, areas that are already warm may result in slower growth with further warming, such as could happen in the northern Scotia Arc (Wiedenmann et al., 2008; Hill et al., 2013). Models of recruitment and population dynamics indicate that the biomass of krill will decline if surface warming continues, but preliminary projections incorporating a range of factors are uncertain (*low confidence*; Murphy et al., 2007, 2012b). Physiological and behavioral responses might also ameliorate impacts. For example, krill are now known to exploit the full depth of the ocean, which could provide escapes from further warming (Schmidt et al., 2011) as well as refuge from air-breathing predators.

The strong dependence of species in more southern regions (e.g., southern west Antarctic Peninsula and Ross Sea region) on sea ice means that changes in sea ice distribution will cause spatial shifts in the structure of ice-obligate food webs (*low confidence*; Murphy et al., 2012b). Projections show that loss of summer sea ice from the west Antarctic Peninsula is expected to result in ice-dependent seals declining and being replaced by other seal species that are not dependent on sea ice (*low confidence*; Siniff et al., 2008; Costa et al., 2010). There is insufficient evidence to determine whether there will be a mismatch in phenologies of different species as a result of changes in the winter sea ice season (timing and winter extent), such as might occur if the timing of sea ice melt was not at a time of optimal growing conditions for phytoplankton (Trathan and Agnew, 2010).

Reductions in krill abundance in the marine food webs around the South Atlantic islands may result in a shift in their structure toward a more fish-centered ecosystem as observed in the Indian Sector (*low confidence*; Trathan, et al., 2007, 2012; Shreeve et al., 2009; Waluda et al., 2010; Murphy et al., 2012a,b). Also, salps have been postulated to be competitors with krill for phytoplankton around the Antarctic Peninsula when oceanic conditions displace shelf and near-shelf waters during times of low sea ice (Ducklow et al., 2012). In the absence of krill, longer food chains have lower trophic efficiency (Muprhy et al., 2013), and the long-term implications of this for higher trophic levels are unknown.

Coastal environments will be impacted by the dynamics of fast ice, ice shelves, and glacier tongues. These factors will positively affect local primary production and food web dynamics (Peck et al., 2009) but negatively affect benthic communities (*low confidence*; Barnes and Souster, 2011). Projections of the response of emperor penguins and Southern Ocean seabirds based on AR4 model outputs for sea ice and temperature in east Antarctica indicate that general declines in these populations are to be expected if sea ice habitats decline in the future (*low confidence*; Barbraud et al., 2011; Jenouvrier et al., 2012). However, these responses are also expected to be regionally specific because of the regional differences in expectations of change in the ice habitats (*high confidence*). Additional studies at other sites are needed to improve confidence levels of predictions.

28.3.3. Terrestrial Environment and Related Ecosystems

28.3.3.1. Arctic

The boreal forest is generally projected by models to move northward under a warming climate, which will displace between 11 and 50% of the tundra within 100 years (Callaghan et al., 2005; Wolf et al., 2008; Tchebakova et al., 2009; Wramneby et al., 2010) in a pattern similar to that which occurred during the early Holocene climatic warming (*high confidence*). Pearson et al. (2013) projected that at least half of vegetated Arctic areas will shift to a different physiognomic class, and woody cover will increase by as much as 52%, in line with what has been occurring in northwest Eurasia (Macias-Fauria et al., 2012).

Dynamic vegetation models applied to Europe and the Barents Region project a general increase in net annual primary production by climate warming and CO_2 fertilization (Wolf et al., 2008; Wramneby et al., 2010; Anisimov et al., 2011). Boreal needle-leaved evergreen coniferous forest replaces tundra and expands into the mountain areas of Fennoscandia, but this advance may be delayed or prevented in regions already occupied by clonal deciduous shrubs whose *in situ* growth has increased significantly in recent decades (Macias-Fauria et al., 2012).

In contrast to these expected results, shrubs, currently expanding in area in many Arctic locations, were modeled to decrease in extent over the next 100 years after an initial increase (Wolf et al., 2008). Also, counterintuitively, tundra areas increased in the projections. This was a result of changes at the highest latitudes that opened land for colonization at a rate exceeding displacement of tundra by shrubs in the south.

Several studies have calculated the magnitude of the effects of vegetation change in the Arctic on negative feedbacks of CO_2 sequestration and increased evapotranspiration and the positive feedback of decreased albedo (Swann et al., 2010; Wramneby et al., 2010; Wolf et al., 2010; Pearson et al., 2013). It is *likely* that vegetation changes will result in an overall positive feedback on the climate.

Recent changes and results of climate change simulation experiments in the field have shown that there are considerable uncertainties in the projected rates of change (e.g., Van Bogaert et al., 2010). Furthermore, the models do not yet include vertebrate and invertebrate herbivory, extreme events such as tundra fire, and extreme winter warming damage or changes in land use that either reduce the rate of vegetation change or open up niches for rapid change. Projections suggest increases in the ranges of the autumn and winter months that have outbreaks in populations resulting in the defoliation of birch forest (Jepsen et al., 2008, 2011) and a general increase in the "background" (non-outbreak) invertebrate herbivores (Wolf et al., 2008).

Animal terrestrial biodiversity is generally projected to increase in the Arctic during warming by immigration of new species from the south, vegetation changes, and indirectly by introduction of invasive species caused by increased human activities and increased survival of such species (*high confidence*; Post et al., 2009; Gilg et al., 2012; CAFF, 2013). Many native Arctic species will *likely* be increasingly threatened during this century.

28.3.3.2. Antarctica

Projected effects of climate change on Antarctic terrestrial species are limited to knowledge of their ecophysiological tolerances to changes in air temperature, wind speed, precipitation (rain and snowfall), permafrost thaw, and exposure of new habitat through glacial/ice retreat. The climate is expected to become more tolerable to a number of species, leading to increases in biomass and extent of existing ecological communities.

The frequency with which new potential colonizing plant and animal species arrive in Antarctica (particularly the Antarctic Peninsula region) from lower latitudes, and the subsequent probability of their successful establishment, will increase with regional climate warming and associated environmental changes (*high confidence*; Chown et al., 2012). Human-assisted transfers of biota may be more important by two orders of magnitude than natural introductions (Frenot et al., 2005) as the transfer is faster and avoids extreme environments such as altitude or oceans (Barnes et al., 2006). The potential for anthropogenic introduction of non-indigenous species to Antarctic terrestrial areas, which could have devastating consequences to the local biodiversity, will increase (*high confidence*; Convey et al., 2009; Hughes and Convey, 2010; Convey, 2011; Braun et al., 2012). At present, established non-indigenous species in the sub- and maritime Antarctic are very restricted in their distributions (Frenot et al., 2005). Climate change could result in a greater rate of spread of invasive species through colonization of areas exposed by glacial retreat, as has occurred at South Georgia (Cook et al., 2010) and in the maritime Antarctic (Olech and Chwedorzewska, 2011). Biosecurity measures may be needed to help control dispersal of established non-indigenous species to new locations, particularly given the expected increase in human activities in terrestrial areas (Hughes and Convey, 2010; Convey et al., 2011). An important gap in understanding is the degree to which climate change may facilitate some established but localized alien species to become invasive and widespread (Frenot et al., 2005; Convey 2010; Hughes and Convey, 2010; Cowan et al., 2011), which has been shown for the sub-Antarctic (Chown et al., 2012).

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic islands, along with the continued increased presence of Antarctic fur seals, are likely to have far greater importance over the time scale under consideration than are those attributable to climate change itself (Convey and Lebouvier, 2009; Turner et al., 2009; Convey, 2010).

28.3.4. Economic Sectors

Projections of economic costs of climate change impacts for different economic sectors in the Arctic are limited, but current assessments suggest that there will be both benefits and costs (AMAP, 2011a; Forbes, 2011). Non-Arctic actors are likely to receive most of the benefits from increased shipping and commercial development of renewable and non-renewable resources, while Indigenous peoples and local Arctic communities will have a harder time maintaining their way of life (Hovelsrud et al., 2011).

Contributing to the complexity of measuring the future economic effects of climate change is the uncertainty in future predictions and the rapid speed of change, which are linked with the uncertainty of the technological and ecological effects of such change (NorAcia, 2010). Communities within the same eco-zone may experience different effects from identical climate-related events because of marked local variations in site, situation, culture, and economy (Clark et al., 2008).

Economic cost estimates have been made for the case of the Alaskan economy, for example, which suggest that a heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). Some Alaskan villages such as Shishmaref, Kivalina, and Newtok have already lost critical infrastructure and services and are becoming unlivable because of permafrost thaw, storm damage, and coastal erosion but the high costs and limitations of government mechanisms are significant barriers to the actual relocation of these communities (Bronen, 2011; Brubaker et al., 2011c; Cochran et al., 2013; Maldonado et al., 2013).

28.3.4.1. Fisheries

Climate change will impact the spatial distribution and catch of some open ocean fisheries in the Barents and Bering Seas (*high confidence*); however, the future of commercial fisheries in the Arctic Ocean is uncertain. There is strong evidence and considerable data showing links between climate-driven shifts in ocean conditions and shifts in the spatial distribution and abundance of commercial species in the Bering and Barents Seas (Section 28.3.2.2.1). In limited cases, coupled biophysical models or climate-enhanced stock projection models have been used to predict future commercial yield or shifts in fishing locations. However, these predictions are uncertain (Huse and Ellingsen, 2008; Ianelli et al., 2011; Wilderbuer et al., 2012). Cheung et al. (2011) used projections from an Earth System Model to estimate shifts in bio-climatic windows that included climate change effects on biogeochemistry (oxygen and acidity) and primary production to project future catch potential of 120 demersal fish and invertebrates. Results from their model suggested that the catch potential will increase in the Barents and Greenland Seas and regions at greater than 70° north latitude (Cheung et al., 2011). In contrast, vulnerability analysis suggests that only a few species are expected to be abundant enough to support viable fisheries in the Arctic Ocean (Hollowed et al., 2013). Potential fisheries for snow crab (*Chionoecetes opilio*) on shelf areas of the Arctic Ocean may be limited by the associated impacts of ocean acidification. If fisheries develop in the Arctic Ocean, adoption of sustainable strategies for management will be a high priority (Molenaar, 2009). The moratorium on fishing in the US portion of the Chukchi and Beaufort Seas would prevent fishing until sufficient data become available to manage the stock sustainably (Wilson and Ormseth, 2009).

Predicting how harvesters will respond to changing economic, institutional, and environmental conditions under climate change is difficult. Current techniques track fishers' choices based on revenues and costs associated with targeting a species in a given time and area with a particular gear given projected changes in the abundance and spatial distribution of target species (Haynie and Pfeiffer, 2012). However, estimates of future revenues and costs will depend, in part, on future demand for fish, global fish markets, and trends in aquaculture practices (Rice and Garcia, 2011; Merino et al., 2012).

28.3.4.2. Forestry and Farming

Climate change is *likely* to have positive impacts for agriculture, including extended growing season (*medium* to *high confidence*; Falloon and Betts, 2009; Grønlund, 2009; Tholstrup and Rasmussen, 2009), although variations across regions are expected (Hovelsrud et al., 2011), and the importance of impacts to the Arctic economy will likely remain minor (Eskeland and Flottorp, 2006). Potential positive effects of climatic warming for forestry include decreased risk of snow damage. Kilpeläinen et al. (2010) estimate a 50% decrease in snow damage in Finland toward the end of the century. A warmer climate is likely to impact access conditions and plant diseases for forestry and farming. Grønlund (2009) found in the case of northern Norway—where about half of the arable land area is covered by forest and 40% by marshland—that the potential harnessing of arable land for farming will be at the cost of forestry production, or dried-up marshlands, which may contribute to more greenhouse emissions. Larger field areas may contribute to land erosion through rainfall and predicted unstable winters, and may increase conditions for plant diseases and fungal infections (Grønlund, 2009). If the winter season continues to shorten due to climate change (Xu et al., 2013), accessibility to logging sites will be negatively affected. Accessibility is higher when frozen ground makes transportation possible in sensitive locations or areas that lack road. If weather changes occur when logging has taken place, sanding of roads may be necessary which carries significant economic costs. Impact on carrying capacity of ground or road accessibility will thus affect forestry economically. Challenges may include limited storage space for wood (Keskitalo, 2008).

28.3.4.3. Infrastructure, Transportation, and Terrestrial Resources

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much of the infrastructure in the North is dependent on the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines, and provide access to remote communities in the winter (*high confidence*; Huntington et al., 2007; Furgal and Prowse, 2008; Sundby and Nakken, 2008; Sherman et al., 2009; West and Hovelsrud, 2010; Forbes, 2011). In the long-term, marine and freshwater transportation will need to shift reliance from ice routes to open-water or land-based transportation systems. Relocation remains one community-based adaptation to deal with projections of persistent flooding and bank erosion (Furgal, 2008; NRTEE, 2009). Changing sea ice (multi-year) conditions are expected to have a regulating impact on marine shipping and coastal infrastructure (i.e., via introduced hazards; Eicken et al., 2009).

By adapting transportation models to integrate monthly climate model (Community Climate System Model 3 (CCSM3)) predictions of air temperature—combined with data sets on land cover, topography, hydrography, built infrastructure, and locations of human settlements—estimates have been made of changes to inland accessibility for landscapes northward of 40°N by the mid-21st century (Stephenson et al., 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000-kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000–2014) for eight circumpolar countries was projected to be –14%, varying from –11 to –82%. In absolute terms, Canada and Russia (both at –13%) account for the majority of declining winter-road potential with approximately 1 × 10^6 km^2 being lost (see Table 28-1). The winter road season has decreased since the 1970s on the Alaskan North Slope, from as much as 200 to 100 days in some areas (Hinzman, et al., 2005).

Climate change is expected to lead to a nearly ice-free Arctic Ocean in late summer and increased navigability of Arctic marine waters within this century. New possibilities for shipping routes and extended use of existing routes may result from increased melting of sea ice (*high confidence*; Corbett et al., 2010; Khon et al., 2010; Paxian et al., 2010; Peters et al., 2011; Stephenson et al., 2011).

Table 28-1 | Annually averaged changes in inland and maritime transportation accessibility by mid-century (2045–2059) versus baseline (2000–2014).

	Change (%) in winter road-accessible land area (km^2) (2000-kg GVWR vehicle)	Change (%) in maritime-accessible ocean area (km^2) (type A vessel)—current EEZ
Canada	–13	19
Finland	–41	0
Greenland	–11	28
Iceland	–82	<1
Norway	–51	2
Russia	–13	16
Sweden	–46	0
USA (Alaska)	–29	5
High seas	n/a	406
Total	–14	23

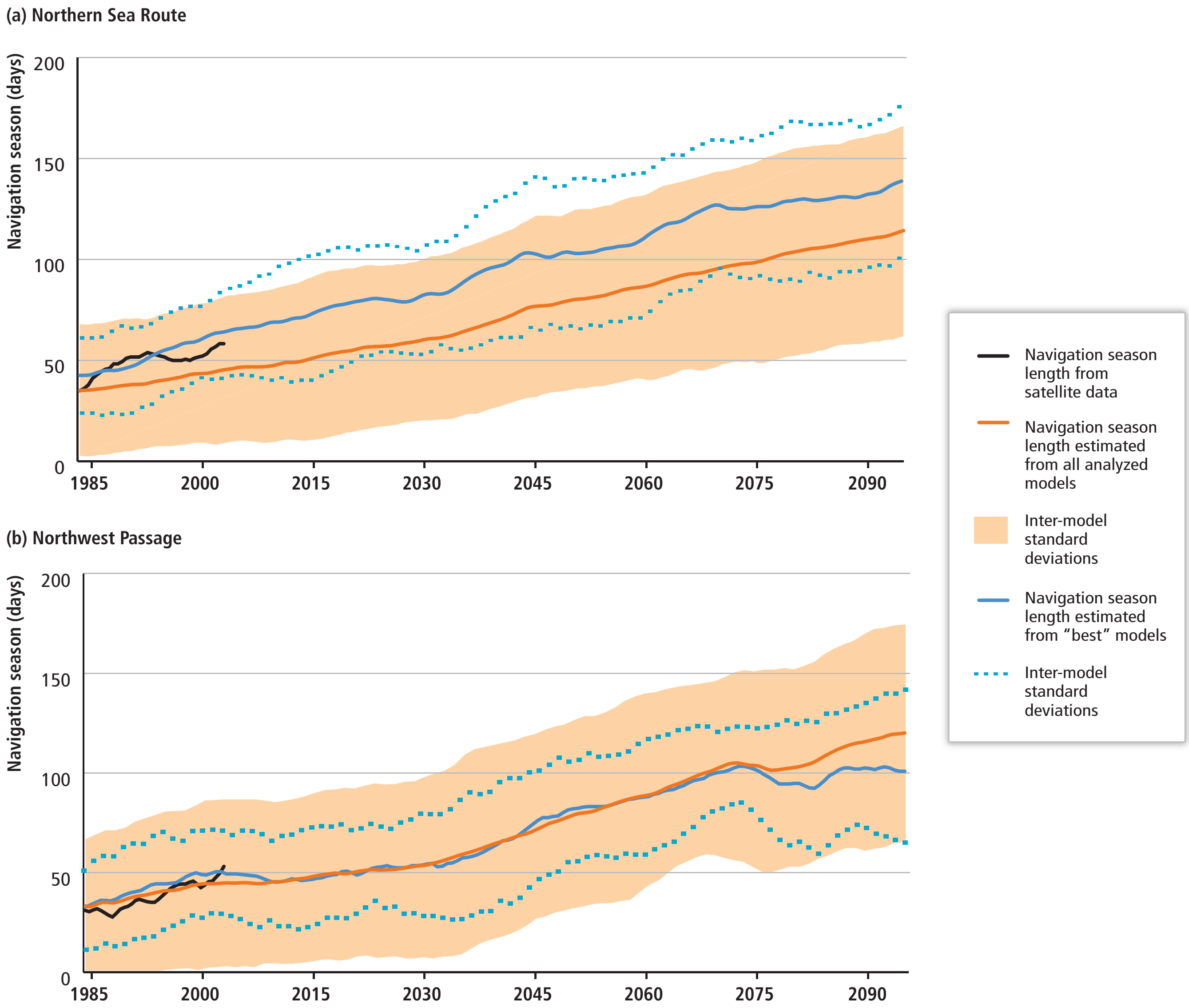


Figure 28-4 | Projected duration of the navigation period (days) over the Northwest Passage and Northern Sea Route (Khon et al., 2010).

Projections made by Stephenson et al. (2011) suggest that all five Arctic littoral states will gain increased maritime access to their current exclusive economic zones, especially Greenland (+28%, relative to baseline), Canada (+19%), Russia (+16%), and the USA (+15%). In contrast, Iceland, Norway, Sweden, and Finland display little or no increase in maritime accessibility (Table 28-1; Stephenson et al., 2011).

General Circulation Models (GCMs) developed for the AR4 generally have underestimated the duration of the ice-free period in the Arctic Ocean and simulate slower changes than those observed in the past decades (Stroeve et al., 2007). Mokhow and Khon (2008) used a subset of climate models that better reproduce observed sea ice dynamics than other GCMs to project the duration of the navigation season along the NSR and through the NWP under the moderate SRES A1B emission scenario. According to their results, by the end of the 21st century, the NSR may be open for navigation 4.5 ± 1.3 months per year, while the NWP may be open 2 to 4 months per year (see Figure 28-4). The models did not predict any significant changes of the ice conditions in the NWP until the early 2030s.

An increase in the length of the summer shipping season, with sea ice duration expected to be 10 days shorter by 2020 and 20 to 30 days shorter by 2080, is likely to be the most obvious impact of changing climate on Arctic marine transportation (Prowse et al., 2009). Reduction in sea ice and increased marine traffic could offer opportunities for economic diversification in new service sectors supporting marine shipping. Loss of sea ice may open up waterways and opportunities for increased cruise traffic (e.g., Glomsrød and Aslaksen, 2009), and add to an already rapid increase in cruise tourism (Howell et al., 2007; Stewart et al., 2007, 2010). Climate change has increased the prevalence of cruise tourism throughout Greenland, Norway, Alaska, and Canada because of decreasing sea ice extent.

Projected declines in sea ice cover leading to development of integrated land and marine transportation networks in northern Canada may stimulate further mine exploration and development (Prowse et al., 2009). These possibilities, however, also come with challenges including their predicted contribution to the largest change in contaminant movement into or within the Arctic, as well as their significant negative impacts on the traditional ways of life of northern residents (Furgal and Prowse, 2008). Added shipping and economic activity will increase the amount of black carbon and reinforce warming trends in the region (Lack and Corbett, 2012), leading to additional economic activity.

A longer shipping season and improved access to ports may lead to increased petroleum activities, although possible increased wave activity and coastal erosion may increase costs related to infrastructure and technology. Peters et al. (2011) find by using a bottom-up shipping model and a detailed global energy market model to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050—and based on estimated sea ice extent—that there will be rapid growth in transit shipping; oil and gas production will be moving into locations requiring more ship transport; and this will lead to rapid growth in emissions from oil and gas transport by ship.

The Arctic contains vast resources of oil, which is hard to replace as transportation fuel, and vast resources of gas, a more climate-benign fuel than coal. Petroleum resources are unevenly distributed among Arctic regions and states. Arctic resources will play a growing role in the world economy, but increased accessibility is expected to create challenges for extraction, transport, engineering, search-and-rescue needs, and responses to accidents (Hovelsrud et al., 2011), and climatic change presents the oil and gas industry with challenges in terms of planning and predictions (Harsem et al., 2011). Increased emissions due to rapid growth in Arctic Ocean transportation of oil and gas are projected (Peters et al., 2011). Owing to high costs and difficult access conditions, the impact on future oil and gas production in the Arctic remains unclear (Peters et al., 2011; Lindholdt and Glomsrød, 2012).

28.4. Human Adaptation

There is general agreement that both Indigenous and non-Indigenous people in the Arctic have a history of adapting to natural variability in the climate and natural resource base, as well as recent socioeconomic, cultural, and technological changes (*high confidence*; Forbes and Stammler, 2009; Wenzel, 2009; Ford and Pearce, 2010; West and Hovelsrud, 2010; Bolton et al., 2011; Cochran et al., 2013). Climate change exacerbates the existing stresses faced by Arctic communities (*high confidence*; Crate and Nuttall, 2009; Rybråten and Hovelsrud, 2010), and is only one of many important factors influencing adaptation (Berrang-Ford et al., 2011). Climate adaptation needs to be seen in the context of these interconnected and mutually reinforcing factors (Tyler et al., 2007; Hovelsrud and Smit, 2010). The challenges faced today by communities in the Arctic are complex and interlinked and are testing their traditional adaptive capacity (*low* to *medium confidence*).

Climatic and other large-scale changes have potentially large effects on Arctic communities, in particular where simple economies leave a narrower range of adaptive choices (Berkes et al., 2003; Anisimov et al., 2007; Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford et al., 2010; Forbes, 2011). There is considerable evidence that changing weather patterns, declining sea ice and river as well as lake ice, thawing permafrost, and plant and animal species' abundance and composition have consequences for communities in the Arctic (see Sections 28.2.4, 28.2.5.2, and 28.3.4). Sea ice is particularly important for coastal communities that rely upon it for transportation to and from hunting areas (Krupnik et al., 2010). Changes in the duration and condition of sea ice and the consequent changes to country food availability significantly impact the well-being of communities (Furgal and Seguin, 2006; Ford and Berrang-Ford, 2009; Ford et al., 2010), outdoor tourism (Dawson et al., 2010), and hunting and fishing (*high confidence*; Wiig et al., 2008; Brander, 2010).

Adaptation to climate change is taking place at the local and regional levels where impacts are often felt most acutely and the resources most readily available (Oskal, 2008; Hovelsrud and Smit, 2010). Current experiences and projections of future conditions often lead to technological adaptation responses such as flood and water management and snow avalanche protection (Hovelsrud and Smit, 2010; West and Hovelsrud, 2010) rather than policy responses (Hedensted Lund et al., 2012; Rudberg et al., 2012). Climate variability and extreme events are found to be salient drivers of adaptation (Amundsen et al., 2010; Berrang-Ford et al., 2011; Dannevig et al., 2012).

The lack of local scale climate projections, combined with uncertainties in future economic, social, and technological developments, often act as barriers to adaptation. These barriers, together with other societal determinants such as ethics, cultures, and attitudes toward risk, may cause inaction (Adger et al., 2009; West and Hovelsrud, 2010). Resolving divergent values across and within different communities poses a challenge for governance regimes. A determining factor in building adaptive capacity is the flexibility of enabling institutions to develop robust options (Forbes et al., 2009; Keskitalo et al., 2009; Hovelsrud and Smit, 2010; Ford and Goldhar, 2012; Whyte, 2013). Refer to Table 28-2 for key climate-related risks and potential adaptation practices. In the North American and Scandinavian context, adaptive co-management responses have been developed through land claims settlements and/or multi-scale institutional cooperation to foster social learning (Armitage et al., 2008; Berkes, 2009).

Indigenous Peoples

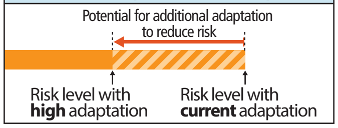
Although Arctic indigenous peoples with traditional lifestyles are facing unprecedented impacts to their ways of life from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they are already implementing creative ways of adapting (*high confidence*; Cruikshank, 2001; Forbes et al., 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Alexander et al., 2011; Cullen-Unsworth et al., 2011).

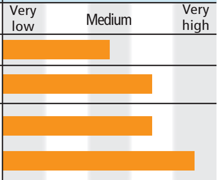
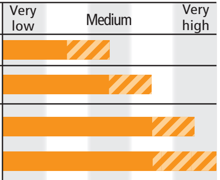
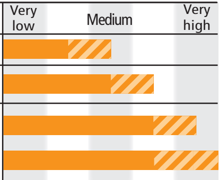
While many of these adaptation activities tend to be short term or reactive in nature (e.g., dealing with other issues such as disaster response planning), some Indigenous communities are beginning to develop more formal adaptation plans (Galloway-McLean, 2010; Brubaker et al., 2011b,c; Nakashima et al., 2012). Comprehensive adaptation planning must take into account underlying social issues of some Indigenous populations when addressing the new challenges from climate and development. Indigenous communities are especially vulnerable to climate change because of their strong dependence on the environment for food, culture, and way of life; their political and economic marginalization; the social, health, and poverty disparities; and community locations

Table 28-2 | Key climate-related risks in the Arctic and Antarctic, and potential adaptation practices.

Climate-related drivers of impacts		
🌡 Warming trend	❄ Snow cover	🌊 Ocean acidification

Level of risk & potential for adaptation



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species´ habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2-4]	• Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations • Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources • Hunting or fishing for different species, if possible, and diversifying income sources	🌡 ❄ 🌊	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Shifting resource bases, land use, and/or settlement areas	🌡 ❄	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Adaptive co-management responses developed through the settlement of land claims	🌡 ❄	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

along exposed ocean, lake, or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen et al., 2010; Cochran et al., 2013).

The adaptive capacity of Arctic Indigenous peoples is largely due to an extensive traditional knowledge and cultural repertoire, and flexible social networks (*medium confidence*; Williams and Hardison, 2013; see Section 12.3). The dynamic nature of traditional knowledge is valuable for adapting to current conditions (Kitti et al., 2006; Tyler et al., 2007; Eira et al., 2012). The sharing of knowledge ensures rapid responses to crises (Ford et al., 2007). In addition, cultural values such as sharing, patience, persistence, calmness, and respect for elders and the environment are important. Some studies suggest that traditional knowledge may not always be sufficient to meet the rapid changes in climate (see Chapter 12) and it may be perceived to be less reliable because the changing conditions are beyond the current knowledge range (Ingram et al., 2002; Ford et al., 2006; Hovelsrud et al., 2010; Valdivia et al., 2010).

Over the last half-century, the adaptive capacity in some Indigenous communities has been challenged by the transition from semi-nomadic hunting groups to permanent settlements, accompanied by impacts to health and well-being from loss of connection to the land, traditional foods, and culture (Ford et al., 2010; Galloway-McLean, 2010). Forced or voluntary migration as an adaptation response can have deep cultural impacts (Shearer, 2011, 2012; Maldonado et al., 2013). On the other hand, the establishment of permanent communities, particularly those associated with new industrial development, can also lead to increasing employment opportunities and income diversification for Indigenous peoples. The intergenerational transfers of knowledge and skills through school curricula, land camps, and involvement in community-based monitoring programs may strengthen adaptive capacity (Forbes 2007; Ford et al., 2007; Hovelsrud and Smit, 2010; Bolton et al., 2011).

Examples of Indigenous adaptation strategies have included changing resource bases; shifting land use and/or settlement areas; combining technologies with traditional knowledge; changing timing and location of hunting, gathering, herding, and fishing areas; and improving communications and education (Galloway-McLean, 2010). Protection of grazing land will be the most important adaptive strategy for reindeer herders under climate change (Forbes et al., 2009; Magga et al., 2011; Kumpula et al., 2012; Degteva and Nellemann, 2013; Mathiesen et al., 2013). Renewable resource harvesting remains a significant component of Arctic livelihoods, and with climate change hunting and fishing has become a riskier undertaking and many communities are already adapting (Gearheard et al., 2011; Laidler et al., 2011). Adaptation includes taking more supplies when hunting, constructing permanent shelters on land as refuges from storms, improved communications infrastructure, greater use of global positioning systems (GPS) for navigation, synthetic aperture radar (SAR) to provide estimates of sea ice conditions (Laidler et al., 2011), and the use of larger or faster vehicles (Ford et al., 2010). Avoiding dangerous terrain can result in longer and time-consuming journeys that can be inconvenient to those with wage-earning employment (Ford et al., 2007).

Reindeer herders have developed a wide range of adaptation strategies in response to changing pasture conditions. These include moving herds to better pastures (Bartsch et al., 2010), providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009), retaining a few castrated reindeer males to break through heavy ice crust (Oskal, 2008; Reinert et al., 2008), ensuring an optimal herd size (Tyler et al., 2007;

Forbes et al., 2009), and creating multicultural initiatives combining traditional with scientific knowledge (Vuojala-Magga et al., 2011). Coastal fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud et al., 2010).

In some Arctic countries Indigenous peoples have successfully negotiated land claims rights and have become key players in addressing climate change (Abele et al., 2009). In some instances, this has given rise to tensions over land/water use between traditional livelihoods and new opportunities, for example, tourism and natural resource development (Forbes et al., 2006; Hovelsrud and Smit, 2010). Some territorial governments in northern Canada have promoted adaptation by providing hunter support programs (Ford et al., 2006, 2010).

Health of many Indigenous people is being affected by the interaction of changes in the climate with ongoing changes in human, economic, and biophysical systems (Donaldson et al., 2010). The distribution of traditional foods between communities and the use of community freezers in the Canadian Arctic has improved food security, an important factor for health (Ford et al., 2010). Although wage employment may enhance the possibilities for adaptive capacity, greater involvement in full-time jobs can threaten social and cultural cohesion and mental well-being by disrupting the traditional cycle of land-based practices (Berner et al., 2005; Furgal, 2008).

28.5. Research and Data Gaps

There remains a poor knowledge of coupling among, and thresholds within, biogeophysical and socioeconomic processes to fully assess the effects of a changing climate, and to separate them from those due to other environmental stressors:

- Existing integrative models are either lacking or insufficiently validated to project and to assess the cascading effects on, and feedbacks from, the systems in the polar regions, in particular socioeconomic systems.
- There is a need to enhance or establish a coordinated network of long-term representative sites for monitoring and assessment of climate change detection and attribution studies in the polar regions. Regional differences and confounding variables will need to be

Frequently Asked Questions

FAQ 28.1 | What will be the net socioeconomic impacts of change in the polar regions?

Climate change will have costs and benefits for polar regions. Climate change, exacerbated by other large-scale changes, can have potentially large effects on Arctic communities, where relatively simple economies leave a narrower range of adaptive choices.

In the Arctic, positive impacts include new possibilities for economic diversification, marine shipping, agricultural production, forestry, and tourism. The Northern Sea Route is predicted to have up to 125 days per year suitable for navigation by 2050, while the heating energy demand in the populated Arctic areas is predicted to decline by 15%. In addition, there could be greater accessibility to offshore mineral and energy resources although challenges related to environmental impacts and traditional livelihoods are possible.

Changing sea ice condition and permafrost thawing may cause damage to bridges, pipelines, drilling platforms, hydropower, and other infrastructure. This poses major economic costs and human risks, although these impacts are closely linked to the design of the structure. Furthermore, warmer winter temperatures will shorten the accessibility of ice roads that are critical for communications between settlements and economic development and have implications for increased costs. Statistically, a long-term mean increase of 2°C to 3°C in autumn and spring air temperature produces an approximately 10- to 15-day delay in freeze-up and advance in break-up, respectively.

Particular concerns are associated with projected increase in the frequency and severity of ice-jam floods on Siberian rivers. They may have potentially catastrophic consequences for the villages and cities located in the river plain, as exemplified by the 2001 Lena River flood, which demolished most of the buildings in the city of Lensk.

Changing sea ice conditions will impact Indigenous livelihoods, and changes in resources, including marine mammals, could represent a significant economic loss for many local communities. Food security and health and well-being are expected to be impacted negatively.

In the Antarctic, tourism is expected to increase, and risks exist of accidental pollution from maritime accidents, along with an increasing likelihood of the introduction of alien species to terrestrial environments. Fishing for Antarctic krill near the Antarctic continent is expected to become more common during winter months in areas where there is less winter sea ice.

Frequently Asked Questions

FAQ 28.2 | Why are changes in sea ice so important to the polar regions?

Sea ice is a dominant feature of polar oceans. Shifts in the distribution and extent of sea ice during the growing season impacts the duration, magnitude, and species composition of primary and secondary production in the polar regions. With less sea ice many marine ecosystems will experience more light, which can accelerate the growth of phytoplankton, and shift the balance between the primary production by ice algae and water-borne phytoplankton, with implications for Arctic food webs. In contrast, sea ice is also an important habitat for juvenile Antarctic krill, providing food and protection from predators. Krill is a basic food source for many species in polar marine ecosystems.

Changes in sea ice will have other impacts, beyond these "bottom-up" consequences for marine food webs. Mammals and birds utilize sea ice as haul-outs during foraging trips (seals, walrus, and polar bears in the Arctic and seals and penguins in the Antarctic). Some seals (e.g., bearded seals in the Arctic and crab eater and leopard seals in the Antarctic) give birth and nurse pups in pack ice. Shifts in the spatial distribution and extent of sea ice will alter the spatial overlap of predators and their prey. According to model projections, within 50 to 70 years, loss of hunting habitats may lead to elimination of polar bears from seasonally ice-covered areas, where two-thirds of their world population currently live. The vulnerability of marine species to changes in sea ice will depend on the exposure to change, which will vary by location, as well as the sensitivity of the species to changing environmental conditions and the adaptive capacity of each species. More open waters and longer ice-free periods in the northern seas enhance the effect of wave action and coastal erosion, with implications for coastal communities and infrastructure.

Although the overall sea ice extent in the Southern Ocean has not changed markedly in recent decades, there have been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc.

considered in designing field and modeling studies. Standardized methods and approaches of biophysical and socioeconomic analysis along with coordinated sampling in more regions will be necessary.

There are more specific research gaps, including:

- Many mechanisms of how climate change and ocean acidification may be affecting polar ecosystems have been proposed but few studies of physiological tolerances of species, long-term field studies of ecosystem effects, and ecosystem modeling studies are available to be able to attribute with high confidence current and future change in these ecosystems to climate change.
- More comprehensive studies including long-term monitoring on the increasing impacts from climate changes on Arctic communities (urban and rural) and their health, well-being, traditional livelihoods, and life ways are needed. There is a need to assess more fully vulnerabilities and to develop response capacities at the local and regional levels.

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Small Islands

Coordinating Lead Authors:
Leonard A. Nurse (Barbados), Roger F. McLean (Australia)

Lead Authors:
John Agard (Trinidad and Tobago), Lino Pascal Briguglio (Malta), Virginie Duvat-Magnan (France), Netatua Pelesikoti (Samoa), Emma Tompkins (UK), Arthur Webb (Fiji)

Contributing Authors:
John Campbell (New Zealand), Dave Chadee (Trinidad and Tobago), Shobha Maharaj (Trinidad and Tobago), Veronique Morin (Canada), Geert Jan van Oldenborgh (Netherlands), Rolph Payet (Seychelles), Daniel Scott (Canada)

Review Editors:
Thomas Spencer (UK), Kazuya Yasuhara (Japan)

Volunteer Chapter Scientist:
Veronique Morin (Canada)

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Executive Summary

Current and future climate-related drivers of risk for small islands during the 21st century include sea level rise (SLR), tropical and extratropical cyclones, increasing air and sea surface temperatures, and changing rainfall patterns (*high confidence*; *robust evidence*, *high agreement*). {WGI AR5 Chapter 14; Table 29-1} Current impacts associated with these changes confirm findings reported on small islands from the Fourth Assessment Report (AR4) and previous IPCC assessments. The future risks associated with these drivers include loss of adaptive capacity {29.6.2.1, 29.6.2.3} and ecosystem services critical to lives and livelihoods in small islands. {29.3.1-3}

SLR poses one of the most widely recognized climate change threats to low-lying coastal areas on islands and atolls (*high confidence*; *robust evidence*, *high agreement*). {29.3.1} It is *virtually certain* that global mean SLR rates are accelerating. {WGI AR5 13.2.2.1} Projected increases to the year 2100 (RCP4.5: 0.35 m to 0.70 m) {WGI AR5 13.5.1; Table 29-1} superimposed on extreme sea level events (e.g., swell waves, storm surges, El Niño-Southern Oscillation) present severe sea flood and erosion risks for low-lying coastal areas and atoll islands (*high confidence*). Likewise, there is *high confidence* that wave over-wash of seawater will degrade fresh groundwater resources {29.3.2} and that sea surface temperature rise will result in increased coral bleaching and reef degradation. {29.3.1.2} Given the dependence of island communities on coral reef ecosystems for a range of services including coastal protection, subsistence fisheries, and tourism, there is *high confidence* that coral reef ecosystem degradation will negatively impact island communities and livelihoods.

Given the inherent physical characteristics of small islands, the AR5 reconfirms the high level of vulnerability of small islands to multiple stressors, both climate and non-climate (*high confidence*; *robust evidence*, *high agreement*). However, the distinction between observed and projected impacts of climate change is often not clear in the literature on small islands (*high agreement*). {29.3} There is evidence that this challenge can be partly overcome through improvements in baseline monitoring of island systems and downscaling of climate-model projections, which would heighten confidence in assessing recent and projected impacts. {WGI AR5 9.6; 29.3-4, 29.9}

Small islands do not have uniform climate change risk profiles (*high confidence*). Rather, their high diversity in both physical and human attributes and their response to climate-related drivers means that climate change impacts, vulnerability, and adaptation will be variable from one island region to another and between countries in the same region. {Figure 29-1; Table 29-3} In the past, this diversity in potential response has not always been adequately integrated in adaptation planning.

There is increasing recognition of the risks to small islands from climate-related processes originating well beyond the borders of an individual nation or island. Such transboundary processes already have a negative impact on small islands (*high confidence*; *robust evidence*, *medium agreement*). These include air-borne dust from the Sahara and Asia, distant-source ocean swells from mid to high latitudes, invasive plant and animal species, and the spread of aquatic pathogens. For island communities the risks associated with existing and future invasive species and human health challenges are projected to increase in a changing climate. {29.5.4}

Adaptation to climate change generates larger benefit to small islands when delivered in conjunction with other development activities, such as disaster risk reduction and community-based approaches to development (*medium confidence*). {29.6.4} Addressing the critical social, economic, and environmental issues of the day, raising awareness, and communicating future risks to local communities {29.6.3} will *likely* increase human and environmental resilience to the longer term impacts of climate change. {29.6.1, 29.6.2.3; Figure 29-5}

Adaptation and mitigation on small islands are not always trade-offs, but can be regarded as complementary components in the response to climate change (*medium confidence*). Examples of adaptation-mitigation interlinkages in small islands include energy supply and use, tourism infrastructure and activities, and functions and services associated with coastal wetlands. The alignment of these sectors for potential emission reductions, together with adaptation, offer co-benefits and opportunities in some small islands. {29.7.2, 29.8} Lessons learned from adaptation and mitigation experiences in one island may offer some guidance to other small island states, though there is *low confidence* in the success of wholesale transfer of adaptation and mitigation options when the local lenses through which they are viewed differ from one island state to the next, given the diverse cultural, socioeconomic, ecological, and political values. {29.6.2, 29.8}

The ability of small islands to undertake adaptation and mitigation programs, and their effectiveness, can be substantially strengthened through appropriate assistance from the international community (*medium confidence*). However, caution is needed to ensure such assistance is not driving the climate change agenda in small islands, as there is a risk that critical challenges confronting island governments and communities may not be addressed. Opportunities for effective adaptation can be found by, for example, empowering communities and optimizing the benefits of local practices that have proven to be efficacious through time, and working synergistically to progress development agendas. {29.6.2.3, 29.6.3, 29.8}

29.1. Introduction

It has long been recognized that greenhouse gas (GHG) emissions from small islands are negligible in relation to global emissions, but that the threats of climate change and sea level rise (SLR) to small islands are very real. Indeed, it has been suggested that the very existence of some atoll nations is threatened by rising sea levels associated with global warming. Although such scenarios are not applicable to all small island nations, there is no doubt that on the whole the impacts of climate change on small islands will have serious negative effects especially on socioeconomic conditions and biophysical resources—although impacts may be reduced through effective adaptation measures.

The small islands considered in this chapter are principally sovereign states and territories located within the tropics of the southern and western Pacific Ocean, central and western Indian Ocean, the Caribbean Sea, and the eastern Atlantic off the coast of West Africa, as well as in the more temperate Mediterranean Sea.

Although these small islands nations are by no means homogeneous politically, socially, or culturally, or in terms of physical size and character or economic development, there has been a tendency to generalize about the potential impacts on small islands and their adaptive capacity. In this chapter we attempt to strike a balance between identifying the differences between small islands and at the same time recognizing that small islands tend to share a number of common characteristics that have distinguished them as a particular group in international affairs. Also in this chapter we reiterate some of the frequently voiced and key concerns relating to climate change impacts, vulnerability, and adaptation while emphasizing a number of additional themes that have emerged in the literature on small islands since the IPCC Fourth Assessment Report (AR4). These include the relationship among climate change policy, activities, and development issues; externally generated transboundary impacts; and the implications of risk in relation to adaptation and the adaptive capacity of small island nations.

29.2. Major Conclusions from Previous Assessments

Small islands were not given a separate chapter in the IPCC First Assessment Report (FAR) in 1990 though they were discussed in the chapter on "World Oceans and Coastal Zones" (Tsyban et al., 1990). Two points were highlighted. First, a 30- to 50-cm SLR projected by 2050 would threaten low islands, and a 1-m rise by 2100 "would render some island countries uninhabitable" (Tegart et al., 1990, p. 4). Second, the costs of protection works to combat SLR would be extremely high for small island nations. Indeed, as a percentage of gross domestic product (GDP), the Maldives, Kiribati, Tuvalu, Tokelau, Anguilla, Turks and Caicos, Marshall Islands, and Seychelles were ranked among the 10 nations with the highest protection costs in relation to GDP (Tsyban et al., 1990). More than 20 years later these two points continue to be emphasized. For instance, although small islands represent only a fraction of total global damage projected to occur as a result of a SLR of 1.0 m by 2100 (*Special Report on Emission Scenarios* (SRES) A1 scenario) the actual damage costs for the small island states is enormous in relation to the size of their economies, with several small island nations being included in the group of 10 countries with the highest relative impact projected for 2100 (Anthoff et al., 2010).

The Second Assessment Report (SAR) in 1995 confirmed the vulnerable state of small islands, now included in a specific chapter titled "Coastal Zones and Small Islands" (Bijlsma et al., 1996). However, importantly, the SAR recognized that both vulnerability and impacts would be highly variable between small islands and that impacts were "likely to be greatest where local environments are already under stress as a result of human activities" (Bijlsma et al., 1996, p. 291). The report also summarized results from the application of a common methodology for vulnerability and adaptation analysis that gave new insights into the socioeconomic implications of SLR for small islands including: negative impacts on virtually all sectors including tourism, freshwater resources, fisheries and agriculture, human settlements, financial services, and human health; protection is likely to be very costly; and adaptation would involve a series of trade-offs. It also noted that major constraints to adaptation on small islands included lack of technology and human resource capacity, serious financial limitations, lack of cultural and social acceptability, and uncertain political and legal frameworks. Integrated coastal and island management was seen as a way of overcoming some of these constraints.

The Third Assessment Report (TAR) in 2001 included a specific chapter on "Small Island States." In confirming previously identified concerns of small island states two factors were highlighted, the first relating to sustainability, noting that "with limited resources and low adaptive capacity, these islands face the considerable challenge of meeting the social and economic needs of their populations in a manner that is sustainable" (Nurse et al., 2001, p. 845). The second noted that there were other issues faced by small island states, concluding that "for most small islands the reality of climate change is just one of many serious challenges with which they are confronted" (Nurse et al., 2001, p. 846). In the present chapter, both of these themes are raised again and assessed in light of recent findings.

Until the AR4 in 2007, SLR had dominated vulnerability and impact studies of small island states. Whilst a broader range of climate change drivers and geographical spread of islands was included in the "Small Islands" chapter, Mimura et al. (2007) prefaced their assessment by noting that the number of "independent scientific studies on climate change and small islands since the TAR" had been quite limited and in their view "the volume of literature in refereed international journals relating to small islands and climate change since publication of the TAR is rather less than that between the SAR in 1995 and TAR in 2001" (Mimura et al., 2007, p. 690).

Since AR4, the literature on small islands and climate change has increased substantially. A number of features distinguish the literature we review here from that included in earlier assessments. First, the literature appears more sophisticated and does not shirk from dealing with the complexity of small island vulnerability, impacts, and adaptation or the differences between islands and island states. Second, and related to the first, the literature is less one-dimensional, and deals with climate change in a multidimensional manner as just one of several stressors on small island nations. Third, the literature also critiques some aspects of climate change policy, notably in relation to critical present-day development and security needs of small islands (Section 29.3.3.1) as well as the possibility that some proposed adaptation measures may prove to be maladaptive (Section 29.8). Fourth, many initiatives have been identified in recent times that will reduce vulnerability and enhance resilience of small islands to ongoing global change including improving risk knowledge and island resource management while also strengthening socioeconomic systems and livelihoods (Hay, 2013).

29.3. Observed Impacts of Climate Change, Including Detection and Attribution

The distinction between observed impacts of climate change and projected impacts is often unclear in the small islands literature and discussions. Publications frequently deal with both aspects of impacts interchangeably, and use observed impacts from, for instance an extreme event, as an analogy to what may happen in the future as a result of climate change (e.g., Lo-Yat et al., 2011). The key climate and ocean drivers of change that impact small islands include variations in air and ocean temperatures; ocean chemistry; rainfall; wind strength and direction; sea levels and wave climate; and particularly the extremes such as tropical cyclones, drought, and distant storm swell events. All have varying impacts, dependent on the magnitude, frequency, and temporal and spatial extent of the event, as well as on the biophysical nature of the island (Figure 29-1) and its social, economic, and political setting.

29.3.1. Observed Impacts on Island Coasts and Marine Biophysical Systems

29.3.1.1. Sea Level Rise, Inundation, and Shoreline Change

SLR poses one of the most widely recognized climate change threats to low-lying coastal areas (Cazenave and Llovel, 2010; Nicholls and Cazenave, 2010; Church and White, 2011). This is particularly important in small islands where the majority of human communities and infrastructure is located in coastal zones with limited on-island relocation opportunities, especially on atoll islands (Woodroffe, 2008) (Figure 29-1). Over much of the 20th century, global mean sea level rose at a rate between 1.3 and 1.7 mm yr^{-1} and since 1993, at a rate between 2.8 and 3.6 mm yr^{-1} (WGI AR5 Table 13.1), and acceleration is detected in longer records since 1870 (Merrifield et al., 2009; Church and White, 2011; see also WGI AR5 Section 13.2.2.1). Rates of SLR, however, are not uniform across the globe and large regional differences have been detected including in the Indian Ocean and tropical Pacific, where in some parts rates have been significantly higher than the global average (Meyssignac et al., 2012; see also Section 5.3.2.2). In the tropical western Pacific, where a large number of small island communities exist, rates up to four times the global average (approximately 12 mm yr^{-1}) have been reported between 1993 and 2009. These are generally thought to describe short-term variations associated with natural cyclic climate phenomena such as El Niño-Southern Oscillation (ENSO), which has a strong modulating effect on sea level variability with lower/higher-than-average sea level during El Niño/La Niña events of the order of ±20 to 30 cm (Cazenave and Remy, 2011; Becker et al., 2012). Large interannual variability in sea level has also been demonstrated from the Indian Ocean (e.g., Chagos Archipelago; Dunne et al., 2012) while Palanisamy et al. (2012) found that over the last 60 years the mean rate of SLR in the Caribbean region was similar to the global average of approximately 1.8 mm yr^{-1}.

There are few long-term sea level records available for individual small island locations. Reported sea flooding and inundation is often associated with transient phenomena, such as storm waves and surges, deep ocean swell, and predicted astronomical tidal cycles (Vassie et al., 2004; Zahibo et al., 2007; Komar and Allan, 2008; Haigh et al., 2011). For example, high spring tide floods at Fongafale Island, Funafuti Atoll, Tuvalu, have been well publicized, and areas of the central portion of Fongafale are

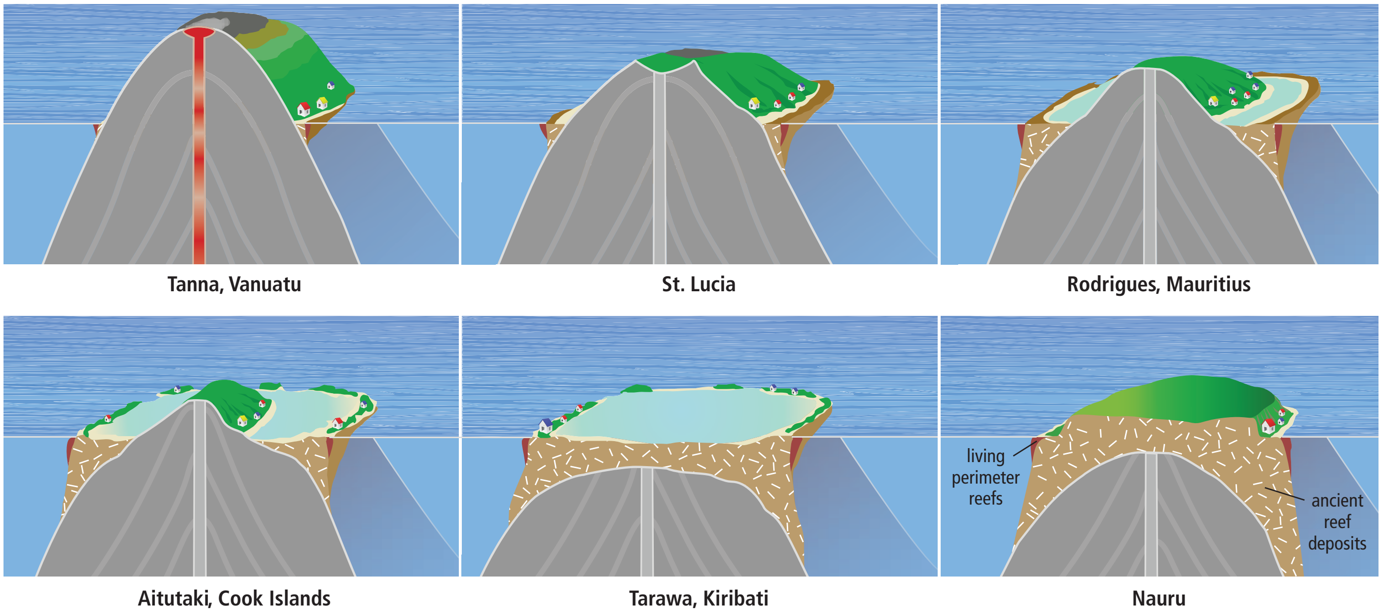
Tanna, Vanuatu
St. Lucia
Rodrigues, Mauritius
Aitutaki, Cook Islands
Tarawa, Kiribati
Nauru

Figure 29-1 | Representative tropical island typologies. From top left: A young, active volcanic island (with altitudinal zonation) and limited living perimeter reefs (red zone at outer reef edge), through to an atoll (center bottom), and raised limestone island (bottom right) dominated by ancient reef deposits (brown + white fleck). Atolls have limited, low-lying land areas but well developed reef/lagoon systems. Islands composed of continental rocks are not included in this figure, but see Table 29-3.

Frequently Asked Questions

FAQ 29.1 | Why is it difficult to detect and attribute changes on small islands to climate change?

In the last 2 or 3 decades many small islands have undergone substantial changes in human settlement patterns and in socioeconomic and environmental conditions. Those changes may have masked any clear evidence of the effects of climate change. For example, on many small islands coastal erosion has been widespread and has adversely affected important tourist facilities, settlements, utilities, and infrastructure. But specific case studies from islands in the Pacific, Indian, and Atlantic Oceans and the Caribbean have shown that human impacts play an important role in this erosion, as do episodic extreme events that have long been part of the natural cycle of events affecting small islands. So although coastal erosion is consistent with models of sea level rise resulting from climate change, determining just how much of this erosion might have been caused by climate change impacts is difficult. Given the range of natural processes and human activities that could impact the coasts of small islands in the future, without more and better empirical monitoring the role of climate change-related processes on small islands may continue to be difficult to identify and quantify.

already below high spring tide level. However, rates of relative SLR at Funafuti between 1950 and 2009 have been approximately three times higher than the global average (Becker et al., 2012), and saline flooding of internal low-lying areas occurs regularly and is expected to become more frequent and extensive over time (Yamano et al., 2007).

Documented cases of coastal inundation and erosion often cite additional circumstances such as vertical subsidence, engineering works, development activities, or beach mining as the causal process. Four examples can be cited. First, on the Torres Islands, Vanuatu communities have been displaced as a result of increasing inundation of low-lying settlement areas owing to a combination of tectonic subsidence and SLR (Ballu et al., 2011). Second, on Anjouan Island, Comores in the Indian Ocean, Sinane et al. (2010) found beach aggregate mining was a major contributing factor influencing rapid beach erosion. Third, the intrinsic exposure of rapidly expanding settlements and agriculture in the low-lying flood prone Rewa Delta, Fiji, is shown by Lata and Nunn (2012) to place populations in increasingly severe conditions of vulnerability to flooding and marine inundation. Fourth, Hoeke et al. (2013) describe a 2008 widespread inundation event that displaced some 63,000 people in Papua New Guinea and Solomon Islands alone. That event was caused primarily by remotely generated swell waves, and the severity of flooding was greatly increased by anomalously high regional sea levels linked with ENSO and ongoing SLR. Such examples serve to highlight that extreme events superimposed on a rising sea level baseline are the main drivers that threaten the habitability of low-lying islands as sea levels continue to rise.

Since the AR4 a number of empirical studies have documented historical changes in island shorelines. Historical shoreline position change over 20 to 60 years on 27 central Pacific atoll islands showed that total land area remained relatively stable in 43% of islands, while another 43% had increased in area, and the rest showed a net reduction in land area (Webb and Kench, 2010). Dynamic responses were also found in a 4-year study of 17 relatively pristine islands on two other central Pacific atolls in Kiribati by Rankey (2011), who concluded that SLR was not likely to be the main influencing factor in these shoreline changes. Similarly in French Polynesia, Yates et al. (2013) showed mixed shoreline change patterns over the last 40 to 50 years with examples of both erosion and accretion in the 47 atoll islands assessed. SLR did not appear to be the primary control on shoreline processes on these islands. On uninhabited Raine Island on the Great Barrier Reef, Dawson and Smithers (2010) also found that shoreline processes were dynamic but that island area and volume increased 6 and 4%, respectively, between 1967 and 2007. Overall, these studies of observed shoreline change on reef islands conclude that for rates of change experienced over recent decades, normal seasonal erosion and accretion processes appear to predominate over any long-term morphological trend or signal at this time. Ford's (2013) investigation of Wotje Atoll, Marshall Islands, also found shoreline variability between 1945 and 2010 but that overall accretion had been more prevalent than erosion up until 2004. From 2004 to the present, 17 out of 18 islands became net erosive, potentially corresponding to the high sea levels in the region over the last 10 years. On the high tropical islands of Kauai and Maui, Hawaii, Romine and Fletcher (2013) found shoreline change was highly variable over the last century but that recently chronic erosion predominated with over 70% of beaches now being erosive. Finally, it is important to note the majority of these studies warn that (1) past changes cannot be simply extrapolated to determine future shoreline responses; and (2) rising sea level will incrementally increase the rate and extent of erosion in the future.

In many locations changing patterns of human settlement and direct impacts on shoreline processes present immediate erosion challenges in populated islands and coastal zones (Yamano et al., 2007; Novelo-Casanova and Suarez, 2010; Storey and Hunter, 2010) and mask attribution to SLR. A study of Majuro atoll (Marshall Islands) found that erosion was widespread but attribution to SLR was obscured by pervasive anthropogenic impacts to the coastal system (Ford, 2012; see Section 5.4.4). Similarly a study of three islands in the Rosario Archipelago (Colombia) reported shoreline retreat over a 50- to 55-year period and found Grande, Rosario, and Tesoro Islands had lost 6.7, 8.2, and 48.7% of their land area, respectively. Erosion was largely attributed to poor management on densely settled Grande Island, while SLR and persistent northeast winds enhanced erosion on uninhabited Rosario and Tesoro (Restrepo et al., 2012). Likewise, Cambers (2009) reported average beach erosion rates of 0.5 m yr^{-1} in eight Caribbean islands from 1985 to 2000. Although the study could not quantify the extent of attribution it noted that greater erosion rates were positively correlated with the number of hurricane events. Alternately, Etienne and Terry (2012) found a Category 4 tropical cyclone that passed within 30 km of Taveuni Island (Fiji) nourished shorelines with fresh coralline sediments despite localized storm damage. Although these studies contribute to improved understanding of island shoreline processes and change since AR4, the warning of increased vulnerability of small island shores and low-lying areas to inundation and erosion in response to SLR and other potential climate change stressors is not diminished.

29.3.1.2. Coastal Ecosystem Change on Small Islands: Coral Reefs and Coastal Wetlands

Coral reefs are an important resource in small tropical islands, and the well-being of many island communities is linked to their ongoing function and productivity. Reefs play a significant role in supplying sediment to island shores and in dissipating wave energy, thus reducing the potential foreshore erosion. They also provide habitat for a host of marine species on which many island communities are dependent for subsistence foods as well as underpinning beach and reef-based tourism and economic activity (Perch-Nielsen, 2010; Bell et al., 2011). The documented sensitivity of coral reef ecosystems to climate change is summarized elsewhere (see Chapter 5; Box CC-CR).

Increased coral bleaching and reduced reef calcification rates due to thermal stress and increasing carbon dioxide (CO_2) concentration are expected to affect the functioning and viability of living reef systems (Hoegh-Guldberg et al., 2007; Eakin et al., 2009). Some studies already implicate thermal stress in reduced coral calcification rates (Tanzil et al., 2009) and regional declines in calcification of corals that form reef framework (De'ath et al., 2009; Cantin et al., 2010). Unprecedented bleaching events have been recorded in the remote Phoenix Islands (Kiribati), with nearly 100% coral mortality in the lagoon and 62% mortality on the outer leeward slopes of the otherwise pristine reefs of Kanton Atoll during 2002–2003 (Alling et al., 2007). Similar patterns of mortality were observed in four other atolls in the Phoenix group and temperature-induced coral bleaching was also recorded in isolated Palmyra Atoll during the 2009 ENSO event (Williams et al., 2010). In 2005 extensive bleaching was recorded at 22 sites around Rodrigues Island in the western Indian Ocean, with up to 75% of the dominant species affected in some areas (Hardman et al., 2007). Studies of the severe 1998 El Niño bleaching event in the tropical Indian Ocean showed reefs in the Maldives, Seychelles, and Chagos Islands were among the most impacted (Cinner et al., 2012; Tkachenko, 2012). In 2005 a reef survey around Barbados following a Caribbean regional bleaching event revealed the most severe bleaching ever recorded, with approximately 70% of corals impacted (Oxenford et al., 2008). Globally, the incidence and implications of temperature-related coral bleaching in small islands is well documented, and combined with the effects of increasing ocean acidification these stressors could threaten the function and persistence of island coral reef ecosystems (see Chapter 5; Box CC-OA).

Island coral reefs have limited defenses against thermal stress and acidification. However, studies such as Cinner et al. (2012) and Tkachenko (2012) highlight that although recovery from bleaching is variable, some reefs show greater resilience than others. There is also some evidence to show that coral reef resilience is enhanced in the absence of other environmental stresses such as declining water quality. In Belize chronologies of growth rates in massive corals (*Montastraea faveolata*) over the past 75 to 150 years suggest that the bleaching event in 1998 was unprecedented and its severity appeared to stem from reduced thermal tolerance related to human coastal development (Carilli et al., 2010). Likewise a study over a 40-year period (1960s–2008) in the Grand Recif of Tulear, Madagascar, concluded that severe degradation of the reef was mostly ascribed to direct anthropogenic disturbance, despite an average 1°C increase in temperature over this period (Harris et al., 2010). Coral recovery following the 2004 bleaching event in the central Pacific atolls of Tarawa and Abaiang (Kiribati) was also noted to be improved in the absence of direct human impacts (Donner et al., 2010), and isolation of bleached reefs was shown by Gilmour et al. (2013) to be less inhibiting to reef recovery than direct human disturbance.

The loss of coral reef habitat has detrimental implications for coastal fisheries (Pratchett et al., 2009) in small islands where reef-based subsistence and tourism activities are often critical to the well-being and economies of islands (Bell et al., 2011). In Kimbe Bay, Papua New Guinea, 65% of coastal fish are dependent on living reefs at some stage in their life cycle and there is evidence that fish abundance declined following degradation of the reef (Jones et al., 2004). Even where coral reef recovery has followed bleaching, reef-associated species composition may not recover to its original state (Pratchett et al., 2009; Donner et al., 2010). Sea surface temperature (SST) anomaly events can be associated with a lag in the larval supply of coral reef fishes, as reported by Lo-Yat et al. (2011) between 1996 and 2000 at Rangiroa Atoll, French Polynesia. Higher temperatures have also been implicated in negatively affecting the spawning of adult reef species (Munday et al., 2009; Donelson et al., 2010).

Like coral reefs, mangroves and seagrass environments provide a range of ecosystem goods and services (Waycott et al., 2009; Polidoro et al., 2010) and both habitats play a significant role in the well-being of small island communities. Mangroves in particular serve a host of commercial and subsistence uses as well as providing natural coastal protection from erosion and storm events (Ellison, 2009; Krauss et al., 2010; Waycott et al., 2011).

SLR is reported as the most significant climate change threat to the survival of mangroves (Waycott et al., 2011). Loss of the seaward edge of mangroves at Hungry Bay, Bermuda, has been reported by Ellison (1993), who attributes this process to SLR and the inability of mangroves to tolerate increased water depth at the seaward margin. Elsewhere in the Caribbean and tropical Pacific, observations vary in regard to the potential for sedimentation rates in mangroves forests to keep pace with SLR (Krauss et al., 2003; McKee et al., 2007). In Kosrae and Pohnpei Islands (Federated States of Micronesia), Krauss et al. (2010) found significant variability in mangrove average soil elevation changes due to deposition from an accretion deficit of 4.95 mm yr^{-1} to an accretion surplus of 3.28 mm yr^{-1} relative to the estimated rate of SLR. Such surpluses are generally reported from high islands where additional sediments can be delivered from terrestrial runoff. However, Rankey (2011) described natural seaward migration (up to 40 m) of some mangrove areas between 1969 and 2009 in atolls in Kiribati, suggesting sediment accretion can also occur in sediment-rich reefal areas and in the absence of terrigenous inputs.

The response of seagrass to climate change is also complex, regionally variable, and manifest in quite different ways. A study of seven species of seagrasses from tropical Green Island, Australia, highlighted the variability in response to heat and light stress (Campbell et al., 2006). Light reduction may be a limiting factor to seagrass growth due to increased water depth and sedimentation (Ralph et al., 2007). Ogston and Field (2010) observed that a 20-cm rise in sea level may double the suspended sediment loads and turbidity in shallow waters on fringing reefs of Molokai, Hawaiian Islands, with negative implications to photosynthetic species such as seagrass. Otherwise, temperature stress is most commonly reported as the main expected climate change impact on seagrass (e.g., Campbell et al., 2006; Waycott et al., 2011). Literature on seagrass diebacks in small islands is scarce but research in the Balearic Islands (Western Mediterranean) has shown that over a 6-year study, seagrass shoot mortality and recruitment rates were negatively influenced by higher temperature (Marbá and Duarte, 2010; see also Section 5.4.2.3 for further discussion of impacts on mangrove and seagrass communities).

29.3.2. Observed Impacts on Terrestrial Systems: Island Biodiversity and Water Resources

Climate change impacts on terrestrial biodiversity on islands, frequently interacting with several other drivers (Blackburn et al., 2004; Didham et al., 2005), fall into three general categories, namely: (1) ecosystem and species horizontal shifts and range decline; (2) altitudinal species range shifts and decline mainly due to temperature increase on high islands; and (3) exotic and pest species range increase and invasions mainly due to temperature increase in high-latitude islands. Owing to the limited area and isolated nature of most islands, these effects are generally magnified compared to continental areas and may cause species loss, especially in tropical islands with high numbers of endemic species. For example, in two low-lying islands in the Bahamas, Greaver and Sternberg (2010) found that during periods of reduced rainfall the shallow freshwater lens subsides and contracts landward and ocean water infiltrates further inland, negatively impacting on coastal strand vegetation. SLR has also been observed to threaten the long-term persistence of freshwater-dependent ecosystems within low-lying islands in the Florida Keys (Goodman et al., 2012). On Sugarloaf Key, Ross et al. (2009) found pine forest area declined from 88 to 30 ha from 1935 to 1991 due to increasing salinization and rising groundwater, with vegetation transitioning to more saline-tolerant species such as mangroves.

Although there are many studies that report observations associated with temperature increases in mid- and high-latitude islands, such as the Falkland Islands and Marion Islands in the south Atlantic and south Indian Ocean respectively (Le Roux et al., 2005; Bokhorst et al., 2007, 2008) and Svalbard in the Arctic (Webb et al., 1998), there are few equivalent studies in tropical small islands. A recent study of the tropical Mauritius kestrel indicates changing rainfall conditions in Mauritius over the last 50 years have resulted in this species having reduced reproductive success due to a mismatch between the timing of breeding and peak food abundance (Senapathi et al., 2011).

Increasing global temperatures may also lead to altitudinal species range shifts and contractions within high islands, with an upward creep of the tree line and associated fauna (Benning et al., 2002; Krushelnycky et al., 2013). For instance, in the central mountain ranges of the subtropical island of Taiwan, Province of China, historical survey and resurvey data from 1906 to 2006 showed that the upper altitudinal limits of plant distributions had risen by about 3.6 m yr^{-1} during the last century in parallel with rising temperatures in the region (Jump et al., 2012). Comparable effects also occur in the tropics such as in Hawaii Volcano National Park, where comparison of sample plots over a 40-year period from 1966/1967 to 2008 show fire-adapted grasses expanded upward along a warming tropical elevation gradient (Angelo and Daehler, 2013). Reduction in the numbers and sizes of endemic populations caused by such habitat constriction and changes in species composition in mountain systems may result in the demise and possibly extinction of endemic species (Pauli et al., 2007; Chen et al., 2009; Sekercioglu et al., 2008; Krushelnycky et al., 2013). Altitudinal temperature change has also been reported to influence the distribution of disease vectors such as mosquitoes, potentially threatening biota unaccustomed to such vectors (Freed et al., 2005; Atkinson and LaPointe, 2009).

Freshwater supply in small island environments has always presented challenges and has been an issue raised in all previous IPCC reports. On high volcanic and granitic islands, small and steep river catchments respond rapidly to rainfall events, and watersheds generally have restricted storage capacity. On porous limestone and low atoll islands, surface runoff is minimal and water rapidly passes through the substrate into the groundwater lens. Rainwater harvesting is also an important contribution to freshwater access, and alternatives such as desalination have had mixed success in small island settings owing to operational costs (White and Falkland, 2010).

Rapidly growing demand, land use change, urbanization, and tourism are already placing significant strain on the limited freshwater reserves in small island environments (Emmanuel and Spence, 2009; Cashman et al., 2010; White and Falkland, 2010). In the Caribbean, where there is considerable variation in the types of freshwater supplies utilized, concern over the status of freshwater availability has been expressed for at least the past 30 years (Cashman et al., 2010). There have also been economic and management failures in the water sector not only in the Caribbean (Mycoo, 2007) but also in small islands in the Indian (Payet and Agricole, 2006) and Pacific Oceans (White et al., 2007; Moglia et al., 2008a,b).

These issues also occur on a background of decreasing rainfall and increasing temperature. Rainfall records averaged over the Caribbean region for 100 years (1900–2000) show a consistent 0.18 mm yr^{-1} reduction in rainfall, a trend that is projected to continue (Jury and Winter, 2010). In contrast, analysis of rainfall data over the past 100 years from the Seychelles has shown substantial variability related to ENSO. Nevertheless an increase in average rainfall from 1959 to 1997 and an increase in temperature of approximately 0.25°C per decade have occurred (Payet and Agricole, 2006). Long-term reduction in streamflow (median reduction of 22 to 23%) has been detected in the Hawaiian Islands over the period 1913–2008, resulting in reduced freshwater availability for both human use and ecological processes (Bassiouni and Oki, 2013). Detection of long-term statistical change in precipitation is an important prerequisite toward a better understanding the impacts of climate change in small island hydrology and water resources.

There is a paucity of empirical evidence linking saline (seawater) intrusion into fresh groundwater reserves due simply to incremental SLR at this time (e.g., Rozell and Wong, 2010). However, this dynamic must be the subject of improved research given the importance of groundwater aquifers in small island environments. White and Falkland's (2010) review of existing small island studies indicates that a sea level increase of up to 1 m would have negligible salinity impacts on atoll island groundwater lenses so long as there is adequate vertical accommodation space, island shores remain intact, rainfall patterns do not change, and direct human impacts are managed. However, wave overtopping and wash-over can be expected to become more frequent with SLR, and this has been shown to impact freshwater lenses dramatically. On Pukapuka Atoll, Cook Islands, storm surge over-wash occurred in 2005. This caused the freshwater lenses to become immediately brackish and took 11 months to recover to conductivity levels appropriate for human use (Terry and Falkland, 2010). The ability of the freshwater lens to float upward within the substrate of an island in step with incremental SLR also means that in low-lying and central areas of many atoll islands the lens may pond at the surface. This phenomenon already occurs in central areas of Fongafale Island, Tuvalu, and during extreme high "king" tides large areas of the inner part of the island become inundated with brackish waters (Yamano et al., 2007; Locke, 2009).

29.3.3. Observed Impacts on Human Systems in Small Islands

29.3.3.1. Observed Impacts on Island Settlements and Tourism

While traditional settlements on high islands in the Pacific were often located inland, the move to coastal locations was encouraged by colonial and religious authorities and more recently through the development of tourism (Barnett and Campbell, 2010). Now the majority of settlement, infrastructure, and development are located on lowlands along the coastal fringe of small islands. In the case of atoll islands, all development and settlement is essentially coastal. It follows that populations, infrastructure, agricultural areas, and fresh groundwater supplies are all vulnerable to extreme tides, wave and surge events, and SLR (Walsh et al., 2012). Population drift from outer islands or from inland, together with rapid population growth in main centers and lack of accommodation space, drives growing populations into ever more vulnerable locations (Connell, 2012). In addition, without adequate resources and planning, engineering solutions such as shoreline reclamation also place communities and infrastructure in positions of increased risk (Yamano et al., 2007; Duvat, 2013).

Many of the environmental issues raised by the media relating to Tuvalu, the Marshall Islands, and Maldives are primarily relevant to the major population center and its surrounds, which are Funafuti, Majuro, and Male, respectively. As an example, Storey and Hunter (2010) indicate the "Kiribati" problem does not refer to the whole of Kiribati but rather to the southern part of Tarawa atoll, where preexisting issues of severe overcrowding, proliferation of informal housing and unplanned settlement, inadequate water supply, poor sanitation and solid waste disposal, pollution, and conflict over land ownership are of concern. They argue that these problems require immediate resolution if the vulnerability of the South Tarawa community to the "real and alarming threat" of climate change is to be managed effectively (Storey and Hunter, 2010).

On Majuro atoll, rapid urban development and the abandonment of traditional settlement patterns has resulted in movement from less vulnerable to more vulnerable locations on the island (Spennemann, 1996). Likewise, geophysical studies of Fongafale Island, the capital of Tuvalu, show that engineering works during World War II, and rapid development and population growth since independence, have led to the settlement of inappropriate shoreline and swampland areas, leaving communities in heightened conditions of vulnerability (e.g., Yamano et al., 2007). Ascribing direct climate change impacts in such disturbed environments is problematic owing to the existing multiple lines of stress on the island's biophysical and social systems. However, it is clear that such preexisting conditions of vulnerability add to the threat of climate change in such locations. Increased risk can also result from lack of awareness, particularly in communities in rural areas and outer islands ("periphery") of archipelagic countries such as Cook Islands, Fiji, Kiribati, and Vanuatu, whose climate change knowledge often contrasts sharply with that of communities in the major centers ("core"). In the core, communities tend to be better informed and have higher levels of awareness about the complex issues associated with climate change than in the periphery (Nunn et al., 2013).

The issue of "coastal squeeze" remains a concern for many small islands as there is a constant struggle to manage the requirements for physical development against the need to maintain ecological balance (Fish et al., 2008; Gero et al., 2011; Mycoo, 2011). Martinique in the Caribbean exemplifies the point, where physical infrastructure prevents the beach and wetlands from retreating landward as a spontaneous adaptation response to increased rates of coastal erosion (Schleupner, 2008). Moreover, intensive coastal development in the limited coastal zone, combined with population growth and tourism, has placed great stress on the coast of some islands and has resulted in dense aggregations of infrastructure and people in potentially vulnerable locations.

Tourism is an important weather and climate-sensitive sector on many small islands and has been assessed on several occasions, including in previous IPCC assessments. There is currently no evidence that observed climatic changes in small island destinations or source markets have permanently altered patterns of demand for tourism to small islands, and the complex mix of factors that actually determines destination choices under a changing climate still need to be fully evaluated (Scott et al., 2012a). However, there are cases reported that clearly show severe weather-related events in a destination country (e.g., heavy, persistent rainfall in Martinique: Hubner and Gössling, 2012; hurricanes in Anguilla: Forster et al., 2012) can significantly influence visitors' perception of the desirability of the location as a vacation choice.

Climate can also impact directly on environmental resources that are major tourism attractions in small islands. Widespread resource degradation challenges such as beach erosion and coral bleaching have been found to negatively impact the perception of destination attractiveness in various locations, for example, in Martinique (Schleupner, 2008), Barbados, and Bonaire (Uyarra et al., 2005). Similarly, dive tourists are well aware of coral bleaching, particularly the experienced diver segment (Gössling et al., 2012a; Klint et al., 2012). Therefore more acute impacts are felt by tourism operators and resorts that cater to these markets. Houston (2002) and Buzinde et al. (2010) also indicate that beach erosion may similarly affect accommodation prices in some destinations. Consequently, some countries have begun to invest in a variety of resource restoration initiatives including artificial beach nourishment, coral and mangrove restoration, and the establishment of marine parks and protected areas (McClanahan et al., 2008; Mycoo and Chadwick, 2012). There is no analysis of how widespread such investments are or their capability to cope effectively with future climate change. The tourism industry and investors are also beginning to consider the climate risk of tourism operations (Scott et al., 2012b), including those associated with the availability of freshwater. Freshwater is limited on many small islands, and changes in its availability or quality during drought events linked to climate change have adverse impacts on tourism operations (UNWTO, 2012). Tourism is a seasonally significant water user in many island destinations, and in times of drought concerns over limited supply for residents and other economic activities become heightened (Gössling et al., 2012b). The increasing use of desalination plants is one adaptation to reduce the risk of water scarcity in tourism operations.

29.3.3.2. Observed Impacts on Human Health

Globally, the effects of climate change on human health will be both direct and indirect, and are expected to exacerbate existing health risks, especially in the most vulnerable communities, where the burden of disease is already high (refer to Sections 11.3, 11.5, 11.6.1). Many small island states currently suffer from climate-sensitive health problems, including morbidity and mortality from extreme weather events, certain vector- and food- and water-borne diseases (Lozano, 2006; Barnett and Campbell, 2010; Cashman et al., 2010; Pulwarty et al., 2010; McMichael and Lindgren, 2011). Extreme weather and climate events such as tropical cyclones, storm surges, flooding, and drought can have both short- and long-term effects on human health, including drowning, injuries, increased disease transmission, and health problems associated with deterioration of water quality and quantity. Most small island nations are in tropical areas with weather conducive to the transmission of diseases such as malaria, dengue, filariasis, and schistosomiasis.

The linkages between human health, climate variability, and seasonal weather have been demonstrated in several recent studies. The Caribbean has been identified as a "highly endemic zone for leptospirosis," with Trinidad and Tobago, Barbados, and Jamaica representing the highest annual incidence (12, 10, and 7.8 cases per 100,000, respectively) in the world, with only the Seychelles being higher (43.2 per 100,000 population) (Pappas et al., 2008). Studies conducted in Guadeloupe demonstrated a link between El Niño occurrence and leptospirosis incidence, with rates increasing to 13 per 100,000 population in El Niño years, as opposed to 4.5 cases per 100,000 inhabitants in La Niña and neutral years (Herrmann-Storck et al., 2008). In addition, epidemiological studies conducted in Trinidad reviewed the incidence of leptospirosis during the period 1996–2007 and showed seasonal patterns in the occurrence of confirmed leptospirosis cases, with significantly ($P < 0.001$) more cases occurring in the wet season, May to November (193 cases), than during the dry season, December to May (66 cases) (Mohan et al., 2009). Recently changes in the epidemiology of leptospirosis have been detected, especially in tropical islands, with the main factors being climatic and anthropogenic ones (Pappas et al., 2008). These factors may be enhanced with increases in ambient temperature and changes in precipitation, vegetation, and water availability as a consequence of climate change (Russell, 2009).

In Pacific islands the incidence of diseases such as malaria and dengue fever has been increasing, especially endemic dengue in Samoa, Tonga, and Kiribati (Russell, 2009). Although studies conducted so far in the Pacific have established a direct link only between malaria, dengue, and climate variability, these and other health risks including from cholera are projected to increase as a consequence of climate change (Russell, 2009; see also Sections 11.2.4-5 for detailed discussion on the link between climate change and projected increases in the outbreak of dengue and cholera). Dengue incidence is also a major health concern in other small island countries, including Trinidad and Tobago, Singapore, Cape Verde, Comoros, and Mauritius (Koh et al., 2008; Chadee, 2009; Van Kleef et al., 2010; Teles, 2011). In the specific cases of Trinidad and Tobago and Singapore the outbreaks have been significantly correlated with rainfall and temperature, respectively (Chadee et al., 2007; Koh et al., 2008).

Previous IPCC assessments have consistently shown that human health on islands can be seriously compromised by lack of access to adequate, safe freshwater and adequate nutrition (Nurse et al., 2001; Mimura et al., 2007). Lovell (2011) notes that in the Pacific many of the anticipated health effects of climate change are expected to be indirect, connected to the increased stress and declining well-being that comes with property damage, loss of economic livelihood, and threatened communities. There is also a growing concern in island communities in the Caribbean Sea and Pacific and Indian Oceans that freshwater scarcity and more intense droughts and storms could lead to a deterioration in standards of sanitation and hygiene (Cashman et al., 2010; McMichael and Lindgren, 2011). In such circumstances, increased exposure to a range of health risks including communicable (transmissible) diseases would be a distinct possibility.

Ciguatera fish poisoning (CFP) occurs in tropical regions and is the most common non-bacterial food-borne illness associated with consumption of fish. Distribution and abundance of the organisms that produce these toxins, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with water temperature. Consequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of CFP in the island regions of the Caribbean (Morrison et al., 2008; Tester et al., 2010), Pacific (Chan et al., 2011; Rongo and van Woesik, 2011), the Mediterranean (Aligizaki and Nikolaidis, 2008; see also Section 29.5.5), and the Canary Islands in the Atlantic (Pérez-Arellano et al., 2005). A recent Caribbean study sought to characterize the relationship between SSTs and CFP incidence and to determine the effects of temperature on the growth rate of organisms responsible for CFP. Results from this work show that in the Lesser Antilles high rates occur in areas that experience the warmest water temperatures and that show the least temperature variability (Tester et al., 2010). There are also high rates in the Pacific in Tokelau, Tuvalu, Kiribati, Cook Islands, and Vanuatu (Chan et al., 2011).

The influence of climatic factors on malaria vector density and parasite development is well established (Chaves and Koenraadt, 2010; Béguin et al., 2011). Previous studies have assessed the potential influence of climate change on malaria, using deterministic or statistical models (Martens et al., 1999; Pascual et al., 2006; Hay et al., 2009; Parham and Michael, 2010). Although the present incidence of malaria on small islands is not reported to be high, favorable environmental and social circumstances for the spread of the disease are present in some island regions and are expected to be enhanced under projected changes in climate in Papua New Guinea, Guyana, Suriname, and French Guyana (Michon et al., 2007; Figueroa, 2008; Rawlins et al., 2008). In the Caribbean, the occurrence of autochthonous malaria in non-endemic island countries in the last 10 years suggests that all of the essential malaria transmission conditions now exist. Rawlins et al. (2008) call for enhanced surveillance, recognizing the possible impact of climate change on the spread of the *Anopheles* mosquito vector and malaria transmission.

29.3.3.3. Observed Impacts of Climate Change on Relocation and Migration

Evidence of human migration as a response to climate change is scarce for small islands. Although there is general agreement that migration is usually driven by multiple factors (Black et al., 2011), several authors highlight the lack of empirical studies of the effect of climate-related factors, such as SLR, on island migration (Mortreux and Barnett, 2009; Lilleør and Van den Broeck, 2011). Furthermore, there is no evidence of any government policy that allows for climate "refugees" from islands to be accepted into another country (Bedford and Bedford, 2010). This finding contrasts with the early desk-based estimates of migration under climate change such as the work of Myers (2002). These early studies have been criticized as they fail to acknowledge the reality of climate impacts on islands, the capacity of islands and islanders to adapt, or the actual drivers of migration (Barnett and O'Neill, 2012).

Studies of island migration commonly reveal the complexity of a decision to migrate and rarely identify a single cause. For example, when looking at historical process of migration within the Mediterranean, it appears that rising levels of income, coupled with a decreased dependence on subsistence agriculture, has left the Mediterranean less vulnerable to all environmental stressors, resulting in a reduced need for mobility to cope with environmental or climatic change (de Haas, 2011). Studies from the Pacific have also shown that culture, lifestyle, and a connection to place are more significant drivers of migration than climate (Barnett and Webber, 2010). For example, a Pacific Access Category of migration has been agreed between New Zealand and Tuvalu that permits 75 Tuvaluans to migrate to New Zealand every year (Kravchenko, 2008). Instead of enabling climate-driven migration, this agreement is designed to facilitate economic and social migration as part of the Pacific Island lifestyle (Shen and Gemenne, 2011). To date there is no unequivocal evidence that reveals migration from islands is being driven by anthropogenic climate change.

There is, however, some evidence that environmental change has played a role in Pacific Island migration in the past (Nunn, 2007). In the Pacific, environmental change has been shown to affect land use and land rights, which in turn have become drivers of migration (Bedford and Bedford, 2010). In a survey of 86 case studies of community relocations in Pacific Islands, Campbell et al. (2005) found that environmental variability and natural hazards accounted for 37 communities relocating. In the Pacific, where land rights are a source of conflict, climate change could increase levels of stress associated with land rights and impact on migration (Campbell, 2010; Weir and Virani, 2011). Although there is not yet a climate fingerprint on migration and resettlement patterns in all small islands, it is clear that there is the potential for human movement as a response to climate change. To understand better the impact of climate change on migration there is an urgent need for robust methods to identify and measure the effects of the drivers of migration on migration and resettlement.

29.3.3.4. Observed Impacts on Island Economies

The economic and environmental vulnerabilities of small islands states are well documented (Briguglio et al., 2009, Bishop, 2012). Such vulnerabilities, which render the states at risk of being harmed by economic and environmental conditions, stem from intrinsic features of these vulnerable states, and are not usually governance induced. However, governance does remain one of the challenges for island countries in the Pacific in the pursuit of sustainable development through economic growth (Prasad, 2008). Economic vulnerability is often the result of a high degree of exposure to economic conditions often outside the control of small island states, exacerbated by dependence on a narrow range of exports and a high degree of dependence on strategic imports, such as food and fuel (Briguglio et al., 2009). This leads to economic volatility, a condition that is harmful for the economy of the islands (Guillaumont, 2010).

There are other economic downsides associated with small size and insularity. Small size leads to high overhead cost per capita, particularly in infrastructural outlays. This is of major relevance to climate change adaptation that often requires upgrades and redesign of island infrastructure. Insularity leads to high cost of transport per unit, associated with purchases of raw materials and industrial supplies in small quantities, and sales of local produced products to distant markets. These disadvantages are associated with the inability of small islands to reap the benefits of economies of scale, resulting in a high cost of doing business in small islands (Winters and Martins, 2004).

High costs are also associated with the small size of island states when impacted by extreme events such as hurricanes and droughts. On small islands such events often disrupt most of the territory, especially on single-island states, and have a very large negative impact on the state's GDP, in comparison with larger and more populous states where individual events generally only affect a small proportion of the country and have a small impact on its GDP (Anthoff et al., 2010). Moreover, the dependence of many small islands on a limited number of economic

Frequently Asked Questions

FAQ 29.2 | Why is the cost of adaptation to climate change so high in small islands?

Adaptation to climate change that involves infrastructural works generally requires large up-front overhead costs, which in the case of small islands cannot be easily downscaled in proportion to the size of the population or territory. This is a major socioeconomic reality that confronts many small islands, notwithstanding the benefits that could accrue to island communities through adaptation. Referred to as "indivisibility" in economics, the problem can be illustrated by the cost of shore protection works aimed at reducing the impact of sea level rise. The unit cost of shoreline protection per capita in small islands is substantially higher than the unit cost for a similar structure in a larger territory with a larger population. This scale-reality applies throughout much of a small island economy including the indivisibility of public utilities, services, and all forms of development. Moreover, the relative impact of an extreme event such as a tropical cyclone that can affect most of a small island's territory has a disproportionate impact on that state's gross domestic product, compared to a larger country where an individual event generally affects a small proportion of its total territory and its GDP. The result is relatively higher adaptation and disaster risk reduction costs per capita in countries with small populations and areas—especially those that are also geographically isolated, have a poor resource base, and have high transport costs.

sectors such as tourism, fisheries, and agricultural crops, all of which are climate sensitive, means that on the one hand climate change adaptation is integral to social stability and economic vitality but that government adaptation efforts are constrained because of the high cost on the other.

29.3.4. Detection and Attribution of Observed Impacts of Climate Change on Small Islands

While exceptional vulnerability of many small islands to future climate change is widely accepted, the foregoing analysis indicates that the scientific literature on observed impacts is quite limited. Detection of past and recent climate change impacts is challenging owing to the presence of other anthropogenic drivers, especially in the constrained environments of small islands. Attribution is further challenged by the strong influence of natural climate variability compared to gradual incremental change of climate drivers. Notwithstanding these limitations, a summary of the relationship between detection and attribution to climate change of several of the phenomena described in the preceding sections has been prepared. Figure 29-2 reflects the degree of confidence in the link between observed changes in several components of the coastal, terrestrial, and human systems of small islands and the drivers of climate change.

29.4. Projected Integrated Climate Change Impacts

Small islands face many challenges in using climate change projections for policy development and decision making (Keener et al., 2012). Among these is the inaction inherent in the mismatch of the short-term time scale on which government decisions are generally taken compared with the long-term time scale required for decisions related to climate change. This is further magnified by the general absence of credible regional socioeconomic scenarios relevant at the spatial scale at which most decisions are taken. Scenarios are an important tool to help decision makers disaggregate vulnerability to the direct physical impacts of the climate signal from the vulnerability associated with socioeconomic conditions and governance. There is, however, a problem in generating formal climate scenarios at the scale of small islands because they are generally much smaller than the resolution of the global climate models. This is because the grid squares in the Global Circulation Models (GCMs) used in the SRES scenarios over the last decade were between 200 and 600 km^2, which provides inadequate resolution over the land areas of most small islands. This has recently improved with the new Representative Concentration Pathway (RCP) scenario GCMs with grid boxes generally between 100 and 200 km^2 in size.

The scale problem has been usually addressed by the implementation of statistical downscaling models that relate GCM output to the historical climate of a local small island data point. The limitation of this approach is the need for observed data ideally for at least 3 decades for a number of representative points on the island, in order to establish the statistical relationships between GCM data and observations. In most small islands long-term quality-controlled climate data are generally sparse, so that in widely dispersed islands such as in the Pacific, observational records are usually supplemented with satellite observations combined with dynamical downscaling computer models (Australian Bureau of Meteorology and CSIRO, 2011a; Keener et al., 2012). However, where adequate local data are available for several stations for at least 30 years, downscaling techniques have demonstrated that they can provide projections at fine scales ranging from about 10 to 25 km^2 (e.g., Charlery and Nurse, 2010; Australian Bureau of Meteorology and CSIRO, 2011a). Even so, most projected changes in climate for the Caribbean Sea, Pacific and Indian Oceans, and Mediterranean islands generally apply to the region as a whole, and this may be adequate to determine general trends in regions where islands are close together.

29.4.1. Non-formal Scenario-based Projected Impacts

Scenarios are often constructed by using a qualitative or broad order of magnitude climate projections approach based on expected changes

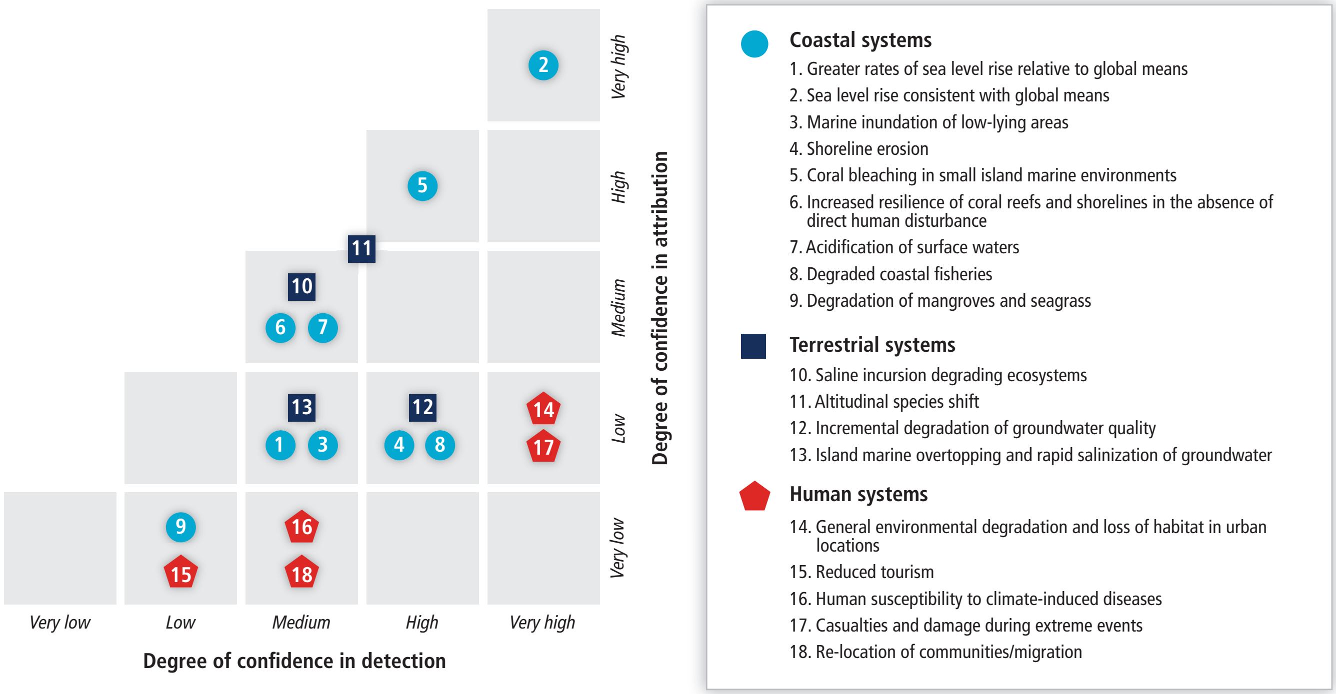

Figure 29-2 | A comparison of the degree of confidence in the detection of observed impacts of climate change on tropical small islands with the degree of confidence in attribution to climate change drivers at this time. For example, the blue symbol No. 2 (Coastal Systems) indicates there is *very high confidence* in both the detection of "sea level rise consistent with global means" and its attribution to climate change drivers; whereas the red symbol No. 17 (Human Systems) indicates that although confidence in detection of "casualties and damage during extreme events" is *very high*, there is at present *low confidence* in the attribution to climate change. It is important to note that *low confidence* in attribution frequently arises owing to the limited research available on small island environments.

in some physical climate signal from literature review rather than projections based on direct location-specific modeling. Usually this is proposed as a "what if" question that is then quantified using a numerical method. For example, in the Pacific, digital elevation models of Fiji's islands have been used to identify high risk areas for flooding based on six scenarios for SLR from 0.09 to 0.88 m in combination with six scenarios for storm surge with return intervals from 1 to 50 years (Gravelle and Mimura, 2008). Another example of qualitative modeling from the Pacific is a case study from Nauru that uses local data and knowledge of climate to assess the GCM projections. It suggests that Nauru should plan for continued ENSO variability in the future with dry years during La Niña and an overall increase in mean rainfall and extreme rainfall events. Climate adaptation concerns that arise include water security and potential changes in extreme wet events that affect infrastructure and human health (Brown et al., 2013a). Climate change also poses risks for food security in the Pacific Islands, including agriculture and fisheries (Barnett, 2011).

Projections have also been used in the islands of the Republic of Baharain to estimate proneness to inundation for SLR of 0.5, 1.0, and 1.5 m (Al-Jeneid et al., 2008). Similarly, in the Caribbean the elevation equivalent of a projected SLR of 1 m has been superimposed on topographic maps to estimate that 49 to 60% of tourist resort properties would be at risk of beach erosion damage, potentially transforming the competitive position and sustainability of coastal tourism destinations in the region (Scott et al., 2012c). This method has also been used to quantify the area loss for more than 12,900 islands and more than 3000 terrestrial vertebrates in the tropical Pacific region for three SLR scenarios. The study estimated that for SLR of 1 m, 37 island endemic species in this region risk complete inundation (Wetzel et al., 2013).

29.4.2. Projected Impacts for Islands Based on Scenario Projections

Another approach to scenario development is to use the region-specific projections more directly. It is worth noting that the broad synthesis in the AR4 of medium emissions climate scenario projections for small island regions (Mimura et al., 2007) shows concordance with the new RCP scenarios (see Table 29-1 and new RCP projections in Figure 29-3). For example, the SRES A1B medium emissions scenario suggests about a 1.8°C to 2.3°C median annual increase in surface temperature in the Caribbean Sea and Indian and Pacific Ocean small islands regions by 2100 compared to a 1980–1999 baseline, with an overall annual decrease in precipitation of about 12% in the Caribbean (WGI AR4 Table 11.1; WGI AR5 Section 14.7.4) and a 3 to 5% increase in the Indian and Pacific Ocean small island regions. Comparative projections for the new RCP4.5 scenario suggests about a 1.2°C to 2.3°C increase in surface temperature by 2100 compared to a 1986–2005 baseline and a decrease in precipitation of about 5 or 6% in the Caribbean and Mediterranean, respectively, signaling potential future problems for agriculture and water availability compared to a 1 to 9% increase in the Indian and Pacific Ocean small islands regions (Table 29-1). However, there are important spatial and high-island topography differences. Thus, for example, among the more dispersed Pacific Islands where the equatorial regions are likely to get wetter and the subtropical high pressure belts

Table 29-1 | Climate change projections for the intermediate low (500–700 ppm CO_2e) Representative Concentration Pathway 4.5 (RCP4.5) scenario for the main small island regions. The table shows the 25th, 50th (median), and 75th percentiles for surface temperature and precipitation based on averages from 42 Coupled Model Intercomparison Project Phase 5 (CMIP5) global models (adapted from WGI AR5 Table 14.1). Mean net regional sea level change is evaluated from 21 CMIP5 models and includes regional non-scenario components (adapted from WGI AR5 Figure 13-20).

Small island region	RCP4.5 annual projected change for 2081–2100 compared to 1986–2005						
	Temperature (°C)			Precipitation (%)			Sea level (m)
	25%	50%	75%	25%	50%	75%	Range
Caribbean	1.2	1.4	1.9	–10	–5	–1	0.5–0.6
Mediterranean	2.0	2.3	2.7	–10	–6	–3	0.4–0.5
Northern tropical Pacific	1.2	1.4	1.7	0	1	4	0.5–0.6
Southern Pacific	1.1	1.2	1.5	0	2	4	0.5–0.6
North Indian Ocean	1.3	1.5	2.0	5	9	20	0.4–0.5
West Indian Ocean	1.2	1.4	1.8	0	2	5	0.5–0.6

drier (as reported by WGI AR5) in regions directly affected by the South Pacific Convergent Zone (SPCZ) and western portion of the Inter-Tropical Convergent Zone (ITCZ), the rainfall outlook is uncertain (WGI AR5 Section 14.7.13). Projections for the Mediterranean islands also differ from those for the tropical small islands. Throughout the Mediterranean region, the length, frequency, and/or intensity of warm spells or heat waves are *very likely* to increase to the year 2100 (WGI AR5 Section 14.7.6). SLR projections in the small islands regions for RCP4.5 are similar to the global projections of 0.41 to 0.71 m (WGI AR5 Section 13.5.1), ranging from 0.5 to 0.6 m by 2100 compared to 1986–2005 in the Caribbean Sea and Pacific and Indian Oceans to 0.4 to 0.5 m in the Mediterranean and north Indian Ocean (Table 29-1).

In the main regions in which most tropical or subtropical small island states are located, there are few independent peer-reviewed scientific publications providing downscaled climate data projections, and even less illustrating the experience gained from their use for policy making. A possible 2°C temperature increase by the year 2100 has potentially far-reaching consequences for sentinel ecosystems such as coral reefs that are important to tropical islands (see Section 6.2.2.4.4). This is because "degree heating months" (DHMs) greater than 2°C per month are the determining threshold for severe coral bleaching (Donner, 2009). For example, in a study of SST across all coral reef regions using GCM ensemble projections forced with five different SRES future emissions scenarios, Donner (2009) concluded that even warming in the future from the current accumulation of GHGs in the atmosphere could cause more than half of the world's coral reefs to experience harmfully frequent thermal stress by 2080. Further, this timeline could be brought forward to as early as 2030 under the A1B medium emissions scenario. He further stated that thermal adaptation of 1.5°C would delay the thermal stress forecast by only 50 to 80 years. Donner (2009) also estimated the year of likelihood of a severe mass coral bleaching event due more than once every 5 years to be 2074 in the Caribbean, 2088 in the western Indian Ocean, 2082 in the central Indian Ocean, 2065 in Micronesia, 2051 in the central Pacific, 2094 in Polynesia, and 2073 in the eastern Pacific small islands regions. Using the new RCP scenarios by comparison, van Hooidonk et al. (2013) found that the onset of annual bleaching conditions is associated with about 510 ppm CO_2-eq. The conclusion based on outputs from a wide range of emissions scenarios and models is that preserving more than 10% of coral reefs worldwide would require limiting warming to less than 1.5°C (1.3°C to 1.8°C Atmosphere-Ocean General Circulation Model (AOGCM) range) compared to pre-industrial levels (Frieler et al., 2013).

Small island economies can also be objectively shown to be at greater risk from SLR in comparison to other geographic areas because most of their population and infrastructure are in the coastal zone. This is demonstrated in a study using the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model to assess the economic impact of substantial SLR in a range of socioeconomic scenarios downscaled to the national level, including the four SRES storylines (Anthoff et al., 2010). Although this study showed that, in magnitude, a few regions will experience most of the absolute costs of SLR by 2100, especially East Asia, North America, Europe, and South Asia, these same results when expressed as percent of GDP showed that most of the top ten and four of the top five most impacted are small islands from the Pacific (Federated States of Micronesia, Palau, Marshall Islands, Nauru) and Caribbean (Bahamas). The point is made that the damage costs for these small island states are enormous in relation to the size of their economies (Nicholls and Tol, 2006) and that, together with deltaic areas, they will find it most difficult to locally raise the finances necessary to implement adequate coastal protection (Anthoff et al., 2010).

In the Caribbean, downscaled climate projections have been generated for some islands using the Hadley Centre PRECIS (Providing REgional Climates for Impact Studies) regional model (Taylor et al., 2007; Stephenson et al., 2008). For the SRES A2 and B2 scenarios, the PRECIS regional climate model projects an increase in temperature across the Caribbean of 1°C to 4°C compared to a 1960–1990 baseline, with increasing rainfall during the latter part of the wet season from November to January in the northern Caribbean (i.e., north of 22°N) and drier conditions in the southern Caribbean linked to changes in the Caribbean Low Level Jet (CLLJ) with a strong tendency to drying in the traditional wet season from June to October (Whyte et al., 2008; Campbell et al., 2011; Taylor et al., 2013). Projected lengthening seasonal dry periods, and increasing frequency of drought are expected to increase demand for water throughout the region under the SRES A1B scenario (Cashman et al., 2010). Decrease in crop yield is also projected in Puerto Rico for the SRES B1 (low), A2 (mid to high), and A1F1 scenarios during September although increased crop yield is suggested during February (Harmsen et al., 2009). Using a tourism demand model linked to the SRES A1F1, A2, B1, and B2 scenarios, the projected climate change heating and drying impacts are also linked to potential aesthetic, physical, and thermal effects that are estimated to cause a change in total regional tourist expenditure of about +321, +356, –118, and -146 million US$ from the least to the most severe emissions scenario, respectively (Moore, 2010).

In the Indian Ocean, representative downscaled projections have been generated for Australia's two Indian Ocean territories, the Cocos (Keeling) Islands and Christmas Island using the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Mark 3.0 climate model with the SRES A2 high-emissions scenario (Maunsell Australia Pty Ltd., 2009). Future climate change projections for the two islands for 2070 include an approximate 1.8°C increase in air temperature by 2070, probable drier dry seasons and wet seasons, about a 40-cm rise in sea level, and a decrease in the number of intense tropical cyclones.

In the western tropical Pacific, extensive climate projections have been made for several Pacific Island countries based on downscaling from an ensemble of models (Australian Bureau of Meteorology and CSIRO, 2011b). The temperature projections in this region dominated by oceans seem less than those seen globally, ranging from +1.5 to 2.0°C for the B1 low-emissions scenario to +2.5 to 3.0°C for the A2 high-emissions scenario by the year 2090 relative to a 20-year period centered on 1990. Notably, extreme rainfall events that currently occur once every 20 years on average are generally simulated to occur four times per 20-year period, on average, by 2055 and seven times per 20-year period, on average, by 2090 under the A2 (high-emissions) scenario (Australian Bureau of Meteorology and CSIRO, 2011b). The results are not very different from the tropical Pacific RCP4.5 projections, with projected temperature increases of about +1.2 to 1.4°C by 2100 and an increase in rainfall of about 4% (Table 29-1). A comprehensive assessment of the vulnerability of the fisheries and aquaculture sectors to climate change in 22 Pacific island countries and territories focused on two future time frames (2035 and 2100) and two SRES emissions scenarios, B1 (low emissions) and A2 (high emissions) (Bell et al., 2013). Many anticipated changes in habitat and resource availability such as coral reef-based fisheries are negative. By contrast, projected changes in tuna fisheries and freshwater aquaculture/fisheries can be positive with implications for government revenue and island food security (Bell et al., 2013). Simulation studies on changes in stocks of skipjack and bigeye tuna in the tropical Pacific area summarized in Table 29-2 and also discussed in Sections 7.4.2.1 and 30.6.2.1.1. Some of these projected changes may favor the large international fishing fleets that can shift operations over large distances compared to local, artisanal fishers (Polovina et al., 2011).

In the Mediterranean islands of Mallorca, Corsica, Sardinia, Crete, and Lesvos, Gritti et al. (2006) simulated the terrestrial vegetation biogeography and distribution dynamics under the SRES A1F1 and B1 scenarios to the year 2050. The simulations indicate that the effects of climate change are expected to be negligible within most ecosystems except for mountainous areas. These areas are projected to be eventually occupied by exotic vegetation types from warmer, drier conditions. Cruz et al. (2009) report similar results for the terrestrial ecosystems of Madeira Island in the Atlantic. Downscaled SRES A2 and B2 scenarios for the periods 2040–2069 and 2070–2099 suggest that the higher altitude native humid forest, called the Laurissilva, may expand upward in altitude, which could lead to a severe reduction of the heath woodland which because it has little upward area to shift may reduce in range or disappear at high altitudes, resulting in the loss of rare and endemic species within this ecosystem.

Table 29-2 | Summary of projected percentage changes in tropical Pacific tuna catches by 2036 and 2100 relative to 1980–2000 for SRES scenarios A2 and B1, and the estimated resulting percentage change to government revenue (after Tables 12.7 and 12.9 of Bell et al., 2011).

Tuna fishery		Change in catch (%)		
		2035: B1/A2	2100: B1	2100: A2
Skipjack tuna	Western fishery	+11	–0.2	–21
	Eastern fishery	+37	+43	+27
	Total	+19	+12	–7
Bigeye tuna	Western fishery	–2	–12	–34
	Eastern fishery	+3	–4	–18
	Total	+0.3	–9	–27
Country		**Change in government revenue (%)**		
		2035: B1/A2	**2100: B1**	**2100: A2**
Federated States of Micronesia		+1 to +2	0 to +1	–1 to –2
Solomon Islands		0 to +0.2	0 to –0.3	0 to +0.8
Kiribati		+11 to +18	+13 to +21	+7 to +12
Tuvalu		+4 to +9	+4 to +10	+2 to +6

29.4.3. Representative Concentration Pathway Projections and Implications for Small Islands

Utilizing updated historical GHG emissions data the scientific community has produced future projections for four plausible new global RCPs to explore a range of global climate signals up to the year 2100 and beyond (e.g., Moss et al., 2010). Typical model ensemble representations of low, intermediate low, intermediate high, and high RCP projections for annual temperature and precipitation in some small islands regions are presented in Figure 29-3. Highlighted in Figure 29-3 is the ensemble mean of each RCP. A more comprehensive compilation of quarterly global RCP projections can be found in the WGI AR5 Annex I: Atlas of Global and Regional Climate Projections.

During negotiations toward a new multilateral climate change regime Small Island Developing States (SIDS) have advocated that any agreement should be based on Global Mean Surface Temperature (GMST) increase "well below" 1.5°C above pre-industrial levels (Hare et al., 2011; Riedy and McGregor, 2011). Inspection of column 1 in Figure 29-3 suggests that for the Caribbean, Indian Ocean, and Pacific SIDS in the tropics, the median projected regional increase is in the range 0.5°C to 0.9°C by 2100 compared to 1986–2005. This, together with the temperature change that has already occurred since the Industrial Revolution, suggests that a temperature "well below" 1.5°C is unlikely to be achieved with the lowest RCP2.6 projection (Peters et al., 2013). By comparison, temperature projections for the intermediate low RCP4.5 scenario (Table 29-1; Figure 29-3) suggest possible 1.2°C to 1.5°C temperature increases in Caribbean, Indian Ocean, and Pacific SIDS by 2100 compared to 1986–2005. Similarly, the projections for the Mediterranean would be about a 2.3°C increase by 2100 compared to 1986–2005 that would represent a 2.7°C increase compared to pre-industrial temperatures. Associated with this change, the Caribbean and Mediterranean regions may experience a noticeable decrease in mean rainfall while the Indian and Pacific Ocean SIDS may experience increased rainfall. These trends accelerate moderately for RCP6.0 and steeply for RCP8.5 (Table 29-1).

29.5. Inter- and Intra-regional Transboundary Impacts on Small Islands

Available literature since AR4 has highlighted previously less well understood impacts on small islands that are generated by processes originating in another region or continent well beyond the borders of an individual archipelagic nation or small island. These are inter-regional transboundary impacts. Intra-regional transboundary impacts originate from a within-region source (e.g., the Caribbean). Some transboundary processes may have positive effects on the receiving small island or nation, though most that are reported have negative impacts. Deciphering a climate change signal in inter- and intra-regional transboundary impacts on small islands is not easy and usually involves a chain of linkages tracing back from island-impact to a distant climate or climate-related bio-physical or human process. Some examples are given below.

29.5.1. Large Ocean Waves from Distant Sources

Unusually large deep ocean swells, generated from sources in the mid- and high latitudes by extratropical cyclones (ETCs) cause considerable damage on the coasts of small islands thousands of kilometers away in the tropics. Impacts include sea flooding and inundation of settlements, infrastructure, and tourism facilities as well as severe erosion of beaches (see also Section 5.4.3.4). Examples from small islands in the Pacific and Caribbean are common, though perhaps the most significant instance, in terms of a harbinger of climate change and SLR, occurred in the

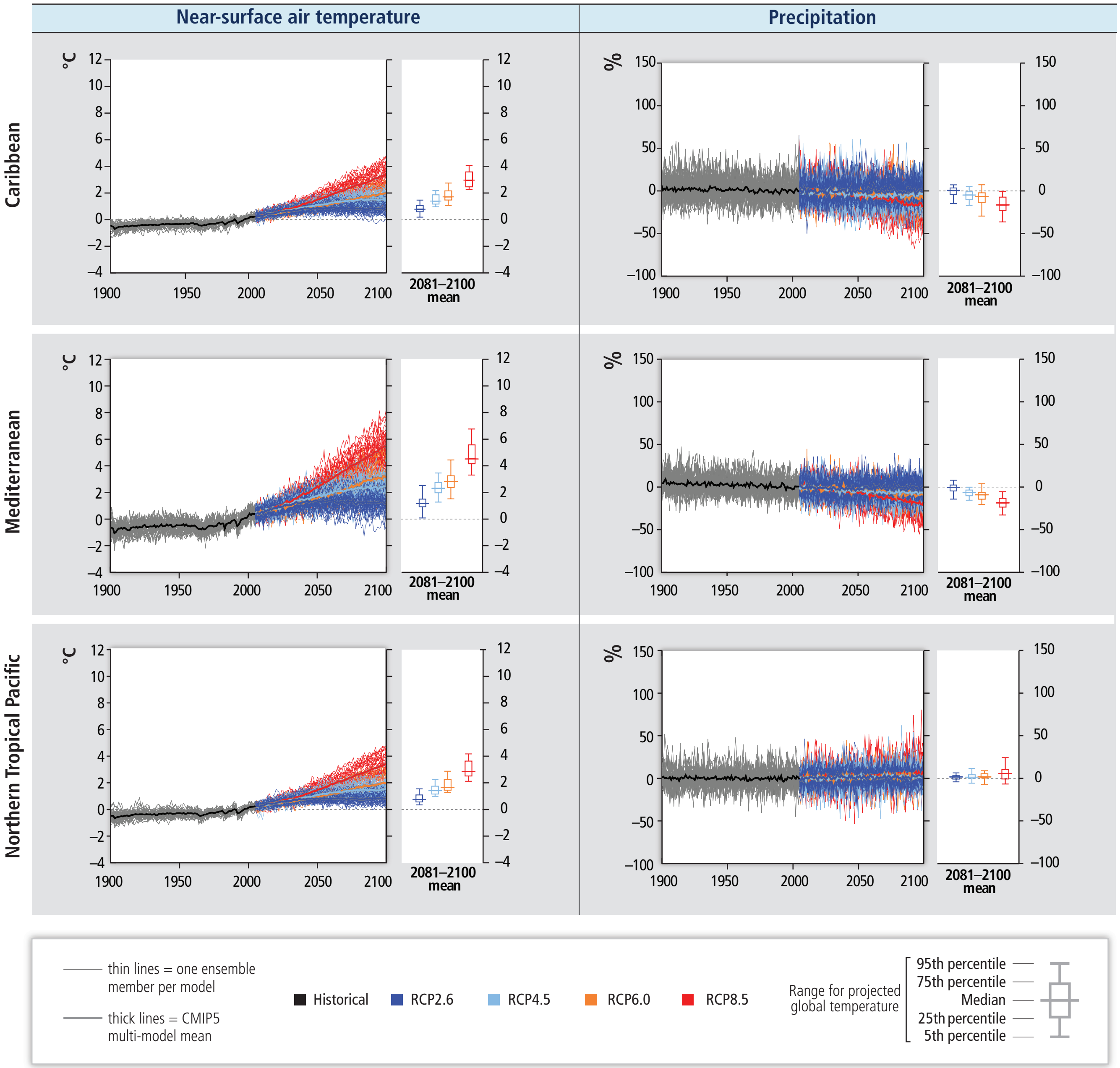

Figure 29-3 | Time series of Representative Concentration Pathway (RCP) scenarios annual projected temperature and precipitation change relative to 1986–2005 for six small islands regions (using regions defined in WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections). Thin lines denote one ensemble member per model, and thick lines the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean. On the righthand side, the 5th, 25th, 50th (median), 75th, and 95th percentiles of the distribution of 20-year mean changes are given for 2081–2100 in the four RCP scenarios. Note that the model ensemble averages in the figure are for grid points over wide areas and encompass many different climate change signals.

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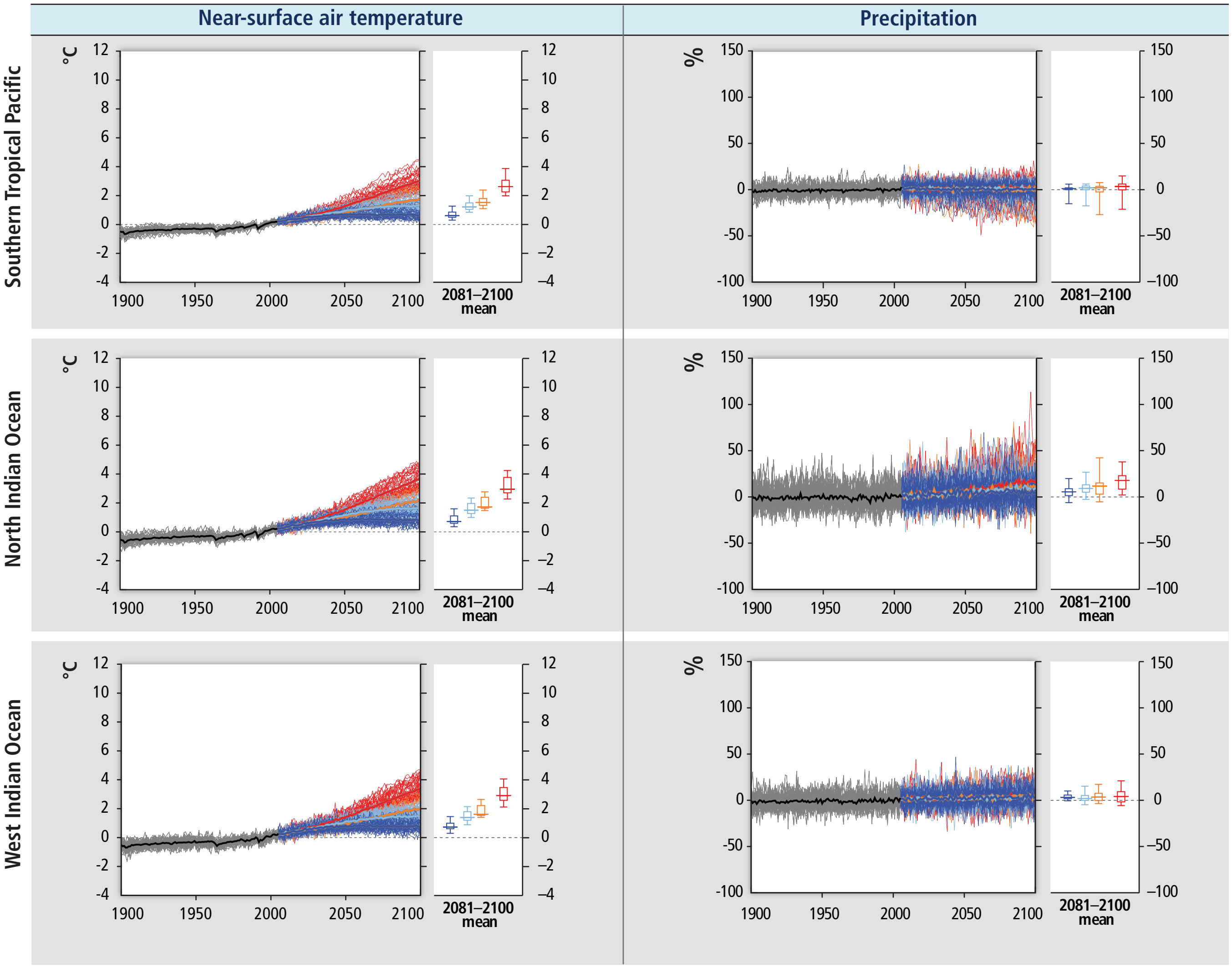
Figure 29-3 (continued)



Maldives in April 1987 when long period swells originating from the Southern Ocean some 6000 km away caused major flooding, damage to property, destruction of sea defenses, and erosion of reclaimed land and islands (Harangozo, 1992). The Maldives and several other island groups in the Indian Ocean have been subject to similar ocean swell events more recently, most notably in May 2007 (Maldives Department of Meteorology, 2007).

In the Caribbean, northerly swells affecting the coasts of islands have been recognized as a significant coastal hazard since the 1950s (Donn and McGuinness, 1959). They cause considerable seasonal damage to beaches, marine ecosystems, and coastal infrastructure throughout the region (Bush et al., 2009; Cambers, 2009). These high-energy events manifest themselves as long period high-amplitude waves that occur during the Northern Hemisphere winter and often impact the normally sheltered, low-energy leeward coasts of the islands. Such swells have even reached the shores of Guyana on the South American mainland as illustrated by a swell event in October 2005 that caused widespread flooding and overtopping and destruction of sea defenses (van Ledden et al., 2009).

Distant origin swells differ from the "normal" wave climate conditions experienced in the Caribbean, particularly with respect to direction of wave approach, wave height, and periodicity and in their morphological impact (Cooper et al., 2013). Swells of similar origin and characteristics also occur in the Pacific (Fletcher et al., 2008; Keener et al., 2012). These events frequently occur in the Hawaiian Islands, where there is evidence of damage to coral growth by swell from the north Pacific, especially during years with a strong El Niño signal (Fletcher et al., 2008).

Hoeke et al. (2013) describe inundation from mid- to high-latitude north and south Pacific waves respectively at Majuro (Marshall Islands) in November and December 1979 and along the Coral Coast (Fiji) in May 2011. They also describe in detail an inundation event in December 2008 that was widespread throughout the western and central Pacific and resulted in waves surging across low-lying islands causing severe damage to housing and infrastructure and key natural resources that affected about 100,000 people across the region. The proximate cause of this event was swell generated in mid-latitudes of the North Pacific Ocean, more than 4000 km from the farthest affected island (Hoeke et al., 2013).

Whereas the origin of the long period ocean swells that impact small islands in the tropical regions come from the mid- and high latitudes in the Pacific, Indian, and Atlantic Oceans, there are also instances of unusually large waves generated from tropical cyclones that spread into the mid- and high latitudes. One example occurred during 1999 when tide gauges at Ascension and St. Helena Islands in the central south Atlantic recorded unusually large deep-ocean swell generated from distant Hurricane Irene (Vassie et al., 2004). The impacts of increasing incidence or severity of storms or cyclones is generally considered from the perspective of direct landfall of such systems, whereas all of these instances serve to show "the potential importance of swells to communities on distant, low-lying coasts, particularly if the climatology of swells is modified under future climate change" (Vassie et al., 2004, p. 1095). From the perspective of those islands that suffer damage from this coastal hazard on an annual basis, this is an area that warrants further investigation. Projected changes in global wind-wave climate to 2070–2100, compared to a base period 1979–2009, show considerable regional and seasonal differences with both decreases and increases in annual mean significant wave height. Of particular relevance in the present context is the projected increase in wave activity in the Southern Ocean, which influences a large portion of the global ocean as swell waves propagate northward into the Pacific, Indian, and Atlantic Oceans (Hemer et al., 2013).

Deep ocean swell waves and elevated sea levels resulting from ETCs are examples of inter-regional transboundary processes; locally generated tropical cyclones (TCs) provide examples of intra-regional transboundary processes. Whereas hurricane force winds, heavy rainfall, and turbulent seas associated with TCs can cause massive damage to both land and coastal systems in tropical small islands, the impacts of sea waves and inundation associated with far distant ETCs are limited to the coastal margins. Nevertheless both storm types result in a range of impacts covering island morphology, natural and ecological systems, island economies, settlements, and human well-being (see Figure 29-4).

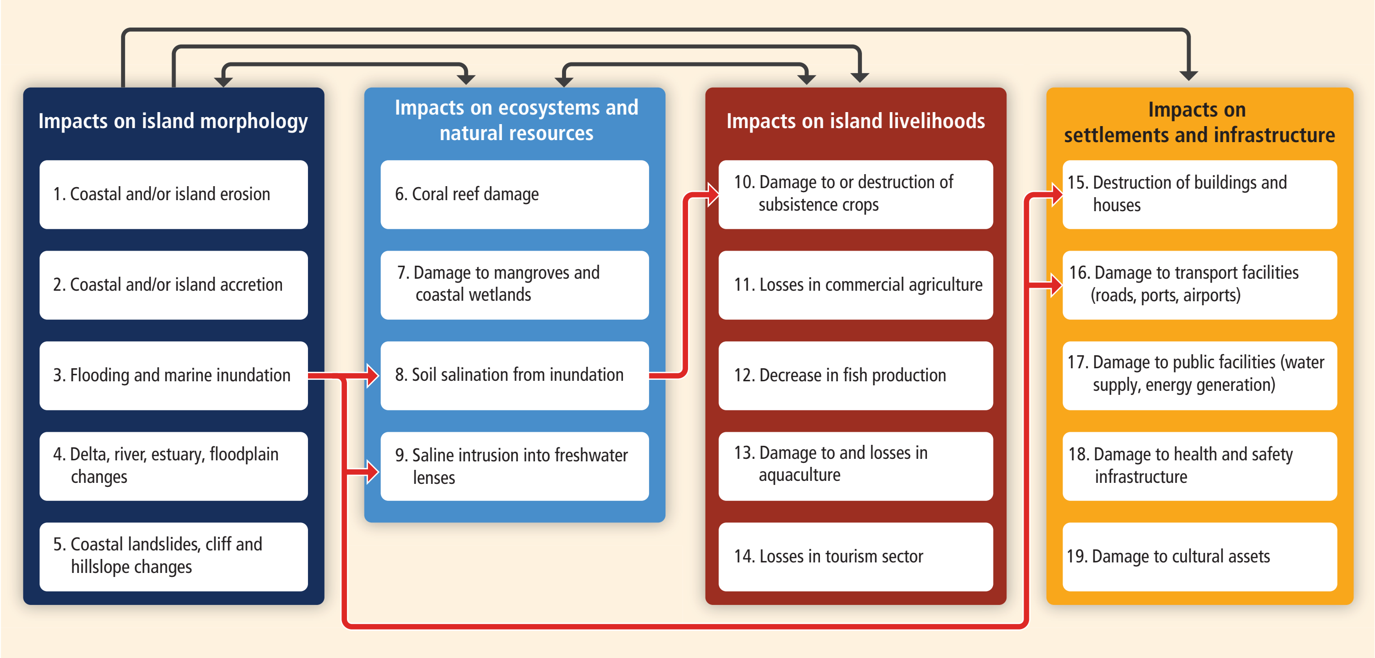


Figure 29-4 | Tropical and extratropical cyclone (ETC) impacts on the coasts of small islands. Four types of impacts are distinguished here, with black arrows showing the connections between them, based on the existing literature. An example of the chain of impacts associated with two ETCs centered to the east of Japan is illustrated by the red arrows. Swell waves generated by these events in December 2008 reached islands in the southwest Pacific and caused extensive flooding (3) that impacted soil quality (8) and freshwater resources (9), and damaged crops (10), buildings (15), and transport facilities (16) in the region (example based on Hoeke et al., 2013).

Examples of tropical cyclone impacts on small island coasts (with reference):
1. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 2. Taveuni, Fiji, March 2010 (Etienne and Terry, 2012); 3. Cook Islands (de Scally, 2008); Society and Autral Islands, French Polynesia, February 2010 (Etienne, 2012); 4. Viti Levu, Fiji, March 1997 (Terry et al., 2002); 5. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 6. Curacao, Bonaire, Netherlands Antilles, November 1999 (Scheffers and Scheffers, 2006); Hawaiian Islands (Fletcher et al., 2008); 7. Bay Islands, Honduras, October 1998 (Cahoon et al., 2003); 8. Marshall Islands, June 1905 (Spennemann, 1996); 9. Pukapuka atoll, Cook Islands, February 2005 (Terry and Falkland, 2010); 10. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 11. 12. 13. Tuamotu Islands, French Polynesia, 1982–1983 (Dupon, 1987); 14. Grenada, September 2004 (OECS, 2004); 15. Grenada, September 2004 (OECS, 2004); Tubuai, Austral Islands, French Polynesia, February 2010 (Etienne, 2012); 16. Vanuatu, February 2004 (Richmond and Sovacool, 2012); Guadeloupe Island, October 2008 (Dorville and Zahibo, 2010); 17. Bora Bora, Raiatea, Maupiti, Tahaa, Huahine, Society Islands, February 2010 (Etienne, 2012); 18. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 19. Tuamotu, French Polynesia, 1982–1983 (Dupon, 1987).

Examples of ETC impacts on small island coasts (with reference):
1. Maldives, April 1987 (Harangozo, 1992); 2. Maldives, January 1955 (Maniku, 1990); 3. Maldives, April 1987 (Harangozo, 1992); 9. Solomon Islands, December 2008 (Hoeke et al., 2013); 10. Chuck, Pohnpei, Kosrae, Federated States of Micronesia, December 2008 (Hoeke et al., 2013); 15. Majuro, Marshall Islands, November 1979 (Hoeke et al., 2013); 16. Coral Coast, Viti Levu, Fiji, May 2011 (Hoeke et al., 2013); 17. Majuro, Kwajalein, Arno, Marshall Islands, December 2008 (Hoeke et al., 2013); 18. Bismark Archipelago, Papua New Guinea, December 2008 (Hoeke et al., 2013).

29.5.2. Transcontinental Dust Clouds and Their Impact

The transport of airborne Saharan dust across the Atlantic and into the Caribbean has engaged the attention of researchers for some time. The resulting dust clouds are known to carry pollen, microbes, insects, bacteria, fungal spores, and various chemicals and pesticides (Prospero et al., 2005; Garrison et al., 2006; Middleton et al., 2008; Monteil, 2008; López-Villarrubia et al., 2010). During major events, dust concentrations can exceed 100 μg m^{-3} (Prospero, 2006). Independent studies using different methodologies have all found a strong positive correlation between dust levels in the Caribbean and periods of drought in the Sahara, while concentrations show a marked decrease during periods of higher rainfall. Consequently, it is argued that higher dust emissions due to increasing aridity in the Sahel and other arid areas could enhance climate change effects over large areas, including the eastern Caribbean and the Mediterranean (Prospero and Lamb, 2003). Similar findings have been reported at Cape Verde where dust emission levels were found to be a factor of nine lower during the decade of the 1950s when rainfall was at or above normal, compared to the 1980s, a period of intense drought in the Sahel region (Nicoll et al., 2011). Dust from the Sahara has also reached the eastern Mediterranean (e.g., Santese et al., 2010) whilst dust from Asia has been transported across the Pacific and Atlantic Oceans and around the world (Uno et al., 2009).

There is also evidence that the transboundary movement of Saharan dust into the island regions of the Caribbean, Pacific, and Mediterranean is associated with various human health problems (Griffin, 2007) including asthma admissions in the Caribbean (Monteil, 2008; Prospero et al., 2008; Monteil and Antoine, 2009) and cardiovascular morbidity in Cyprus in the Mediterranean (Middleton et al., 2008), and is found to be a risk factor in respiratory and obstructive pulmonary disease in the Cape Verde islands (Martins et al., 2009). These findings underscore the need for further research into the link among climate change, airborne aerosols, and human health in localities such as oceanic islands far distant from the continental source of the particulates.

29.5.3. Movement and Impact of Introduced and Invasive Species across Boundaries

Invasive species are colonizer species that establish populations outside their normal distribution ranges. The spread of invasive alien species is regarded as a significant transboundary threat to the health of biodiversity and ecosystems, and has emerged as a major factor in species decline, extinction, and loss of biodiversity goods and services worldwide. This is particularly true of islands, where both endemicity and vulnerability to introduced species tend to be high (Reaser et al., 2007; Westphal et al., 2008; Kenis et al., 2009; Rocha et al., 2009; Kueffer et al., 2010). The extent to which alien invasive species successfully establish themselves at new locations in a changing climate will be dependent on many variables, but non-climate factors such as ease of access to migration pathways, suitability of the destination, ability to compete and adapt to new environments, and susceptibility to invasion of host ecosystems are deemed to be critical. This is borne out, for example, by Le Roux et al. (2008), who studied the effect of the invasive weed *Miconia calvescens* in New Caledonia, Society Islands, and Marquesas Islands; by Gillespie et al. (2008) in an analysis of the spread of *Leucaena leucocephala*, *Miconia calvescens*, *Psidium* sp., and *Schinus terebinthifolius* in the Hawaiian Islands; and by Christenhusz and Toivonen (2008), who showed the potential for rapid spread and establishment of the oriental vessel fern, *Angiopteris evecta*, from the South Pacific throughout the tropics. Mutualism between an invasive ant and locally honeydew-producing insects has been strongly associated with damage to the native and functionally important tree species *Pisonia grandis* on Cousine Island, Seychelles (Gaigher et al., 2011).

While invasive alien species constitute a major threat to biodiversity in small islands, the removal of such species can result in recovery and return of species richness. This has been demonstrated in Mauritius by Baider and Florens (2011), where some forested areas were weeded of alien plants and after a decade the forest had recovered close to its initial condition. They concluded, given the severity of alien plant invasion in Mauritius, that their example can "be seen as a relevant model for a whole swath of other island nations and territories around the world particularly in the Pacific and Indian Oceans" (Baider and Florens, 2011, p. 2645).

The movement of aquatic and terrestrial invasive fauna within and across regions will almost certainly exacerbate the threat posed by climate change in island regions, and could impose significant environmental, economic, and social costs. Recent research has shown that the invasion of the Caribbean Sea by the Indo-Pacific lionfish (*Pterois volitans*), a highly efficient and successful predator, is a major contributor to observed increases in algal dominance in coral and sponge communities in the Bahamas and elsewhere in the region. The consequential damage to these ecosystems has been attributed to a significant decline in herbivores due to predation by lionfish (Albins and Hixon, 2008; Schofield, 2010; Green et al., 2011; Lesser and Slattery, 2011). Although there is no evidence that the lionfish invasion is climate-related, the concern is that when combined with preexisting stress factors the natural resilience of Caribbean reef communities will decrease (Green et al., 2012; Albins and Hixon, 2013), making them more susceptible to climate change effects such as bleaching. Englund (2008) has documented the negative effects of invasive species on native aquatic insects on Hawaii and French Polynesia, and their potential role in the extirpation of native aquatic invertebrates in the Pacific. Similarly, there is evidence that on the island of Oahu introduced slugs appear to be "skewing species abundance in favour of certain non-native and native plants," by altering the "rank order of seedling survival rates," thereby undermining the ability of preferred species (e.g., the endangered *C. superba*) to compete effectively (Joe and Daehler, 2008, p. 253).

29.5.4. Spread of Aquatic Pathogens within Island Regions

The mass mortality of the black sea urchin, *Diadema antillarum*, in the Caribbean basin during the early 1980s demonstrates the ease with which ecological threats in one part of a region can be disseminated to other jurisdictions thousands of kilometers away. The die-off was first observed in the waters off Panama around January 1983, and within 13 months the disease epidemic had spread rapidly through the Caribbean Sea, affecting practically all island reefs, as far away as Tobago some 2000 km to the south and Bermuda some 4000 km to the east. The diadema population in the wider Caribbean declined by more than 93% as a consequence of this single episode (Lessios, 1988, 1995) As *D. antillarum* is one of the principal grazers that removes macroalgae from reefs and thus promotes juvenile coral recruitment, the collateral damage was severe, as the region's corals suffered from high morbidity and mortality for decades thereafter (Carpenter and Edmunds, 2006; Idjadi et al., 2010).

There are other climate-sensitive diseases such as yellow, white, and black band; white plague; and white pox that travel across national boundaries and infect coral reefs directly. This is variously supported by examples from the Indo-Pacific and Caribbean relating to the role of bacterial infections in white syndrome and yellow band disease (Piskorska et al., 2007; Cervino et al., 2008); the impact of microbial pathogens as stressors on benthic communities in the Mediterranean associated with warming seawater (Danovaro et al., 2009); and an increasing evidence of white, yellow, and black band disease associated with Caribbean and Atlantic reefs (Brandt and McManus, 2009; Miller, J. et al., 2009; Rosenberg et al., 2009; Weil and Croquer, 2009; Weil and Rogers, 2011).

29.5.5. Transboundary Movements and Human Health

For island communities the transboundary implications of existing and future human health challenges are projected to increase in a changing climate. For instance, the aggressive spread of the invasive giant African snail, *Achatina fulica*, throughout the Caribbean, Indo-Pacific Islands, and Hawaii is not only assessed to be a severe threat to native snails and other fauna (e.g., native gastropods), flora, and crop agriculture, but is also identified as a vector for certain human diseases such as meningitis (Reaser et al., 2007; Meyer et al., 2008; Thiengo et al., 2010).

Like other aquatic pathogens, ciguatoxins that cause ciguatera fish poisoning may be readily dispersed by currents across and within boundaries in tropical and subtropical waters. Ciguatoxins are known to be highly temperature-sensitive and may flourish when certain seawater temperature thresholds are reached, as has been noted in the South Pacific (Llewellyn, 2010), Cook Islands (Rongo and van Woesik, 2011), Kiribati (Chan et al., 2011), the Caribbean and Atlantic (Otero et al., 2010; Tester et al., 2010), and Mediterranean (Aligizaki and Nikolaidis, 2008; see also Section 29.3.3.2).

29.6. Adaptation and Management of Risks

Islands face risks from both climate-related hazards that have occurred for centuries, as well as new risks from climate change. There have been extensive studies of the risks associated with past climate-related hazards and adaptations to these, such as tropical cyclones, drought, and disease, and their attendant impacts on human health, tourism, fisheries, and other areas (Bijlsma et al., 1996; Cronk 1997; Solomon and Forbes 1999; Pelling and Uitto 2001). There have also been many studies that have used a variety of vulnerability, risk, and adaptation assessment methods particularly in the Pacific that have recently been summarized by Hay et al. (2013). But for most islands, there is very little published literature documenting the probability, frequency, severity, or consequences of climate change risks such as SLR, ocean acidification, and salinization of freshwater resources—or associated adaptation measures. Projections of future climate change risks are limited by the lack of model skill in projecting the climatic variables that matter to small islands, notably tropical cyclone frequency and intensity, wind speed and direction, precipitation, sea level, ocean temperature, and ocean acidification (Brown et al., 2013b); inadequate projections of regional sea levels (Willis and Church, 2012); and a lack of long-term baseline monitoring of changes in climatic risk, or to ground-truth models (Voccia, 2012), such as risk of saline intrusion, risk of invasive species, risk of biodiversity loss, or risk of large ocean waves. In their absence, qualitative studies have documented perceptions of change in current risks (Fazey et al., 2011; Lata and Nunn, 2012), reviewed effective coping mechanisms for current stressors (Bunce et al., 2009; Campbell et al., 2011) and have considered future scenarios of change (Weir and Virani, 2011). These studies highlight that change is occurring, but they do not quantify the probability, speed, scale, or distribution of future climate risks. The lack of quantitative published assessments of climate risk for many small islands means that future adaptation decisions have to rely on analogs of responses to past and present weather extremes and climate variability, or assumed/hypothesized impacts of

Table 29-3 | Types of island in the Pacific region and implications for hydro-meteorological hazards (after Campbell, 2009).

Island type and size		Island elevation, slope, rainfall	Implications for hazard
Continental	• Large • High biodiversity • Well-developed soils	• High elevations • River flood plains • Orographic rainfall	River flooding more likely to be a problem than in other island types. In Papua New Guinea, high elevations expose areas to frost (extreme during El Niño).
Volcanic high islands	• Relatively small land area • Barrier reefs • Different stages of erosion	• Steep slopes • Less well-developed river systems • Orographic rainfall	Because of size, few areas are not exposed to tropical cyclones. Streams and rivers are subject to flash flooding. Barrier reefs may ameliorate storm surge.
Atolls	• Very small land area • Small islets surround a lagoon • Larger islets on windward side • Shore platform on windward side • No or minimal soil	• Very low elevations • Convectional rainfall • No surface (fresh) water • Ghyben–Herzberg (freshwater) lens	Exposed to storm surge, "king" tides, and high waves. Narrow resource base. Exposed to freshwater shortages and drought. Water problems may lead to health hazards.
Raised limestone islands	• Concave inner basin • Narrow coastal plains • No or minimal soil	• Steep outer slopes • Sharp karst topography • No surface water	Depending on height, may be exposed to storm surge. Exposed to freshwater shortages and drought. Water problems may lead to health hazards.

climate change based on island type (see Table 29-3). Differences in island type and differences in exposure to climate forcing and hazards vary with island form, providing a framework for consideration of vulnerability and adaptation strategies. Place-based understanding of island landscapes and of processes operating on individual islands is critical (Forbes et al., 2013).

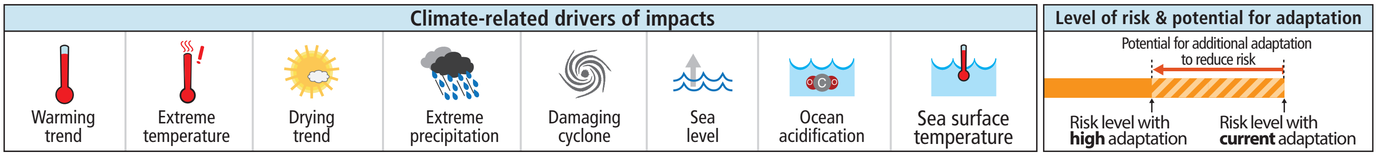
29.6.1. Addressing Current Vulnerabilities on Small Islands

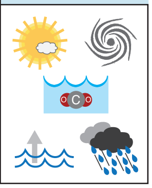
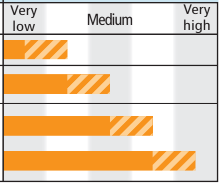
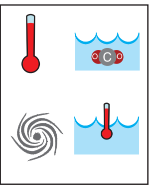
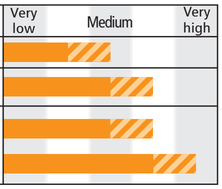
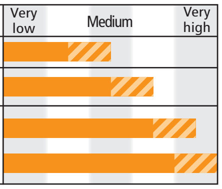
Islands are heterogeneous in geomorphology, culture, ecosystems, populations, and hence also in their vulnerability to climate change. Vulnerabilities and adaptation needs are as diverse as the variety of islands between regions and even within nation states (e.g., in Solomon Islands; Rasmussen et al., 2011), often with little climate adaptation occurring in peripheral islands, for example, in parts of the Pacific (Nunn et al., 2013). Quantitative comparison of vulnerability is difficult owing to the paucity of vulnerability indicators. Generic indices of national level vulnerability continue to emerge (Cardona, 2007) but only a minority are focused on small islands (e.g., Blancard and Hoarau, 2013). The island-specific indicators that exist often suffer from lack of data (Peduzzi et al., 2009; Hughes et al., 2012), use indicators that are not relevant in all islands (Barnett and Campbell, 2010), or use data of limited quality for islands, such as SLR (as used in Wheeler, 2011). As a result indicators of vulnerability for small islands often misrepresent actual vulnerability. Recent moves toward participatory approaches that link scientific knowledge with local visions of vulnerability (see Park et al., 2012) offer an important way forward to understanding island vulnerability in the absence of certainty in model-based scenarios.

Island vulnerability is often a function of four key stressors: physical, socioeconomic, socio-ecological, and climate-induced, whose reinforcing mechanisms are important in determining the magnitude of impacts. Geophysical characteristics of islands (see Table 29-2; Figure 29-1) create inherent physical vulnerabilities. Thus, for example the Azores (Portugal) face seismic, landslide, and tsunami risks (Coutinho et al., 2009). Socioeconomic vulnerabilities are related to ongoing challenges of managing urbanization, pollution, and sanitation, both in small island states and non-sovereign islands as highlighted by Storey and Hunter (2010) in Kiribati, López-Marrero and Yarnal (2010) in Puerto Rico, and in Mayotte, France (Le Masson and Kelman, 2011). Socio-ecological stresses, such as habitat loss and degradation, invasive species (described in Sax and Gaines, 2008), overexploitation, pollution, human encroachment, and disease can harm biodiversity (Kingsford et al., 2009; Caujape-Castells et al., 2010), and reduce the ability of socio-ecological systems to bounce back after shocks.

To understand climate vulnerability on islands, it is necessary to assess all of these dimensions of vulnerability (Rasmussen et al., 2011). For example, with individual ecosystems such as coral reef ecosystems, those already under stress from non-climate factors are more at risk from climate change than those that are unstressed (Hughes et al., 2003; Maina et al., 2011). Evidence is starting to emerge that shows the same applies at the island scale. In Majuro atoll (Marshall Islands), 34 to 37 years of aerial photography shows that socio-ecological stress is exacerbating shoreline change associated with SLR, especially on the lagoon side of islands (Ford, 2012; see also Section 29.3.1.1). Islands faced with multiple stressors can therefore be assumed to be more at risk from climate impacts.

Table 29-4 | Selected key risks and potential for adaptation for small islands from the present day to the long term.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services, and economic stability (*high confidence*) [29.6, 29.8, Figure 29-4]	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Maintenance and enhancement of ecosystem functions and services and of water and food security • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Decline and possible loss of coral reef ecosystems in small islands through thermal stress (*high confidence*) [29.3.1.2]	Limited coral reef adaptation responses; however, minimizing the negative impact of anthrogopenic stresses (ie: water quality change, destructive fishing practices) may increase resilience.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas (*high confidence*) [29.4, Table 29-1; WGI AR5 13.5, Table 13.5]	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

Despite the limited ability of continental scale models to predict climate risks for specific islands, or the limited capacity of island vulnerability indicators, scenario based damage assessments can be undertaken. Storm surge risks have been effectively modeled for the Andaman and Nicobar Islands (Kumar et al., 2008). Rainfall-induced landslide risk maps have been produced for both Jamaica (Miller, S. et al., 2009) and the Chuuk Islands (Federated States of Micronesia; Harp et al., 2009). However, the probability of change in frequency and severity of extreme rainfall events and storm surges remains poorly understood for most small islands. Other risks, such as the climate change-driven health risks from the spread of infectious disease, loss of settlements and infrastructure, and decline of ecosystems that affect island economies, livelihoods, and human well-being also remain under-researched. Nevertheless, it is possible to consider these risks along with the threat of rising sea level and suggest a range of contemporary and future adaptation issues and prospects for small islands (see Table 29-4).

29.6.2. Practical Experiences of Adaptation on Small Islands

There is disagreement about whether islands and islanders have successfully adapted to past weather variability and climate change. Nunn (2007) argues that past climate changes have had a "crisis effect" on prehistoric societies in much of the Pacific Basin. In contrast, a variety of studies argue that past experiences of hydro-meteorological extreme events have enabled islands to become resilient to weather extremes (Barnett, 2001). Resilience appears to come from both a belief in their own capacity (Adger and Brown, 2009; Kuruppu and Liverman, 2011), and a familiarity with their environment and understanding of what is needed to adapt (Tompkins et al., 2009; Le Masson and Kelman, 2011). For example, compared to communities in the larger countries of Madagascar, Tanzania, and Kenya, the Indian Ocean islands (Seychelles and Mauritius) were found to have: comparatively high capacity to anticipate change and prepare strategies; self-awareness of human impact on environment; willingness to change occupation; livelihood diversity; social capital; material assets; and access to technology and infrastructure—all of which produced high adaptive capacity (Cinner et al., 2012). Despite this resilience, islands are assumed to be generically vulnerable to long term future climate change (Myers, 2002; Parks and Roberts, 2006).

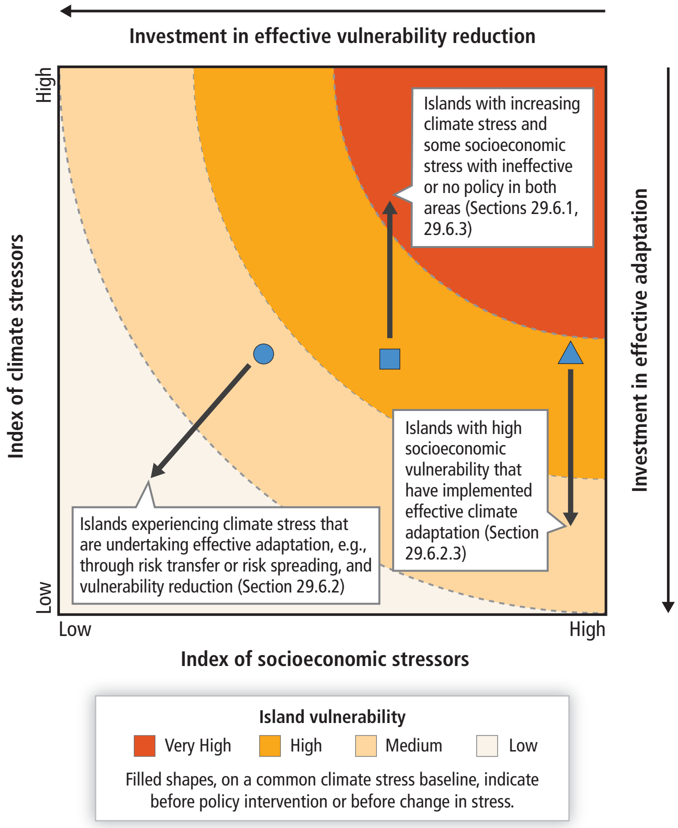


Figure 29-5 | The impact of alternative climate change adaptation actions or policies.

There are many ways in which *in situ* climate adaptation can be undertaken: reducing socioeconomic vulnerabilities, building adaptive capacity, enhancing disaster risk reduction, or building longer term climate resilience (e.g., see McGray et al., 2007; Eakin et al., 2009). Figure 29-5 highlights the implications of the various options. Not all adaptations are equally appropriate in all contexts. Understanding the baseline conditions and stresses (both climate and other) are important in understanding which climate change adaptation option will generate the greatest benefits. On small islands where resources are often limited, recognizing the starting point for action is critical to maximizing the benefits from adaptation. The following section considers the benefits of pursuing the various options.

29.6.2.1. Building Adaptive Capacity with Traditional Knowledge, Technologies, and Skills on Small Islands

As in previous IPCC assessments, there is continuing strong support for the incorporation of indigenous knowledge into adaptation planning. However, this is moderated by the recognition that current practices alone may not be adequate to cope with future climate extremes or trend changes. The ability of a small island population to deal with current climate risks may be positively correlated with the ability to adapt to future climate change, but evidence confirming this remains limited (such as Lefale, 2010). Consequently, this section focuses on evidence for adaptive capacity that reduces vulnerability to existing stressors, enables adaptation to current stresses, and supports current disaster risk management.

Traditional knowledge has proven to be useful in short-term weather forecasting (e.g., Lefale, 2010) although evidence is inconclusive on local capacity to observe long-term climate change (e.g., Hornidge and Scholtes, 2011). In Solomon Islands, Lauer and Aswani (2010) found mixed ability to detect change in spatial cover of seagrass meadows. In Jamaica, Gamble et al. (2010) reported a high level of agreement between farmers' perception of increasing drought incidence and statistical analysis of precipitation and vegetation data for the area. In this case farmers' perceptions clearly validated the observational data and vice versa. Despite some claims that vulnerability reduction in indigenous communities in small islands may be best tackled by combining indigenous and Western knowledge in a culturally compatible and sustainable manner (Mercer et al., 2007), given the small number of studies in this area, there is not sufficient evidence to determine the effectiveness and limits to the use of traditional methods of weather forecasting under climate change on small islands.

Traditional technologies and skills can be effective for current disaster risk management but there is currently a lack of supporting evidence to suggest that they will be equally appropriate under changing cultural conditions and future climate changes on islands. Campbell (2009) identified that traditional disaster reduction measures used in Pacific islands focused around maintaining food security, building community cooperation, and protecting settlements and inhabitants. Examples of actions to maintain food security include: the production and storage of food surpluses, such as yam and breadfruit buried in leaf-lined pits to ferment; high levels of agricultural diversity to minimize specific damage to any one crop; and the growth of robust famine crops, unused in times of plenty that could be used in emergencies (Campbell, 2009). Two discrete studies from Solomon Islands highlight the importance of traditional patterns of social organization within communities to support food security under social and environmental change (Reenberg et al., 2008; Mertz et al., 2010). In both studies the strategy of relying on traditional systems of organization for farming and land use management have been shown to work effectively—largely as there has been little cultural and demographic change. Nonetheless there are physical and cultural limits to traditional disaster risk management. In relation to the ability to store surplus production on atoll islands, on Rongelap in the Marshall Islands, surpluses are avoided, or are redistributed to support community bonds (Bridges and McClatchey, 2009). Further, traditional approaches that Pacific island communities have used for survival for millennia (such as building elevated settlements and resilient structures, and working collectively) have been abandoned or forgotten due to processes of globalization, colonialism, and development (Campbell, 2009). Ongoing processes of rapid urbanization and loss of language and tradition suggest that traditional approaches may not always be efficacious in longer term adaptation.

Traditional construction methods have long been identified across the Pacific as a means of reducing vulnerability to tropical cyclones and floods in rural areas. In Solomon Islands traditional practices include: elevating concrete floors on Ontong Java to keep floors dry during heavy rainfall events; building low, aerodynamic houses with sago palm leaves as roofing material on Tikopia as preparedness for tropical cyclones; and in Bellona local perceptions are that houses constructed from modern materials and practices are more easily destroyed by tropical cyclones, implying that traditional construction methods are perceived to be more resilient in the face of extreme weather (Rasmussen et al., 2009). In parallel, Campbell (2009) documents the characteristics of traditional building styles (in Fiji, Samoa, and Tonga) where relatively steep hipped roofs, well bound connections and joints, and airtight spaces with few windows or doors offer some degree of wind resistance. Traditional building measures can also reduce damages associated with earthquakes, as evidenced in Haiti (Audefroy, 2011). By reducing damage caused by other stresses (such as earthquakes), adaptive capacity is more likely to be maintained. The quality of home construction is critical to its wind resistance. If inadequately detailed, home construction will fail irrespective of method. Although some traditional measures could be challenged as potentially risky—for example, using palm leaves, rather than metal roofs as a preparation for tropical cyclone impacts—the documentation of traditional approaches, with an evaluation of their effectiveness remains urgently needed. Squatter settlements in urban areas, especially on steep hillsides in the Caribbean, often use poor construction practices frequently driven by poverty and inadequate building code enforcement (Prevatt et al., 2010).

Traditional systems appear less effective when multiple civilization-nature stresses are introduced. For example, in Reunion and Mayotte, population growth, and consequent rises in land and house prices, have led low-income families to settle closer to hazardous slopes that are prone to landslides and to river banks which are prone to flooding (Le Masson and Kelman, 2011). Traditional belief systems can also limit adaptive capacity. Thus, for example, in two Fijian villages, approximately half of survey respondents identified divine will as the cause of climate change (Lata and Nunn, 2012). These findings reinforce earlier studies in Tuvalu (Mortreux and Barnett, 2009), and more widely across the Pacific (Barnett and Campbell, 2010). The importance of taking into account local interests and traditional knowledge in adaptation in small islands is emphasized by Kelman and West (2009) and McNamara and Westoby (2011), yet evidence does not yet exist that reveals the limits to such knowledge, such as in the context of rapid socio-ecological change, or the impact of belief systems on adaptive capacity.

While there is clear evidence that traditional knowledge networks, technologies, and skills can be used effectively to support adaptation in certain contexts, the limits to these tools are not well understood. To date research in the Pacific and Caribbean dominates small island climate change work. More detailed studies on small islands in the central and western Indian Ocean, the Mediterranean, and the central and eastern Atlantic would improve understanding on this topic.

29.6.2.2. Addressing Risks on Small Islands

Relative to other areas, small islands are disproportionately affected by current hydro-meteorological extreme events, both in terms of the percentage of the population affected and losses as a percentage of GDP (Anthoff et al., 2010; Table 29-5). Under climate change the risks of damage and associated losses are expected to continue to rise (Nicholls and Cazenave, 2010). Yet much of the existing literature on climate risk in small islands does not consider how to address high future risks, but instead focuses on managing present-day risks through risk transfer, risk spreading, or risk avoidance. Risk transfer is largely undertaken through insurance; risk spreading through access to and use of common property resources, livelihood diversification, or mutual support through networks (see Section 29.6.2.3); and risk avoidance through structural engineering measures or migration (see Section 29.6.2.4).

Risk transfer through insurance markets has had limited uptake in small islands, as insurance markets do not function as effectively as they do in larger locations, in part owing to a small demand for the insurance products (Heger et al., 2008). In the case of insurance for farmers, researchers found that a lack of demand for insurance products (in their study countries: Grenada, Jamaica, Fiji, and Vanuatu) meant an under-supply of customized food insurance products, which in turn contributed to a lack of demand for insurance (Angelucci and Conforti, 2010). Alternatives exist such as index-based schemes that provide payouts based on the crossing of a physical threshold, for example, when rainfall

Table 29-5 | Top ten countries in the Asia–Pacific region based on absolute and relative physical exposure to storms and impact on GDP (between 1998 and 2009; after Tables 1.10 and 1.11 of ESCAP and UNISDR, 2010).

Rank	Absolute exposure (millions affected)	Relative exposure (% of population affected)	Absolute GDP loss (US$ billions)	Loss (% of GDP)
1	Japan (30.9)	Northern Mariana Islands (58.2)	Japan (1,226.7)	Northern Mariana Islands (59.4)
2	Philippines (12.1)	Niue (25.4)	Republic of Korea (35.6)	Vanuatu (27.1)
3	China (11.1)	Japan (24.2)	China (28.5)	Niue (24.9)
4	India (10.7)	Philippines (23.6)	Philippines (24.3)	Fiji (24.1)
5	Bangladesh (7.5)	Fiji (23.1)	Hong Kong (13.3)	Japan (23.9)
6	Republic of Korea (2.4)	Samoa (21.4)	India (8.0)	Philippines (23.9)
7	Myanmar (1.2)	New Caledonia (20.7)	Bangladesh (3.9)	New Caledonia (22.4)
8	Vietnam (0.8)	Vanuatu (18.3)	Northern Mariana Islands (1.5)	Samoa (19.2)
9	Hong Kong (0.4)	Tonga (18.1)	Australia (0.8)	Tonga (17.4)
10	Pakistan (0.3)	Cook Islands (10.5)	New Caledonia (0.7)	Bangladesh (5.9)

Note: Small islands are highlighted in yellow.

drops below a certain level, rather than on drought damage sustained (Linnerooth-Bayer and Mechler, 2009). The potential for index-based insurance for climate stressors on islands is under-researched and there remains limited evidence of the long-term effectiveness of index-based or pooled-risk insurance in supporting household level adaptation. Small island governments also face expensive climate risk insurance. The Caribbean Catastrophe Risk Insurance Facility (CCRIF), which has been operating since 2007, pools Caribbean-wide country-level risks into a central, more diversified risk portfolio—offering lower premiums for participating national governments (CCRIF, 2008). The potential for a similar scheme in the Pacific is being explored (ADB, 2009; Cummins and Mahul, 2009).

Risk can be spread socially, for example, through social networks and familial ties (see also Section 29.6.2.3), or ecologically, for example, by changing resource management approach. Social networks can be used to spread risk among households. In Fiji, after Tropical Cyclone Ami in 2003, households whose homes were not affected by the cyclone increased their fishing effort to support those whose homes were damaged (Takasaki, 2011)—mutual support formed a central pillar for community-based adaptation. In the case of natural systems, risks can be spread through enhancing representation of habitat types and replication of species, for example, through the creation of marine protected areas, around key refuges that protect a diversity of habitat, that cover an adequate proportion of the habitat and that protect critical areas such as nursery grounds and fish spawning aggregation areas (McLeod et al., 2009). Locally Managed Marine Areas—which involve the local community in the management and protection of their local marine environment—have proven to be effective in increasing biodiversity, and in reducing poverty in areas dependent on marine resources in several Pacific islands (Techera, 2008; Game et al., 2011). By creating a network of protected areas supported by local communities the risks associated with some forms of climate change can be spread and potentially reduced (Mills et al., 2010) although such initiatives may not preserve thermally sensitive corals in the face of rising SST.

Risk avoidance through engineered structures can reduce risk from some climate-related hazards (*medium evidence*, *medium agreement*). In Jamaica, recommendations to reduce rainfall-driven land surface movements resulting in landslides include: engineering structures such as soil nailing, gabion baskets (i.e., cages filled with rocks), rip rapped surfaces (i.e., permanent cover with rock), and retaining walls together with engineered drainage systems (Miller, S. et al., 2009). Engineering principles to reduce residential damage from hurricanes have been identified, tested, and recommended for decades in the Caribbean. However, expected levels of success have often not been achieved owing to inadequate training of construction workers, minimal inspection of new buildings, and lack of enforcement of building code requirements (Prevatt et al., 2010). Some island states do not even have the technical or financial capacity to build effective shore protection structures, as highlighted by a recent assessment in south Tarawa, Kiribati (Duvat, 2013).

In addition, not all engineered structures are seen as effective risk avoidance mechanisms. In the Azores archipelago, a proliferation of permanent engineered structures along the coastline to prevent erosion have resulted in a loss of natural shoreline protection against wave erosion (Calado et al., 2011). In Barbados it is recognized that seawalls can protect human assets in areas prone to high levels of erosion; however, they can also cause sediment starvation in other areas, interfere with natural processes of habitat migration, and cause coastal squeeze, which may render them less desirable for long-term adaptation (Mycoo and Chadwick, 2012; see also Section 5.4.2.1). To reduce erosion risk an approach with less detrimental downstream effects that also supports tourism is beach nourishment. This is increasingly being recommended, for example, in the Caribbean (Mycoo and Chadwick, 2012), the Mediterranean (Anagnostou et al., 2011), and western Indian Ocean (Duvat, 2009). Beach nourishment, however, is not without its challenges, as requirements such as site-specific oceanographic and wave climate data, adequate sand resources, and critical engineering design skills may not be readily available in some small islands.

29.6.2.3. Working Collectively to Address Climate Impacts on Small Islands

More attention is being focused on the relevance and application of community-based adaptation (CBA) principles to island communities, to facilitate adaptation planning and implementation (Warrick, 2009; Kelman et al., 2011) and to tackle rural poverty in resource-dependent communities (Techera, 2008). CBA research is focusing on empowerment that helps people to help themselves, for example, through marine catch monitoring (Breckwoldt and Seidel, 2012), while addressing local priorities and building on local knowledge and capacity. This approach to adaptation is being promoted as an appropriate strategy for small islands, as it is something done "with" rather than "to" communities (Warrick, 2009). Nonetheless externally driven programs to encourage community-level action have produced some evidence of effective adaptation. Both Limalevu et al. (2010) and Dumaru (2010) describe the outcomes of externally led pilot CBA projects (addressing water security and coastal management) implemented in villages across Fiji, notably more effective management of local water resources through capacity building; enhanced knowledge of climate change; and the establishment of mechanisms to facilitate greater access to technical and financial resources from outside the community. More long-term monitoring and evaluation of the effectiveness of community level action is needed.

Collaboration between stakeholders can lessen the occurrence of simple mistakes that can reduce the effectiveness of adaptation actions (*medium evidence*, *medium agreement*). Evidence from the eastern Caribbean suggests that adaptations taken by individual households to reduce landslide risk—building simple retaining walls—can be ineffective compared to community-level responses (Anderson et al., 2011). Landslide risk can be significantly reduced through better hillside drainage. In the eastern Caribbean, community groups, with input from engineers, have constructed these networks of drains to capture surface runoff, household roof water, and gray water. Case studies from Fiji and Samoa in which multi-stakeholder and multi-sector participatory approaches were used to help enhance resilience of local residents to the adverse impacts of disasters and climate change (Gero et al., 2011) further support this view. In the case of community-based disaster risk reduction (CBDRR), Pelling (2011) notes that buy-in from local and municipal governments is needed, as well as strong preexisting relationships founded on routine daily activities, to make CBDRR effective. Research from both Solomon Islands and the Cayman Islands reinforce the conclusion that drivers of community resilience to hazard maps closely onto factors driving successful governance of the commons, that is, community cohesion, effective leadership, and community buy-in to collective action (Tompkins et al., 2008; Schwarz et al., 2011). Where community organizations are operating in isolation, or where there is limited coordination and collaboration, community vulnerability is expected to increase (Ferdinand et al., 2012). Strong local networks, and trusting relationships between communities and government, appear to be key elements in adaptation, in terms of maintaining sustainable agriculture and in disaster risk management (*medium evidence*, *high agreement*).

All of these studies reinforce the earlier work of Barnett (2001), providing empirical evidence that supporting community-led approaches to disaster risk reduction and hazard management may contribute to greater community engagement with anticipatory adaptation. However, it is not yet possible to identify the extent to which climate resilience is either a coincidental benefit of island lifestyle and culture, or a purposeful approach, such as the community benefits gained from reciprocity among kinship groups (Campbell, 2009).

29.6.2.4. Addressing Long-Term Climate Impacts and Migration on Small Islands

SLR poses one of the most widely recognized climate change threats to low-lying coastal areas on islands (Section 29.3.1). However, long-term climate impacts depend on the type of island (see Figure 29-1) and the adaptation strategy adopted. Small island states have 16% of their land area in low elevation coastal areas (<10 m) as opposed to a global average of 2%, and the largest proportion of low-elevation coastal urban land area: 13% (along with Australia and New Zealand), in contrast to the global average of 8% (McGranahan et al., 2007). Statistics like these underpin the widely held view about small islands being "overwhelmed" by rising seas associated with SLR (Loughry and McAdam, 2008; Laczko and Aghazarm, 2009; Yamamoto and Esteban, 2010; Berringer, 2012; Dema, 2012; Gordon-Clark, 2012; Lazrus, 2012). Yet there remains *limited evidence* as to which regions (Caribbean, Pacific and Indian Oceans, West African islands) will experience the largest SLR (Willis and Church, 2012) and which islands will experience the worst climate impacts. Nicholls et al. (2011) have modeled impacts of 4°C warming, producing a 0.5 to 2.0 m SLR, to assess the impacts on land loss and migration. With no adaptation occurring, they estimate that this could produce displacement of between 1.2 and 2.2 million people from the Caribbean and Indian and Pacific Oceans. More research is needed to produce *robust agreement* on the impact of SLR on small islands, and on the range of adaptation strategies that could be appropriate for different island types under those scenarios. Research into the possible un-inhabitability of islands has to be undertaken sensitively to avoid short-term risks (i.e., to avoid depopulation and ultimately island abandonment) associated with a loss of confidence in an island's future (McNamara and Gibson, 2009; McLeman, 2011).

Owing to the high costs of adapting on islands, it has been suggested that there will be a need for migration (Biermann and Boas, 2010; Gemenne, 2011; Nicholls et al., 2011; Voccia 2012). Relocation and displacement are frequently cited as outcomes of SLR, salinization, and land loss on islands (Byravan and Rajan, 2006; Kolmannskog and Trebbi, 2010; see also Section 29.3.3.3). Climate stress is occurring at the same time as the growth in rural to urban migration. The latter is leading to squatter settlements that strain urban infrastructure—notably sewerage, waste management, transport, and electricity (Connell and Lea, 2002; Jones, 2005). Urban squatters on islands often live in highly exposed locations, lacking basic amenities, leaving them highly vulnerable to climate risks (Baker, 2012). However, a lack of research in this area makes it difficult to draw clear conclusions on the impact of climate change on the growing number of urban migrants in islands.

Recent examples of environmental stress-driven relocation and displacement provide contemporary analogs of climate-induced migration. Evidence of post-natural disaster migration has been documented in the Caribbean in relation to hurricanes (McLeman and Hunter, 2010) and in the Carteret Islands, Papua New Guinea, where during an exceptionally high inundation event in 2008 (see Section 29.5.1.1) islanders sought refuge on neighboring Bougainville Island (Jarvis, 2010). Drawing any strong conclusions from this literature is challenging, as there is little understanding of how to measure the effect of the environmental signal in migration patterns (Krishnamurthy, 2012; Afifi et al., 2013). Although the example of the Carteret Islands cannot be described as evidence of adaptation to climate change, it suggests that under some extreme scenarios island communities may need to consider relocating in the future (Gemenne, 2011). In reality, financial and legal barriers are expected to inhibit significant levels of international environmentally induced migration in the Pacific (Barnett and Chamberlain, 2010).

29.6.3. Barriers and Limits to Adaptation in Small Island Settings

Since publication of the SAR in 1996, significant barriers to climate change adaptation strategies in island settings have been discussed in considerable detail. Barriers include inadequate access to financial, technological, and human resources; issues related to cultural and social acceptability of measures; constraints imposed by the existing political and legal framework; the emphasis on island development as opposed to sustainability; a tendency to focus on addressing short-term climate variability rather than long-term climate change; and community preferences for "hard" adaptation measures such as seawalls instead of "soft" measures such as beach nourishment (Sovacool, 2012). Heger et al. (2008) recognized that more diversified economies have more robust responses to climate stress, yet most small islands lack economies of scale in production, thus specializing in niche markets and developing monocultures (e.g., sugar or bananas). Non-sovereign island states face additional exogenous barriers to adaptation. For example, islands such as Réunion and Mayotte benefit from the provision of social services somewhat similar to what obtains in the Metropole, but not the level of enforcement of building codes and land use planning as in France (Le Masson and Kelman, 2011). Owing to their nature and complexity, these constraints will not be easily eliminated in the short term and will require ongoing attention if their impact is to be minimized over time. Exogenous factors such as the comparatively few assessments of social vulnerability to climate change, adaptation potential, or resilience for island communities (Barnett, 2010) limit current understanding. In part this is due to the particularities of islands—both their heterogeneity and their difference from mainland locations—as well as the limitations of climate models in delivering robust science for small islands. It remains the case that, 13 years after Nurse et al. (2001) noted that downscaled global climate models do not provide a complete or necessarily accurate picture of climate vulnerabilities on islands, there is still little climate impacts research that reflects local concerns and contexts (Barnett et al., 2008).

Although lack of access to adequate financial, technological and human resources is often cited as the most critical constraint, experience has shown that endogenous factors such as culture, ethics, knowledge, and attitudes to risk are important in constraining adaptation. Translating the word "climate" into Marshallese implies cosmos, nature, and culture as well as weather and climate (Rudiak-Gould, 2012). Such cultural misunderstandings can create both barriers to action and novel ways of engaging with climate change. The lack of local support (owing to encroachment on traditional lands) for the development of new infiltration galleries to augment freshwater supply on Tarawa atoll, Kiribati, highlights the importance of social acceptability (Moglia et al., 2008a,b). Such considerations have led to the conclusion that there is still much to be learned about the drivers of past adaptation and how "mainstreaming" into national programs and policies, widely acclaimed to be a virtually indispensable strategy, can practically be achieved (Mercer et al., 2007; Adger et al., 2009; Mertz et al., 2009).

Notwithstanding the extensive and ever-growing body of literature on the subject, there is still a relatively low level of awareness and understanding at the community level on many islands about the nature of the threat posed by climate change (Nunn, 2009). Even where the threat has been identified, it is often not considered an urgent issue, or a local priority, as exemplified in Malta (Akerlof et al., 2010) and Funafuti, Tuvalu (Mortreux and Barnett, 2009). Lack of awareness, knowledge, and understanding can function as an effective barrier to the implementation and ultimate success of adaptation programs. This is borne out in both Fiji and Kiribati, where researchers found that spiritual beliefs, traditional governance mechanisms, and a short-term approach to planning were barriers to community engagement and understanding of climate change (Kuruppu, 2009; Lata and Nunn, 2012). Although widely acknowledged to be critical in small islands, few initiatives pay little more than perfunctory attention to the importance of awareness, knowledge, and understanding in climate change adaptation planning. Hence, the renewed call for adaptation initiatives to include and focus directly on these elements on an ongoing basis (e.g., Crump, 2008; Kelman and West, 2009; Kelman, 2010; Gero et al., 2011; Kuruppu and Liverman, 2011) is timely, if these barriers are to be eventually removed.

29.6.4. Mainstreaming and Integrating Climate Change into Development Plans and Policies

There is a growing body of literature that discusses the benefits and possibilities of mainstreaming or integrating climate change policies in development plans. Various mechanisms through which development agencies as well as donor and recipient countries can seek to capitalize on the opportunities to mainstream are beginning to emerge (see, e.g., Klein et al., 2007; Mertz et al., 2009). Agrawala and van Aalst (2008) provide examples, from Fiji and elsewhere, of where synergies (and trade-offs) can be found in integrating adaptation to climate change into development cooperation activities, notably in the areas of disaster risk reduction, community-based approaches to development, and building adaptive capacity. Boyd et al. (2009) support the need for more rapid integration of adaptation into development planning, to ensure that adaptation is not side-lined, or treated separately from sectoral policies. Although there are synergies and benefits to be derived from the integration of climate change and development policies, care is needed to avoid institutional overlaps, and differences in language and approach— which can give rise to conflict (Schipper and Pelling, 2006). Overall, there appears to be an emerging consensus around the views expressed by Swart and Raes (2007) that climate change and development strategies should be considered as complementary, and that some elements such as land and water management and urban, peri-urban, and rural planning provide important adaptation, development, and mitigation opportunities. Although the potential to deliver such an integrated approach may be reasonably strong in urban centers on islands, there appears to be limited capacity to mainstream climate change adaptation into local decision making in out-lying islands or peripheral areas (Nunn et al., 2013).

29.7. Adaptation and Mitigation Interactions

GHG emissions from most small islands are negligible in relation to global emissions, yet small islands will most probably be highly impacted by climate change (Srinivasan, 2010). However, many small island governments and communities have chosen to attempt to reduce their GHG emissions because of the cost and the potential co-benefits and synergies. Malta and Cyprus are obliged to do so in line with EU climate and energy policies. This section considers some of the interlinkages between adaptation and mitigation on small islands and the potential synergies, conflicts, trade-offs, and risks. Unfortunately there is relatively little research on the emissions reduction potential of small islands, and far less on the interlinkages between climate change adaptation and emissions reduction in small islands. Therefore in this section a number of assumptions are made about how and where adaptation and mitigation actions interact.

29.7.1. Assumptions/Uncertainties Associated with Adaptation and Mitigation Responses

Small islands are not homogeneous. Rather they have diverse geophysical characteristics and economic structures (see Table 29-2; Figure 29-1). Following Nunn (2009), the combination of island geography and economic types informs the extent to which adaptation and mitigation actions might interact. The geography and location of islands affect their sensitivity to hydro-meteorological and related hazards such as cyclones, floods, droughts, invasive alien species, vector-borne disease, and landslides. On the other hand, the capacity of island residents to cope is often related to income levels, resources endowment, technology, and knowledge (see Section 29.6.2).

The potential for mitigation and emissions reductions in islands depends to a large extent on their size and stage of economic development. In the small and less developed islands key "mitigation" sectors including energy, transport, industry, built environment, agriculture, forestry, or waste management sectors are generally relatively small (IPCC, 2007; Swart and Raes, 2007). Hence opportunities for emissions reductions are usually quite limited and are mostly associated with electricity generation and utilization of vehicles. More mitigation opportunities should exist in more economically advanced and larger islands that rely on forms of production that utilize fossil fuels, including manufacturing, and where vehicle usage is extensive and electricity-driven home appliances, such as air conditioners and water heaters, are extensively used.

In the absence of significant mitigation efforts at the global scale, adaptation interventions could become very costly and difficult to implement, once certain thresholds of change are reached (Birkmann, 2011; Nelson, 2011). Nicholls et al. (2011) make a similar observation with respect to coastal protection as a response to SLR. They suggest that if global mean temperatures increase by around 4°C (which may lead to sea level rise between 0.5 m and 2 m) the likelihood of successful coastal protection in some locations, such as low-lying small islands, will be low. Consequently, it is argued that the relocation of communities would be a likely outcome in such circumstances (Nicholls et al., 2011).

29.7.2. Potential Synergies and Conflicts

IPCC (2007) suggest that adaptation and mitigation interactions occur in one of four main ways: adaptations that result in GHG emissions reduction; mitigation options that facilitate adaptation; policy decisions that couple adaptation and mitigation effects; and trade-offs and synergies between adaptation and mitigation. Each of these opportunities is considered using three examples: coastal forestry, energy supply, and tourism.

Small islands have relatively large coastal zones (in comparison to land area) and most development (as well as potential mitigation and adaptation activities) are located in the coastal zone. Coastal ecosystems (coral reefs, seagrasses, and mangroves) play an important role in protecting coastal communities from wave erosion, tropical cyclones, storm surges, and even moderate tsunami waves (Cochard et al., 2008). Although coastal forests—including both endemic and exotic species, especially mangroves—are seen as effective adaptation options ("bioshields"; Feagin et al., 2010) in the coastal zones, they also play an important role in mitigation as carbon sinks (van der Werf et al., 2009). Thus, the management and conservation of mangrove forests has the potential to generate synergies between climate change adaptation and mitigation. However, despite this knowledge, population, development, and agricultural pressures have constrained the expansion of island forest carbon stocks (Fox et al., 2010) while Gilman et al. (2008) note that such pressures can also reduce the buffering capacity of coastal vegetation systems.

Renewable energy resources on small islands have only recently been considered within the context of long-term energy security (Chen et al., 2007; Praene et al., 2012). Stuart (2006) speculates that the lack of uptake of renewable technologies to date might be due to historical commitments to conventional fossil fuel-based infrastructure, and a lack of resources to undertake research and development of alternatives. Those islands that have introduced renewable energy technologies have often done so with support from international development agencies (Dornan, 2011). Despite this, there remain significant barriers to the wider institutionalization of renewable technologies in small islands. Research in Europe and the USA has shown the mitigation and cost savings benefits of Energy Service Companies (ESCOs): companies that enter into medium- to long-term performance-based contracts with energy users, invest in energy-efficiency measures in buildings and firms, and profit from the ensuing energy savings measures for the premises (see, e.g., Steinberger et al., 2009). Potential benefits exist in creating the opportunity for ESCOs to operate in small islands. Preliminary evidence from Fiji suggests that if the incentive mechanisms can be resolved, and information asymmetries between service providers and users can be aligned, ESCOs could provide an opportunity to expand renewable technologies (Dornan, 2009). IPCC (2011) presents examples of opportunities for renewable energy, including wind energy sources, as deployed in the Canary Islands.

The transition toward renewable energy sources away from fossil fuel dependence has been partly driven by economic motives, notably to avoid oil price volatility and its impact. The development of hydro-power (in Fiji, for example) necessitates protection and management of the water catchment zones, and thus could lead to improved management of the water resources—a critical adaptation consideration for areas expected to experience a decrease in average rainfall as a result of climate change. While the cost effectiveness of renewable technologies is critical, placing it within the context of water adaptation could enhance project viability (Dornan, 2009). Cost-benefit analyses have shown that in southeast Mediterranean islands photovoltaic generation and storage systems may be more cost-effective than existing thermal power stations (Kaldellis, 2008; Kaldellis et al., 2009).

Energy prices in small islands are among the highest anywhere in the world, mainly because of their dependence on imported fossil fuel, and limited ability to reap the benefits of economies of scale including bulk buying. Recent studies show that the energy sectors in small islands may be transformed into sustainable growth entities mainly through the judicious exploitation of renewable energy sources, combined with the implementation of energy-efficiency measures (van Alphen et al., 2008; Banuri, 2009; Mohanty, 2012; Rogers et al., 2012). Realizing the potential for such transformation, the countries comprising the Alliance of Small Island States (AOSIS) launched SIDS Dock, which is intended to function as a "docking station" to connect the energy sector in small island developing states with the international finance, technology, and carbon markets with the objective of pooling and optimizing energy-efficiency goods and services for the benefit of the group. This initiative seeks to decrease energy dependence in small island developing states, while generating financial resources to support low carbon growth and adaptation interventions.

Many small islands rely heavily on the foreign exchange from tourism to expand and develop their economies, including the costs of mitigation and adaptation. Tourism, particularly in small islands, often relies on coastal and terrestrial ecosystems to provide visitor attractions and accommodation space. Recognizing the relationship between ecosystem services and tourism in Jamaica, Thomas-Hope and Jardine-Comrie (2007) suggest that sustainable tourism planning should include activities undertaken by the industry, that is, tertiary treatment of waste and reuse of water, as well as composting organic material and investing in renewable energy. Gössling and Schumacher (2010) and others who have examined the linkages between GHG emissions and sustainable tourism argue that the tourism sector (operators and tourists) should pay to promote sustainable tourism, especially where they benefit directly from environmental services sustained by these investments.

29.8. Facilitating Adaptation and Avoiding Maladaptation

Although there is a clear consensus that adaptation to the risks posed by global climate change is necessary and urgent in small islands, the implementation of specific strategies and options is a complex process that requires critical evaluation of multiple factors, if expected outcomes are to be achieved (Kelman and West, 2009; Barnett and O'Neill, 2012). These considerations may include, *inter alia*, prior experience with similar or related threats, efficacy of the strategies or options and their co-benefits, costs (monetary and non-monetary), availability of alternatives, and social acceptability. In addition, previous work (e.g., Adger et al., 2005) has emphasized the relevance of scale as a critical factor when assessing the efficacy and value of adaptation strategies, as the extent to which an option is perceived to be a success, failure, or maladaptive may be conditioned by whether it is being assessed as a response to climate variability (shorter term) or climate change (longer term).

As in other regions, adaptation in islands is locally delivered and context specific (Tompkins et al., 2010). Yet, sectors and communities on small islands are often so intricately linked that there are many potential pathways that may lead to maladaptation, be it via increased GHG emissions, foreclosure of future options, or burdensome opportunity costs on local communities. There is also a concern that some types of interventions may actually be maladaptive. For example, Barnett and O'Neill (2012) suggest that strategies such as resettlement and migration should be regarded as options of "last resort" on islands, as they may actually discourage viable adaptation initiatives, by fostering over-dependence on external support. They further argue that *a priori* acceptance of adaptation as an efficacious option for places like the Pacific Islands may also act as a disincentive for reducing GHG emissions (Barnett and O'Neill, 2012).

Notwithstanding the observations of Barnett and O'Neill (2012), there is a concern that early foreclosure of this option might well prove maladaptive, if location-specific circumstances show such action to be efficacious in the longer term. For example, Bunce et al. (2009) have shown that, as an adaptive response to poverty, young fishers from Rodrigues Island periodically resort to temporary migration to the main capital island, Mauritius, where greater employment prospects exist. The case study of the residents of Nauru, who contemplated resettlement

Frequently Asked Questions

FAQ 29.3 | Is it appropriate to transfer adaptation and mitigation strategies between and within small island countries and regions?

Although lessons learned from adaptation and mitigation experiences in one island or island region may offer some guidance, caution must be exercised to ensure that the transfer of such experiences is appropriate to local biophysical, social, economic, political, and cultural circumstances. If this approach is not purposefully incorporated into the implementation process, it is possible that maladaptation and inappropriate mitigation may result. It is therefore necessary to carefully assess the risk profile of each individual island so as to ensure that any investments in adaptation and mitigation are context specific. The varying risk profiles between individual small islands and small island regions have not always been adequately acknowledged in the past.

in Australia after the collapse of phosphate mining (their only revenue source) in the 1950s, provides helpful insight into the complex social, economic, and cultural challenges associated with environmentally triggered migration (Tabucanon and Opeskin, 2011). Negotiations with the Government of Australia collapsed before a mutually acceptable agreement was reached, and the Nauruans opted to abandon the proposal to relocate (Tabucanon and Opeskin, 2011). Overall, however, it is suggested that states contemplating long-term, off-island migration may wish to consider early proactive planning, as resettlement of entire communities might prove to be socially, culturally, and economically disruptive (Campbell, 2010; McMichael et al., 2012; see also Section 29.3.3.3). A related challenge facing small islands is the need to find the middle ground between resettlement and objective assessment of other appropriate adaptation choices.

Similarly, although insurance is being promoted as an element of the overall climate change response strategy in some island regions, for example, the Caribbean, concerns have been expressed about possible linkages to maladaptation. The potential consequences include the imposition of exorbitant premiums that are beyond the capacity of resource-scarce governments as the perception of climate change risks increase, discriminatory coverage of sectors that may not align with local priorities, and tacit encouragement for the state, individuals, and the private sector to engage in behavior that is not risk-averse, for example, development in hazard-prone areas (Herweijer et al., 2009; Linnerooth-Bayer et al., 2011; Thomas and Leichenko, 2011; van Nostrand and Nevius, 2011). Likewise, although the exploitation of renewable energy is vital to the sustainable development of small islands, more attention needs to be paid to the development of energy storage technologies, if rapid transition from conventional fuels is to be achieved in an efficient manner. This is especially important in the case of intermittent energy sources (e.g., solar and wind), as the cost of current storage technologies can frustrate achievement of full conversion to renewable energy. Thus to avoid the possibility of maladaptation in the sector, countries may wish to consider engaging in comprehensive planning, including considerations relating to energy storage (Krajačić et al., 2010; Bazilian et al., 2011).

Recent studies have demonstrated that opportunities exist in island environments for avoiding maladaptation. Studies have shown that decisions about adaptation choices and their implementation are best facilitated where there is constructive engagement with the communities at risk, in a manner that fosters transparency and trust (van Aalst et al., 2008; López-Marrero, 2010). Further, some analysts argue that adaptation choices are often subjective in nature and suggest that participatory stakeholder involvement can yield valuable information about the priorities and expectations that communities attach to the sector for which adaptation is being sought.

The point is underscored by Moreno and Becken (2009), whose study of the tourism sector on the Mamanuca islands (Fiji) clearly demonstrates that approaches that explicitly integrate stakeholders into each step of the process from vulnerability assessment right through to consideration of alternatives measures can provide a sound basis for assisting destinations with the implementation of appropriate adaptation interventions. This view is supported by Dulal et al. (2009), who argue that the most vulnerable groups in the Caribbean—the poor, elderly, indigenous communities, and rural children—will be at greater risk of being marginalized, if adaptation is not informed by equitable and participatory frameworks.

Other studies reveal that new paradigms whose adoption can reduce the risk of maladaptation in island environments are emerging across various sectors. In the area of natural resource management, Hansen et al. (2010) suggest that the use of protected areas for climate refugia, reduction of non-climate stressors on ecosystems, and adoption of adaptive management approaches, combined with reduction of GHG emissions wherever possible, may prove to be more effective response strategies than traditional conservation approaches. Other strategic approaches, including the implementation of multi-sectoral and cross-sectoral measures, also facilitate adaptation in a more equitable, integrated, and sustainable manner. Similarly, "no-regret" measures such as wastewater recycling, trickle irrigation, conversion to non-fossil fuel-based energy, and transportation which offer collateral benefits with or without the threat of climate change and "low-regret" strategies, which may increase existing operational costs only marginally, are becoming increasingly attractive options to island governments (Gravelle and Mimura, 2008; Heltberg et al., 2009; Howard et al., 2010). Together, these constitute valid risk management approaches, as they are designed to assist communities in making prudent, but necessary decisions in the face of an uncertain future.

Some authors suggest that caution is needed to ensure that donors are not driving the adaptation and mitigation agenda in small islands, as there is a risk that donor-driven adaptation or mitigation may not always address the salient challenges on small islands, and may lead to inadequate adaptation or a waste of scarce resources (Nunn, 2009; Barnett, 2010). Others argue that donor-led initiatives may unintentionally cause enhanced vulnerability by supporting adaptation strategies that are externally derived, rather than optimizing the benefits of local practices that have proven to be efficacious through time (Reenberg et al., 2008; Campbell and Beckford, 2009; Kelman and West, 2009).

29.9. Research and Data Gaps

Several advances have taken place in our understanding of the observed and potential effects of climate change on small islands since the AR4. These cover a range of themes including dynamic downscaling of scenarios appropriate for small islands; impacts of transboundary processes generated well beyond the borders of an individual nation or island; barriers to adaptation in small islands and how they may be overcome; the relationships between climate change adaptation and disaster risk reduction; and the relationships between climate change adaptation, maladaptation, and sustainable development.

It is also evident that much further work is required on these themes in small island situations, especially comparative research. Important information and data gaps and many uncertainties still exist on impacts, vulnerability, and adaptation in small islands. These include:

- **Lack of climate change and socioeconomic scenarios and data at the required scale for small islands**. Although some advances have been made (Taylor et al., 2007; Australian Bureau of Meteorology and CSIRO, 2011a,b), much of the work in the

Caribbean, Pacific and Indian Oceans, and Mediterranean islands is focused at the regional scale rather than being country specific. Because most socioeconomic decisions are taken at the local level, there is a need for a more extensive database of simulations of future small island climates and socioeconomic conditions at smaller spatial scales.

- **Difficulties in detecting and attributing past impacts on small islands to climate change processes.** Further investigation of the observed impacts of weather, climate, and ocean events that may be related to climate change is required to clarify the relative role of climate change and non-climate change drivers.
- **Uncertainty in the projections is not a sufficiently valid reason to postpone adaptation planning in small islands.** In several small islands adaptation is being progressed without a full understanding of past or potential impacts and vulnerability. Although assessment of future impacts is hampered because of uncertainty in climate projections at the local island level, alternative scenarios based on a general understanding of broad trends could be used in vulnerability and sensitivity studies to guide adaptation strategies.
- **Need for a range of climate change-related projections beyond temperature and sea level.** Generally, climate-model projections of temperature and sea level have been satisfactory, but there are strong requirements for projections for other variables that are of critical importance to small islands. These include rainfall and drought, wind direction and strength, tropical storms and wave climate, and recognition that transboundary processes are also significant in a small island context. Although some such work has been undertaken for some parts of the Pacific (Australian Bureau of Meteorology and CSIRO, 2011a,b), similar work still needs to be carried out in other small island regions. In addition, the reliability of existing projections for some of the other parameters needs to be improved and the data should be in suitable formats for use in risk assessments.
- **Need to acknowledge the heterogeneity and complexity of small island states and territories.** Although small islands have several characteristics in common, neither the variety nor complexity of small islands is sufficiently reflected in the literature. Thus, transfer of data and practices from a continental situation, or from one small island state to another, needs to be done with care and in a manner that takes full cognizance of such heterogeneity and complexity.
- **Within-country and -territory differences need to be better understood**. Many of the environmental and human impacts reported in the literature on islands have been attributed to the whole country, when in fact they refer only to the major center or town or region. There is need for more work on rural areas, outer islands, and secondary communities. Several examples of such research have been cited in this chapter. Also it should be noted that some small island states are single islands and others highly fragmented multiple islands.
- **Lack of investment and attention to climate and environmental monitoring frameworks in small islands.** A fundamental gap in the ability to improve empirical understanding of present and future climate change impacts is the lack of climate and environmental monitoring frameworks that in turn hampers the level of confidence with which adaptation responses can be designed and implemented.
- **Economic and social costs of climate change impacts and adaptation options are rarely known.** In small island states and territories the costs of past weather, climate, and ocean events are poorly known and further research is required to identify such costs, and to determine the economic and societal costs of climate change impacts and the costs of adaptation options to minimize those impacts.

The foregoing list is a sample of the gaps, needs, and research agenda that urgently need to be filled for small islands. Although some countries have begun to fill these gaps, this work needs to be replicated and expanded across all island regions to improve the database available for ongoing climate change assessments. Such information would raise the level of confidence in the adaptation planning and implementation process in small islands.

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The Ocean

Coordinating Lead Authors:
Ove Hoegh-Guldberg (Australia), Rongshuo Cai (China)

Lead Authors:
Elvira S. Poloczanska (Australia), Peter G. Brewer (USA), Svein Sundby (Norway), Karim Hilmi (Morocco), Victoria J. Fabry (USA), Sukgeun Jung (Republic of Korea)

Contributing Authors:
William Skirving (USA), Dáithí Stone (Canada/South Africa/USA), Michael T. Burrows (UK), Johann Bell (New Caledonia), Long Cao (China), Simon Donner (Canada), C. Mark Eakin (USA), Arne Eide (Norway), Benjamin Halpern (USA), Charles R. McClain (USA), Mary I. O'Connor (Canada), Camille Parmesan (USA), R. Ian Perry (Canada), Anthony J. Richardson (Australia), Christopher J. Brown (Australia), David Schoeman (Australia), Sergio Signorini (USA), William Sydeman (USA), Rui Zhang (China), Ruben van Hooidonk (USA), Stewart M. McKinnell (PICES/Canada)

Review Editors:
Carol Turley (UK), Ly Omar (Senegal)

Volunteer Chapter Scientists:
Jo Davy (New Zealand), Sarah Lee (USA)

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Executive Summary

The Ocean plays a central role in Earth's climate and has absorbed 93% of the extra energy from the enhanced greenhouse effect and approximately 30% of anthropogenic carbon dioxide (CO_2) from the atmosphere. Regional responses are addressed here by dividing the Ocean into seven sub-regions: High-Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), Coastal Boundary Systems (CBS), Equatorial Upwelling Systems (EUS), Subtropical Gyres (STG), Semi-Enclosed Seas (SES), and the Deep Sea (DS; >1000 m). An eighth region, Polar Seas, is dealt with by Chapter 28. {Figure 30-1; WGI AR5 6.3.1; WGI AR5 Boxes 3.1, 3.8}

Global average sea surface temperatures have increased since both the beginning of the 20th century and the 1950s (certain). The average sea surface temperature (SST) of the Indian, Atlantic, and Pacific Oceans has increased by 0.65°C, 0.41°C, and 0.31°C, respectively, over the period 1950–2009 (*very likely*, *p*-value ≤ 0.05). Changes in the surface temperatures of the ocean basins are consistent with temperature trends simulated by ocean-atmosphere models with anthropogenic greenhouse gas (GHG) forcing over the past century (*high confidence*). Sub-regions within the Ocean also show *robust evidence* of change, with the influence of long-term patterns of variability (e.g., Pacific Decadal Oscillation (PDO); Atlantic Multi-decadal Oscillation (AMO)) contributing to variability at regional scales, and making changes due to climate change harder to distinguish and attribute. {30.3.1; Figure 30-2e-g; Table 30-1; WGI AR5 2.4.2-3, 3.2, 10.4.1, 14}

Uptake of CO_2 has decreased ocean pH (approximately 0.1 unit over 100 years), fundamentally changing ocean carbonate chemistry in all ocean sub-regions, particularly at high latitudes (*high confidence*). The current rate of ocean acidification is unprecedented within the last 65 Ma (*high confidence*), if not the last 300 Ma (*medium confidence*). Warming temperatures, and declining pH and carbonate ion concentrations, represent risks to the productivity of fisheries and aquaculture, and the security of regional livelihoods given the direct and indirect effects of these variables on physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function) and ecosystem processes (e.g., primary productivity, reef building and erosion) (*high confidence*). {6.1.2, 6.2-3, 30.3.2, 30.6; WGI AR5 3.8.2; WGI AR5 Boxes 3.2, 5.3.1}

Regional changes observed in winds, surface salinity, stratification, ocean currents, nutrient availability, and oxygen depth profile in many regions may be a result of anthropogenic GHG emissions (*low* to *medium confidence*). Marine organisms and ecosystems are *likely* to change in response to these regional changes, although evidence is limited and responses uncertain. {6.2-3, 30.3, 30.5; WGI AR5 2.7, 3.3-8, 10.4.2, 10.4.4}

Most, if not all, of the Ocean will continue to warm and acidify, although the rates will vary regionally (*high confidence*). Differences between Representative Concentration Pathways (RCPs) are *very likely* to be minimal until 2040 (*high confidence*). Projected temperatures of the surface layers of the Ocean, however, diverge as the 21st century unfolds and will be 1°C to 3°C higher by 2100 under RCP8.5 than RCP2.6 across most ocean sub-regions. The projected changes in ocean temperature pose serious risks and vulnerabilities to ocean ecosystems and dependent human communities (*robust evidence*, *high agreement*; *high confidence*). {6.5, 30.3.1-2, 30.7.1; Figure 30-2e-g; Table 30-3; WGI AR5 11.3.3, 12.4.7; WGI AR5 Box 1.1}

Rapid changes in physical and chemical conditions within ocean sub-regions have already affected the distribution and abundance of marine organisms and ecosystems. Responses of species and ecosystems to climate change have been observed from every ocean sub-region (*high confidence*). Marine organisms are moving to higher latitudes, consistent with warming trends (*high confidence*), with fish and zooplankton migrating at the fastest rates, particularly in HLSBS regions. Changes to sea temperature have also altered the phenology, or timing of key life-history events such as plankton blooms, and migratory patterns and spawning in fish and invertebrates, over recent decades (*medium confidence*). There is *medium* to *high agreement* that these changes pose significant uncertainties and risks to fisheries, aquaculture, and other coastal activities. Ocean acidification maybe driving similar changes (*low confidence*), although there is *limited evidence* and *low agreement* at present. The associated risks will intensify as ocean warming and acidification continue. {6.3-4, 30.4-5; Table 30-3; Box CC-MB}

Regional risks and vulnerabilities to ocean warming and acidification can be compounded by non-climate related stressors such as pollution, nutrient runoff from land, and over-exploitation of marine resources, as well as natural climate variability (*high confidence*). These influences confound the detection and attribution of the impacts of climate change and ocean acidification on ecosystems yet may also represent opportunities for reducing risks through management strategies aimed at reducing their influence, especially in CBS, SES, and HLSBS. {5.3.4, 18.3.3-4, 30.1.2, 30.5-6}

Recent changes to wind and ocean mixing within the highly productive HLSBS, EBUE, and EUS are *likely* to influence energy transfer to higher trophic levels and microbial processes. There is, however, *limited evidence* and *low agreement* on the direction and magnitude of these changes and their relationship to ocean warming and acidification (*low confidence*). In cases where Net Primary Productivity (NPP) increases or is not consumed (e.g., Benguela EBUE, *low confidence*), the increased transfer of organic carbon to deep regions can stimulate microbial respiration and reduce O_2 levels (*medium confidence*). Oxygen concentrations are also declining in the tropical Pacific, Atlantic, and Indian Oceans (particularly EUS) due to reduced O_2 solubility at higher temperatures, and changes in ocean ventilation and circulation. {6.3.3, 30.3, 30.5.1-2, 30.5.5; Box CC-PP; WGI AR5 3.8.3}

Global warming will result in more frequent extreme events and greater associated risks to ocean ecosystems (*high confidence*). In some cases (e.g., mass coral bleaching and mortality), projected increases will eliminate ecosystems, and increase risks and vulnerabilities to coastal livelihoods and food security (e.g., CBS in Southeast Asia; SES, CBS, and STG in the Indo-Pacific) (*medium* to *high confidence*). Reducing stressors not related to climate change represents an opportunity to strengthen the ecological resilience within these regions, which may help them survive some projected changes in ocean temperature and chemistry. {5.4, 30.5.3-4, 30.5.6, 30.6.1; Figure 30-4; Box CC-CR; IPCC, 2012}

The highly productive HLSBS in the Northeastern Atlantic has changed in response to warming (*medium evidence*, *high agreement*), with a range of consequences for fisheries. These ecosystems are responding to recent warming, with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganization of fish assemblages (*high confidence*). There is *medium confidence* that these changes will have both positive and negative implications depending on the particular HLSBS fishery and the time frame. {6.4.1.1, 6.5.3, 30.5.1, 30.6.2.1; Boxes CC-MB, 6-1}

EUS, which support highly productive fisheries off equatorial Africa and South America, have warmed over the past 60 years (Pacific EUS: 0.43°C, Atlantic EUS: 0.54°C; *very likely*, p-value ≤ 0.05). Although warming is consistent with changes in upwelling intensity, there is *low confidence* in our understanding of how EUS will change, especially in how El Niño-Southern Oscillation (ENSO) and other patterns of variability will interact in a warmer world. The risk, however, of changes to upwelling increases with average global temperature, posing significant uncertainties for dependent ecosystems, communities, and fisheries. {30.5.2; WGI AR5 14.4}

The surface waters of the SES show significant warming from 1982 and most CBS show significant warming since 1950. Warming of the Mediterranean has led to the recent spread of tropical species invading from the Atlantic and Indian Oceans. Projected warming increases the risk of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and the formation of additional hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). In some CBS, such as the East China Sea and Gulf of Mexico, these changes are further influenced by the contribution of nutrients from coastal pollution contributing to the expansion of hypoxic (low O_2) zones. These changes are *likely* to influence regional ecosystems as well as dependent industries such as fisheries and tourism, although there is *low confidence* in the understanding of potential changes and impacts. {5.3.4.3, 30.5.3-4; Table 30-1}

Coral reefs within CBS, SES, and STG are rapidly declining as a result of local stressors (i.e., coastal pollution, overexploitation) and climate change (*high confidence*). Elevated sea temperatures drive impacts such as mass coral bleaching and mortality (*very high confidence*), with an analysis of the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble projecting the loss of coral reefs from most sites globally by 2050 under mid to high rates of ocean warming (*very likely*). {29.3.1.2, 30.5.3-4, 30.5.6; Figure 30-10; Box CC-CR}

The productive EBUE and EUS involve upwelling waters that are naturally high in CO_2 concentrations and low in pH, and hence are potentially vulnerable to ocean warming and acidification (*medium confidence*). There is *limited evidence* and *low agreement* as to how upwelling systems are *likely* to change (*low confidence*). Declining O_2 and shoaling of the aragonite saturation horizon through ocean acidification increase the risk of upwelling water being low in pH and O_2, with impacts on coastal ecosystems and fisheries, as has been seen already (e.g., California Current EBUE). These risks and uncertainties are *likely* to involve significant challenges for fisheries and associated livelihoods along the west coasts of South America, Africa, and North America (*low* to *medium confidence*). {22.3.2.3, 30.3.2.2, 30.5.2, 30.5.5; Boxes CC-UP, CC-PP}

Chlorophyll concentrations measured by satellites have decreased in the STG of the North Pacific, Indian, and North Atlantic Oceans by 9%, 12%, and 11%, respectively, over and above the inherent seasonal and interannual variability from 1998 to 2010 (*high confidence*; p-value ≤ 0.05). Significant warming over this period has resulted in increased water column stratification, reduced mixed layer depth, and possibly decreases in nutrient availability and ecosystem productivity (*limited evidence*, *medium agreement*). The short time frame of these studies against well-established patterns of long-term variability leads to the conclusion that these changes are *about as likely as not* due to climate change. {6.3.4, 30.5.6; Table 30-1; Box CC-PP; WGI AR5 3.8.4}

The world's most abundant yet difficult to access habitat, the DS, is changing (*limited evidence*, *medium agreement*), with warming between 700 and 2000 m from 1957 to 2010 *likely* to involve a significant anthropogenic signal (*medium confidence*). Decreased primary productivity of surface waters (e.g., STG) is *likely* to reduce the availability of organic carbon to DS ecosystems. Understanding of the risks of climate change and ocean acidification to the DS is important given the size of the DS region but is limited (*low confidence*). {30.5.7; Figure 30-2; WGI AR5 3.2.4; WGI AR5 Figures 3.2, 3.9}

Changes to surface wind and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy, and mineral extraction (*medium confidence*). Risks to equipment and people may be reduced through the design and use of ocean-based infrastructure, together with the evolution of policy (*medium agreement*). Risks and uncertainties will increase with further climate change. New opportunities as well as risks for shipping, energy, and mineral extraction, and international issues over access and vulnerability, may accompany warming waters, particularly at high latitudes. {10.2.2, 10.4.4, 28.2.6, 28.3.4, 30.3.1, 30.6.2; IPCC, 2012}

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries, as well as benefits (*high agreement*). Climate change is a risk to the sustainability of capture fisheries and aquaculture development, adding to the threats of over-fishing and other non-climate stressors. In EUS and STG, shifts in the distribution and abundance of large pelagic fish stocks will have the potential to create "winners" and "losers" among island nations and economies. There has been a boost in fish stocks of high-latitude fisheries in the HLSBS of the North Pacific and North Atlantic, partly as a result of 30 years of increase in temperature. This is *very likely* to continue, although some fish stocks will eventually decline. A number of practical adaptation options and supporting international policies can minimize the risks and maximize the opportunities. {7.4.2, 7.5.1.1.2, 29.4, 30.6-7}

Adaptation strategies for ocean regions beyond coastal waters are generally poorly developed but will benefit from international legislation and expert networks, as well as marine spatial planning (*high agreement*). Fisheries and aquaculture industries with high technology and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling, and resource assessments. For smaller scale fisheries and developing nations, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. Building strategies that include climate forecasting and early-warning systems can reduce impacts of warming and ocean acidification in the short term. Overall, there is a strong need to develop ecosystem-based monitoring and adaptation strategies to mitigate rapidly growing risks and uncertainties to the coastal and oceanic industries, communities, and nations (*high agreement*). {7.5.1.1, 30.6}

Significant opportunity exists within the Ocean and its sub-regions for reducing the CO_2 flux to the atmosphere (*limited evidence*, *medium agreement*). Ecosystems such as mangroves, seagrass, and salt marsh offer important carbon storage and sequestration opportunities (e.g., Blue Carbon; *limited evidence*, *medium agreement*). Blue Carbon strategies can also be justified in terms of the ecosystem services provided by coastal vegetated habitats such as protection against coastal erosion and storm damage, and maintenance of habitats for fisheries species. Sequestration of anthropogenic CO_2 into deep ocean areas still faces considerable hurdles with respect to the expense, legality, and vulnerability of storage sites and infrastructure. There are also significant opportunities with the Ocean for the development of offshore renewable energy such as wind and tidal power. {5.5.7, 30.6.1, 30.6.4}

International frameworks for collaboration and decision making are critically important for coordinating policy that will enable mitigation and adaptation by the Ocean sectors to global climate change (e.g., United Nations Convention on the Law of the Sea (UNCLOS)). These international frameworks offer an opportunity to solve problems collectively, including improving fisheries management across national borders (e.g., reducing illegal, unreported, and unregulated (IUU) fishing), responding to extreme events, and strengthening international food security. Given the importance of the Ocean to all countries, there is a need for the international community to progress rapidly to a "whole of ocean" strategy for responding to the risks and challenges posed by anthropogenic ocean warming and acidification. {30.7.2}

30.1. Introduction

The Ocean exerts a profound influence as part of the Earth, interacting with its atmosphere, cryosphere, land, and biosphere to produce planetary conditions. It also directly influences human welfare through the provision and transport of food and resources, as well as by providing cultural and economic benefits. The Ocean also contributes to human welfare indirectly through the regulation of atmospheric gas content and the distribution of heat and water across the planet. This chapter examines the extent to which regional changes to the Ocean can be accurately detected and attributed to anthropogenic climate change and ocean acidification, building on the conclusions of Chapter 6, which focuses on the marine physiological and ecological responses to climate change and ocean acidification. Detailed assessment of the role of recent physical and chemical changes within the Ocean to anthropogenic climate change is provided in WGI AR5 (particularly Chapters 2, 3, 13, and 14). In this chapter, impacts, risks, and vulnerabilities associated with climate change and ocean acidification are assessed for seven ocean sub-regions, and the expected consequences and adaptation options for key ocean-based sectors are discussed. Polar oceans (defined by the presence of sea ice in the north and by the Polar Front in the south) are considered in Chapter 28.

Given that climate change affects coastal and low-lying sub-regions of multiple nations, detailed discussion of potential risks and consequences for these regions occurs in the relevant chapters of this report (e.g., Chapters 5 and 29, as well as other regional sections).

30.1.1. Major Sub-regions within the Ocean

The Ocean represents a vast region that stretches from the high tide mark to the deepest oceanic trench (11,030 m) and occupies 71% of the Earth's surface. The total volume of the Ocean is approximately 1.3 billion km^3, with approximately 72% of this volume being below 1000 m (Deep Sea (DS); Section 30.5.7). There are considerable challenges in assessing the regional impacts of climate change on the Ocean. Devising an appropriate structure to explore the influence of climate change across the entire Ocean region and the broad diversity of life forms and habitats is challenging. Longhurst (1998) identified more than 50 distinct ecological provinces in the Ocean, defined by physical characteristics and the structure and function of phytoplankton communities. Longhurst's scheme, however, yields far more sub-regions than could be sensibly discussed in the space allocated within AR5. Consequently, comparable principles were used with a division of the non-polar ocean into seven larger sub-regions similar to Barber (1988). It is recognized that these sub-regions do not always match physical-chemical patterns or specific geographies, and that they interact strongly with terrestrial regions through weather systems and the exchange of materials. Different ocean sub-regions may also have substantially different primary productivities and fishery catch. Notably, more than 80% of fishery catch is associated with three ocean sub-regions: Northern Hemisphere High-Latitude Spring Bloom Systems (HLSBS), Coastal Boundary Systems (CBS), and Eastern Boundary Upwelling Ecosystems (EBUE; Table SM30-1, Figure 30-1). The DS (>1000 m) is included as a separate category that overlaps with the six other ocean sub-regions dealt with in this chapter.

30.1.2. Detection and Attribution of Climate Change and Ocean Acidification in Ocean Sub-regions

The central goal of this chapter is to assess the recent literature on the Ocean as a region for changes that can be attributed to climate change and/or ocean acidification. Detailed assessments of recent physical and chemical changes in the Ocean are outlined in WGI AR5 Chapters 2, 3, 6, 10, 13, and 14. The detection and attribution of climate change and ocean acidification on marine organisms and ecosystems is addressed in Chapter 6. This chapter draws on these chapters to investigate regional changes in the physical, chemical, ecological, and socioeconomic aspects of the Ocean and the extent to which they can be attributed to climate change and ocean acidification.

Generally, successful attribution to climate change occurs when the full range of possible forcing factors is considered and those related to climate change are found to be the most probable explanation for the detected change in question (Section 18.2.1.1). Comparing detected changes with the expectations of well-established scientific evidence also plays a central role in the successful attribution of detected changes. This was attempted for seven sub-regions of the Ocean. There are a number of general limitations to the detection and attribution of impacts to climate change and ocean acidification that are discussed elsewhere (Section 18.2.1) along with challenges (Section 18.2.2). Different approaches and "best practice" guidelines are discussed in WGI AR5 Chapters 10 and 18, as well as in several other places (Hegerl et al., 2007, 2010; Stott et al., 2010). The fragmentary nature of ocean observing, structural uncertainty in model simulations, the influence of long-term variability, and confounding factors unrelated to climate change (e.g., pollution, introduced species, over-exploitation of fisheries) represent major challenges (Halpern et al., 2008; Hoegh-Guldberg et al., 2011b; Parmesan et al., 2011). Different factors may also interact synergistically or antagonistically with each other and climate change, further challenging the process of detection and attribution (Hegerl et al., 2007, 2010).

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change and ocean acidification on the Ocean as a region was not included in recent IPCC assessments, although a chapter devoted to the Ocean in the Second Assessment Report (SAR) did "attempt to assess the impacts of projected regional and global climate changes on the oceans" (Ittekkot et al., 1996). The fact that assessments for ocean and coastal systems are spread throughout previous IPCC assessment reports reduces the opportunity for synthesizing the detection and attribution of climate change and ocean acidification across the physical, chemical, ecological, and socioeconomic components of the Ocean and its sub-regions. The IPCC Fourth Assessment Report (AR4) concluded, however, that, while terrestrial sub-regions are warming faster than the oceans, "Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been taking up over 80% of the heat being added to the climate system" (AR4 Synthesis Report, p. 30). AR4 also concluded that sea levels had risen due to the thermal expansion of the Ocean but recognized that

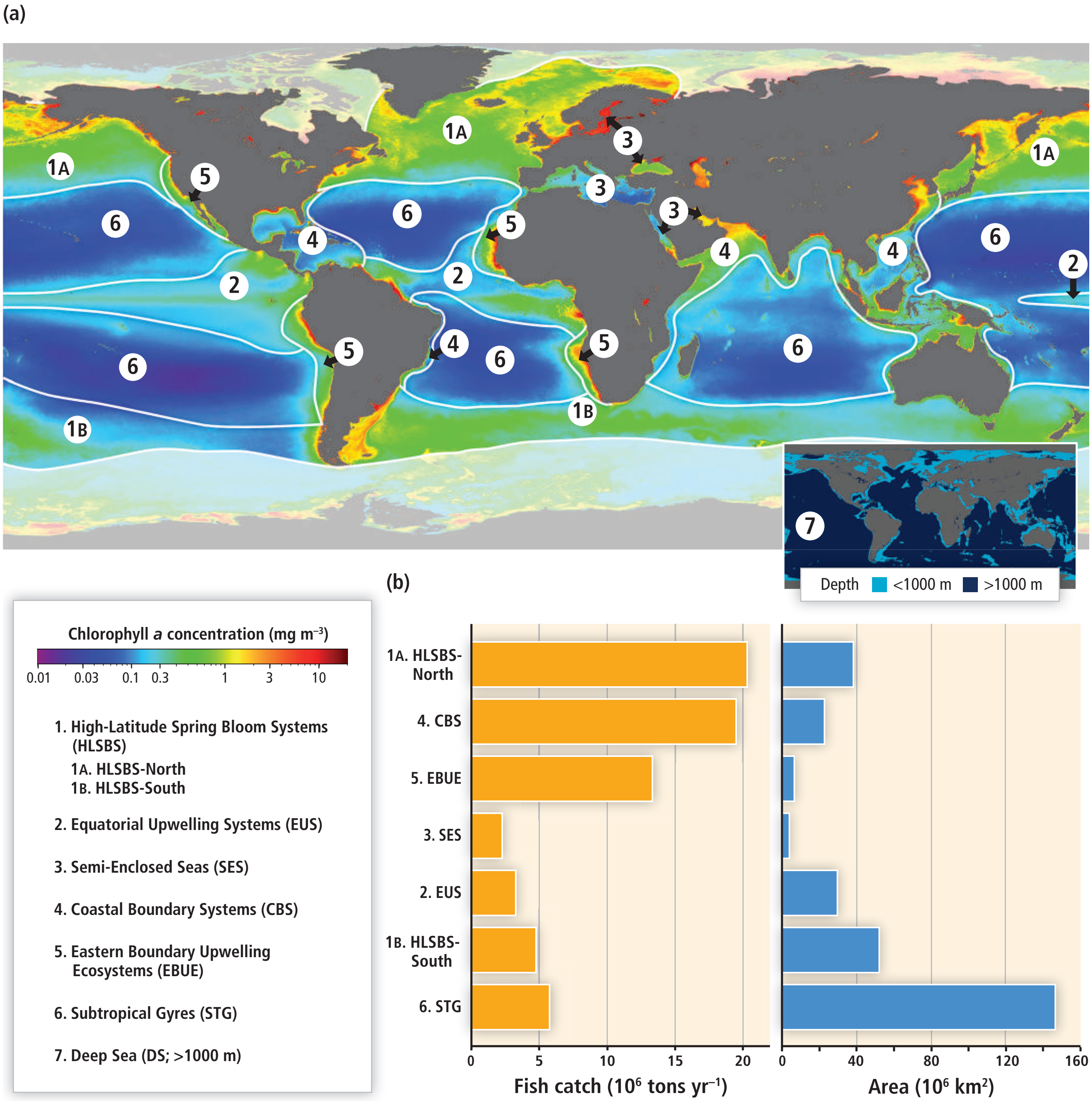


Figure 30-1 | (a) Separation of the world's oceans into seven major sub-regions (excluding an eighth area, Polar Oceans, which is considered in Chapter 28; white shaded area). The chlorophyll-*a* signal measured by SeaWiFS and averaged over the period from Sep 4, 1997 to 30 Nov 2010 (NASA) provides a proxy for differences in marine productivity (with the caveats provided in Box CC-PP). Ecosystem structure and functioning, as well as key oceanographic features, provided the basis for separating the Ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea (DS) habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). (b) Relationship between fish catch and area for each ocean subregion. Left panel: average fish catch (as millions tons yr^{-1}) for the period 1970–2006. Right panel: surface area (millions km^2). The top three bars (subregions HLSBS-North, CBS, and EBUE) cover 19% of the world oceans' area and provide 76% of the world's fish catches. Values for fish catch, area, and primary productivity of the ocean sub-regions are listed in Table SM30-1.

our understanding of the dynamics of glaciers and ice sheets was "too limited to assess their likelihood or provide a best estimate or an upper boundary for sea level rise" (WGI AR4 SPM). Changes to ocean temperature and density have been identified as having the potential to alter large-scale ocean circulation. AR4 concluded that, with respect to the Meridional Overturning Circulation (MOC), "it is *very likely* that up to the end of the 20th century the MOC was changing significantly at interannual to decadal time scales" (WGI AR4 Box 5.1, p. 397), despite limited evidence of a slowing MOC.

According to AR4, "Sea-level rise over the last 100 to150 years is probably contributing to coastal erosion in many places," including the east coast of the United States and the United Kingdom (WGII AR4 Section 1.3.3.1, p. 92). The AR4 assessment was *virtually certain* that rising atmospheric carbon dioxide (CO_2) had changed carbonate chemistry of the ocean (i.e., buffering capacity, carbonate and bicarbonate concentrations), and that a decrease in surface pH of 0.1 had occurred over the global ocean (calculated from the uptake of anthropogenic CO_2 between 1750 and 1994; Sabine et al., 2004; Raven et al., 2005; WGI AR4 Section 5.4.2.3; WGI AR4 Table 7.3). Large-scale changes in ocean salinity were also observed from 1955 to 1998 and were "characterized by a global freshening in sub-polar latitudes and salinification of shallower parts of the tropical and subtropical oceans" (WGI AR4 Chapter 5 ES, p. 387). In this case, freshening was observed in the Pacific, with increased salinity being observed in the Atlantic and Indian Oceans (WGI AR4 Sections 5.3.2-5). These changes in surface salinity were qualitatively consistent with expected changes to surface freshwater flux. Freshening of mid- and high-latitude waters together with increased salinity at low latitudes were seen as evidence "of changes in precipitation and evaporation over the oceans" (WGI AR4 SPM, p. 7).

Substantial evidence presented in AR4 indicated that changing ocean conditions have extensively influenced marine ecosystems (WGII AR4 Table 1.5). AR4 noted that there is an "accumulating body of evidence to suggest that many marine ecosystems, including managed fisheries, are responding to changes in regional climate caused predominately by warming of air and sea surface temperatures (SST) and to a lesser extent by modification of precipitation regimes and wind patterns" (WGII AR4 Section 1.3.4.2, p. 94). Observed changes in marine ecosystems and managed fisheries reported within AR4 included changes to plankton community structure and productivity, the phenology and biogeography of coastal species, intertidal communities on rocky shores, kelp forests, and the distribution of pathogens and invasive species. Changes were also observed in coral reefs (primarily increased mass coral bleaching and mortality) and migratory patterns and trophic interactions of marine birds, reptiles, and mammals, as well as of a range of other marine organisms and ecosystems (WGII AR4 Table 1.5), although a separate exercise in detection and attribution of changes due to climate change (as done for terrestrial studies) was not done as part of AR4.

30.3. Recent Changes and Projections of Future Ocean Conditions

Evidence that increasing concentrations of atmospheric CO_2 have resulted in the warming and acidification of the upper layers of the Ocean has strengthened since AR4. Understanding the full suite of physical and chemical changes to the Ocean is critical to the interpretation of the past and future responses of marine organisms and ecosystems, especially with respect to the implications for coastal and low-lying areas.

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

The Ocean has absorbed 93% of the extra heat arising from the enhanced greenhouse effect (1971–2010), with most of the warming (64%) occurring in the upper (0 to 700 m) ocean (1971–2010; WGI AR5 Section 3.2.3, Figure 3.2, Box 3.1). It is certain that global average SSTs have increased since the beginning of the 20th century, with improvements and growth of data sets and archives, and the understanding of errors and biases since AR4 (WGI AR5 Section 2.4.2). It is *virtually certain* that the upper ocean (0 to 700 m depth) has warmed from 1971 to 2010 (Figure 30-2a), while it is *likely* that the surface layers of the Ocean have warmed from the 1870s to 1971. Rates of increase in temperature are highest near the surface of the Ocean (>0.1°C per decade in the upper 75 m from 1971 to 2010) decreasing with depth (0.015°C per decade at 700 m; Figure 30-2b,c). It is *very likely* that the intensification of this warming near the surface has increased thermal stratification of the upper ocean by about 4% between 0 and 200 m depth from 1971 to 2010 in all parts of the ocean north of 40°S. It is *likely* that the Ocean has warmed between 700 and 2000 m from 1957 to 2010, with the warming signal becoming less apparent or non-existent at deeper depths (WGI AR5 Sections 3.2.1-3, Figures 3.1, 3.2, 3.9). These changes include a significant anthropogenic signal (*virtually certain*; Gleckler et al., 2012; Pierce et al., 2012), with the surface waters of all three ocean basins warming at different rates that exceed those expected if there were no changes to greenhouse gas (GHG) forcing over the past century (Figure 30-2e,f,g). In this respect, the observed record also falls within the range of historical model outputs that include increases in the concentration of GHGs as opposed to models that do not (Figure 30-2e,f,g).

Data archives such as Hadley Centre Interpolated SST 1.1 (HadISST1.1) contain SSTs reconstructed from a range of sources, allowing an opportunity to explore mean monthly, gridded, global SST from 1870 to the present (Rayner et al., 2003). The published HadISST1.1 data set (higher temporal and spatial resolution than HadSST3) was used to explore trends in historic SST within the sub-regions of the Ocean (Figure 30-1a; see definition of regions in Figure SM30-1 and Table SM30-2, column 1). The median SST for 1871–1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the UK Met Office Marine Data Bank (MDB) to produce monthly globally complete fields of SST on a 1° latitude-longitude SST grid from 1870 to the present.

The surface layers of the three ocean basins have warmed (p-value ≤ 0.05, *very likely*), with the Indian Ocean (0.11°C per decade) warming faster than the Atlantic (0.07°C per decade) and Pacific (0.05°C per decade) Oceans (*high confidence*; Table 30-1). This is consistent with the depth-averaged (0 to 700 m) temperature trend observed from 1971 to 2010 (Figure 30-2a).

While some regions (e.g., North Pacific) did not show a clear warming trend, most regions showed either significant warming in the average temperature, or significant warming in either/or the warmest and coolest months of the year, over the period 1950–2009 (HadISST1.1 data; Table 30-1). Trends in SST show considerable sub-regional variability (Table 30-1; Figure 30-2a). Notably, the average temperature of most HLSBS did not increase significantly from 1950 to 2009 (except in the Indian Ocean; Table 30-1) yet the temperatures of the warmest month (North and South Atlantic, and Southeastern Pacific) and of the coolest month (North and South Atlantic, and South Pacific) showed significant upward trends over this period (p-value ≤ 0.05; Table 30-1).

The two EUS warmed from 1950 to 2009 (Pacific EUS: 0.07°C per decade, Atlantic EUS: 0.09°C per decade; Table 30-1). The average monthly SST of the SES did not warm significantly, although the temperature of the coolest month increased significantly within the Baltic Sea (0.35°C per decade or 2.11°C from 1950 to 2009), as did the temperatures of the warmest months in the Black (0.14°C per decade or 0.83°C from 1950 to 2009), Mediterranean (0.11°C per decade or 0.66°C from 1950 to 2009), and Red (0.05°C per decade or 0.28°C from 1950 to 2009) Seas over the period 1950–2009 (*very likely*; Table 30-1). Studies over shorter periods (e.g., 1982–2006; Belkin, 2009) report significant increases in average SST of the Baltic (1.35°C), Black (0.96°C), Red (0.74°C), and Mediterranean (0.71°C) Seas. Such studies

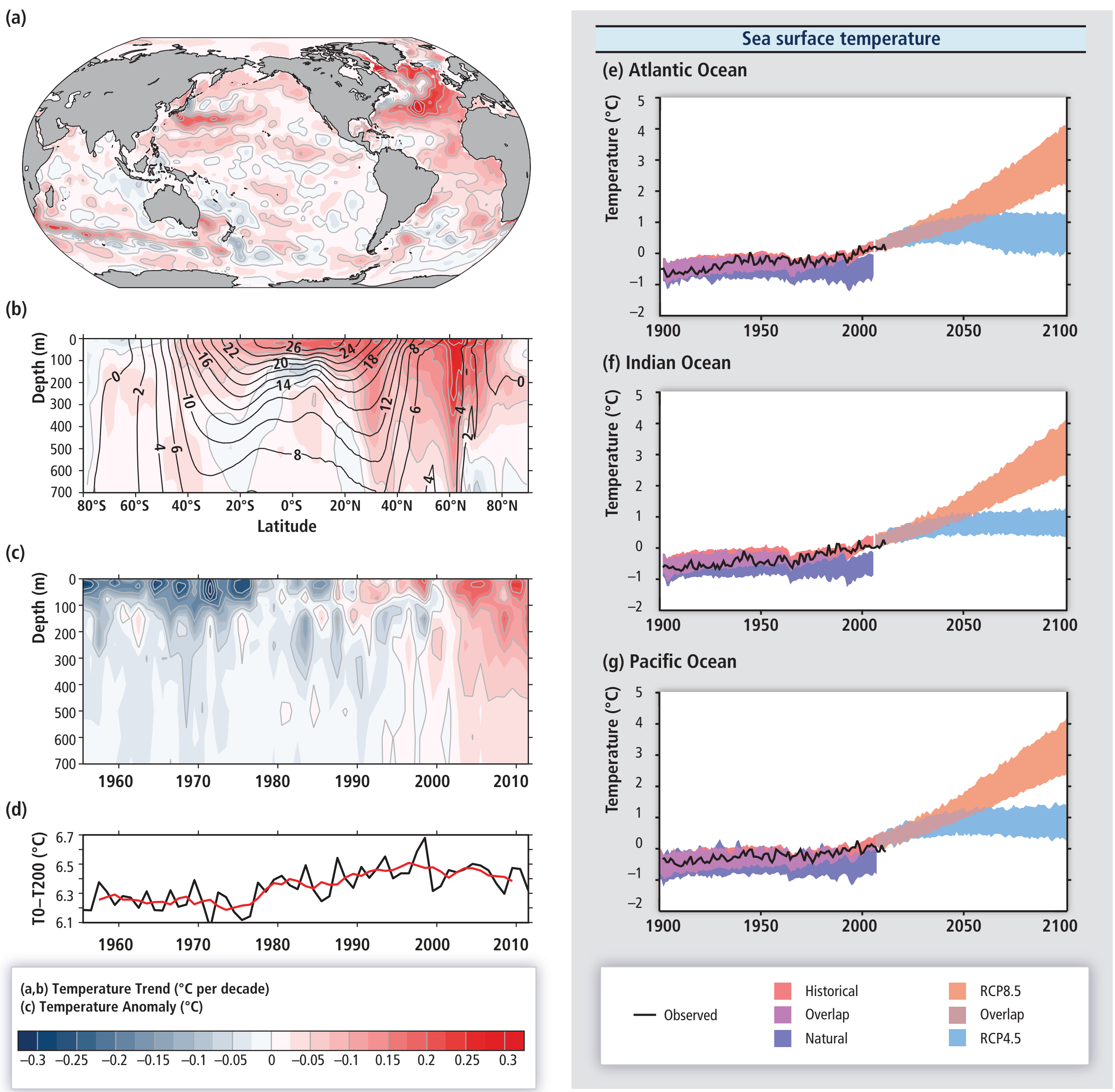


Figure 30-2 | (a) Depth-averaged 0 to 700 m temperature trend for 1971–2010 (longitude vs. latitude, colors and gray contours in degrees Celsius per decade). (b) Zonally averaged temperature trends (latitude vs. depth, colors and gray contours in degrees Celsius per decade) for 1971–2010, with zonally averaged mean temperature over plotted (black contours in degrees Celsius). (c) Globally averaged temperature anomaly (time vs. depth, colors and gray contours in degrees Celsius) relative to the 1971–2010 mean. (d) Globally averaged temperature difference between the Ocean surface and 200 m depth (black: annual values; red: 5-year running mean). [(a–d) from WGI AR5 Figure 3.1] (e)–(g) Observed and simulated variations in past and projected future annual average sea surface temperature over three ocean basins (excluding regions within 300 km of the coast). The black line shows estimates from Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1) observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), and the Representative Concentration Pathways (RCPs; blue: RCP4.5; orange: RCP8.5). Data are anomalies from the 1986–2006 average of the HadISST1.1 data (for the HadISST1.1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Panels (a)-(d) originally presented in WGI AR5 Fig 3.1 and Box 21-2.

Table 30-1 | Regional changes in sea surface temperature (SST) over the period 1950–2009 using the ocean regionalization specified in Figure 30-1(a) (for further details on regions defined for analysis, see Figure SM30-1 and Table SM30-2, column 1). A linear regression was fitted to the average of all 1×1 degree monthly SST data extracted from the Hadley Centre HadISST1.1 data set (Rayner et al., 2003) for each sub-region over the period 1950–2009. All SST values less than –1.8°C, together with all SST pixels that were flagged as being sea ice, were reset to the freezing point of seawater (–1.8°C) to reflect the sea temperature under the ice. Separate analyses were also done to explore trends in the temperatures extracted from the coldest-ranked and the warmest-ranked month of each year (Table SM30-2). The table includes the slope of the regression (°C per decade), the *p*-value for the slope being different from zero and the total change over 60 years (i.e., the slope of linear regression multiplied by six decades) for each category. The *p*-values that exceed 0.05 plus the associated slope and change values have an orange background, denoting the lower statistical confidence in the slope being different from zero (no slope). Note that changes with higher *p*-values may still describe informative trends although the level of confidence that the slope is different from zero is lower.

Sub-region	Area	Regression slope			Total change over 60 years			*p*-value, slope different from zero		
		°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)	Change over 60 years (coolest month)	Change over 60 years (all months)	Change over 60 years (warmest month)	°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)
1. High-Latitude Spring Bloom Systems (HLSBS)	Indian Ocean	0.056	0.087	0.145	0.336	0.522	0.870	0.000	0.003	0.000
	North Atlantic Ocean	0.054	0.073	0.116	0.324	0.438	0.696	0.001	0.15	0.000
	South Atlantic Ocean	0.087	0.063	0.097	0.522	0.378	0.582	0.000	0.098	0.000
	North Pacific Ocean (west)	0.052	0.071	0.013	0.312	0.426	0.078	0.52	0.403	0.462
	North Pacific Ocean (east)	0.016	0.04	0.016	0.096	0.24	0.096	0.643	0.53	0.444
	North Pacific Ocean	0.033	0.055	0.015	0.198	0.33	0.09	0.284	0.456	0.319
	South Pacific Ocean (west)	0.043	0.017	0.044	0.258	0.102	0.264	0.016	0.652	0.147
	South Pacific Ocean (east)	0.047	0.031	0.052	0.282	0.186	0.312	0.000	0.396	0.003
	South Pacific Ocean	0.046	0.027	0.050	0.276	0.162	0.300	0.000	0.467	0.000
2. Equatorial Upwelling Systems (EUS)	Atlantic Equatorial Upwelling	0.101	0.090	0.079	0.606	0.540	0.474	0.000	0.000	0.000
	Pacific Equatorial Upwelling	0.079	0.071	0.065	0.474	0.426	0.39	0.096	0.001	0.071
3. Semi-Enclosed Seas (SES)	Arabian Gulf	0.027	0.099	0.042	0.162	0.594	0.252	0.577	0.305	0.282
	Baltic Sea	0.352	0.165	0.06	2.112	0.99	0.36	0.000	0.155	0.299
	Black Sea	–0.004	0.053	0.139	–0.024	0.318	0.834	0.943	0.683	0.009
	Mediterranean Sea	0.035	0.084	0.110	0.21	0.504	0.660	0.083	0.32	0.006
	Red Sea	0.033	0.07	0.047	0.198	0.42	0.282	0.203	0.138	0.042
4. Coastal Boundary Systems (CBS)	Atlantic Ocean (west)	0.137	0.123	0.127	0.822	0.738	0.762	0.000	0.000	0.000
	Caribbean Sea/Gulf of Mexico	0.023	0.024	0.019	0.138	0.144	0.114	0.193	0.498	0.281
	Indian Ocean (west)	0.097	0.100	0.096	0.582	0.600	0.576	0.000	0.000	0.000
	Indian Ocean (east)	0.099	0.092	0.080	0.594	0.552	0.480	0.000	0.000	0.000
	Indian Ocean (east), Southeast Asia, Pacific Ocean (west)	0.144	0.134	0.107	0.864	0.804	0.642	0.000	0.000	0.000
5. Eastern Boundary Upwelling Ecosystems (EBUE)	Benguela Current	0.062	0.032	0.002	0.372	0.192	0.012	0.012	0.437	0.958
	California Current	0.117	0.122	0.076	0.702	0.732	0.456	0.026	0.011	0.125
	Canary Current	0.054	0.089	0.106	0.324	0.534	0.636	0.166	0.014	0.000
	Humboldt Current	0.051	0.059	0.104	0.306	0.354	0.624	0.285	0.205	0.013
6. Subtropical Gyres (STG)	Indian Ocean	0.141	0.112	0.103	0.846	0.672	0.618	0.000	0.000	0.000
	North Atlantic Ocean	0.042	0.046	0.029	0.252	0.276	0.174	0.048	0.276	0.038
	South Atlantic Ocean	0.079	0.083	0.098	0.474	0.498	0.588	0.000	0.017	0.000
	North Pacific Ocean (west)	0.065	0.071	0.059	0.390	0.426	0.354	0.000	0.018	0.000
	North Pacific Ocean (east)	0.008	0.042	0.051	0.048	0.252	0.306	0.617	0.133	0.014
	North Pacific Ocean	0.034	0.055	0.051	0.204	0.33	0.306	0.001	0.053	0.000
	South Pacific Ocean (west)	0.060	0.076	0.092	0.360	0.456	0.552	0.002	0.000	0.000
	South Pacific Ocean (east)	0.055	0.056	0.088	0.330	0.336	0.528	0.000	0.058	0.000
	South Pacific Ocean	0.056	0.060	0.089	0.336	0.360	0.534	0.000	0.027	0.000

Continued next page →

Table 30-1 (continued)

	Sub-region	Regression slope			Total change over 60 years			*p*-value, slope different from zero		
		°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)	Change over 60 years (coolest month)	Change over 60 years (all months)	Change over 60 years (warmest month)	°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)
Coral Reef Provinces; see Figure 30-4(b)	Caribbean Sea/Gulf of Mexico	0.026	0.024	0.023	0.156	0.144	0.138	0.107	0.382	0.203
	Coral Triangle and Southeast Asia	0.137	0.131	0.098	0.822	0.786	0.588	0.000	0.000	0.000
	Indian Ocean (east)	0.081	0.097	0.116	0.486	0.582	0.696	0.000	0.000	0.000
	Indian Ocean (west)	0.091	0.100	0.102	0.546	0.600	0.612	0.000	0.000	0.000
	Pacific Ocean (east)	0.079	0.094	0.101	0.474	0.564	0.606	0.106	0.000	0.023
	Pacific Ocean (west)	0.072	0.073	0.073	0.432	0.438	0.438	0.000	0.000	0.000
Basin Scale	North Atlantic Ocean	0.045	0.061	0.090	0.270	0.366	0.540	0.002	0.198	0.000
	South Atlantic Ocean	0.076	0.074	0.101	0.456	0.444	0.606	0.000	0.041	0.000
	Atlantic Ocean	0.060	0.068	0.091	0.360	0.408	0.546	0.000	0.000	0.000
	North Pacific Ocean	0.030	0.052	0.046	0.180	0.312	0.276	0.000	0.248	0.006
	South Pacific Ocean	0.055	0.048	0.075	0.330	0.288	0.450	0.000	0.115	0.000
	Pacific Ocean	0.043	0.052	0.046	0.258	0.312	0.276	0.000	0.000	0.006
	Indian Ocean	0.130	0.108	0.106	0.780	0.648	0.636	0.000	0.000	0.000

are complicated by the influence of patterns of long-term variability and by the small size and land-locked nature of SES. Coastal Boundary Systems (except the Caribbean and Gulf of Mexico) all showed highly significant (*p*-value ≤ 0.05) warming (0.09°C to 0.13°C per decade; Table 30-1). Among the EBUE, the Canary and Californian Current regions exhibited a significant rate of change in the average SST (0.09°C per decade and 0.12°C per decade, respectively; *p*-value ≤ 0.05), while the Benguela and Humboldt Currents did not show significant temperature changes from 1950 to 2009 (*p*-value ≤ 0.05; Table 30-1). There was some variability between EUBEs in terms of the behavior of the coolest and warmest months. The temperature of the coolest month increased significantly from 1950 to 2009 in the case of the Benguela and California Currents (0.06°C per decade and 0.12°C per decade, respectively; p-value ≤ 0.05), while there was a significant increase in the temperature of the warmest month in the case of the Canary and Humboldt Currents (0.11°C per decade and 0.10°C per decade, respectively; Table 30-1).

The average temperature of STG showed complex patterns with increasing temperatures (1950–2009) in the Indian, South Atlantic, and South Pacific Oceans (*very likely*; 0.11°C, 0.08°C, and 0.06°C per decade, respectively; *p*-value ≤ 0.05), but not in the North Atlantic or North Pacific Ocean (*p*-value ≤ 0.05). These rates are half the value reported over shorter periods (e.g., 1998–2010; Table 1 in Signorini and McClain, 2012) and based on NOAA_OI_SST_V2 data. Given the sensitivity of coral reefs to temperature (Eakin et al., 2010; Strong et al., 2011; Lough, 2012; Box CC-CR), trends in key coral reef regions were also examined using the World Resources Institute's Reefs at Risk report (www.wri.org) to identify HadISST1.1 grid cells containing coral reefs (Figure 30-4b). Grouping the results into six major coral reef regions, coral reef waters (with the notable exception of the Gulf of Mexico and Caribbean) were found to show strong increases in average temperature (0.07°C to 0.13°C per decade) as well as the temperature of the coolest (0.07°C to 0.14°C decade) and warmest months (*very likely*) (0.07°C to 0.12°C per decade; Table 30-1). These trends in temperature have resulted in an absolute increase in sea temperature of 0.44°C to 0.79°C from 1950 to 2009.

Given the essential role that temperature plays in the biology and ecology of marine organisms (Box CC-MB; Sections 6.2-3; Pörtner, 2002; Poloczanska et al., 2013), the speed of isotherm migration ultimately determines the speed at which populations must either move, adapt, or acclimate to changing sea temperatures (Pörtner, 2002; Burrows et al., 2011; Hoegh-Guldberg, 2012). Burrows et al. (2011) calculated the rate at which isotherms are migrating as the ratio of the rate of SST change (°C yr^{-1}) to the spatial gradient of temperature (°C km^{-1}) over the period 1960–2009 (Figure 30-3). Although many of these temperature trajectories are toward the polar regions, some are not and are influenced by features such as coastlines. This analysis and others (e.g., North Atlantic; González-Taboada and Anadón, 2012) reveals that isotherms in the Ocean are moving at high velocities (to over 200 km per decade), especially at low latitudes (*high confidence*; Figure 30-3). Other sub-regions showed smaller velocities with contracting isotherms (cooling) in some areas (e.g., the Central and North Pacific, and Atlantic Oceans; Figure 30-3). There are also changes in the timing of seasonal temperatures in both spring and fall/autumn (Burrows et al., 2011; Poloczanska et al., 2013), which, together with other variables (e.g., light, food availability, geography), are *likely* to affect biological processes such as the migration of species to higher latitudes, and the timing and synchrony of reproductive and other seasonal behaviors.

Excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) significantly affect marine organisms and ecosystems (Hoegh-Guldberg, 1999; Bensoussan et al., 2010; Crisci et al., 2011; Harley, 2011). Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly is useful in understanding recent changes to

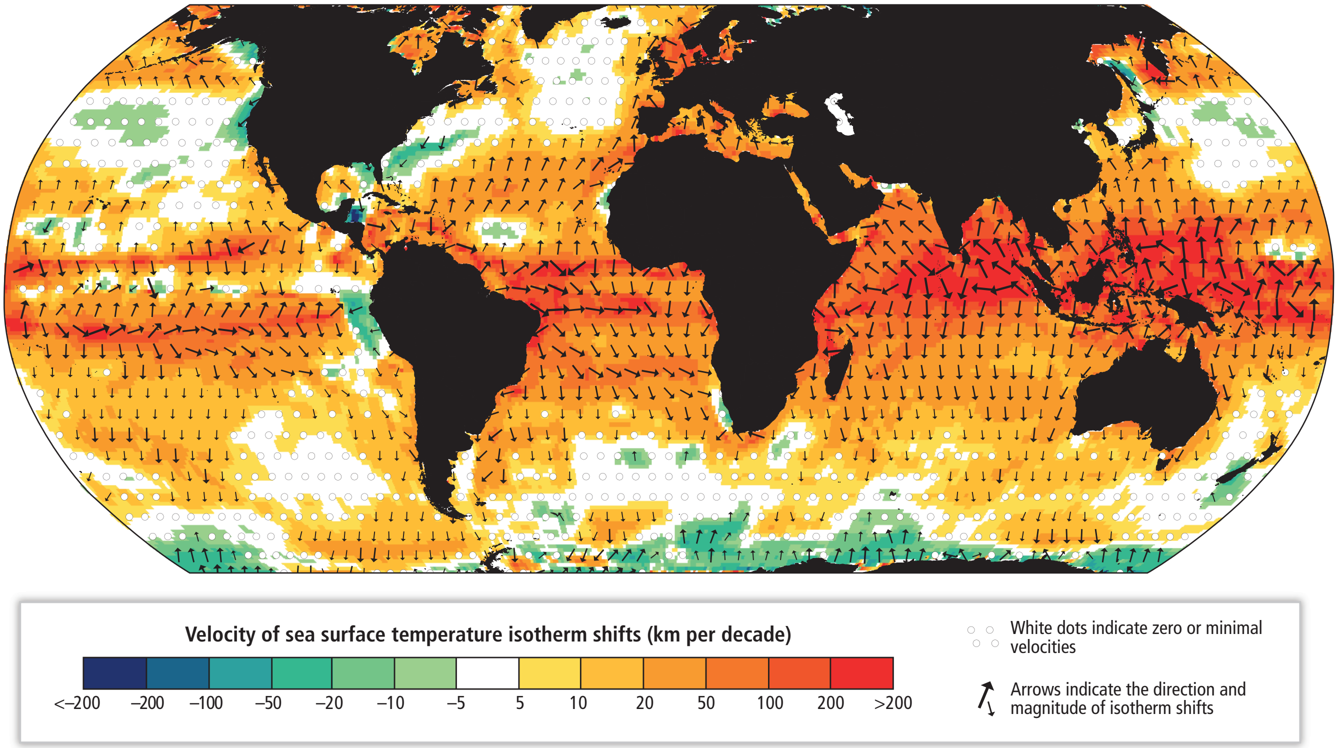


Figure 30-3 | Velocity at which sea surface temperature (SST) isotherms shifted (km per decade) over the period 1960–2009 calculated using Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1), with arrows indicating the direction and magnitude of shifts. Velocity of climate change is obtained by dividing the temperature trend in °C per decade by the local spatial gradient °C km^{-1}. The direction of movement of SST isotherms are denoted by the direction of the spatial gradient and the sign of the temperature trend: toward locally cooler areas with a local warming trend or toward locally warmer areas where temperatures are cooling. Adapted from Burrows et al., 2011.

organisms and ecosystems (e.g., coral reefs and thermal anomalies; Strong et al., 2011). The total heat stress accumulated over the period 1981–2010 was calculated using the methodology of Donner et al. (2007) and a reference climatology based on 1985–2000 in which the highest monthly SST was used to define the thermal threshold, above which accumulated thermal stress was calculated as "exposure time multiplied by stress" or Degree Heating Months (DHM) as the running total over 4 consecutive months. While most sub-regions of the Ocean experienced an accumulation of heat stress (relative to a climatology based on the period 1985–2000), equatorial and high-latitude sub-regions in the Pacific and Atlantic Oceans have the greatest levels of accumulated heat stress (Figure 30-4a). These are areas rich in thermally sensitive coral reefs (Figure 30-4b; Strong et al., 2011). There was also a higher proportion of years that have had at least one stress event (DHM > 1) in the last 30 years (1981–2010, Figure 30-4c) than in the preceding 30 years (1951–1980; Figure 30-4c,d).

The three ocean basins will continue warming under moderate (RCP4.5) to high (RCP8.5) emission trajectories (*high confidence*) and will only stabilize over the second half of the century in the case of low range scenarios such as RCP2.6 (Figure 30-2e,f,g; WGI AR5 AI.4–AI.8). Projected changes were also examined for specific ocean sub-regions using ensemble averages from Atmosphere-Ocean General Circulation Models (AOGCM) simulations available in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (Table SM30-3) for the four scenarios of the future (RCP2.6, RCP4.5, RCP6.0, and RCP8.5; van Vuuren et al., 2011). Ensemble averages for each RCP are based on simulations from 10 to 16 individual models (Table SM30-3). The subset of CMIP5 models were chosen because each has historic runs enabling the derivation of the maximum monthly mean (MMM) climatology from 1985 to 2000, ensuring that all anomalies were comparable across time periods and across RCPs (Figure 30-10). Model hind-cast changes matched those observed for ocean sub-regions for the period 1980–2009 (HadISST1.1; Figure 30-2), with the model ensemble slightly overestimating the extent of change across the different ocean sub-regions (slope of observed/model = 0.81, $r^2 = 0.76$, p-value ≤ 0.001). In this way, the absolute amount of change projected to occur in the ocean sub-regions was calculated for near-term (2010–2039) and long-term (2070–2099) periods (Table SM30-4). In the near term, changes in the temperature projected for the surface layers of the Ocean were largely indistinguishable between the different RCP scenarios owing to the similarity in forcing up to 2040. By the end of the century, however, SSTs across the ocean sub-regions were 1.8°C to 3.3°C higher under RCP8.5 than those projected to occur under RCP2.6 (Table SM30-4; Figure 30-2e,f,g). The implications of these projected changes on the structure and function of oceanic systems are discussed below.

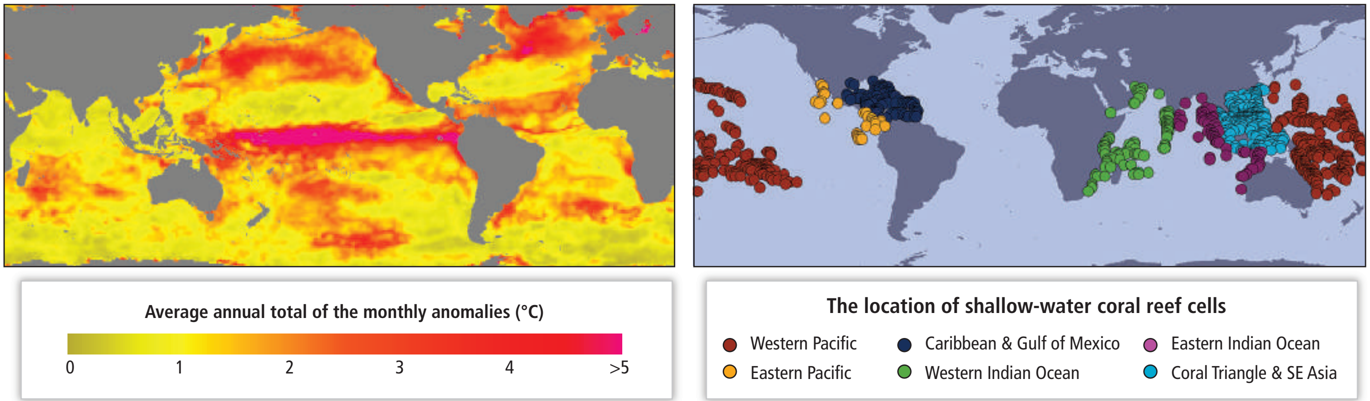
30.3.1.2. Sea Level

The rate of sea level rise (SLR) since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). Over the period 1901–2010, global mean sea level (GMSL) rose by 0.19 (0.17 to 0.21) m (WGI AR5 Figure SPM.3; WGI AR5 Sections 3.7, 5.6, 13.2). It is *very likely* that the mean rate of global averaged SLR was 1.7 (1.5 to 1.9) mm yr^{-1} between 1901 and 2010, 2.0 (1.7 to 2.3) mm yr^{-1}

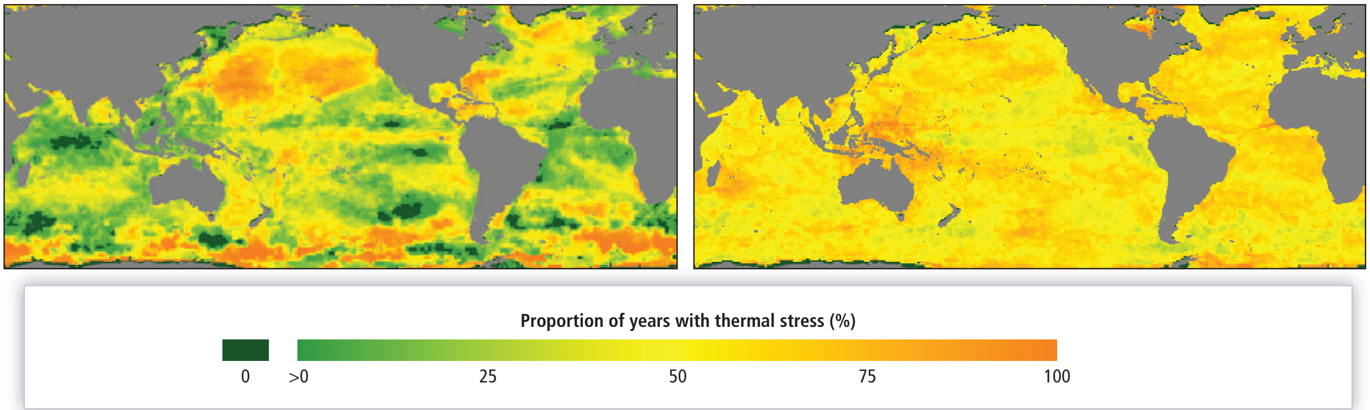
between 1971 and 2010, and 3.2 (2.8 to 3.6) mm yr^{-1} between 1993 and 2010 (WGI AR5 SPM, Section 3.7). These observations are consistent with thermal expansion of the Ocean due to warming plus the addition of water from loss of mass by melting glaciers and ice sheets. Current rates of SLR vary geographically, and can be higher or lower than the GMSL for several decades at time due to fluctuations in natural variability and ocean circulation (Figure 30-5). For example, rates of SLR are up to three times higher than the GMSL in the Western Pacific and Southeast Asian region, and decreasing in many parts of the Eastern Pacific for the period 1993–2012 as measured by satellite altimetry (Figure 30-5; WGI AR5 Section 13.6.5).

SLR under increasing atmospheric GHG concentrations will continue for hundreds of years, with the extent and rate of the increase in GMSL being dependent on the emission scenario. Central to this analysis is the millennial-scale commitment to further SLR that is *likely* to arise from the loss of mass of the Greenland and Antarctic ice sheets (WGI AR5 Section 13.5.4, Figure 13.13). SLR is *very likely* to increase during the 21st century relative to the period 1971–2010 due to increased ocean warming and the continued contribution of water from loss of mass from glaciers and ice sheets. There is *medium confidence* that median SLR by 2081–2100 relative to 1986–2005 will be (5 to 95% range of process-based models): 0.44 m for RCP2.6, 0.53 m for RCP4.5, 0.55 m for RCP6.0, and 0.74 m for RCP8.5. Higher values of SLR are possible but are not backed by sufficient evidence to enable reliable estimates of the probability of specific outcomes. Many semi-empirical model projections of GMSL rise are higher than process-based model projections (up to about twice as large), but there is no consensus in the scientific community about their reliability and there is thus *low confidence* in their projections (WGI AR5 Sections 13.5.2, 13.5.3, Table 13.6, Figure 13.12).

It is considered *very likely* that increases in sea level will result in greater levels of coastal flooding and more frequent extremes by 2050 (WGI AR5 Section 13.7.2; IPCC, 2012). It is *about as likely as not* that the frequency of the most intense storms will increase in some ocean basins,


(a) Total thermal stress for the period 1981–2010

(b) Coral reef provinces and locations


(c) Proportion of years with thermal stress (1951–1980)

(d) Proportion of years with thermal stress (1981–2010)

Figure 30-4 | Recent changes in thermal stress calculated using Hadley Centre Interpolated sea surface temperature data (HadISST1.1). A monthly climatology was created by averaging the HadISST monthly SST values over a reference period of 1985–2000 to create 12 averages, one for each month of the year. The Maximum Monthly Mean climatology was created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each sea surface temperature value, but allowing values to be recorded only if they were greater than zero (Donner et al., 2007). Two measures of the change in thermal stress were calculated as a result: The total thermal stress for the period 1981–2010, calculated by summing all monthly thermal anomalies for each grid cell (a); and the proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951–1980 (c) and 1981–2010 (d). The location of coral reef grid cells used in Table 30-1 and for comparison to regional heat stress is depicted in (b). Each dot is positioned over a 1 × 1 degree grid cell within which lies at least one carbonate coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk report (http://www.wri.org). The six regions are as follows: red—Western Pacific Ocean; yellow—Eastern Pacific Ocean; dark blue—Caribbean and Gulf of Mexico; green—Western Indian Ocean; purple—Eastern Indian Ocean; and light blue—Coral Triangle and Southeast Asia.

although there is *medium agreement* that the global frequency of tropical cyclones is *likely* to decrease or remain constant (WGI AR5 Sections 14.6, 14.8). Although understanding of associated risks is relatively undeveloped, coastal and low-lying areas, particularly in southern Asia, as well as the Pacific Ocean and North Atlantic regions, face increased flood risk (Sections 5.3.3.2, 8.2.3.3, 9.3.4.3). Future impacts of SLR include increasing penetration of storm surges into coastal areas and changing patterns of shoreline erosion (Section 5.3), as well as the inundation of coastal aquifers by saltwater (Sections 5.4.2.5, 29.3.2). Regionally, some natural ecosystems may reduce in extent (e.g., mangroves), although examples of habitat expansion have been reported (Brown et al., 2011). Overall, changes to sea level are *very likely* to modify coastal ecosystems such as beaches, salt marshes, coral reefs, and mangroves (Section 5.4.2; Box CC-CR), especially where rates of sea level rise are highest (e.g., Southeast Asia and the Western Pacific).

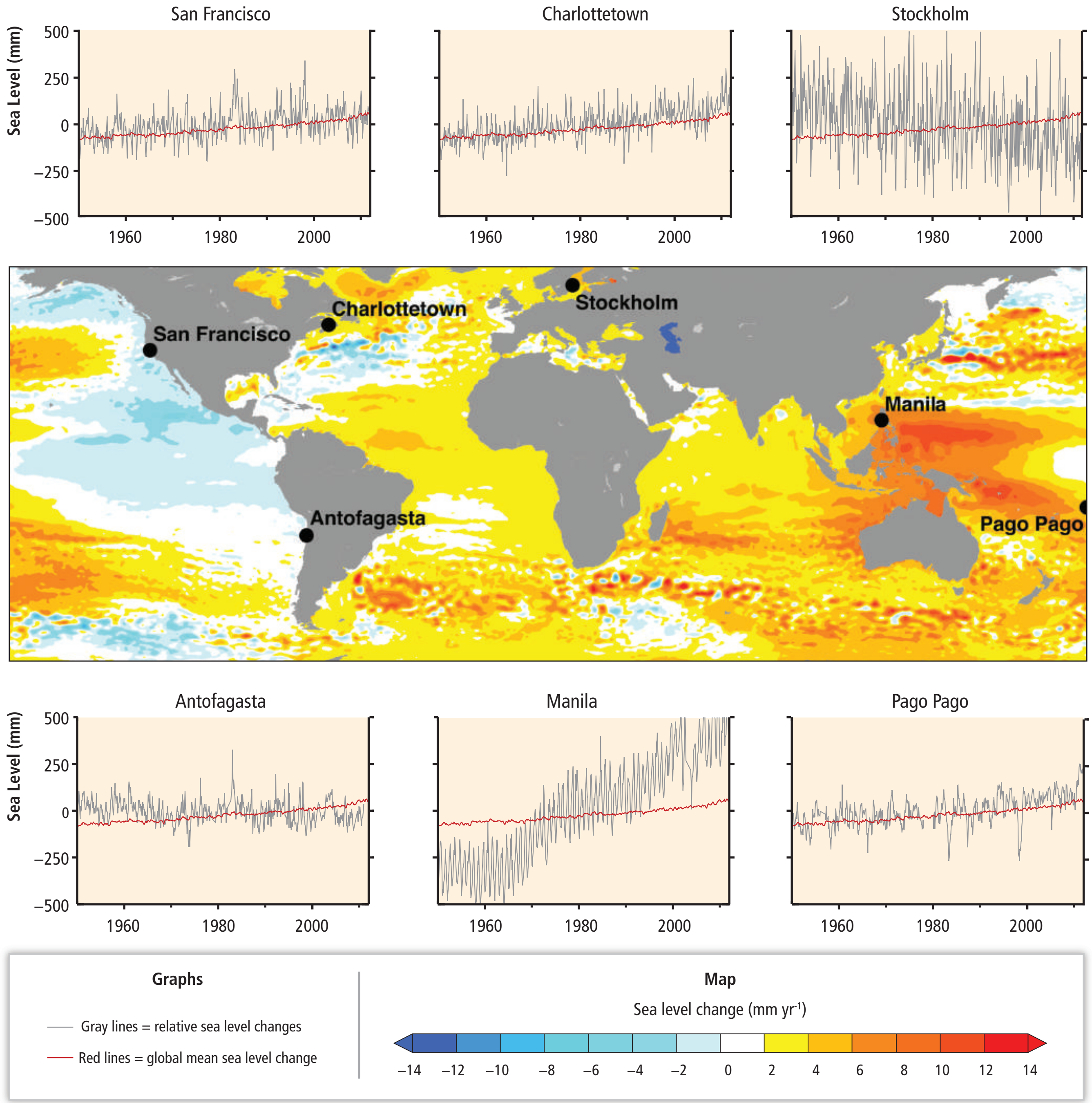


Figure 30-5 | Map of the rate of change in sea surface height (geocentric sea level) for the period 1993–2012 derived from satellite altimetry. Also shown are relative sea level changes (gray lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is shown (red lines) with each tide gauge time series. The relatively large short-term oscillations in local sea level (gray lines) are due to the natural climate variability and ocean circulation. For example, the large regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation. Figure originally presented in WGI AR5 FAQ 13.1, Figure 1.

30.3.1.3. Ocean Circulation, Surface Wind, and Waves

Circulation of atmosphere and ocean (and their interactions) drives much of the chemical, physical, and biological characteristics of the Ocean, shaping phenomena such as ocean ventilation, coastal upwelling, primary production, and biogeochemical cycling. Critical factors for transporting nutrients from deep waters to the marine primary producers in the upper layers of the ocean include wind-driven mixing and upwelling.

There has been a poleward movement of circulation features, including a widening of the tropical belt, contraction of the northern polar vortex, and a shift of storm tracks and jet streams to higher latitudes (*medium confidence*; WGI AR5 Sections 2.7.5-6, 2.7.8; WGI AR5 Box 2.5). Long-term patterns of variability (years to decades) continue to prevent robust conclusions regarding long-term changes in atmospheric circulation and winds in many cases (WGI AR5 Section 2.7.5). There is *high confidence*, however, that the increase in northern mid-latitude westerly winds from the 1950s to the 1990s, and the weakening of the Pacific Walker Circulation from the late 19th century to the 1990s, have been largely offset by recent changes (WGI AR5 Sections 2.7.5, 2.7.8; WGI AR5 Box 2.5). Wind stress has increased since the early 1980s over the Southern Ocean (*medium confidence*; WGI AR5 Section 3.4.4), and tropical Pacific since 1990 (*medium confidence*), while zonal mean wind stress may have declined by 7% in the equatorial Pacific from 1862–1990 due to weakening of the tropical Walker Circulation (*medium confidence*; WGI AR5 Section 3.4.4; Vecchi et al., 2006). For example, it is *very likely* that the subtropical gyres of the major ocean basins have expanded and strengthened since 1993. However, the short-term nature of observing means that these changes are *as likely as not* to be due to decadal variability and/or due to longer term trends in wind forcing associated with climate change (WGI AR5 Section 3.6). Other evidence of changes in ocean circulation is limited to relatively short-term records that suffer from low temporal and spatial coverage. Therefore, there is *very low confidence* that multi-decadal trends in ocean circulation can be separated from decadal variability (WGI AR5 Section 3.6.6). There is no evidence of a long-term trend in large-scale currents such as the Atlantic Meridional Overturning Circulation (AMOC), Indonesian Throughflow (ITF), the Antarctic Circumpolar Current (ACC), or the transport of water between the Atlantic Ocean and Nordic Seas (WGI AR5 Section 3.6; WGI AR5 Figures 3.10, 3.11).

Wind speeds may have increased within the regions of EBUE (*low confidence* in attribution to climate; e.g., California Current, WGI AR5 Section 2.7.2). Changing wind regimes have the potential to influence mixed layer depth (MLD) and upwelling intensity in highly productive sub-regions of the world’s oceans, although there is *low agreement* as to whether or not upwelling will intensify or not under rapid climate change (Bakun, 1990; Bakun et al., 2010; Box CC-UP).

Surface waves are influenced by wind stress, although understanding trends remains a challenge due to limited data. There is *medium confidence* that significant wave height (SWH) has increased since the mid-1950s over much of the North Atlantic north of 45°N, with typical winter season trends of up to 20 cm per decade (WGI AR5 Section 3.4.5). There is *low confidence* in the current understanding of how SWH will change over the coming decades and century for most of the Ocean. It remains an important knowledge gap (WGI AR5 Section 3.4).

30.3.1.4. Solar Insolation and Clouds

Solar insolation plays a crucially important role in the biology of many marine organisms, not only as a source of energy for photosynthesis but also as a potential co-stressor in the photic zone (with temperature), as is seen during mass coral bleaching and mortality events (e.g., Hoegh-Guldberg, 1999). Global surface solar insolation (from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis Project; Kalnay et al., 1996) decreased by 4.3 W m^{-2} per decade from the 1950s until 1991, after which it increased at 3.3 W m^{-2} per decade until 1999 (Ohmura, 2009; Wild, 2009), matching a broad suite of evidence from many land-based sites (WGI AR5 Section 2.3.3). Although there is consistency between independent data sets for particular regions, there is substantial ambiguity and therefore *low confidence* in observations of global-scale cloud variability and trends (WGI AR5 Section 2.5.6). There is also *low confidence* in projections of how cloudiness, solar insolation, and precipitation will change as the planet warms due to the large interannual and decadal variability (El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)), short observation time series, and uneven spatial sampling, particularly in the early record (before 1950; WGI AR5 Section 2.5.8).

30.3.1.5. Storm Systems

As agents of water column mixing, storms (from small atmospheric disturbances to intense tropical cyclones) can remix nutrients from deeper areas into the photic zone of the Ocean, stimulating productivity. Storms can also reduce local sea temperatures and associated stress by remixing heat into the deeper layers of the Ocean (Carrigan and Puotinen, 2011). Large storms can destroy coastal infrastructure and coastal habitats such as coral reefs and mangrove forests, which can take decades to recover (Lotze et al., 2011; De’ath et al., 2012).

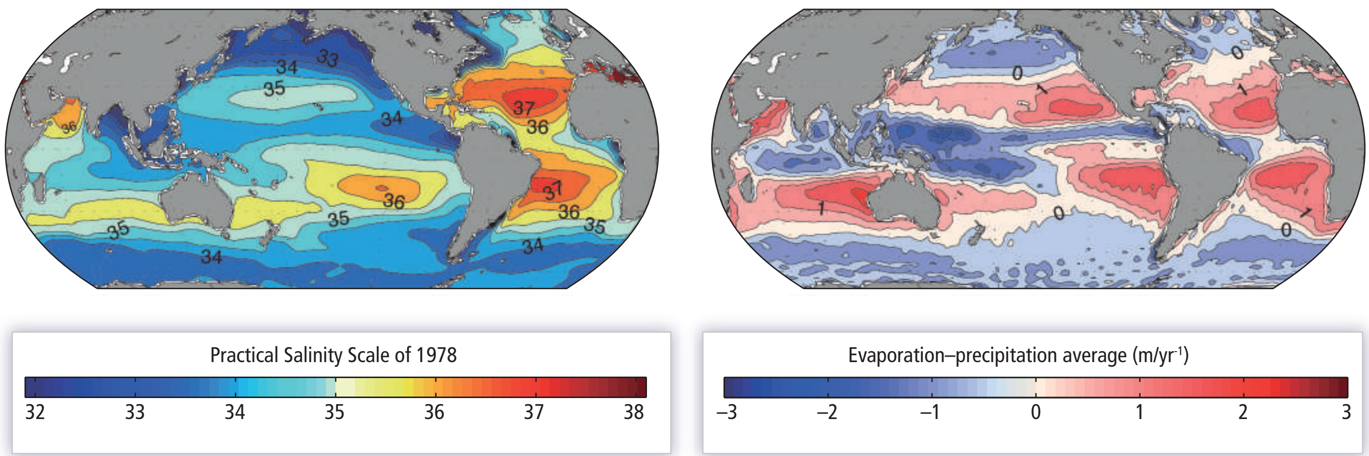
Although there is *low confidence* for long-term trends in tropical cyclone activity globally (largely due to the lack of reliable long-term data sets), it is *virtually certain* that the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (WGI AR5 Section 2.6.3). There is *medium agreement* that the frequency of the most intense cyclones in the Atlantic has increased since 1987 (WGI AR5 Section 2.6.3) and *robust evidence* of inter-decadal changes in the storm track activity within the North Pacific and North Atlantic (Lee et al., 2012). It is also *likely* that there has been a decrease in the number of land-falling tropical cyclones along the East Australian coast since the 19th century (WGI AR5 Section 2.6.3; Callaghan and Power, 2011). It is *likely* that these patterns are influenced by interannual variability such as ENSO, with land-falling tropical cyclones being twice as common in La Niña versus El Niño years (*high confidence*; Callaghan and Power, 2011). There has been an increase in the number of intense wintertime extratropical cyclone systems since the 1950s in the North Pacific. Similar trends have been reported for the Asian region, although analyses are limited in terms of the spatial and temporal coverage of reliable records (WGI AR5 Section 2.6.4). There is *low confidence*, however, in large-scale trends in storminess or storminess proxies over the last century owing to the lack of long-term data and inconsistencies between studies (WGI AR5 Section 2.6.4).

30.3.1.6. Thermal Stratification

As heat has accumulated in the Ocean there has been a 4% increase in thermal stratification of the upper layers in most ocean regions (0 to 200 m, 40-year record) north of 40°S (WGI AR5 Section 3.2.2). Increasing thermal stratification has reduced ocean ventilation and the depth of mixing in many ocean sub-regions (*medium confidence*; WGI AR5 Section 3.8.3). This in turn reduces the availability of inorganic nutrients and consequently primary productivity (*medium confidence*; Section 6.3.4). In the STG, which dominate the three major ocean basins (Section 30.5.6), satellite-derived estimates of surface chlorophyll and primary production decreased between 1999 and 2007 (Box CC-PP). In contrast, however, *in situ* observations at fixed stations in the North Pacific and North Atlantic Oceans (Hawaii Ocean Time-series (HOT) and Bermuda Atlantic Time-series Study (BATS)) showed increases in nutrient and chlorophyll levels and primary production over the same period, suggesting that other processes (e.g., ENSO, PDO, North Atlantic Oscillation (NAO), winds, eddies, advection) can counteract broad-scale trends at local scales (Box CC-PP). The continued warming of the surface layers of the Ocean will *very likely* further enhance stratification and potentially limit the nutrient supply to the euphotic zone in some areas. The response of upwelling to global warming is *likely* to vary between regions and represents a complex interplay between local and global variables and processes (Box CC-UW).

(a) Climatological-mean sea surface salinity (1955–2005)

(b) Annual mean evaporation–precipitation (1950–2000)



(c) The 58-year (2008 minus 1950) sea surface salinity change

(d) The 30-year (2003–2007 average centered at 2005, minus the 1960–1989 average centered at 1975) sea surface salinity difference

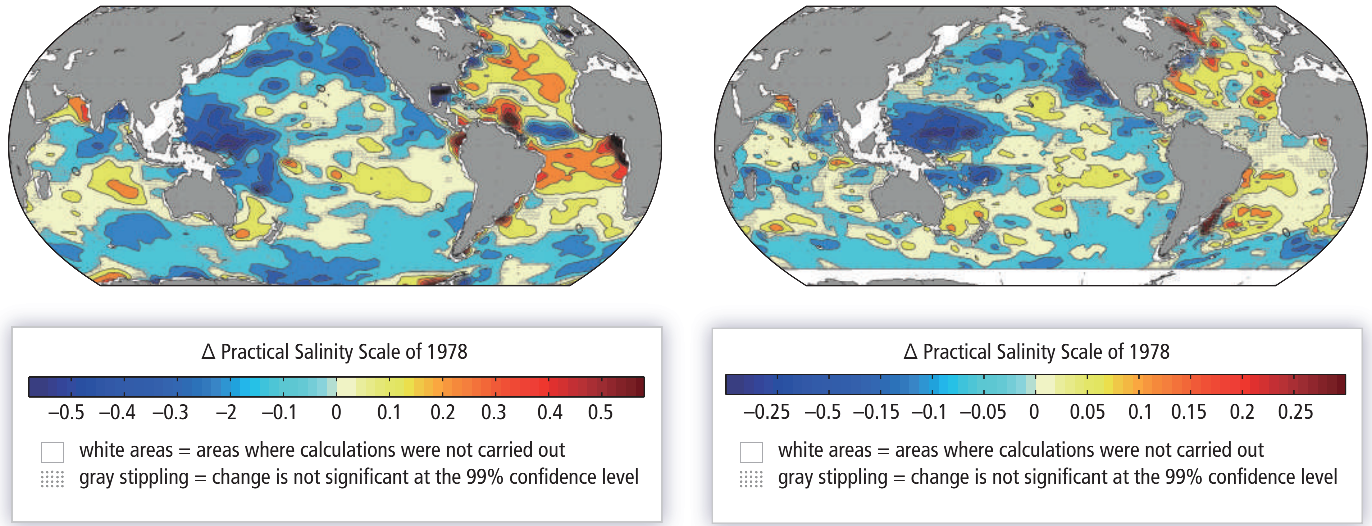


Figure 30-6 | (a) The 1955–2005 climatological-mean sea surface salinity (Antonov et al., 2010) color contoured at 0.5 Practical Salinity Scale 1978 (PSS78) intervals (black lines). (b) Annual mean evaporation-precipitation averaged over the period 1950–2000 (National Centers for Environmental Prediction (NCEP)) color contoured at 0.5 m yr–1 intervals (black lines). (c) The 58-year (2008 minus 1950) sea surface salinity change derived from the linear trend (PSS78), with seasonal and El Niño-Southern Oscillation (ENSO) signals removed (Durack and Wijffels, 2010) color contoured at 0.116 PSS78 intervals (black lines). (d) The 30-year (2003–2007 average centered at 2005, minus the 1960–1989 average centered at 1975) sea surface salinity difference (PSS78) (Hosoda et al., 2009) color contoured at 0.06 PSS78 intervals (black lines). Contour intervals in (c) and (d) are chosen so that the trends can be easily compared, given the different time intervals in the two analyzes. White areas in (c) and (d) are marginal seas where the calculations are not carried out. Regions where the change is not significant at the 99% confidence level are stippled in gray. Figure originally presented as WGI AR5 Figure 3.4. All salinity values quoted in the chapter are expressed on the Practical Salinity Scale 1978 (PSS78) (Lewis and Fofonoff, 1979).

30.3.2. Chemical Changes

30.3.2.1. Surface Salinity

The global water cycle is dominated by evaporation and precipitation occurring over ocean regions, with surface ocean salinity varying with temperature, solar radiation, cloud cover, and ocean circulation (Deser et al., 2004). Changes in salinity influence stratification of water masses and circulation. Ocean salinity varies regionally (Figure 30-6a) and is a function of the balance between evaporation and precipitation (Durack and Wijffels, 2010; WGI AR5 Section 3.3). Evaporation-dominated regions (Figure 30-6b) such as the STG and Atlantic and Western Indian Oceans (WGI AR5 Section 3.3.3) have elevated salinity, while areas of high precipitation such as the North Pacific, northeastern Indian Ocean, Southeast Asia, and the eastern Pacific have relatively low salinities (WGI AR5 Section 3.3.3; Figure 30-6a). It is *likely* that large-scale trends in salinity have also occurred in the Ocean interior, deriving from changes to salinity at the surface and subsequent subduction (WGI AR5 Section 3.3).

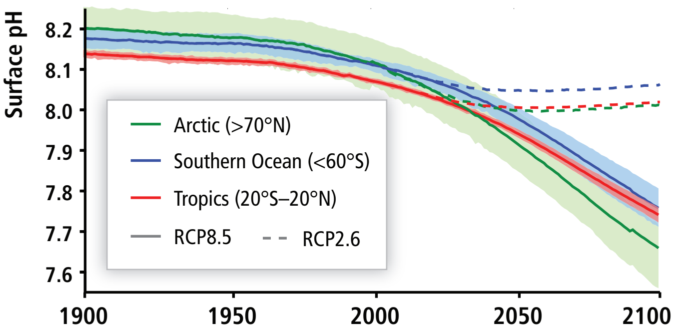
Salinity trends are consistent with the amplification of the global hydrological cycle (Durack et al., 2012; Pierce et al., 2012), a consequence of a warmer atmosphere *very likely* producing the observed trend in greater precipitation, evaporation, atmospheric moisture (Figure 30-6b), and extreme events (WGI AR5 Sections 2.6.2.1, 3.3.4; IPCC, 2012). Spatial patterns in salinity and evaporation-precipitation are correlated, providing indirect evidence that these processes have been enhanced since the 1950s (WGI AR5 Sections 3.3.2-4; WGI AR5 Figures 3.4, 3.5, 3.20d; WGI AR5 FAQ 3.3). These trends in salinity are *very likely* to have a discernible contribution from anthropogenic climate change (WGI AR5 Section 10.4.2). The combined changes in surface salinity and temperature are consistent with changes expected due to anthropogenic forcing of the climate system and are inconsistent with the effects of natural climate variability, either internal to the climate system (e.g., ENSO, PDO; Figure 30-6c,d) or external to it (e.g., solar forcing or volcanic eruptions; Pierce et al., 2012). There is *high confidence* between climate models that the observed trends in ocean salinity will continue as average global temperature increases (Durack and Wijffels, 2010; Terray et al., 2012). Ramifications of these changes are largely unknown but are of interest given the role of ocean salinity and temperature in fundamental processes such as the AMOC.

30.3.2.2. Ocean Acidification

The Ocean has absorbed approximately 30% of atmospheric CO_2 from human activities, resulting in decreased ocean pH and carbonate ion concentrations, and increased bicarbonate ion concentrations (Box CC-OA; WGI AR5 Box 3.2; WGI AR5 Figure SM30-2). The chemical response to increased CO_2 dissolving into the Ocean from the atmosphere is known with *very high confidence* (WGI AR5 Section 6.4.4). Factors such as temperature, biological processes, and sea ice (WGI AR5 Section 6.4) play significant roles in determining the saturation state of seawater for polymorphs (i.e., different crystalline forms) of calcium carbonate. Consequently, pH and the solubility of aragonite and calcite are naturally lower at high latitudes and in upwelling areas (e.g., California Current EBUE), where organisms and ecosystems may be relatively more exposed to ocean acidification as a result (Feely et al., 2012; Gruber et al., 2012; Figures 30-7a,b, SM30-2). Aragonite and calcite concentrations vary with depth, with under-saturation occurring at deeper depths in the Atlantic (calcite: 3500 to 4500 m, aragonite: 400 to 3000 m) as opposed to the Pacific and Indian Oceans (calcite: 100 to 3000 m, aragonite: 100 to 1200 m; Feely et al., 2004, 2009; Orr et al., 2005; Figure 30-8).

Surface ocean pH has decreased by approximately 0.1 pH units since the beginning of the Industrial Revolution (*high confidence*) (Figure 30-7a; WGI AR5 Section 3.8.2; WGI AR5 Box 3.2), with pH decreasing at the rate of –0.0013 and 0.0024 pH units yr^{-1} (WGI AR5 Section 3.8.2; WGI AR5 Table 3.2). The presence of anthropogenic CO_2 diminishes with

(a) Surface pH



(b) Change in surface pH in 2090s from 1990s (RCP8.5)

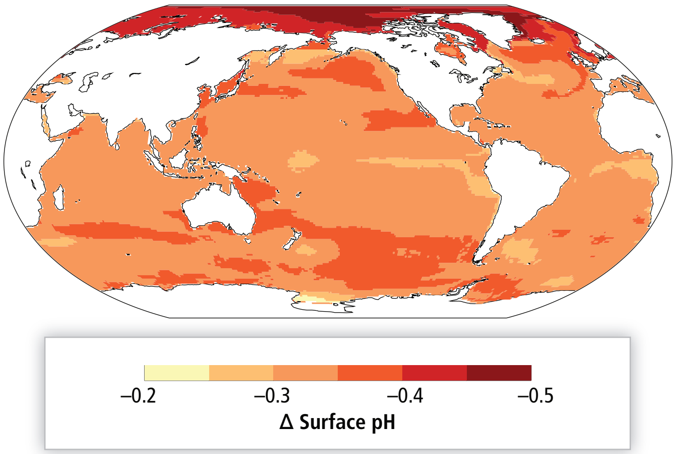


Figure 30-7 | Projected ocean acidification from 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System models under RCP8.5 (other Representative Concentration Pathway (RCP) scenarios have also been run with the CMIP5 Models): (a) Time series of surface pH shown as the mean (solid line) and range of models (shaded area), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue). (b) Maps of the median model's change in surface pH from 1990s. Panel (a) also includes mean model results from RCP2.6 (dashed lines). Over most of the Ocean, gridded data products of carbonate system variables are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following (Orr et al., 2005). Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), the results are shown without bias correction. The bias correction reduces the range of model projections by up to a factor of four; for example, in panel (a) compare the large range of model projections for the Arctic (without bias correction) to the smaller range in the Southern Ocean (with bias correction). Figure originally presented in WGI AR5 Figure 6.28.

depth. The saturation horizons of both polymorphs of calcium carbonate, however, are shoaling rapidly (1 to 2 m yr^{-1}, and up to 5 m yr^{-1} in regions such as the California Current (Orr et al., 2005; Feely et al., 2012). Further increases in atmospheric CO_2 are *virtually certain* to further acidify the Ocean and change its carbonate chemistry (Figures SM30-2, 30-7, 30-8). Doubling atmospheric CO_2 (~RCP4.5; Rogelj et al., 2012) will decrease ocean pH by another 0.1 unit and decrease carbonate ion concentrations by approximately 100 µmol kg^{-1} in tropical oceans (Figure 30-8a) from the present-day average of 250 µmol kg^{-1} (*high confidence*). Projected changes for the open Ocean by 2100 (Figures 30-7, 30-8) range from a pH change of –0.14 unit with RCP2.6 (421 ppm CO_2, +1°C, 22% reduction of carbonate ion concentration) to a pH change of –0.43 unit with RCP8.5

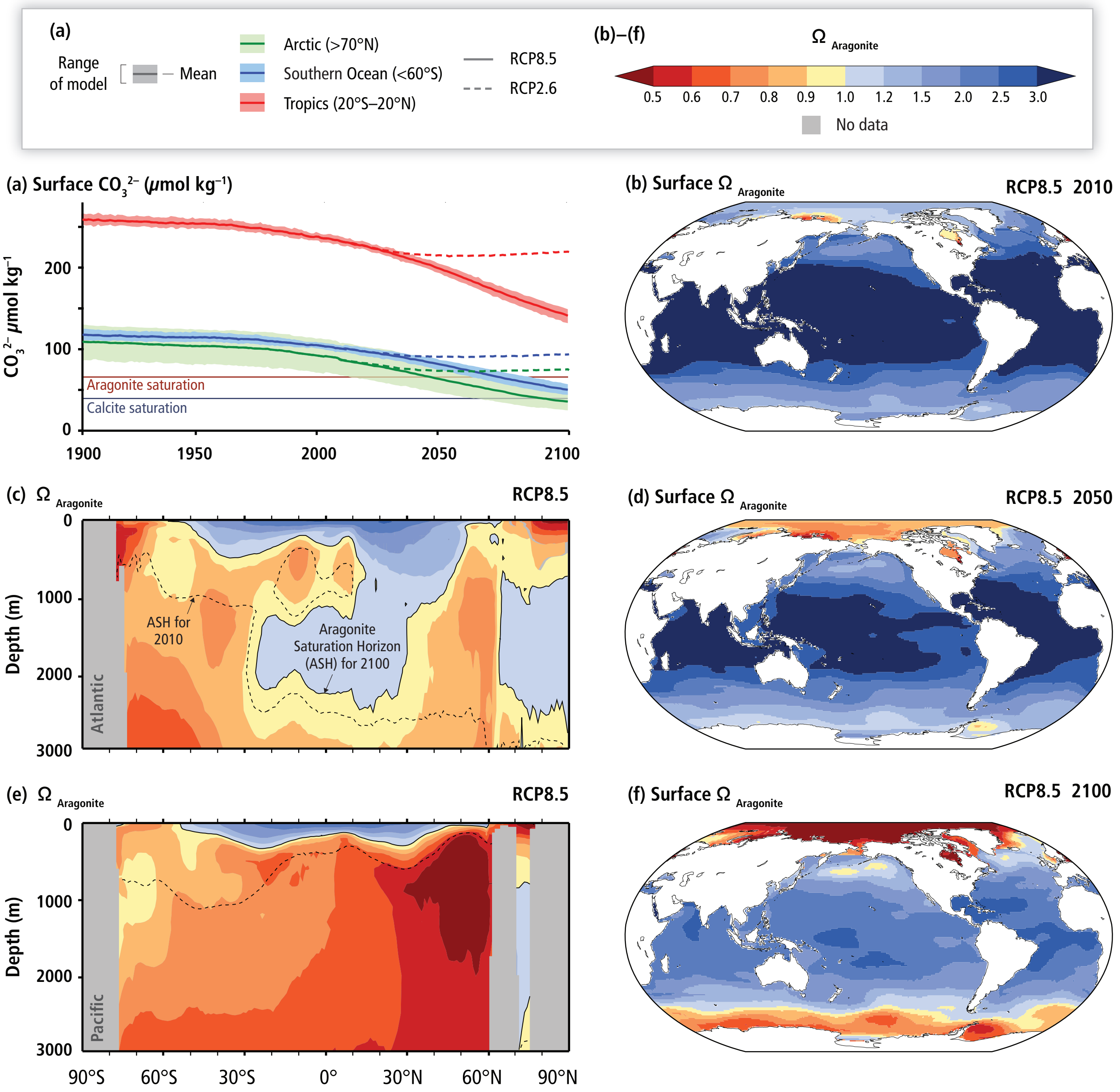


Figure 30-8 | Projected aragonite saturation state ($\Omega_{Aragonite}$) from 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Models under Representative Concentration Pathway 8.5 (RCP8.5) scenario. (a) Time series of surface carbonate ion (CO_3^{2-}) concentration shown as the mean (solid line) and range of models (shaded area), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue); maps of the median model's surface $\Omega_{Aragonite}$ in (b) 2010, (d) 2050, and (f) 2100; and zonal mean sections (latitude vs. depth) of $\Omega_{Aragonite}$ in 2100 over (c) the Atlantic Ocean and (e) the Pacific Ocean, while the ASH (Aragonite Saturation Horizon) is shown for 2010 (dotted line) and 2100 (solid line). Panel (a) also includes mean model results from RCP2.6 (dashed lines). As for Figure 30-7, gridded data products of carbonate system variables (Key et al., 2004) are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following Orr et al. (2005). Where gridded data products are unavailable (Arctic Ocean, all marginal seas, and the Ocean near Indonesia), results are shown without bias correction. Figure originally presented in WGI AR5 Figure 6.29.

(936 ppm CO_2, +3.7°C, 56% reduction of carbonate ion concentration). The saturation horizons will also become significantly shallower in all oceans (with the aragonite saturation horizon between 0 and 1500 m in the Atlantic Ocean and 0 and 600 m (poles vs. equator) in the Pacific Ocean; Sabine et al., 2004; Orr et al., 2005; WGI AR5 Section 6.4.4; WGI AR5 Figure 6.28). Trends toward under-saturation of aragonite and calcite will also partly depend on ocean temperature, with surface polar waters expected to become seasonally under-saturated with respect to aragonite and calcite within a couple of decades (Figure 30-8c,d,e,f; Box CC-OA; McNeil and Matear, 2008).

Overall, observations from a wide range of laboratory, mesocosm, and field studies reveal that marine macro-organisms and ocean processes are sensitive to the levels of ocean acidification projected under elevated atmospheric CO_2 (*high confidence*; Box CC-OA, Section 6.3.2; Munday et al., 2009; Kroeker et al., 2013). Ecosystems that are characterized by high rates of calcium carbonate deposition (e.g., coral reefs, calcareous plankton communities) are sensitive to decreases in the saturation states of aragonite and calcite (*high confidence*). These changes are *very likely* to have broad consequences such as the loss of three-dimensional coral reef frameworks (Hoegh-Guldberg et al., 2007; Manzello et al., 2008; Fabricius et al., 2011; Andersson and Gledhill, 2013; Dove et al., 2013) and restructuring of food webs at relatively small (~50 ppm) additional increases in atmospheric CO_2. Projected shoaling of the aragonite and calcite saturation horizons are *likely* to impact deep water (100 to 2000 m) communities of scleractinian corals and other benthic organisms as atmospheric CO_2 increases (Orr et al., 2005; Guinotte et al., 2006; WGI AR5 Section 6.4.4), although studies from the Mediterranean and seamounts off southwest Australia report that some deep water corals may be less sensitive (Thresher et al., 2011; Maier et al., 2013). Organisms are also sensitive to changes in pH with respect to physiological processes such as respiration and neural function (Section 6.3.2). Owing to the relatively short history, yet growing effort, to understand the implications of rapid changes in pH and ocean carbonate chemistry, there are a growing number of organisms and processes reported to be sensitive. The impact of ocean acidification on marine organisms and ecosystems continues to raise serious scientific concern, especially given that the current rate of ocean acidification (at least 10 to 100 times faster than the recent glacial transitions (Caldeira and Wickett, 2003; Hoegh-Guldberg et al., 2007)) is unprecedented within the last 65 Ma (*high confidence*; Ridgwell and Schmidt, 2010) and possibly 300 Ma of Earth history (*medium confidence*; Hönisch et al., 2012; Section 6.1.2).

30.3.2.3. Oxygen Concentration

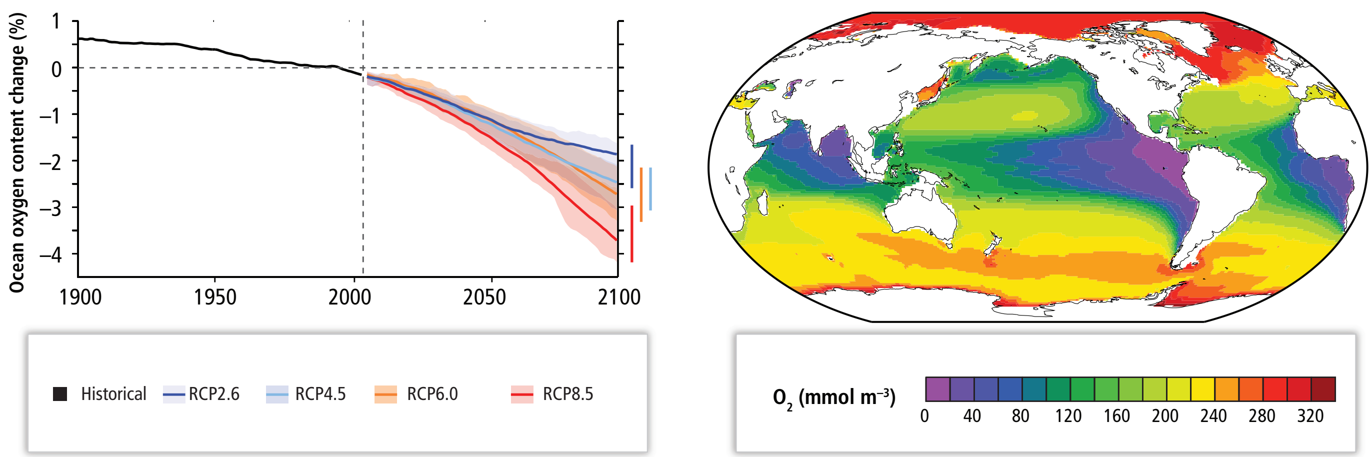
Dissolved O_2 is a major determinant of the distribution and abundance of marine organisms (Section 6.3.3). Oxygen concentrations vary across ocean basins and are lower in the eastern Pacific and Atlantic basins, and northern Indian Ocean (Figure 30-9b; Section 6.1.1.3). In contrast, some of the highest concentrations of O_2 are associated with cooler high-latitude waters (Figure 30-9b). There is *high agreement* among analyses providing *medium confidence* that O_2 concentrations have decreased in the upper layers of the Ocean since the 1960s, particularly in the equatorial Pacific and Atlantic Oceans (WGI AR5 Section 3.8.3; WGI AR5 Figure 3.20). A formal fingerprint analysis undertaken by Andrews et al. (2013) concluded that recent decreases in oceanic O_2 are due to external influences (*very likely*). Conversely, O_2 has increased in the North and South Pacific, North Atlantic, and Indian Oceans, and is consistent with greater mixing and ventilation due to strengthening wind systems (WGI AR5 Section 3.8.3). The reduction in O_2 concentration in some areas of the Ocean is consistent with that expected from higher ocean temperatures and a reduction in mixing (increasing stratification) (WGI AR5 Section 3.8.3). Analysis of ocean O_2 trends over time (Helm et al., 2011b) reveals that the decline in O_2 solubility with increased temperature is responsible for no more than 15% of the observed change. The remaining 85%, consequently, is associated with increased deep-sea microbial respiration and reduced O_2 supply due to increased ocean stratification (WGI AR5 Section 6.1.1.3). In coastal areas, eutrophication can lead to increased transport of organic carbon into adjacent ocean habitats where microbial metabolism is stimulated, resulting in a rapid drawdown of O_2 (Weeks et al., 2002; Rabalais et al., 2009; Bakun et al., 2010).

The development of hypoxic conditions (defined as O_2 concentrations below ~60 µmol kg^{-1}) over recent decades has been documented across

Frequently Asked Questions

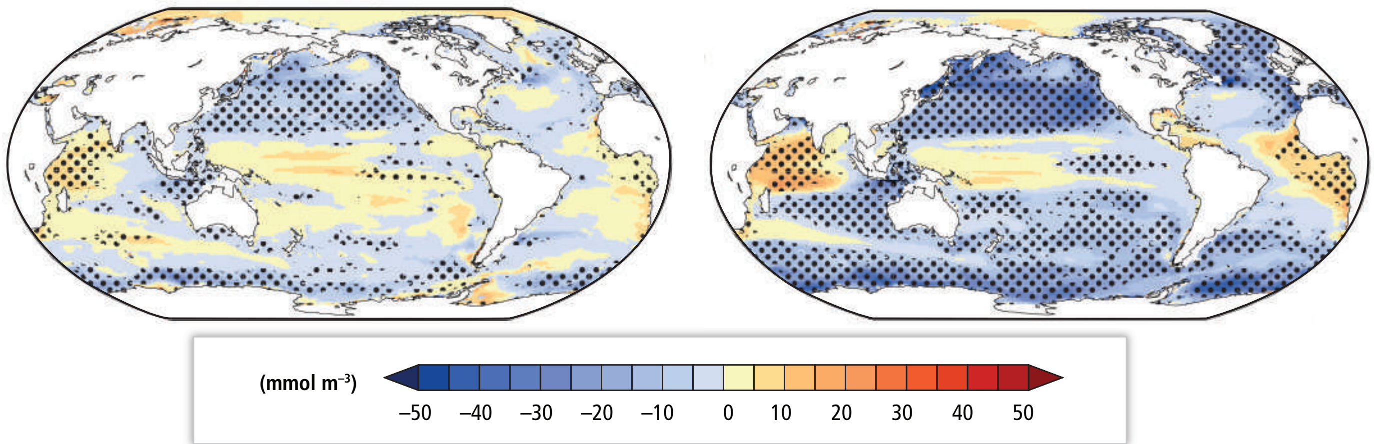
FAQ 30.1 | Can we reverse the impacts of climate change on the ocean?

In less than 150 years, greenhouse gas (GHG) emissions have resulted in such major physical and chemical changes in our oceans that it will take thousands of years to reverse them. There are a number of reasons for this. Given its large mass and high heat capacity, the ability of the Ocean to absorb heat is 1000 times larger than that of the atmosphere. The Ocean has absorbed at least nine-tenths of the Earth's heat gain between 1971 and 2010. To reverse that heating, the warmer upper layers of the Ocean have to mix with the colder deeper layers. That mixing can take as much as 1000 years. This means it will take centuries to millennia for deep ocean temperatures to warm in response to today's surface conditions, and at least as long for ocean warming to reverse after atmospheric GHG concentrations decrease (*virtually certain*). But climate change-caused alteration of basic conditions in the Ocean is not just about temperature. The Ocean becomes more acidic as more carbon dioxide (CO_2) enters it and will take tens of thousands of years to reverse these profound changes to the carbonate chemistry of the ocean (*virtually certain*). These enormous physical and chemical changes are producing sweeping and profound changes in marine ecosystems. Large and abrupt changes to these ecosystems are unlikely to be reversible in the short to medium term (*high confidence*).



(a) Ocean oxygen content change (%)

(b) Oxygen concentrations in the 1990s (200–600 m)



(c) 2090s, changes from 1990s (RCP2.6)

(d) 2090s, changes from 1990s (RCP8.5)

Figure 30-9 | (a) Simulated changes in dissolved O_2 (mean and model range as shading) relative to 1990s for Representative Concentration Pathway 2.6 (RCP2.6), RCP4.5, RCP6.0, and RCP8.5. (b) Multi-model mean dissolved O_2 (mmol m^{-3}) in the main thermocline (200 to 600 m depth average) for the 1990s, and changes in the 2090s relative to 1990s for RCP2.6 (c) and RCP8.5 (d). To indicate consistency in the sign of change, regions are stippled when at least 80% of models agree on the sign of the mean change. These diagnostics are detailed in Cocco et al. (2013) in a previous model intercomparison using the Special Report on Emission Scenarios (SRES)-A2 scenario and have been applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) models here. Models used: Community Earth System Model 1–Biogeochemical (CESM1-BGC), Geophysical Fluid Dynamics Laboratory–Earth System Model 2G (GFDL-ESM2G), Geophysical Fluid Dynamics Laboratory–Earth System Model 2M (GFDL-ESM2M), Hadley Centre Global Environmental Model 2–Earth System (HadGEM2-ES), Institute Pierre Simon Laplace–Coupled Model 5A–Low Resolution (IPSL-CM5A-LR), Institute Pierre Simon Laplace–Coupled Model 5A–Medium Resolution (IPSL-CM5A-MR), Max Planck Institute–Earth System Model–Low Resolution (MPI-ESM-LR), Max Planck Institute–Earth System Model–Medium Resolution (MPI-ESM-MR), Norwegian Earth System Model 1 (Emissions capable) (NorESM1). Figure originally presented in WGI AR5 Figure 6.30.

a wide array of ocean sub-regions including some SES (e.g., Black and Baltic Seas), the Arabian Sea, and the California, Humboldt, and Benguela Current systems, where eruptions of hypoxic, sulfide-laden water have also occurred in some cases (Weeks et al., 2002). Localized, seasonal hypoxic "dead zones" have emerged in economically valuable coastal areas such as the Gulf of Mexico (Turner et al., 2008; Rabalais et al., 2010), the Baltic Sea (Conley et al., 2009), and the Black Sea (Kideys, 2002; Ukrainskii and Popov, 2009) in connection with nutrient fluxes from land. Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, the minimum O_2 threshold (less than 2 mg l^{-1} or ~60 µmol^{-1}) is found at 300 m depth and upwelling of increasingly hypoxic waters is well documented (Karstensen et al., 2008). Hypoxic waters in the northern Arabian Sea and Bay of Bengal are located close to continental shelf areas. Long-term measurements reveal that O_2 concentrations are declining in these waters, with *medium evidence* that economically significant mesopelagic fish populations are being threatened by a reduction in suitable habitat as respiratory stress increases (Koslow et al., 2011). It should be noted that hypoxia profiles based on a critical threshold of 60 µmol kg^{-1} can convey an overly simplistic message given that critical concentrations of O_2 in this regard are very much species, size, temperature, and life history stage specific. This variability in sensitivity is, however, a critical determinant for any attempt to understand how ecosystems will respond to changing future O_2 levels (Section 6.3.3).

There is *high agreement* among modeling studies that O_2 concentrations will continue to decrease in most parts of the Ocean due to the effect of temperature on O_2 solubility, microbial respiration rates, ocean ventilation, and ocean stratification (Figure 30-9c,d; WGI AR5 Table 6.14; Andrews et al., 2013), with implications for nutrient and carbon cycling, ocean productivity, marine habitats, and ecosystem structure (Section 6.3.5). The outcomes of these global changes are *very likely* to be influenced by regional differences in variables such as wind stress, coastal processes, and the supply of organic matter.

30.4. Global Patterns in the Response of Marine Organisms to Climate Change and Ocean Acidification

Given the close relationship between organisms and ecosystems with the physical and chemical elements of the environment, changes are expected in the distribution and abundance of marine organisms in response to ocean warming and acidification (Section 6.3; Boxes CC-MB, CC-OA). Our understanding of the relationship between ocean warming and acidification reveals that relatively small changes in temperature and other variables can result in often large biological responses that range from simple linear trends to more complex non-linear outcomes. There has been an increase in studies that focus on the influence and consequences of climate change for marine ecosystems since AR4 (Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013), representing an opportunity to examine, and potentially attribute, detected changes within the Ocean to climate change.

Evidence of global and regional responses of marine organisms to recent climate change has been shown through assessments of multiple studies focused on single species, populations, and ecosystems (Tasker, 2008; Thackeray et al., 2010; Przeslawski et al., 2012; Poloczanska et al., 2013). The most comprehensive assessment, in terms of geographic spread and number of observed responses, is that of Poloczanska et al. (2013). This study reveals a coherent pattern in observed responses of ocean life to recent climate change across regions and taxonomic groups, with 81% of responses by organisms and ecosystems being consistent with expected changes to recent climate change (*high confidence*; Box CC-MB). On average, spring events in the Ocean have advanced by 4.4 ± 0.7 days per decade (mean ± SE) and the leading edges of species' distributions have extended (generally poleward) by 72.0 ± 0.35 km per decade. Values were calculated from data series ranging from the 1920s to 2010, although all series included data after 1990. The fastest range shifts generally occurred in regions of high thermal velocity (the speed and direction at which isotherms move (Burrows et al., 2011; Section 30.3.1.1)). Subsequently, Pinsky et al. (2013), using a database of 360 fish and invertebrate species and species groups from coastal waters around North America, showed differences in the speed and directions that species shift can be explained by differences in local climate velocities (Box CC-MB).

30.5. Regional Impacts, Risks, and Vulnerabilities: Present and Future

This section explores the impacts, risks, and vulnerabilities of climate change for the seven sub-regions within the Ocean. There is considerable variability from region to region, especially in the extent and interaction of climate change and non-climate change stressors. Although the latter may complicate attribution attempts in many sub-regions, interactions between the two groups of stressors may also represent opportunities to reduce the overall effects on marine organisms and processes of the environmental changes being driven by climate change (including ocean acidification) (Crain et al., 2008; Griffith et al., 2012).

30.5.1. High-Latitude Spring Bloom Systems

High-Latitude Spring Bloom Systems (HLSBSs) stretch from 35°N to the edge of the winter sea ice (and from 35°S to the polar front) and provide 36% of world's fish catch (Figure 30-1b). Although much of the North Pacific is iron limited (Martin and Fitzwater, 1988) and lacks a classical spring bloom (McAllister et al., 1960), strong seasonal variability of primary productivity is pronounced at all high latitudes because of seasonally varying photoperiod and water column stability (Racault et al., 2012). Efficient transfer of marine primary and secondary production to higher trophic levels, including commercial fish species, is influenced by the magnitude as well as the spatial and temporal synchrony between successive trophic production peaks (Hjort, 1914; Cushing, 1990; Beaugrand et al., 2003; Beaugrand and Reid, 2003).

Frequently Asked Questions

FAQ 30.2 | Does slower warming in the Ocean mean less impact on plants and animals?

The greater thermal inertia of the Ocean means that temperature anomalies and extremes are lower than those seen on land. This does not necessarily mean that impacts of ocean warming are less for the ocean than for land. A large body of evidence reveals that small amounts of warming in the Ocean can have large effects on ocean ecosystems. For example, relatively small increases in sea temperature (as little as 1°C to 2°C) can cause mass coral bleaching and mortality across hundreds of square kilometers of coral reef (*high confidence*). Other analyses have revealed that increased temperatures are spreading rapidly across the world's oceans (measured as the movement of bands of equal water temperature or isotherms). This rate of warming presents challenges to organisms and ecosystems as they try to migrate to cooler regions as the Ocean continues to warm. Rapid environmental change also poses steep challenges to evolutionary processes, especially where relatively long-lived organisms such as corals and fish are concerned (*high confidence*).

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The average temperature of the surface waters of the North Atlantic HLSBS has warmed by 0.07°C per decade, resulting in an increase in sea temperature of 0.44°C between 1950 and 2009 (*likely*) (*p*-value = 0.15; Table 30-1). Over the same period, both winter and summer temperatures have increased significantly (0.05°C per decade and 0.12°C per decade respectively, *p*-value ≤ 0.05). Since the 1970s, the Atlantic Ocean has warmed more than any other ocean basin (0.3°C per decade; Figure 30-2a; WGI AR5 Section 3.2.2), with greatest warming rates over European continental shelf areas such as the southern North Sea, the Gulf Stream front, the sub-polar gyres, and the Labrador Sea (MacKenzie and Schiedek, 2007a,b; Levitus et al., 2009; Lee et al., 2011; González-Taboada and Anadón, 2012). Basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming and the current warm phase of the Atlantic Multi-decadal Oscillation (AMO) (Wang and Dong, 2010; WGI AR5 Section 14.7.6).

The North Atlantic is one of the most intensively fished ocean sub-regions. The major areas for harvesting marine living resources span the eastern North American, European, and Icelandic shelves (Livingston and Tjelmeland, 2000). In addition, the deep regions of the Nordic Seas and the Irminger Sea contain large populations of pelagic fish such as herring, blue whiting, and mackerel and mesopelagic fish such as pearlsides and redfish. The region covers a wide latitudinal range from 35°N to 80°N and, hence, a large span in thermal habitats. This is reflected in the latitudinal gradient from subtropical/temperate species along the southern fringe to boreal/arctic species along the northern fringe.

Climate change is *virtually certain* to drive major changes to the northern fringes of the Atlantic HLSBS by 2100. For the Barents Sea region, which borders the HLSBS and Arctic regions, modeling projections from 1995 to 2060 (SRES B2 scenario) gave an increase in phytoplankton production of 8%, an increase in Atlantic zooplankton production of 20%, and a decrease of Arctic zooplankton production of 50% (Ellingsen et al., 2008). These changes result in a total increase in zooplankton production in the HLSBS section of the Barents Sea and a decrease in the Arctic section. Together with poleward shifts of fish species, a substantial increase in fish biomass and catch is also *very likely* at the northern fringes of the HLSBS (Cheung et al., 2011). However, for some species such as capelin, which feeds in summer at the ice edge and spawns in spring at the southern Atlantic Norwegian/Murman coast of the Barents Sea, the continuous temperature increase is *very likely* to cause discontinuous changes in conditions. The limited migration potential for this small pelagic fish is also *likely* to drive an eastward shift in spawning areas to new spawning grounds along the Novaja Semlja coast (Huse and Ellingsen, 2008).

Observations of fish and other species moving to higher latitudes (Beare et al., 2005; Perry et al., 2005; Collie et al., 2008; Lucey and Nye, 2010) within the North Atlantic HLSBS are consistent with results of modeling exercises (Stenevik and Sundby, 2007; Cheung et al., 2011). Examples from the Barents (Section 28.2.2.1), Nordic, and North Seas (Box 6-1; Section 23.4.6) show how warming from the early 1980s influenced North Atlantic ecosystems, where substantial biological impacts such as large-scale modification of the phenology, abundance, and distribution of plankton assemblages and reorganization of fish assemblages have been observed (Beaugrand et al., 2002; Edwards, 2004; Edwards and Richardson, 2004; Tasker, 2008; Nye et al., 2009; Head and Pepin, 2010; Simpson et al., 2011). The ranges of some cold-water zooplankton assemblages in the northeast Atlantic have contracted towards the Arctic since 1958, and have been replaced by warm-water zooplankton assemblages (specifically copepods) (*high confidence*), which moved up to 1000 km northward (Beaugrand et al., 2002; Beaugrand, 2009). Although changes to surface circulation may have played a role (Reid et al., 2001), the primary driver of the shift was shown to be regional warming (Beaugrand et al., 2002; Beaugrand, 2004). Reorganization of zooplankton communities and an observed decline in mean size has implications for energy transfer to higher trophic levels including commercial fish stocks (Beaugrand et al., 2003; Kirby and Beaugrand, 2009; Lindley et al., 2010; Section 23.4.6). Warm-water species of fish have increased in abundance on both sides of the North Atlantic (*medium confidence*; Beare et al., 2005; Collie et al., 2008; Genner et al., 2010; Hermant et al., 2010; Lucey and Nye, 2010; Simpson et al., 2011). The diversity of zooplankton and fish has increased as more diverse warm-water assemblages extend northward in response to changing environmental conditions (*high confidence*; Kane, 2007; Hiddink and ter Hofstede, 2008; Beaugrand, 2009; Mountain and Kane, 2010; ter Hofstede et al., 2010; Box 6-1; Section 23.4.6).

The past decade has been the warmest decade ever recorded in the Barents Sea, resulting in large populations of krill shrimp and pelagic and demersal fish stocks linked to the Atlantic and boreal ecosystem of the Barents Sea (*high confidence*; Johannesen et al., 2012; Section 28.2.2.1). Recruitment to boreal fish stocks such as cod, haddock, and herring has increased (Eriksen et al., 2012). The relatively warm Atlantic waters have advanced northward and eastward (Årthun et al., 2012) and sea ice has retreated along with the Arctic water masses. As a result, boreal euphausiids, which are mainly confined to Atlantic water, have increased in biomass and distribution (Dalpadado et al., 2012), enhancing growth of young cod *Gadus morhua* (boreal) as well as the more Arctic (arcto-boreal) capelin (*Mallotus villosus*). The abundance of amphipods of more Arctic origin has decreased, resulting in poorer feeding conditions for polar zooplankton predators such as polar cod (*Boreogadus saida*). Blue whiting (*Micromesistius poutassou*), which spawns west of the British Isles and feeds on zooplankton in the Norwegian Sea during the summer, extended their summer feeding distribution into the Barents Sea during the recent warm period.

The Norwegian Sea is one of the two core regions for the herbivore copepod *Calanus finmarchicus*, an important prey species for pelagic fish and early life stages of all fish around the rim of this high-latitude sea including the North Sea and the Barents Sea (Sundby, 2000). *C. finmarchicus* is the main food item for some of the world's largest fish stocks such as the Norwegian spring-spawning herring (*Clupea harengus*), blue whiting (*M. poutassou*), and northeast Atlantic mackerel (*Scomber scombrus*). These stocks have increased considerably during the recent warming that started in the early 1980s (Huse et al., 2012). The individual size of herring has also increased, enabling longer feeding migrations to utilize boreal zooplankton occurring closer to distant Arctic water masses. Mackerel (*Scomber scombrus*) has advanced northward and westward into Icelandic waters (Astthorsson et al., 2012) and was even observed in East Greenland water in summer 2013 (Nøttestad et al., 2013). Since 2004, the sum of spawning stock biomass of the three pelagic fish species (herring, blue whiting, and mackerel) leveled out at around 16 million tonnes.

Observed changes in the phenology of plankton groups in the North Sea over the past 50 years are driven by climate forcing, in particular regional warming (*high confidence*; Edwards and Richardson, 2004; Wiltshire and Manly, 2004; Wiltshire et al., 2008; Lindley et al., 2010; Lindley and Kirby, 2010; Schluter et al., 2010), although responses are species-specific with substantial variation within functional groups (Edwards and Richardson, 2004; Box 6-1). For example, the peak maximum abundance of the copepod *C. finmarchicus* advanced by 10 days from the 1960s to the 2000s, but its warm-water equivalent, *C. helgolandicus*, did not advance (Bonnet et al., 2005). In the North Sea, bottom temperatures in winter have warmed by 1.6°C (1980–2004; Dulvy et al., 2008). The whole demersal fish community shifted deeper by 3.6 m per decade over the period 1980–2004, although mean latitude of the whole community did not show net displacement (Dulvy et al., 2008). Within the community, cool-water specialists generally shifted northward while abundant warm-water species shifted southward, reflecting winter warming of the southern North Sea. The cold winter temperatures of the shallow regions of the southern North Sea have acted to exclude species with warm-water affinities. Trawl survey data from the rapidly warming southern North Sea suggests waves of immigration by southern species such as red mullet (*Mullus surmuletus*), anchovy (*Engraulis encrasicholus*), and sardines (*Sardina pilchardus*), linked to increasing population sizes and warming temperatures (Beare et al., 2004, 2005).

In the northeast Atlantic, range expansions and contractions linked to changing climate have also been observed in benthic crustaceans, bivalves, gastropods, and polychaetes (*medium confidence*; Mieszkowska et al., 2007; Beukema et al., 2009; Berke et al., 2010). For example, the southern range limit of the common intertidal barnacle, *Semibalanus balanoides*, contracted northward along European coastlines at a rate of 15 to 50 km per decade since 1872, and its retreat is attributed to reproductive failure as winter temperatures warm (Southward et al., 2005; Wethey and Woodin, 2008). *Chthamalus montagui*, its warm-water competitor, increased in abundance to occupy the niche vacated by *S. balanoides* (*high confidence*; Southward et al., 1995; Poloczanska et al., 2008).

Many of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing, that span periods of cooling and warming over the past century, are from the northeast Atlantic (Toresen and Østvedt, 2000; Southward et al., 2005; Sundby and Nakken, 2008; Edwards et al., 2010; Poloczanska et al., 2013). Meta-analysis of 288 long-term data sets (spanning up to 90 years) of zooplankton, benthic invertebrates, fish, and seabirds from the OSPAR Commission Maritime Area in the North-east Atlantic showed widespread changes in distribution, abundance, and seasonality that were consistent (77%) with expectations from enhanced greenhouse warming (Tasker, 2008). The study brought together evidence of changes in ocean climate and ecological responses across a range of species that encompassed both exploited and unexploited species from a variety of information types including peer-reviewed reports from International Council for the Exploration of the Sea (ICES) Working Groups. In particular, observations indicated poleward shifts in zooplankton communities, increasing abundance of fish species in the northern part of their ranges and decreases in southern parts, and the expansion of benthic species into more northerly or less coastal areas (*high confidence*).

The major portion of the literature on the influence of climate change on the North Atlantic region covers time spans that are longer than for most other sub-regions of the Ocean. Even here, however, the bulk of the literature is limited to the last 30 to 50 years. The few publications covering the first half of the 20th century represent an important longer term perspective on the influence of climate change (Toresen and Østvedt, 2000; Drinkwater, 2006; Sundby and Nakken, 2008; Bañón, 2009; Astthorsson et al., 2012). For example, distinct changes in fauna were associated with a pronounced warming period over 1920–1940 (Wood and Overland, 2010), when fish and other fauna shifted northward (Iversen, 1934; Southward et al., 2005; Drinkwater, 2006; Hátún et al., 2009). The major lesson from these reports is that a rapid large-scale temperature increase occurred in the high-latitude North Atlantic between the 1920s and 1940s, with basin-scale consequences for marine ecosystems that are comparable to warming and observed impacts over the last 30 years. The former event was of great concern within the scientific community, particularly during the late 1940s and early 1950s (Iversen, 1934; Tåning, 1949, 1953; Southward, 1980). However, with the subsequent long-term cooling in the 1970s, discussion around climate responses was discontinued (Southward, 1980). The centennial-long perspective indicates that multi-decadal variability has played a major role in changes observed over the past 30 years. The 150-year instrumental record shows distinct warm phases of the AMO during approximately 1930–1965 and from 1995, and cool phases between approximately 1900–1930 and 1960–1995 (WGI AR5 Section 14.7.6). However, it is *virtually certain* that the enhanced warming in recent decades cannot be explained without external forcing (WGI AR5 Section 10.3.1.1.3). Understanding the changes in inter-decadal variability over the next century is particularly important. The current warm phase of the AMO is *likely* to terminate in the next few decades, leading to a cooling influence in the North Atlantic and potentially offsetting some of the effects of global warming (WGI AR5 Sections 11.3.2.4.1, 14.7.6). Over the transition period, the climate of the North Atlantic is *likely* to change more rapidly than during previous transitions since 1900.

30.5.1.1.2. North Pacific

Sub-decadal variability in the North Pacific HLSBS is dominated by ENSO (Trenberth, 1990; WGI AR5 Section 14.4). Unlike the North Atlantic HLSBS, the North Pacific HLSBS does not show any significant trends in temperature over time, *very likely* as a consequence of climate variability influences on long-term warming patterns (1950–2009; Table 30-1). Decadal and longer periods of variability in the North Pacific are reflected in the principal mode, the Pacific Decadal Oscillation (PDO; WGI AR5 Section 14.7.3), with periodicities in SST of both 15 to 25 years and 50 to 70 years (Minobe, 1997; Mantua and Hare, 2002). Further modes of climate variability include the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al., 2008; Chhak et al., 2009). The PDO exhibits SST anomalies of one sign along the eastern boundary and the opposite sign in western and central Pacific. The PDO has been reported to have an anthropogenic component (Bonfils and Santer, 2011) but confidence in this is *very low* (*limited evidence*, *low agreement*; WGI AR5 Section 10.3.3). The interplay of the phases of these modes of variability has strong influence on high-latitude Pacific ecosystems (*very high confidence*). In the space of 3 years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) (McKinnell et al., 2010; McKinnell and Dagg, 2010). This rapid change was accompanied by large changes in primary productivity, zooplankton communities, and fish and seabird populations (McKinnell et al., 2010; McKinnell and Dagg, 2010; Batten and Walne, 2011; Bi et al., 2011; Keister et al., 2011).

Climate transitions among phases of variability tend to be characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter (Hunt et al., 2002; Peterson and Schwing, 2003; Litzow and Ciannelli, 2007; Litzow et al., 2008; Alheit, 2009). Periods of broad-scale environmental change were observed across high-latitude ecosystems in the North Pacific HLSBS (eastern Bering Sea and Gulf of Alaska) during 1976–1978, 1987–1989, and 1998–1999. These periods were associated with regime shifts in foraging fish that occurred in 1979–1982, 1988–1992, and 1998–2001. The changes indicate how basin-scale variability such as the PDO can manifest across distinct ecosystems (Overland et al., 2008; Link et al., 2009a,b). Phenological shifts observed in the zooplankton communities of the North Pacific were *very likely* in response to decadal climate variability, with distinct changes noted after the climate shifts of the 1970s and 1990s (Mackas et al., 1998; Peterson and Schwing, 2003; Chiba et al., 2006). Modeling evidence suggests a weak shift in PDO toward more occurrences of the negative phase but the credibility of projections remains uncertain (WGI AR5 Section 14.7.3). It is *about as likely as not* that the PDO will change its form or behavior in the future (WGI AR5 Section 14.7.3).

The Kuroshio-Oyashio Extension (KOE) in the northwest Pacific displays pronounced decadal-scale variability (Yatsu et al., 2008; Sugisaki et al., 2010). "Warm periods" in the mid-1970s and late 1980s were accompanied by dramatic changes in pelagic ecosystems and sardine and anchovy stocks (Chiba et al., 2008; Yatsu et al., 2008). Observations and climate model simulations indicate that global warming is *likely* to further alter the dynamics of the Kuroshio Current and the KOE over the coming century (McPhaden and Zhang, 2002; Sakamoto et al., 2005; Wu et al., 2012; Zhang et al., 2014). Alteration of the KOE will alter the timing, magnitude, and structure of spring blooms in the western Pacific and have implications for pelagic fish recruitment, production, and biogeochemical cycles (Ito et al., 2004; Hashioka et al., 2009; Yatsu et al., 2013).

Commercial catches of salmon species in the North Pacific HLSBS follow decadal fluctuations in climate (Hare and Mantua, 2000; Mantua and Hare, 2002). Catches peaked in the warm periods of the 1930s–1940s and 1990s–2000s, with 2009 yielding the highest catch to date, and warming trends are *about as likely as not* to have contributed to recent peaks in some sub-regions (Morita et al., 2006; Irvine and Fukuwaka, 2011). Poleward range shifts of some large pelagic fish in the western North Pacific, such as yellowtail *Seriola quinqueradiata* and Spanish mackerel *Scomberomorus niphonius*, were attributed, in part, to regional warming (*high confidence*) and these two species are projected to shift 39 to 71 km poleward from the 2000s to 2030s under SRES A1B (Tian et al., 2012; Jung et al., 2014). Anticipating ecological responses to future anthropogenic climate change also requires evaluation of the role of changes to climate beyond warming per se. For example, declining sea level pressure in the North Pacific is *likely* influenced by anthropogenic forcing (Gillett et al., 2003; Gillett and Stott, 2009; WGI AR5 Section 10.3.3.4) and sea level pressure in turn is related to atmospheric climate parameters (e.g., turbulent mixing via wind stress) that regulate commercially significant fish populations (Wilderbuer et al., 2002).

The northern fringe of the Bering Sea is among the most productive of marine sub-regions and includes the world's largest single-species fishery, walleye pollock (*Theragra chalcogramma*; Hunt et al., 2010). This region underwent major changes in recent decades as a result of climate variability, climate change, and fishing impacts (Litzow et al., 2008; Mueter and Litzow, 2008; Jin et al., 2009; Hunt et al., 2010; Section 28.2.2.1). Seasonal sea ice cover declined since the 1990s (to 2006), although there is no linear trend between 1953 and 2006, and the initiation of spring ice retreat over the southeastern Bering Sea shelf started to occur earlier (Wang et al., 2007a). Concurrent with the retreat of the "cold pool," an area of reduced water temperature (<2°C) on the northern Bering Sea shelf that is formed as a consequence of sea ice and is maintained over summer (Hunt et al., 2010), bottom trawl surveys of fish and invertebrates show a significant community-wide northward distribution shift and a colonization of the former cold pool areas by sub-Arctic fauna (*high confidence*; Wang et al., 2006a; Mueter and Litzow, 2008).

Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, waters low in dissolved O_2 (Oxygen Minimum Zone (OMZ)) are found at 300 m depth (Karstensen et al., 2008). Sporadic upwelling of these low-O_2 waters along the continental shelf is well documented, where biological respiration can further reduce dissolved O_2 levels and result in hypoxic or anoxic conditions that lead to mortality of coastal fishes and invertebrates (Grantham et al., 2004; Chan et al., 2008). The magnitude and severity of seasonal hypoxic conditions in shallow-shelf waters of the eastern North Pacific HLSBS increased in recent decades (Bograd et al., 2008; Chan et al., 2008). In addition, minimum pH values in the water column usually occur near the depths of the OMZ (WGI AR5 Box 3.2). A shoaling of the aragonite saturation horizon has *likely* resulted in low-aragonite conditions within the density layers being upwelled on the shelf of the west coast of the USA, increasing the risk of seasonally upwelled water being relatively acidified (Feely et al., 2008) with observed impacts on Pacific oyster (*Crassostrea gigas*) hatcheries (Barton et al., 2012). In the time period 1991–2006, reductions in pH in the North Pacific between 800 and ~100 m were attributed in approximately equal measure to anthropogenic and natural variations (Byrne et al., 2010; WGI AR5 Section 3.8.2; WGI AR5 Figure 3.19).

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the Southern Hemisphere are much less pronounced and are of smaller magnitude than those at Northern Hemisphere high latitudes (Yoder et al., 1993). The Southern Hemisphere HLSBS is broadly bounded by the subtropical front and the sub-Antarctic front. Associated with the subtropical front is intense biological activity of bloom-forming coccolithophores (phytoplankton) (Brown and Yoder, 1994). The calcifying plankton assemblages play a key role in carbon cycles in the region and the transport of carbon to deep ocean sediments. The coccolithophore, *Emiliania huxleyi*, extended its range south of 60° in the southwest Pacific (141°E to 145°E) over the 2 decades since 1983 (Cubillos et al., 2007). Although the drivers for this range extension are not clear, it was proposed that the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

Large regions of the sub-Antarctic surface waters are *likely* to become undersaturated with respect to aragonite during winter by 2030, which will impact calcifying plankton and Southern Ocean ecosystems (McNeil and Matear, 2008; Bednaršek et al., 2012; Section 28.2.2.2). Shell weights of the modern foraminifer, *Globigerina bulloides*, in the sediments of the sub-Antarctic region of the HLSBS south of Australia were observed to be 30 to 35% lower than those from sediment cores representing preindustrial periods, consistent with a recent decline in pH (Moy et al., 2009). Examination of the pteropod, *Limacina helicina antarctica*, captured from polar waters further south shows severe levels of shell dissolution consistent with the shoaling of the aragonite saturation horizon and indicates that the impact of ocean acidification is already occurring (Bednaršek et al., 2012).

While the South Pacific HLSBS has not shown warming overall, both the warmest and coolest months show a slight, but significant, increase over time (both 0.05°C per decade from 1950 to 2009, p-value $\leq$ 0.05; Table 30-1), although some areas within this sub-region have warmed. For example, the western Tasman Sea has shown enhanced warming since 1900 as compared to average global trends (*high confidence*). This has been driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific STG and intensification of the southward-flowing East Australian Current (EAC; Cai, 2006; Hill et al., 2008; Wu et al., 2012; WGI AR5 Section 3.6.2). Model simulations suggest both stratospheric ozone depletion and greenhouse forcing contribute to the observed trend in wind stress (Cai and Cowan, 2007). Coinciding with this warming and intensified EAC is the observation that a number of benthic invertebrates, fish, and zooplankton are now found further south than they were in the mid-20th century (Ling, 2008; Pitt et al., 2010; Last et al., 2011). Warming facilitated the establishment of the grazing urchin, *Centrostephanus rodgersii*, in eastern Tasmania during the late 1970s (*high confidence*), which has resulted in deleterious effects on macroalgal beds (Ling, 2008; Ling et al., 2008, 2009; Banks et al., 2010).

30.5.1.2. Key Risks and Vulnerabilities

Projected changes to the temperature of surface waters match those of the past 50 years, with average sea temperatures in the HLSBS regions projected to increase by 0.35°C to 1.17°C in the near term (2010–2039) and by 1.70°C to 4.84°C over the long term (2010–2099) under the "business as usual" (BAU) RCP8.5 scenario (Table SM30-4). Under the lower case scenario considered here (RCP2.6), projected rates of regional warming are much lower (0.12°C to 0.79°C) in the near term, with slight cooling for some regions in the long term (–0.16°C to 1.46°C). Risks to HLSBS from warming of surface waters include changes to primary production and carbon cycling, and the reorganization of ecosystems in response to warmer and more acidified oceans. Both primary production and the timing of the spring bloom in HLSBS are very sensitive to environmental change. Latitudinal shifts in the distribution of phyto- and zooplankton communities will alter seasonality, community composition, and bloom dynamics (Beaugrand, 2009; Ito et al., 2010; Shoji et al., 2011). Alteration of the structure and composition of plankton communities can propagate through high-latitude food webs due to tight trophic linkages (Edwards and Richardson, 2004; Beaugrand et al., 2010; Beaugrand and Kirby, 2010). Mechanisms are complex, and tend to be non-linear, with impacts on ecosystems, fisheries, and biogeochemical cycles being hard to project with any certainty (Box CC-PP). A reorganization of commercial fish stocks, with attendant social and economic disruption, is a key risk of ongoing climate change in HLSBS sub-regions. AR4 reported that the productivity of some marine fisheries is *likely* to increase in the North Atlantic (WGII AR4 Sections 10.4.1, 12.4.7). A large number of publications since then has substantially extended documentation of these trends and has begun to elucidate the nuances in how marine ecosystems and organisms respond (Sumaila et al., 2011).

An additional risk exists for sub-polar areas from the loss of seasonal sea ice. Decreases in seasonal sea ice are *very likely* to lead to increases in the length of the growth season and the intensity of the light available to fuel phytoplankton growth and, hence, enhance primary production and attending modifications of ecosystem structure (Arrigo et al., 2008). In the long term, however, primary production may decrease due to the reduced supply of nutrients to the surface layers (Box CC-PP). The decline in Arctic sea ice will open ecological dispersal pathways, as well as new shipping routes (Section 30.6.2.3), between the North Atlantic and the North Pacific; large numbers of the Pacific diatom, *Neodenticula seminae*, were found in the North Atlantic in 1999 (Reid et al., 2007).

HLSBSs are also vulnerable to rapid changes in the carbonate chemistry of ocean waters. Ocean acidification will produce additional and large-scale challenges. There is *medium agreement* that calcifying organisms in these regions will be negatively affected by ocean acidification, with substantial impacts on higher trophic levels, although there is *limited evidence* at this point.

30.5.2. Equatorial Upwelling Systems

The largest upwelling systems are found in the equatorial regions of the eastern Pacific and Atlantic Oceans (Figure 30-1a). Equatorial Upwelling Systems (EUS) produce highly productive "cold tongues" that stretch westward across equatorial areas, which is different from other upwelling systems (e.g., EBUE; Section 30.5.5). The associated upwelling is a consequence of the Earth's rotation and easterly (westward) winds and currents, which drive water northward and southward at the northern and southern edges of these sub-regions. As result, cold, nutrient-rich, and high CO_2/low pH waters are transported from the deeper layers of the Ocean to the surface, driving high levels of primary productivity that support 4.7% of total global fisheries productivity (Table SM30-1; Figure 30-1b). Interannual modes of variability (e.g., ENSO; WGI AR5 Section 14.4) dominate EUS, particularly in the Pacific (Barber et al., 1994; McCarthy et al., 1996; Signorini et al., 1999; Le Borgne et al., 2002;

Christian and Murtugudde, 2003; Mestas-Nuñez and Miller, 2006; Pennington et al., 2006; Wang et al., 2006b). Upwelling of the Pacific EUS declines during El Niño events, when the trade winds weaken, or even reverse, and is strengthened during La Niña events. ENSO periodicity controls primary productivity and consequently has a strong influence over associated fisheries production (Mestas-Nuñez and Miller, 2006). The Intertropical Convergence Zone (ITCZ; WGI AR5 Section 14.3.1.1), an important determinant of regional ocean temperature, is located at the edges of the Indian and Pacific equatorial upwelling zone and influences a range of variables including productivity, fisheries, and precipitation. The EUS are also affected by inter-decadal variability (e.g., Inter-decadal Pacific Oscillation (IPO); Power et al., 1999; WGI AR5 Section 14.3).

30.5.2.1. Observed Changes and Potential Impacts

The average sea temperature associated with the EUS has increased significantly (p-value ≤ 0.05), by 0.43°C and 0.54°C from 1950 to 2009 in the Pacific and Atlantic EUS, respectively (Table 30-1). In the Pacific, regional variability in SST trends is driven by the temporal patterns in ENSO and the more frequent El Niño Modoki or Central Pacific El Niño events in recent decades (*high confidence*; Ashok et al., 2007; Yu and Kao, 2007; Lee and McPhaden, 2010; WGI AR5 Section 14.2.4.4). The faster warming of the Atlantic EUS is *likely* to be associated with a weakening of upwelling (Tokinaga and Xie, 2011). SLR in the eastern equatorial Pacific has been decreasing by up to –10 mm yr^{-1} since 1993 (Church et al., 2006; Figure 30-5).

Coral reefs in the EUS of the eastern Pacific (e.g., Galápagos and Cocos Islands) have relatively low species diversity and poorly developed carbonate reef frameworks, due to the low pH and aragonite saturation of upwelling waters (*high confidence*; Glynn, 2001; Manzello et al., 2008; Manzello, 2010). Prolonged periods of elevated temperature associated with El Niño have negatively affected corals, kelps, and associated organisms, and resulted in several possible local extinctions (*high confidence*; Glynn, 2011). Since 1985, coral reefs from west of South America to the Gilbert Islands of Kiribati have experienced the highest levels of thermal stress relative to other areas (Donner et al., 2010). In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific (Glynn, 1984; Baker et al., 2008). Subsequent canonical El Niño and Central Pacific El Niño events in 1997/1998, 2002/2003, 2004/2005, and 2009/2010 (WGI AR5 Section 14.4.2; WGI AR5 Figure 14.13) triggered mass coral bleaching by adding to the background increases in sea temperatures (*high confidence*; Donner et al., 2010; Obura and Mangubhai, 2011; Vargas-Ángel et al., 2011). In some locations, impacts of El Niño have also interacted with other anthropogenic changes, such as those arising from changes to fishing pressure (Edgar et al., 2010), further complicating the attribution of recent ecological changes to climate change.

30.5.2.2. Key Risks and Vulnerabilities

Climate models indicate that ENSO is *virtually certain* to continue to be a major driver of oceanic variability over the coming century, although not all models can accurately replicate its behavior (WGI AR5 Section 9.5.3). Superposition of a warming ocean on future ENSO activity (possibly modified in frequency and intensity) is *likely* to result in oceanic conditions that are different from those experienced during past El Niño and La Niña events (Power and Smith, 2007). Temperatures within EUS sub-regions are projected to continue to warm significantly (p-value ≤ 0.05). Under RCP8.5, SST of the Atlantic EUS is projected to increase by 0.81°C over 2010–2039 and 2.56°C over 2010–2099, with similar increases projected for the Pacific EUS (Table SM30-4). Differences between RCPs for the two EUS become clear beyond mid-century, with warming of SST over 2010–2099 being 0.43°C and 0.46°C under RCP2.6, and 3.01°C and 3.03°C under RCP8.5, for Pacific and Atlantic EUS respectively (Table SM30-4). These projected increases in sea temperature will increase heat stress and ultimately irreversibly degrade marine ecosystems such as coral reefs (*very likely*). Further increases in atmospheric CO_2 will cause additional decrease in pH and aragonite saturation of surface waters (adding to the low pH and aragonite saturation of upwelling conditions), with significant differences between emission trajectories by the middle of the century. These changes in ocean carbonate chemistry are *very likely* to negatively affect some

Frequently Asked Questions

FAQ 30.3 | How will marine primary productivity change with ocean warming and acidification?

Drifting microscopic plants known as phytoplankton are the dominant marine primary producers at the base of the marine food chain. Their photosynthetic activity is critically important to life in general. It provides oxygen, supports marine food webs, and influences global biogeochemical cycles. Changes in marine primary productivity in response to climate change remain the single biggest uncertainty in predicting the magnitude and direction of future changes in fisheries and marine ecosystems (*low confidence*). Changes have been reported to a range of different ocean systems (e.g., High-Latitude Spring Bloom Systems, Subtropical Gyre Systems, Equatorial Upwelling Systems, and Eastern Boundary Upwelling Ecosystems), some of which are consistent with changes in ocean temperature, mixing, and circulation. However, direct attribution of these changes to climate change is made difficult by long-term patterns of variability that influence productivity of different parts of the Ocean (e.g., Pacific Decadal Oscillation). Given the importance of this question for ocean ecosystems and fisheries, longer time series studies for understanding how these systems are changing as a result of climate change are a priority (*high agreement*).

marine calcifiers, although many of the species from this region are adapted to the low aragonite and calcite saturation states that result from equatorial upwelling, albeit with much lower rates of calcification (Manzello, 2010; Friedrich et al., 2012). A substantial risk exists with respect to the synergistic interactions between sea temperature and declining pH, especially as to how they influence a large number of key biological processes (Box CC-OA).

There is *low confidence* in the current understanding of how (or if) climate change will influence the behavior of ENSO and other long-term climate patterns (Collins et al., 2010; WGI AR5 Section 12.4.4.2). There is also low agreement between different CMIP5 General Circulation Models (GCMs) on how ocean warming will affect ENSO, with no significant change to ENSO amplitude in half of the models examined, and both increasing and decreasing activity in others (Guilyardi et al., 2012). These differences appear to be a consequence of the delicate balance within ENSO between dampening and amplifying feedbacks, and the different emphasis given to these processes within the different GCMs (Collins et al., 2010). Other studies have looked at the interaction between the STG and EUS, and warming of surface waters in the Pacific, with at least one study projecting the possible expansion of the STG at the expense of the EUS (Polovina et al., 2011). In the latter case, the area of equatorial upwelling within the North Pacific would decrease by 28%, and primary production and fish catch by 15%, by 2100. Many of the projected changes imply additional consequences for pelagic fisheries resulting from the migration of fish stocks deriving from changing distribution of particular sea temperatures (Lehodey et al., 2006, 2008, 2011; Cheung et al., 2010; Sumaila et al., 2011; Bell et al., 2013b). These projections suggest that fisheries within EUS will experience increased vulnerability as a result of climate change (*low confidence*).

30.5.3. Semi-Enclosed Seas

Semi-Enclosed Seas (SES) represent a subset of ocean sub-regions that are largely land locked and consequently heavily influenced by surrounding landscapes and local climates (Healy and Harada, 1991). In most cases, they support small but regionally significant fisheries (3.3% of global production; Table SM30-1; Figure 30-1b) and opportunities for other industries such as tourism. Five SES (all over 200,000 km^2 with single entrances <120 km wide) are considered here. This particular geography results in reduced circulation and exchange with ocean waters, and jurisdictions for these water bodies that are shared by two or more neighboring states. In many cases, the small volume and disconnected nature of SES (relative to coastal and oceanic environments) makes them highly vulnerable to both local and global stressors, especially with respect to the much reduced options for the migration of organisms as conditions change.

30.5.3.1. Observed Changes and Potential Impacts

30.5.3.1.1. Arabian Gulf

The Arabian Gulf (also referred to as the Persian Gulf), along with the Red Sea, is the world's warmest sea, with both extreme negative and positive temperature excursions (annual temperature range of 12°C to 35°C). Like other SES, the Arabian Gulf is particularly vulnerable to changing environmental conditions as a result of its landlocked nature. Trends in SST were not significant over the period 1950–2009 (Table 30-1), which is probably due to long-term variability, and a consequence of regional and abrupt changes that occurred in the late 1980s (Conversi et al., 2010). In keeping with this, recent (1985–2002) localized analyses (e.g., Kuwait Bay) show strong and significant warming trends (based in this case on Advanced Very High Resolution Radiometer (AVHRR) National Oceanic and Atmospheric Administration (NOAA) satellite data) of 0.6°C per decade (Al-Rashidi et al., 2009). There is *limited evidence* and *low agreement* as to how this variability influences marine ecosystems and human activities within the Arabian Gulf, although impacts on some ecosystem components (e.g., coral reefs) have been defined to some extent. The mass coral bleaching and mortality that occurred in 1996 and 1998 were a direct result of the sensitivity of reef-building corals to unusually elevated sea temperatures (*high confidence*; Riegl, 2002, 2003; Box CC-CR). These changes to coral reefs have resulted in a loss of fish species that feed on coral-associated invertebrates while herbivores and planktivorous fish abundances have increased (*medium confidence*; Riegl, 2002). Despite coral ecosystems in this sub-region being adapted to some of the highest temperatures in shallow seas on Earth, anthropogenic climate change is driving higher frequencies and intensities of mass coral bleaching and mortality (Riegl et al., 2011). Other biological changes (e.g., harmful algal blooms and fish kills; Heil et al., 2001) have been associated with the increasing sea temperatures of the Arabian Gulf, although attribution to increasing temperatures as opposed to other factors (e.g., water quality) is limited (Bauman et al., 2010).

30.5.3.1.2. Red Sea

Few studies have focused on attributing recent changes in Red Sea ecosystems to climate change (including ocean acidification). The Red Sea warmed by 0.74°C from 1982 to 2006 (Belkin, 2009), although trends in the average SST, however, are not significant from 1950 to 2009 (p-value > 0.05; Table 30-1) owing to a high degree of variability involved when longer periods were examined (supplementary material in Belkin, 2009). The temperature of the warmest month of the year, however, showed a significant increase over the 60-year period (0.05°C per decade; Table 30-1). Regional trends within the Red Sea may also differ, with at least one other study reporting higher rates of warming for the central Red Sea (1.46°C, relative to 1950–1997 NOAA Extended Reconstructed SST (ERSST) v3b climatology; Cantin et al., 2010).

Long-term monitoring of coral community structure and size over 20 years shows that average colony size of corals has declined (*high confidence*) and species' latitudinal limits may have changed (*medium confidence*). The decline in average colony size is ascribed to heat-mediated bleaching as well as increases in coral diseases and crown of thorns starfish (*Acanthaster* sp.) predation (Riegl et al., 2012). The patterns of this decline correlate well with the pattern of recent heating in the Red Sea (Raitsos et al., 2011), with the biggest changes being seen in the southern part of the Red Sea. Skeletal growth of the long-lived massive coral *Diploastrea heliopora* has declined significantly, *very likely* due to warming temperatures (*medium confidence*; p-value ≥ 0.05; Cantin et al., 2010).

Cantin et al. (2010) proposed that the massive coral *Diploastrea helipora* will cease to grow in the central Red Sea by 2070 under SRES A1B and A2 (*medium confidence*), although this may not hold for other coral species. For example, an increase in linear extension of *Porites* corals, beginning in the 1980s, was recorded in the northern Red Sea (Heiss, 1996), where temperatures have increased by 0.74ºC from 1982 to 2006 (Belkin, 2009), suggesting that these corals were living in sub-optimal conditions (cooler waters). They may therefore benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline, as they are doing in other oceans. Riegl and Piller (2003) concluded that coral habitats at moderate depths in the Red Sea might provide important refugia from some aspects of climate change in the future (*limited evidence*). Silverman et al. (2007) quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate chemistry (pH, aragonite saturation). Their results demonstrate a strong negative effect of ocean acidification on ecosystem-scale calcification and decalcification, and show that small changes in carbonate dissolution could have large-scale implications for the long-term persistence of carbonate coral reef systems within the Red Sea (Silverman et al., 2007, 2009).

30.5.3.1.3. Black Sea

The temperature of the surface waters of the Black Sea increased by 0.96ºC from 1982 to 2006 (Belkin, 2009), which is consistent with other studies (*high confidence*; Buongiorno Nardelli et al., 2010; Bozkurt and Sen, 2011). As with other SES (i.e., Arabian Gulf and Baltic, Mediterranean, and Red Seas), longer data sets do not reveal a significant trend due to large-scale variability prior to 1982, which may be due to the influence of AMO, NAO, and other long-term sources of variability (Table 30-1; supplementary material in Belkin, 2009). Buongiorno Nardelli et al. (2010) observed that short-term SST variability (week-month) is strongly influenced by interactions with the overlying atmosphere, which itself is strongly influenced by the surrounding land temperatures. As with the Mediterranean and Red Seas, however, a significant upward trend in the temperature is recorded in the warmest month of the year over the period 1950–2009 (Table 30-1). Freshwater discharge from rivers draining into the Black Sea has remained more or less constant since the early 1960s (Ludwig et al., 2009). Increasing water temperature has steadily eliminated the Cold Intermediate Layer (CIL; temperatures below 8°C) throughout the Black Sea basin over 1991–2003 (*high confidence*; Oguz et al., 2003). Reduced water column mixing and upwelling during warmer winter periods has reduced the supply of nutrients to the upper layers of the Black Sea (Oguz et al., 2003) and expanded areas of low O_2 in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin (*high confidence*; Murray et al., 1989). These changes coincided with the collapse of fish stocks and the invasion by the ctenophore, *Mnemiopsis leidyi*, in the 1980s (Oguz et al., 2008), while inputs of nutrients such as phosphate from the Danube River has decreased strongly since 1992–1993 (Oguz and Velikova, 2010). Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s (Yunev et al., 2007; Oguz and Velikova, 2010). The Black Sea system is very dynamic and is strongly affected by non-climate stressors in addition to climate change, making attribution of detected trends to climate change difficult.

30.5.3.1.4. Baltic Sea

Temperatures in the highly dynamic Baltic Sea increased substantially since the early 1980s (Aleksandrov et al., 2009; Belkin, 2009), with increases of 1.35°C (1982–2006) being among the highest rate of change seen in any SES (Belkin, 2009). Increases of this magnitude are not seen in longer records throughout the Baltic Sea (1861–2001: MacKenzie et al., 2007; MacKenzie and Schiedek, 2007a,b; 1900–1998: Madsen and Højerslev, 2009). The salinity of the surface and near bottom waters of the Baltic Sea, for example, Gdansk Basin (Aleksandrov et al., 2009) and central Baltic (Fonselius and Valderrama, 2003; Möllmann et al., 2003), decreased from 1975 to 2000, due to changing rainfall and river runoff, and a reduction in the pulses of seawater (vital for oxygenation and related chemical changes) from the North Sea through its opening via the Kattegat (*high confidence*; Samuelsson, 1996; Conley et al., 2009; Hänninen and Vuorinen, 2011). There is a strong vertical zonation within the Baltic Sea in terms of the availability of O_2. The shallow sub-regions of the Baltic are relatively well oxygenated. However, O_2 levels are low in the deeper basins, producing conditions in which organisms and ecosystems are exposed to prolonged hypoxia.

The annual biomass of phytoplankton has declined almost threefold in the Baltic Transition Zone (Kattegat, Belt Sea) and Western Baltic Sea since 1979 (Henriksen, 2009), reputedly due to changing nitrogen loads in the Danish Straits (*medium confidence*) in addition to increasing sea temperature (*very likely*; Madsen and Højerslev, 2009). Reduced phytoplankton production may have decreased the productivity of fisheries in the western Baltic Sea and the Transition Zone (*low* to *medium confidence*; Chassot et al., 2007). Decreasing salinity in the Baltic deep basins may also affect zooplankton reproduction, especially that of the copepod *Pseudocalanus acuspes*, contributing to density-dependent decrease in growth of the commercially important herring and sprat stocks (*high confidence*; Möllmann et al., 2003, 2005; Casini et al., 2011). The strong relationship between phytoplankton and fish production, and increasing sea temperature, decreasing salinity, and other environmental factors, suggests that major changes in fisheries production will occur as sea temperatures increase and the hydrological cycle in the Baltic region changes (*high confidence*; MacKenzie et al., 2012). A combination of climate change-induced oceanographic changes (i.e., decreased salinity and increased temperatures), eutrophication, and overfishing have resulted in major changes in trophic structure in the deep basins of the Baltic Sea (Möllmann et al., 2009). This had important implications for cod, a commercially important top predator (*medium confidence*; Lindegren et al., 2010).

30.5.3.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and Central Europe. SST within the Mediterranean increased by 0.43°C from 1957 to 2008 (supplementary material in Belkin, 2009), although analysis of data from 1950 to 2009 detected only a significant trend in summer temperature (0.11°C per decade, p-value ≤ 0.05; Table 30-1) due to large fluctuations in SST prior to the 1980s. Surface temperatures increased in the Mediterranean Sea consistent with significant increases in SST at a number of monitoring sites (*robust evidence*, *high agreement*; e.g., Coma et al., 2009; Conversi et al., 2010; Calvo et al., 2011). It is *likely* that temperatures, along with salinity, have also increased at depth (400 m or more) in the western Mediterranean Sea over the past 30 to 40 years which, when analyzed in the context of heat budget and water flux of the Mediterranean, is consistent with anthropogenic greenhouse warming (Bethoux et al., 1990; Rixen et al., 2005; Vargas-Yáñez et al., 2010). Large-scale variability such as the AMO and NAO can obscure or accentuate the overall warming trend (Marullo et al., 2011; WGI AR5 Sections 14.5.1, 14.7.6). Relatively warm episodes in the 1870s, 1930–1970s, and since the mid-1990s, for example, exhibit an influence of the AMO (Kerr, 2000; Moron, 2003). Reported temperature anomalies in the Mediterranean, often locally manifesting themselves as periods of low wind, increased water column stratification, and a deepening thermocline, are associated with positive phases of the NAO index (Molinero et al., 2005; Lejeusne et al., 2010).

Sea levels have increased rapidly in some areas over recent decades and are also strongly influenced by NAO phases. The rate has been approximately 3.4 mm yr^{-1} (1990–2009) in the northwest Mediterranean (*high confidence*; Calvo et al., 2011). These influences are reduced when measurements are pooled over longer time scales, resulting in a lower rate of SLR (Massuti et al., 2008). If the positive phase of the NAO is more frequent in the future (Terray et al., 2004; Kuzmina et al., 2005; WGI AR5 Section 14.4.2), then future SLR may be slightly suppressed as a result of atmospheric influences (*medium confidence*; Jordà et al., 2012). As temperatures have increased, the Mediterranean has become more saline (+0.035 to 0.040 psu from 1950 to 2000; Rixen et al., 2005) with the length of the thermal stratification period persisting twice as long in 2006 as it did in 1974 (Coma et al., 2009).

Conditions within the Mediterranean Sea changed abruptly and synchronously with similar changes across the North, Baltic, and Black Seas in the late 1980s (Conversi et al., 2010), which possibly explains the lack of trend in SES SST when examined from 1950 to 2009 (Table 30-1). These changes in physical conditions (increased temperature, higher sea level pressure, positive NAO index) also coincided with step changes in the diversity and abundance of zooplankton, decreases in stock abundance of anchovies and the frequency of "red tides," and increases in mucilage outbreaks (Conversi et al., 2010). Mucilage outbreaks are strongly associated with warmer and more stratified water columns (*high confidence*), and lead to a greater abundance and diversity of marine microbes and potentially disease-causing organisms (*likely*; Danovaro et al., 2009). Increasing temperatures are also driving the northward spread of warm-water species (*medium confidence*) such as the sardine *Sardinella aurita* (Sabatés et al., 2006; Tsikliras, 2008), and have contributed to the spread of the invading Atlantic coral *Oculina patagonia* (Serrano et al., 2013). The recent spread of warm-water species that have invaded through the Straits of Gibraltar and the Suez Canal into cooler northern areas is leading to the "tropicalization" of Mediterranean fauna (*high confidence*; Bianchi, 2007; Ben Rais Lasram and Mouillot, 2008; CIESM, 2008; Galil, 2008, 2011). Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin (Raitsos et al., 2010; Section 23.6.5).

In addition to general warming patterns, periods of extreme temperatures have had large-scale and negative consequences for Mediterranean marine ecosystems. Unprecedented mass mortality events, which affected at least 25 prominent invertebrate species, occurred during the summers of 1999, 2003, and 2006 across hundreds of kilometers of coastline in the northwest Mediterranean Sea (*very high confidence*; Cerrano et al., 2000; Garrabou et al., 2009; Calvo et al., 2011; Crisci et al., 2011). Events coincided with either short periods (2 to 5 days: 2003, 2006) of high sea temperatures (27°C) or longer periods (30 to 40 days) of modestly high temperatures (24°C: 1999; Bensoussan et al., 2010; Crisci et al., 2011). Impacts on marine organisms have been reported in response to the extreme conditions during these events (e.g., gorgonian coral mortality; Coma et al., 2009), shoot mortality, and anomalous flowering of seagrasses (*high confidence*; Diaz-Almela et al., 2007; Marbà and Duarte, 2010). The frequency and intensity of these types of heat stress events are expected to increase as sea temperatures increase (*high confidence*).

Longer-term data series (over several decades) of changes in relative acidity of the Mediterranean Sea are scarce (Calvo et al., 2011; The MerMex Group, 2011). Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05 to 0.14 pH units since the preindustrial period (*medium confidence*; Luchetta et al., 2010; Touratier and Goyet, 2011). Anthropogenic CO_2 has penetrated the entire Mediterranean water column, with the western basin being more contaminated than the eastern basin (Touratier and Goyet, 2011). Studies that have explored the consequences of ocean acidification for the biology and ecology of the Mediterranean Sea are rare (Martin and Gattuso, 2009; Rodolfo-Metalpa et al., 2010; Movilla et al., 2012), although insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia in Italy, where biodiversity decreases with decreasing pH toward the vents, with a notable decline in calcifiers (Hall-Spencer et al., 2008). Transplants of corals, molluscs, and bryozoans along the acidification gradients around seeps reveal a low level of vulnerability to CO_2 levels expected over the next 100 years (*low confidence*; Rodolfo-Metalpa et al., 2010, 2011). However, periods of high temperature can increase vulnerability to ocean acidification, thereby increasing the long-term risk posed to Mediterranean organisms and ecosystems as temperatures warm. Significantly, some organisms such as seagrasses and some macroalgae appeared to benefit from local ocean acidification (Hall-Spencer et al., 2008).

30.5.3.2. Key Risks and Vulnerabilities

SES are highly vulnerable to changes in global temperature on account of their small volume and landlocked nature. Consequently, SES will respond faster than most other parts of the Ocean (*high confidence*). Risks to ecosystems within SES are *likely* to increase as water columns become further stratified under increased warming, promoting hypoxia at depth and reducing nutrient supply to the upper water column (*medium evidence*, *high agreement*). The impact of rising temperatures on SES is exacerbated by their vulnerability to other human influences such as over-exploitation, pollution, and enhanced runoff from modified coastlines. Due to a mixture of global and local human stressors, key fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years (*medium confidence*). A major risk exists for SES from projected increases in the frequency of temperature extremes that drive mass mortality events, increasing water column stabilization leading to reduced mixing, and changes to the distribution and abundance of marine organisms. The vulnerability of marine ecosystems, fisheries, and human communities associated with the SES will continue to increase as global temperatures increase.

Sea temperatures are *very likely* to increase in the five SES under moderate (RCP6.0) to high (RCP8.5) future scenarios. Under BAU (RCP8.5; Table SM30-3), sea temperatures in the SES are projected to increase by 0.93°C to 1.24°C over 2010–2039 (Table SM30-4). Increases of 3.45°C to 4.37°C are projected over 2010–2099, with the greatest increases projected for the surface waters of the Baltic Sea (4.37°C) and Arabian Gulf (4.26°C), and lower yet substantial amounts of warming in the Red Sea (3.45°C) (Table SM30-4). The heat content added to these small ocean regions is *very likely* to increase stratification, which will reduce the nutrient supply to the upper layers of the water column, reducing primary productivity and driving major changes to the structure and productivity of fisheries. Reduced mixing and ventilation, along with increased microbial metabolism, will *very likely* increase hypoxia and expand the number and extent of "dead zones." Changing rainfall intensity (Section 23.3; WGI AR5 Section 12.4.5) can exert a strong influence on the physical and chemical conditions within SES, and in some cases will combine with other climatic changes to transform these areas. These changes are likely to increase the risk of reduced bottom-water O_2 levels to Baltic and Black Sea ecosystems (due to reduced solubility, increased stratification, and microbial respiration), which is *very likely* to affect fisheries. These changes will increase the frequency and intensity of impacts arising from heat stress, based on responses to temperature extremes seen over the past 30 years, such as the mass mortality of benthic organisms that occurred in the Mediterranean Sea during the summers of 1999, 2003, and 2006, and the Arabian Gulf in 1996 and 1998. Extreme temperature events such as heat waves are projected to increase (*high confidence*; Section 23.2; IPCC, 2012). Projections similar to those outlined in Section 30.5.4.2 can be applied to the coral reefs of the Arabian Gulf and the Red Sea, where temperatures are *very likely* to increase above established thresholds for mass coral bleaching and mortality (*very high confidence*; Figure 30-10).

30.5.4. Coastal Boundary Systems

The Coastal Boundary Systems (CBS) are highly productive regions, comprising 10.6% of primary production and 28.0% of global fisheries production (Table SM30-1; Figure 30-1b). The CBS include the marginal seas of the northwest Pacific, Indian, and Atlantic Oceans, encompassing the Bohai/Yellow Sea, East China Sea, South China Sea, and Southeast Asian Seas (e.g., the Timor, Arafura, and Sulu Seas, and the northern coast of Australia) in the Pacific; the Arabian Sea, Somali Current system, East Africa coast, Mozambique Channel, and Madagascar in the Indian Ocean; and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean). Some CBS are dominated by powerful currents such as the Kuroshio (Pacific), or are strongly influenced by monsoons (e.g., Asian-Australian and African monsoons).

30.5.4.1. Observed Changes and Potential Impacts

Many ecosystems within the CBS are strongly affected by the local activities of often-dense coastal human populations. Activities such as the overexploitation of fisheries, unsustainable coastal development, and pollution have resulted in the widespread degradation of CBS ecosystems (Burke et al., 2002, 2011). These influences have combined with steadily increasing ocean temperature and acidification to drive major changes to a range of important ecosystems over the past 50 years. Understanding the interactions between climate change and non-climate change drivers is a central part of the detection and attribution process within the CBS.

Overall, the CBS warmed by 0.14°C to 0.80°C from 1950 to 2009 (Table 30-1), although changes within the Gulf of Mexico/Caribbean Sea sub-region were not significant (p-value > 0.05) over this period. Key sub-regions within the CBS such as the Coral Triangle and Western Indian Ocean warmed by 0.79°C and 0.60°C, respectively, from 1950 to 2009 (Table 30-1). Rates of SLR vary from decreasing sea levels (–5 to –10 mm yr^{-1}) to low (2 to 3 mm yr^{-1}, Caribbean) to very high (10 mm yr^{-1}, Southeast Asia; Figure 30-5) rates of increase. Ocean acidification also varies from region to region (Figure SM30-2), and is influenced by oceanographic and coastal processes, which often have a large human component.

30.5.4.1.1. Bohai/Yellow Sea/East China Sea

The Bohai Sea, Yellow Sea, and the East China Sea (ECS) are shallow marginal seas along the edge of the northwest Pacific that are strongly influenced by the Kuroshio Current (Matsuno et al., 2009), the East Asian Monsoon (EAM), and major rivers such as the Yellow (Huang He) and Yangtze (Changjiang) Rivers. Upwelling of the Kuroshio sub-surface waters provides abundant nutrients that support high levels of primary productivity (Wong et al., 2000, 2001). The ecosystems of the ECS are heavily affected by human activities (e.g., overfishing and pollution), which tend to compound the influence and consequences of climate change.

SST within the ECS has increased rapidly since the early 1980s (*high confidence*; Lin et al., 2005; Jung, 2008; Cai et al., 2011; Tian et al., 2012). The largest increases in SST have occurred in the ECS in winter (1.96°C, 1955–2005) and in the Yellow Sea in summer (1.10°C, 1971–2006; Cai et al., 2011). These changes in SST are closely linked to a weakening of the EAM (e.g., Cai et al., 2006, 2011; Tang et al., 2009) and increasing warmth of the Kuroshio Current (Qi et al., 2010; Zhang et al., 2011; Wu et al., 2012). At the same time, dissolved O_2 has decreased (Lin et al., 2005; Jung, 2008; Qi et al., 2010), with an associated increase in the extent of the hypoxic areas in coastal areas of the Yellow Sea/ECS (Jung, 2008; Tang, 2009; Ning et al., 2011).

Primary productivity, biomass yields, and fish capture rates have experienced large changes within the ECS over the past decades (*limited evidence*, *medium agreement*; *low confidence*; Tang et al., 2003; Lin et al., 2005; Tang, 2009). Fluctuations in herring abundance appear to closely track SST shifts within the Yellow Sea (Tang, 2009). For plankton and fish species, the proportions of warm-water species relative to warm-temperate species in the Changjiang River Estuary (extending to the southern Taiwan Strait) have changed over past decades (Zhang et al., 2005; Ma et al., 2009; Lin and Yang, 2011). Northward shifts in catch distribution for some pelagic fish species in Korean waters were driven, in part, by warming SST (*medium confidence*; Jung et al., 2014). The frequency of harmful algal blooms and blooms of the giant jellyfish *Nemopilema nomurai* in the offshore area of the ECS have increased and have been associated with ocean warming and other factors such as eutrophication (Ye and Huang, 2003; Tang, 2009; Cai and Tan, 2010). Although attribution of these changes to anthropogenic climate change is complicated by the increasing influence of non-climate-related human activities, many of these changes are consistent with those expected as SST increases.

30.5.4.1.2. South China Sea

The South China Sea (SCS) is surrounded by continental areas and includes large numbers of islands, and is connected to the Pacific, ECS, and Sulu Sea by straits such as the Luzon and Taiwan Strait. The region is greatly influenced by cyclones/typhoons, and by the Pearl, Red, and Mekong Rivers. The region has a distinct seasonal circulation and is greatly influenced by the southwest monsoon (in summer), the Kuroshio Current, and northeast monsoon (in winter). The SCS includes significant commercial fisheries areas and includes coral reefs, mangroves, and seagrass beds.

The surface waters of the SCS have been warming steadily from 1945 to 1999 with the annual mean SST in the central SCS increasing by 0.92°C (1950–2006; Cai et al., 2009), a rate similar to that observed for the entire Indo-Pacific/Southeast Asian CBS from 1950 to 2009 (0.80°C; Table 30-1). Significant freshening in the SCS intermediate layer since the 1960s has been observed (Liu et al., 2007). The temperature change of the upper layers of the SCS has made a significant contribution to sea level variation, which is heterogeneous in space and time (Li et al., 2002; Cheng and Qi, 2007; Liu et al., 2007).

Identifying the extent to which climate change is influencing the SCS is difficult due to confounding non-climate change factors and their interactions (e.g., local human pollution, over-exploitation together with "natural" climate variability such as EAM, ENSO, and PDO). Changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries, and the size of demersal trawl catches in the northern SCS observed over the period 1976–2004 (*limited evidence*, *medium agreement*; Ning et al., 2009). Coral reefs and mangroves are degrading rapidly as a result of both climate change and non-climate change-related factors (*very likely*; Box CC-CR; Chen et al., 2009; China-SNAP, 2011; Zhao et al., 2012). Mass coral bleaching and mortality of coral reefs within the SCS were triggered by elevated temperatures in 1998 and 2007 (Yu et al., 2006; Li et al., 2011). Conversely, warming enabled the establishment of a high-latitude, non-carbonate, coral community in Daya Bay in northern SCS, although this community has recently degraded as a result of increasing anthropogenic stresses (Chen et al., 2009; Qiu et al., 2010).

30.5.4.1.3. Southeast Asian Seas

The Southeast Asian Seas (SAS) include an archipelago of diverse islands that interact with the westward flow of the North Equatorial Current and the Indonesian Throughflow (Figure 30-1a). A large part of this region is referred to as the "Coral Triangle" (Veron et al., 2009). The world's most biologically diverse marine area, it includes parts of Malaysia, Indonesia, the Philippines, Timor Leste, the Solomon Islands, and Papua New Guinea. SST increased significantly from 1985 to 2006 (Peñaflor et al., 2009; McLeod et al., 2010), although with considerable spatial variation. Trends examined over longer periods (1950–2009) show significant warming (+0.80°C, p-value ≤ 0.05; Table 30-1). The sea level is rising by up to 10 mm yr^{-1} in much of this region (Church et al., 2004, 2006; Green et al., 2010). Like other tropical areas in the world, coral reefs within SAS have experienced periods of elevated temperature, which has driven several mass coral bleaching and mortality events since the early 1980s (*high confidence*; Hoegh-Guldberg et al., 2009; McLeod et al., 2010; Figure 30-10a). The most recent occurred during warm conditions in 2010 (Krishnan et al., 2011). These changes are the result of increasing ocean temperatures and are *very likely* to be a consequence of anthropogenic climate change (*high confidence*; Box CC-CR; WGI AR5 Section 10.4.1). Although calcification rates of some key organisms (e.g., reef-building corals; Tanzil et al., 2009) have slowed over the past 2 decades, it is not possible to conclude that the changes are due to ocean acidification. While a large part of the decline in coral reefs has been due to increasing local stresses (principally destructive fishing, declining water quality, and over-exploitation of key reef species), projected increases in SST represent a major challenge for these valuable ecosystems (*high agreement*; Burke et al., 2002; Burke and Maidens, 2004).

30.5.4.1.4. Arabian Sea and Somali Current

The Arabian Sea and Somali Current are relatively productive ocean areas, being strongly influenced by upwelling and the monsoonal system. Wind-generated upwelling enhances primary production in the western Arabian Sea (Prakash and Ramesh, 2007). Several key fisheries within this region are under escalating pressure from both fishing and climate change. SST increased by 0.18°C and 0.26°C in the Arabian Sea and Somali Current, respectively, from 1982 to 2006 (HadSST2; Rayner et al., 2003; Belkin, 2009), which is consistent with the overall warming of the Western Indian Ocean portion of the CBS from 1950 to 2009 (0.60°C; Table 30-1). Salinity of surface waters in the Arabian Sea increased by 0.5 to 1.0% over the past 60 years (Figure 30-6c), due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf. As in other tropical sub-regions, increasing sea temperatures have increased the frequency of mass coral bleaching and mortality within this region (Wilkinson and Hodgson, 1999; Goreau et al., 2000; Wilkinson, 2004).

The aragonite saturation horizon in both the Arabian Sea and Bay of Bengal is now 100 to 200 m shallower than in preindustrial times as a result of ocean acidification (*medium confidence*; Feely et al., 2004). Shoaling of the aragonite saturation horizon is *likely* to affect a range of organisms and processes, such as the depth distribution of pteropods (zooplankton) in the western Arabian Sea (*medium confidence*; Hitchcock et al., 2002; Mohan et al., 2006). More than 50% of the area of OMZs in the world's oceans occur in the Arabian Sea and Bay of Bengal and long-term measurements reveal that O_2 concentrations are declining in this region (*high confidence*; Helly and Levin, 2004; Karstensen et al., 2008; Stramma et al., 2010; Section 30.3.2.3). The information regarding the consequences of climate change within this region is undeveloped and suggests that important physical, chemical, and biological responses to climate change need to be the focus of further investigation.

30.5.4.1.5. East Africa coast and Madagascar

The Western Indian Ocean strongly influences the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagos (Comoros, Mauritius, and the Seychelles). Sea temperatures in the Western Indian Ocean have increased by 0.60°C over 1950–2009 (*high confidence*; p-value ≤ 0.05; Table 30-1), increasing the frequency of positive thermal anomalies that have triggered mass coral bleaching and mortality events across the region over the past 2 decades (*high confidence*; Baker et al., 2008; Nakamura et al., 2011; Box CC-HS). Trends in changes in SST and surface salinity vary with location along the East African coastline, with faster rates at higher latitudes (Figure 30-2). Periods of heat stress over the past 20 years have triggered mass coral bleaching and mortality on coral reef ecosystems within this region (McClanahan et al., 2007, 2009a,b,c; Ateweberhan and McClanahan, 2010; Ateweberhan et al., 2011). Steadily increasing sea temperatures have also produced anomalous growth rates in long-lived corals such as *Porites* (*high confidence*; McClanahan et al., 2009b). Differences in the susceptibility of reef-building corals to stress from rising sea temperatures has also resulted in changes to the composition of coral (*high confidence*; p-value ≤ 0.05; McClanahan et al., 2007) and benthic fish communities (*high confidence*; p-value ≤ 0.05; Graham et al., 2008; Pratchett et al., 2011a). These changes are *very likely* to alter species composition and potentially the productivity of coastal fisheries (*robust evidence*, *high agreement*; *high confidence*; Jury et al., 2010), although there may be a significant lag between the loss of coral communities and the subsequent changes in the abundance and community structure of fish populations (p-value ≤ 0.05; Graham et al., 2007). Some of these potential changes can be adverted or reduced by interventions such as the establishment of marine protected areas and changes to fishing management (McClanahan et al., 2008; Cinner et al., 2009; Jury et al., 2010; MacNeil et al., 2010).

30.5.4.1.6. Gulf of Mexico and Caribbean Sea

The Gulf of Mexico and Caribbean Sea form a semi-contained maritime province within the Western Atlantic. These areas are dominated by a range of activities including mineral extraction, fishing, and tourism, which provide employment and opportunity for almost 75 million people who live in coastal areas of the USA, Mexico, and a range of other Caribbean nations (Adams et al., 2004). The Gulf of Mexico and Caribbean Sea have warmed by 0.31°C and 0.50°C, respectively, from 1982 to 2006 (*very likely*; Belkin, 2009). Warming trends are not significant from 1950 to 2009 (Table 30-1), which may be partly due to spatial variability in warming patterns (Section 30.5.3.1). The Caribbean region has experienced a sustained decrease in aragonite saturation state from 1996 to 2006 (*very likely*; Gledhill et al., 2008). Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2 to 3 mm yr^{-1} from 1950 to 2000 (Church et al., 2004; Zervas, 2009).

Understanding influences of climate change on ocean ecosystems in this region is complicated by the confounding influence of growing human populations and activities. The recent expansion of the seasonal hypoxic zone, and the associated "dead zone," in the Gulf of Mexico has been attributed to nitrogen inputs driven by land management (Turner and Rabalais, 1994; Donner et al., 2004) and changes to river flows, wind patterns, and thermal stratification of Gulf waters (*high confidence*; Justić et al., 1996, 2007; Levin et al., 2009; Rabalais et al., 2009). The increases in coastal pollution and fishing have potentially interacted with climate change to exacerbate impacts on marine ecosystems within this region (Sections 5.3.4, 29.3). These changes have often been abrupt and non-linear (Taylor et al., 2012).

A combination of local and global disturbances has driven a large-scale loss of reef-building corals across the Caribbean Sea since the late 1970s (*high confidence*; Hughes, 1994; Gardner et al., 2003). Record thermal stress in 2005 triggered the largest mass coral bleaching and mortality event on record for the region, damaging coral reefs across hundreds of square kilometers in the eastern Caribbean Sea (*high confidence*; Donner et al., 2007; Eakin et al., 2010). Although conditions in 2010 were milder than in 2005, elevated temperatures still occurred in some parts of the Caribbean (Smith et al., 2013). Increasing temperatures in the Caribbean have also been implicated in the spread of marine diseases (Harvell et al., 1999, 2002, 2004) and some introduced species (*likely*; Firth et al., 2011). As in other sub-regions, pelagic fish species are sensitive to changes in sea temperature and modify their distribution and abundance accordingly (Muhling et al., 2011). Fish and invertebrate assemblages in the Gulf of Mexico have shifted deeper in response to SST warming over 1970s–2011 (*medium confidence*; Pinsky et al., 2013).

Coral ecosystems in the Caribbean Sea are at risk from ocean acidification (*very likely*; Albright et al., 2010; Albright and Langdon, 2011), although impacts have yet to be observed under field conditions. Ocean acidification may also be altering patterns of fish recruitment to coral reefs, although direct evidence for how this has affected Caribbean species is lacking (*low confidence*; Dixson et al., 2008, 2010; Munday et al., 2009).

30.5.4.2. Key Risks and Vulnerabilities

Worldwide, 850 million people live within 100 km of tropical coastal ecosystems such as coral reefs and mangroves deriving multiple benefits including food, coastal protection, cultural services, and income from industries such as fishing and tourism (Burke et al., 2011). Marine ecosystems within the CBS are sensitive to increasing sea temperatures (Figure 30-10), although detection and attribution are complicated by the significant influence and interaction with non-climate change stressors (water quality, over-exploitation of fisheries, coastal degradation; Box CC-CR). Warming is likely to have changed the primary productivity of ocean waters, placing valuable ecosystems and fisheries within the ECS at risk (*low* to *medium confidence*). Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of the CBS. Given the consequences for coastal ecosystems and fisheries, these changes are *very likely* to increase the vulnerability of coastal communities throughout the CBS.

Sea temperatures are increasing within many parts of CBS ecosystems (1950–2009; Table 30-1), and will continue to do so over the next few decades and century. Sea temperatures are projected to change by

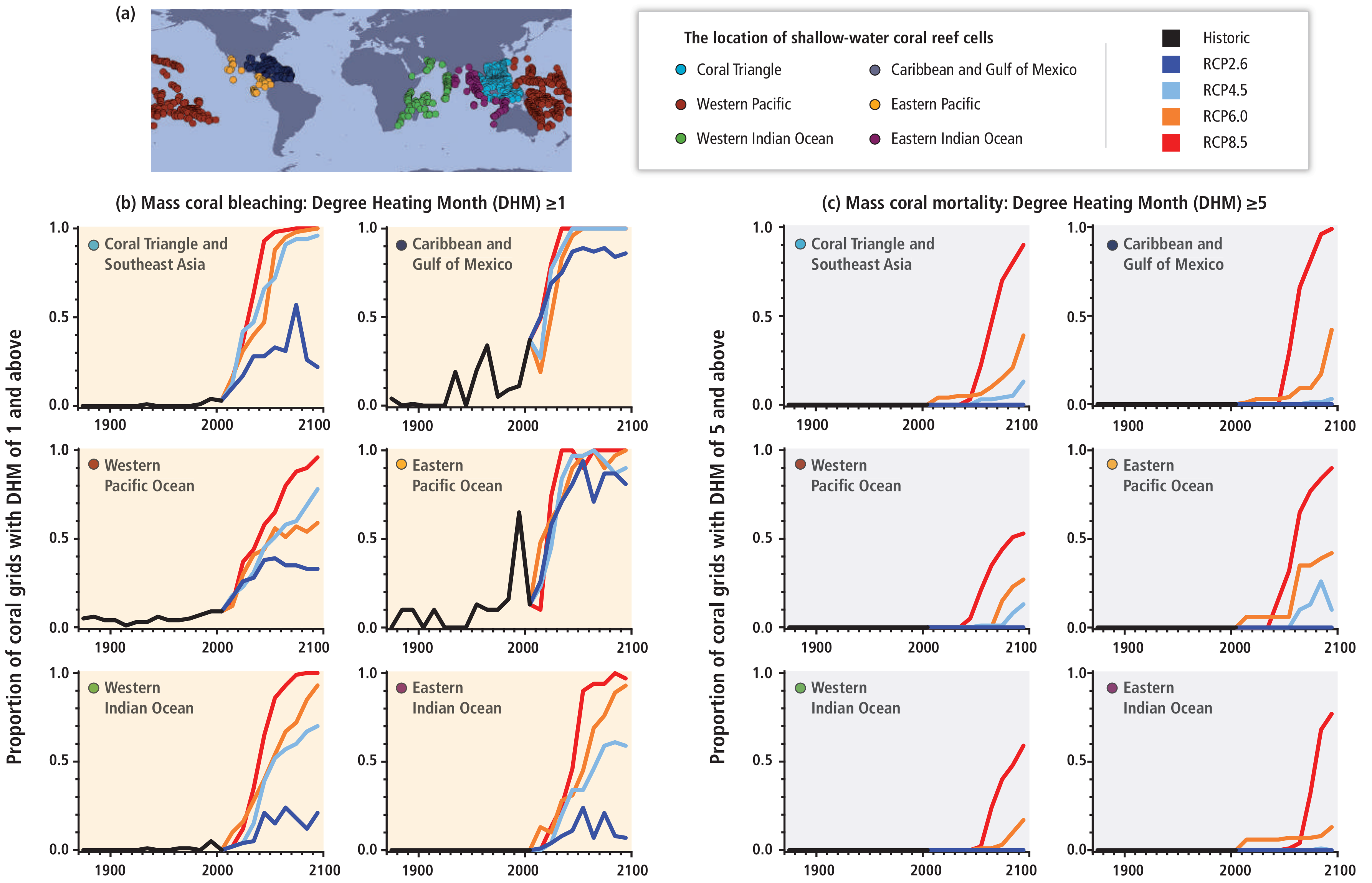


Figure 30-10 | Annual maximum proportions of reef pixels with Degree Heating Months (DHM, Donner et al., 2007) for each of the six coral regions (a, Figure 30-4b)—(b) DHM ≥1 (used for projecting the incidence of coral bleaching; Strong et al., 1997, 2011) and (c) DHM ≥5 (associated with bleaching followed by significant mortality; Eakin et al., 2010)—for the period 1870–2009 using the Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1) data set. The black line on each graph is the maximum annual area value for each decade over the period 1870–2009. This value is continued through 2010–2099 using Coupled Model Intercomparison Project Phase 5 (CMIP5) data and splits into the four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, and 8.5). DHM were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHM, the annual percentage of grid cells with DHM ≥1 and DHM ≥5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010–2099 are the average of these maximum proportion values for each RCP. Monthly sea surface temperature anomalies were derived using a 1985–2000 maximum monthly mean climatology derived in the calculations for Figure 30-4. This was done separately for HadISST1.1, the CMIP5 models, and each of the four RCPs, at each grid cell for every region. DHMs were then derived by adding up the monthly anomalies using a 4-month rolling sum. Figure SM30-3 presents past and future sea temperatures for the six major coral reef provinces under historic, un-forced, RCP4.5 and RCP8.5 scenarios.

0.34°C to 0.50°C over the near term (2010–2039) and by 0.23°C to 0.74°C over the long term (2010–2099) under the lowest RCP scenario (RCP2.6). Under BAU (RCP8.5), CBS sea temperatures are projected to increase by 0.62°C to 0.85°C over the near term and 2.44°C to 3.32°C over the long term (Table SM30-4). Given the large-scale impacts (e.g., mass coral bleaching and mortality events) that have occurred in response to much smaller changes in the past over CBS regions (0.14°C to 0.80°C from 1950–2009; Table 30-1), the projected changes of 2.44°C to 3.32°C over 2010–2099 are *very likely* to have large-scale and negative consequences for the structure and function of many CBS ecosystems (*virtually certain*), especially given the observed sensitivity of coral reefs to relatively small increases in temperature over the past 3 decades (Hoegh-Guldberg, 1999; Eakin et al., 2010; Lough, 2012).

It is *very likely* that coral-dominated reef ecosystems within the CBS (and elsewhere) will continue to decline and will consequently provide significantly less ecosystem goods and services for coastal communities if sea temperatures increase by more than 1°C above current temperatures (Box CC-CR; Figure 30-10). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle sub-regions (Strong et al., 1997, 2011; Hoegh-Guldberg, 1999), with the exposure to higher temperatures that are projected under medium (RCP4.5) to high (RCP8.5) scenarios, reveals that both coral reef-rich regions are *virtually certain* to experience levels of thermal stress ($DHM \geq 1$) that cause coral bleaching every 1 to 2 years by the mid- to late part of this century (*robust evidence*, *high agreement*; *very high confidence*; Figures 30-4b,c, 30-10, 30-12, SM30-3; van Hooidonk et al., 2013). The frequency of mass mortality events ($DHM \geq 5$; Figure 30-10a,b,c) also increases toward a situation whereevents that occur every 1 to 2 years by the mid- to late part of this century under low to high climate change scenarios (*robust evidence*, *high agreement*; *very high confidence*; Hoegh-Guldberg, 1999; Donner et al., 2005; Frieler et al., 2012). Mass mortality events that affect coral reefs will result in changes to community composition in the near term (2010–2039; Berumen and Pratchett, 2006; Adjeroud et al., 2009) and a continuing downward trend in coral cover in the longer term (Gardner et al., 2003; Bruno and Selig, 2007; Baker et al., 2008).

It is *virtually certain* that composition of coral reef fish populations (Graham et al., 2007; Pratchett et al., 2008, 2011a,b) will change. The productivity of many fisheries will decrease (*limited evidence*, *medium agreement*) as waters warm, acidify, and stratify, and as crucial habitat, such as coral reefs, degrade (*low confidence*). These changes are *very likely* to increase the vulnerability of millions of people who live in coastal communities and depend directly on fisheries and other goods and services provided by ecosystems such as coral reefs (Hoegh-Guldberg et al., 2009; McLeod et al., 2010).

30.5.5. Eastern Boundary Upwelling Ecosystems

The Eastern Boundary Upwelling Ecosystems (EBUE) include the California, Peru/Humboldt, Canary/northwest Africa, and Benguela Currents. They are highly productive sub-regions with rates of primary productivity that may exceed 1000 g C m^{-2} yr^{-1}. Although these provinces comprise less than 2% of the Ocean area, they contribute nearly 7% of marine primary production (Figure 30-1b) and more than 20% of the world's marine capture fisheries (Pauly and Christensen, 1995). Catches in the EBUE are dominated by planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous benthic fish such as hake. Nutrient input from upwelling of cooler waters stimulates primary production that is transferred to mid and upper trophic levels, resulting in substantial fish, seabird, and marine mammal populations. As a result, the EBUE are considered "hotspots" of productivity and biodiversity (Block et al., 2011). The high level of productivity is a result of large-scale atmospheric pressure gradients and wind systems that advect surface waters offshore, leading to the upwelling of cold, nutrient-rich waters from depth (Box CC-UP; Chavez and Messie, 2009; Chavez et al., 2011). Upwelling waters are typically low in pH and high in CO_2, and are likely to continue to enhance changes in pH and CO_2 resulting from rising atmospheric CO_2 (Feely et al., 2008; Gruber, 2011).

30.5.5.1. Observed Changes and Potential Impacts

There are extensive studies of the coupled climate-ecosystem dynamics of individual EBUE (e.g., California Current). Decadal variability poses challenges to the detection and attribution of changes within the EBUE to anthropogenic climate change, although there are a number of long-term studies that have been able to provide insight into the patterns of change and their causes. Like other ocean sub-regions, EBUE are projected to warm under climate change, with increased stratification and intensified winds as westerly winds shift poleward (*likely*). However, cooling has also been predicted for some EBUE, resulting from the intensification of wind-driven upwelling (Bakun, 1990). The California and Canary Currents have warmed by 0.73°C and 0.53°C (*very likely*; p-value ≤ 0.05, 1950–2009; Table 30-1), respectively, while no significant trend was detected in the sea surface temperatures of the Benguela (p-value = 0.44) and Humboldt Currents (p-value = 0.21) from 1950 to 2009 (Table 30-1). These trends match shorter-term trends for various EBUE using Pathfinder version 5 data (Demarcq, 2009). These differences are *likely* to be the result of differences in the influence of long-term variability and the specific responses of coastal wind systems to warming, although an analysis of wind data over the same period did not pick up clear trends (*low confidence*, with respect to long-term wind trends; Demarcq, 2009; Barton et al., 2013).

How climate change will influence ocean upwelling is central to resolving ecosystem and fishery responses within each EBUE. There is considerable debate, however, as to whether or not climate change will drive an intensification of upwelling (e.g., Bakun et al., 2010; Narayan et al., 2010; Barton et al., 2013) in all regions. This debate is outlined in Box CC-UP. EBUE are also areas of naturally low pH and high CO_2 concentrations due to upwelling, and consequently may be vulnerable to ocean acidification and its synergistic impacts (Barton et al., 2012). A full understanding of the consequences of ocean acidification for marine organisms and ecosystems is discussed elsewhere (Boxes CC-OA, CC-UP; Sections 6.2, 6.3.2; Kroeker et al., 2013; WGI AR5 Section 6.4).

30.5.5.1.1. Canary Current

Part of the North Atlantic STG, the Canary Current extends from northern Morocco southwestward to the North Atlantic Equatorial Current. It is linked with the Portugal Current (which is sometimes considered part of the Canary Current) upstream. The coastal upwelling system, however, is limited to a narrow belt along the Saharan west coast to the coast of Guinea, with the most intense upwelling occurring centrally, along the coasts of Mauritania (15°N to 20°N) and Morocco (21°N to 26°N). Total fish catches, comprising mainly coastal pelagic sardines, sardinellas, anchovies, and mackerel, have fluctuated around 2 million tonnes yr^{-1} since the 1970s (www.seaaroundus.org/lme/27.aspx). Contrasting with the other EBUE, fishing productivity is modest, probably partly due to the legacy of uncontrolled fishing in the 1960s (Arístegui et al., 2009).

Most observations suggest that the Canary Current has warmed since the early 1980s (Arístegui et al., 2009; Belkin, 2009; Demarcq, 2009; Barton et al., 2013), with analysis of HadISST1.1 data from 1950 to 2009 indicating warming of 0.53°C from 1950–2009 (p-value ≤ 0.05; Table 30-1). Gómez-Gesteira et al. (2008) suggest a 20 and 45% decrease in the strength of upwelling in winter and summer, respectively, from 1967 to 2006, consistent with a decrease in wind strength and direction over the past 60 years. More recently, Barton et al. (2013) show no clear increasing or decreasing trend in wind strength over the past 60 years, and a lack of agreement among wind trends and variability from different wind products (e.g., Pacific Fisheries Environmental Laboratory (PFEL), International Comprehensive Ocean-Atmosphere Data Set (ICOADS), Wave- and Anemometer-based Sea Surface Wind (WASWind)). Barton et al. (2013) present no evidence for changes in upwelling intensity, with the exception of upwelling off northwest Spain, where winds are becoming slightly less favorable. Alteration of wind direction and strength influences upwelling and hence nutrient concentrations; however, nutrient levels can also change in response to other variables such as the supply of iron-laden dust from the Sahara (Alonso-Pérez et al., 2011). There is *medium evidence* and *medium agreement* that primary production in the Canary Current has decreased over the past 2 decades (Arístegui et al., 2009; Demarcq, 2009), in contrast to the nearby upwelling region off northwest Spain where no significant trend was observed (Bode et al., 2011). Satellite chlorophyll records (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectrometer (MODIS)) are relatively short, making it difficult to distinguish the influence of warming oceans from longer term patterns of variability (Arístegui et al., 2009; Henson et al., 2010). Changing temperature has resulted in changes to important fisheries species. For example, Mauritanian waters have become more suitable as feeding and spawning areas for some fisheries species (e.g., *Sardinella aurita*) as temperatures increased (Zeeberg et al., 2008). Clear attribution of these changes depends on the linkage between the Azores High and global temperature, and on longer records for both physical and biological systems, as pointed out for data sets in general (Arístegui et al., 2009; Henson et al., 2010).

30.5.5.1.2. Benguela Current

The Benguela Current originates from the eastward-flowing, cold South Atlantic Current, flows northward along the southwest coast of Africa, and is bounded north and south by the warm-water Angola and Agulhas Currents, respectively. Upwelling is strongest and most persistent toward the center of the system in the Lüderitz-Orange River upwelling cell (Hutchings et al., 2009). Fish catch reached a peak in the late 1970s of 2.8 million tonnes yr^{-1} (www.seaaroundus.org/lme/29/1.aspx), before declines in the northern Benguela, due to overfishing and inter-decadal environmental variability, resulted in a reduced catch of around 1 million tonnes yr^{-1} (present) (Cury and Shannon, 2004; Heymans et al., 2004; Hutchings et al., 2009). Offshore commercial fisheries currently comprise sardine, anchovy, horse mackerel, and hake, while the inshore artisanal and recreational fisheries comprise a variety of fish species mostly caught by hook and line.

Most research on the Benguela Current has focused on fisheries and oceanography, with little emphasis on climate change. As with the other EBUE, strong interannual and inter-decadal variability in physical oceanography make the detection and attribution of biophysical trends to climate change difficult. Nevertheless, the physical conditions of the Benguela Current are highly sensitive to climate variability over a range of scales, especially to atmospheric teleconnections that alter local wind stress (Hutchings et al., 2009; Leduc et al., 2010; Richter et al., 2010; Rouault et al., 2010). Consequently, there is *medium agreement*, despite *limited evidence* (Demarcq, 2009), that upwelling intensity and associated variables (e.g., temperature, nutrient, and O_2 concentrations) from the Benguela system will change as a result of climate change (Box CC-UP).

The temperature of the surface waters of the Benguela Current did not increase from 1950 to 2009 (p-value $> +0.05$; Table 30-1), although shorter records show an decrease in the south-central Benguela Current (0.35°C to 0.55°C per decade; Rouault et al., 2010) or an increase for the whole Benguela region (0.24°C; Belkin, 2009). These differences between short versus long records indicate the substantial influence of long-term variability on the Benguela system (Belkin, 2009). Information on other potential consequences of climate change within the Benguela system is sparse. SLR is similar to the global mean, although it has not been measured rigorously within the Benguela (Brundrit, 1995; Veitch, 2007). Although upwelling water in the northern and southern portions of the Benguela Current exhibits elevated and suppressed partial pressure of CO_2, respectively (Santana-Casiano et al., 2009), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, although periodic hypoxic events in the Benguela system are largely driven by natural advective processes, these may be exacerbated by future climate change (Monteiro et al., 2008; Bakun et al., 2010).

Despite its apparent sensitivity to environmental variability, there is *limited evidence* of ecological changes in the Benguela Current EBUE due to climate change (Poloczanska et al., 2013). For example, pelagic fish (Roy et al., 2007), benthic crustaceans (Cockcroft et al., 2008), and seabirds (Crawford et al., 2008) have demonstrated general eastward range shifts around the Cape of Good Hope. Although these may be associated with increased upwelling along the South African south coast, specific studies that attribute these changes to anthropogenic climate change are lacking. Trawl surveys of demersal fish and cephalopod species showed consistently predictable "hotspots" of species richness over a 20- to 30-year study period (the earliest surveys since 1984 off South Africa) that were associated with greater depths and cooler bottom waters (Kirkman et al., 2013). However, major changes in the structure and function of the demersal community have been shown in some parts of the Benguela Current EBUE in response to environmental change, for example, due predominantly to fishing pressure in the 1960s and environmental forcing in the early 2000s in the southern Benguela (Howard et al., 2007); therefore, changes driven by climate change may eventually affect the persistence of these biodiversity hotspots (Kirkman et al., 2013).

30.5.5.1.3. California Current

The California Current spans approximately 23° of latitude from central Baja California, Mexico, to central British Columbia, Canada, linking the North Pacific Current (West Wind Drift) with the North Equatorial and Kuroshio Currents to form the North Pacific Gyre. High productivity driven by advective transport and upwelling (Hickey, 1979; Chelton et al., 1982; Checkley and Barth, 2009; Auad et al., 2011) supports well-studied ecosystems and fisheries. Fish catches have been approximately 0.6 million tonnes yr^{-1} since 1950 (www.seaaroundus.org/lme/3.aspx), which makes it the lowest catch of the four EBUE. The ecosystem supports the foraging and reproductive activities of 2 to 6 million seabirds from around 100 species (Tyler et al., 1993). Marine mammals are diverse and relatively abundant, including recovering populations of humpback whales, among other species (Barlow et al., 2008).

The average temperature of the California Current warmed by 0.73°C from 1950 to 2009 (p-value ≤ 0.05; Table 30-1) and by 0.14°C to 0.80°C from 1985 to 2007 (Demarcq, 2009). Like other EBUE, the California Current is characterized by large-scale interannual and inter-decadal climate-ecosystem variability (McGowan et al., 1998; Hare and Mantua, 2000; Chavez et al., 2003; Checkley and Barth, 2009). During an El Niño, coastally trapped Kelvin waves from the tropics deepen the thermocline, thereby severely reducing upwelling and increasing ocean temperatures from California to Washington (Peterson and Schwing, 2003; King et al., 2011). Atmospheric teleconnections to the tropical Pacific alter wind stress and coastal upwelling. Therefore, the ENSO is intimately linked with Bakun's (1990) upwelling intensification hypothesis (Box CC-UP). Inter-decadal variability in the California Current stems from variability in the Pacific-North America pattern (Overland et al., 2010), which is influenced by the PDO (Mantua et al., 1997; Peterson and Schwing, 2003) and the NPGO (Di Lorenzo et al., 2008). The major effects of the PDO and NPGO appear north of 39°N (Di Lorenzo et al., 2008; Menge et al., 2009).

There is *robust evidence* and *medium agreement* that the California Current has experienced a decrease in the number of upwelling events (23 to 40%), but an increase in duration of individual events, resulting in an increase of the overall magnitude of upwelling events from 1967 to 2010 (*high confidence*; Demarcq, 2009; Iles et al., 2012). This is consistent with changes expected under climate change yet remains complicated by the influence of decadal-scale variability (*low confidence*; Iles et al., 2012). Oxygen concentrations have also undergone large and consistent decreases from 1984 to 2006 throughout the California Current, with the largest relative decreases occurring below the thermocline (21% at 300 m). The hypoxic boundary layer (<60 µmol kg^{-1}) has also shoaled by up to 90 m in some regions (Bograd et al., 2008). These changes are consistent with the increased input of organic carbon into deeper layers from enhanced upwelling and productivity, which stimulates microbial activity and results in the drawdown of O_2 (*likely*, Bakun et al., 2010; but see also McClatchie et al., 2010; Koslow et al., 2011; WGI AR5 Section 3.8.3). These changes are *likely* to have reduced the available habitat for key benthic communities as well as fish and other mobile species (Stramma et al., 2010). Increasing microbial activity will also increase the partial pressure of CO_2, decreasing the pH and carbonate concentration of seawater. Together with the shoaling of the saturation horizon, these changes have increased the incidence of low O_2 and low pH water flowing onto the continental shelf (*high confidence*; 40 to 120 m; Feely et al., 2008), causing problems for industries such as the shellfish aquaculture industry (Barton et al., 2012).

30.5.5.1.4. Humboldt Current

The Humboldt Current is the largest of the four EBUE, covering an area larger than the other three combined. It comprises the eastern edge of the South Pacific Gyre, linking the northern part of the Antarctic Circumpolar Current with the Pacific South Equatorial Current. Although the primary productivity per unit area is modest compared to that of the other EBUE, the total Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since the 1960s) of 8 million tonnes yr^{-1} (www.seaaroundus.org/lme/13/1.aspx), although decadal-scale variations range from 2.5 to 13 million tonnes yr^{-1}. While anchovies currently contribute 80% of the total catch, they alternate with sardines on a multi-decadal scale, with their dynamics mediated by the approach and retreat of subtropical waters to and from the coast (Alheit and Bakun, 2010). This variability does not appear to be changing due to anthropogenic climate change. Thus, from the late 1970s to the early 1990s, sardines were more important (Chavez et al., 2003). The other major commercial fish species are jack mackerel among the pelagic fish and hake among the demersal fish.

The Humboldt Current EBUE did not show an overall warming trend in SST over the last 60 years (p-value > 0.05; Table 30-1), which is consistent with other data sets (1982–2006, HadISST1.1: Belkin, 2009; 1985–2007, Pathfinder: Demarcq, 2009). Wind speed has increased in the central portions of the Humboldt Current, although wind has decreased in its southern and northern sections (Demarcq, 2009). The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity exerting opposing drivers on upwelling and which, if they intensify, would decrease temperatures (*limited evidence*, *medium agreement*). Similar to the Canary Current EBUE, however, there was a significant increase in the temperatures of the warmest month of the year over the period 1950–2009 (p-value ≤ 0.05; Table 30-1).

Primary production is suppressed during warm El Niño events and amplified during cooler La Niña phases, these changes then propagate through to higher trophic levels (Chavez et al., 2003; Tam et al., 2008; Taylor et al., 2008). However, in addition to trophic changes, there is also a direct thermal impact on organisms, which varies depending on the thermal adaptation window for each species (*high confidence*). A 37-year zooplankton time series for the coast of Peru showed no persistent trend in abundance and diversity (Ayón et al., 2004), although observed shifts coincided with the shifts in the regional SST. As for other EBUE, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least two studies (Mendelssohn and Schwing, 2002; Gutiérrez et al.,

2011) provide additional evidence that the northern Humboldt Current has cooled (due to upwelling intensification) since the 1950s, a trend matched by increasing primary production. This is not entirely consistent with the lack of significant change over the period 1950–2009 (p-value > 0.05; Table 30-1). Nevertheless, these relationships are *likely* to be complex in their origin, especially in their sensitivity to the long-term changes associated with ENSO and PDO, and the fact that areas within the Humboldt Current EBUE may be showing different behaviors.

30.5.5.2. Key Risks and Vulnerabilities

EBUE are vulnerable to changes that influence the intensity of currents, upwelling, and mixing (and hence changes in SST, wind strength and direction), as well as O_2 content, carbonate chemistry, nutrient content, and the supply of organic carbon to deep offshore locations (*robust evidence*, *high agreement*; *high confidence*). The extent to which any particular EBUE is vulnerable to these factors depends on location (Figure 3 from Gruber, 2011) and other factors such as alternative sources of nutrient input and fishing pressure (Bakun et al., 2010). This complex interplay between regional and global drivers means that our understanding of how factors such as upwelling within the EBUE will respond to further climate change is uncertain (Box CC-UP; Rykaczewski and Dunne, 2010).

In the GCM ensembles examined (Table SM30-3), modest rates of warming (0.22°C to 0.93°C) occur within the four EBUEs in the near term. Over 2010–2099, however, EBUE SSTs warm by 0.07°C to 1.02°C under RCP2.6, and 2.52°C to 3.51°C under RCP8.5 (Table SM30-4). These high temperatures have the potential to increase stratification of the water column and substantially reduce overall mixing in some areas. In contrast, the potential strengthening of coastal wind systems would intensify upwelling and stimulate primary productivity through the increased injection of nutrients into the photic zone of the EBUE (Box CC-UP). Garreaud and Falvey (2009) explored how wind stress along the South American coast would change by 2100 under SRES B2 and A2 scenarios. Using an ensemble of 15 GCMs, southerly wind systems upwelling increased along the subtropical coast of South America, extending and strengthening conditions for upwelling.

Changes in the intensity of upwelling within the EBUE will drive fundamental changes to the abundance, distribution, and viability of resident organisms, although an understanding of their nature and direction is limited. In some cases, large-scale decreases in primary productivity and dependent fisheries are projected to occur for EBUE ecosystems (Blanchard et al., 2012), while other projections question the strong connection between primary productivity and fisheries production (Arístegui et al., 2009). Increased upwelling intensity also has potential disadvantages. Elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed, where it is *virtually certain* to increase microbial respiration and hence increase low O_2 stress (Weeks et al., 2002; Bakun et al., 2010). Increased wind stress may also increase turbulence, breaking up food concentrations (affecting trophic transfer), or causing excessive offshore advection, which could remove plankton from shelf habitats. The central issue for the EBUE is therefore whether or not upwelling will intensify and, if so, whether the negative consequences (e.g., reduced O_2 and elevated CO_2) associated with upwelling intensification will outweigh potential benefits from increased primary production and fisheries catch.

30.5.6. Subtropical Gyres

Subtropical gyres (STG) dominate the Pacific, Atlantic, and Indian Oceans (Figure 30-1a), and consist of large stable water masses that circulate clockwise (Northern Hemisphere) and anticlockwise (Southern Hemisphere) due to the Coriolis Effect. The oligotrophic areas at the core of the STG represent one of the largest habitats on Earth, contributing 21.2% of ocean primary productivity and 8.3% of the

Frequently Asked Questions

FAQ 30.4 | Will climate change increase the number of "dead zones" in the oceans?

Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms. Dead zones are persistent hypoxic conditions where the water doesn't have enough dissolved oxygen to support oxygen-dependent marine species. These areas exist all over the world and are expanding, with impacts on coastal ecosystems and fisheries (*high confidence*). Dead zones are caused by several factors, particularly eutrophication where too many nutrients run off coastal cities and agricultural areas into rivers that carry these materials out to sea. This stimulates primary production, leading to a greater supply of organic carbon, which can sink into the deeper layers of the ocean. As microbial activity is stimulated, there is a sharp reduction in dissolved oxygen levels and an increased risk of dead zones (*high confidence*). Climate change can influence the distribution of dead zones by increasing water temperature and hence microbial activity, as well as reducing mixing (i.e., increasing layering or stratification) of the Ocean, thereby reducing mixing of oxygen-rich surface layers into the deeper parts of the Ocean. In other areas, increased upwelling can lead to stimulated productivity, which can also lead to more organic carbon entering the deep ocean, where it is consumed, decreasing oxygen levels (*medium confidence*). Managing local factors such as the input of nutrients into coastal regions can play an important role in reducing the rate at which dead zones are spreading across the world's oceans (*high agreement*).

global fish catch (Figure 30-1b; Table SM30-1). A number of small island nations are found within this region. While many of the observed changes within these nations have been described in previous chapters (e.g., Sections 5.3-4, 29.3-5), region-wide issues and consequences are discussed here due to the strong linkages between ocean and coastal issues.

30.5.6.1. Observed Changes and Potential Impacts

The central portions of the STG are oligotrophic (Figure SM30-1). Temperatures within the STG of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL), and South Atlantic (SATL) have increased at rates of 0.020°C, 0.024°C, 0.032°C, 0.025°C, and 0.027°C yr^{-1} from 1998 to 2010, respectively (Signorini and McClain, 2012). This is consistent with increases observed from 1950 to 2009 (0.25°C to 0.67°C; Table 30-1). However, differences among studies done over differing time periods emphasize the importance of long-term patterns of variability. Salinity has decreased across the North and South Pacific STG (Figure 30-6c; WGI AR5 Section 3.3.3.1), consistent with warmer sea temperatures and an intensification of the hydrological cycle (Boyer, 2005).

The North and South Pacific STG have expanded since 1993 (*high confidence*), with these changes *likely* being the consequence of a combination of wind forcing and long-term variability (Parrish et al., 2000; WGI AR5 Section 3.6.3). Chlorophyll levels, as determined by remote-sensing of ocean color (Box CC-UP), have decreased in the NPAC, IOCE, and NATL by 9, 12, and 11%, respectively (p-value ≤ 0.5; Signorini and McClain, 2012) over and above the inherent seasonal and interannual variability from 1998 to 2010 (Vantrepotte and Mélin, 2011). Chlorophyll levels did not change in the remaining two gyres (SPAC and SATL, and confirmed for SPAC by Lee and McPhaden (2010) and Lee et al. (2010)). Furthermore, over the period 1998–2007, median cell diameter of key phytoplankton species exhibited statistically significant linear declines of about 2% in the North and South Pacific, and 4% in the North Atlantic Ocean (Polovina and Woodworth, 2012). Changes in chlorophyll and primary productivity in these sub-regions have been noted before (McClain et al., 2004; Gregg et al., 2005; Polovina et al., 2008) and are influenced by seasonal and longer-term sources of variability (e.g., ENSO, PDO; Section 6.3.4; Figure 6-9). These changes represent a significant expansion of the world's most unproductive waters, although caution must be exercised given the limitations of satellite detection methods (Box CC-PP) and the shortness of records relative to longer-term patterns of climate variability. There is *high confidence* that changes that reduce the vertical transport of nutrients into the euphotic zone (e.g., decreased wind speed, increasing surface temperatures, and stratification) will reduce the rate of primary productivity and hence fisheries.

30.5.6.1.1. Pacific Ocean Subtropical Gyres

Pacific climate is heavily influenced by the position of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation (WGI AR5 Section 14.3.1). These features are also strongly influenced by interannual to inter-decadal climate patterns of variability including ENSO and PDO. The current understanding of how ENSO and PDO will change as average global temperatures increase is not clear (*low confidence*; Collins et al., 2010; WGI AR5 Section 12.4.4.2). The position of both the ITCZ and SPCZ vary seasonally and with ENSO (Lough et al., 2011), with a northward migration during the Northern Hemisphere summer and a southward migration during the Southern Hemisphere summer. These changes, along with the West Pacific Monsoon, determine the timing and extent of the wet and dry seasons in SPAC and NPAC sub-regions (Ganachaud et al., 2011). Tropical cyclones are prominent in the Pacific (particularly the western Pacific), and CBS sub-regions between 10° and 30° north and south of the equator, although the associated storm systems may occasionally reach higher latitudes. Spatial patterns of cyclones vary with ENSO, spreading out from the Coral Sea to the Marquesas Islands during El Niño and contracting back to the Coral Sea, New Caledonia, and Vanuatu during La Niña (Lough et al., 2011). Historically, there have been almost twice as many land-falling tropical cyclones in La Niña as opposed to El Niño years off the east coast of Australia, with a declining trend in the number of severe tropical cyclones from 0.45 per year in the early 1870s to 0.17 per year in recent times (Callaghan and Power, 2011).

The Pacific Ocean underwent an abrupt shift to warmer sea temperatures in the mid-1970s as a result of both natural (e.g., IPO) and climate forcing (*high confidence*; Meehl et al., 2009). This change coincided with changes to total rainfall, rain days, and dry spells across the Pacific, with the direction of change depending on the location relative to the SPCZ. Countries such as the Cook Islands, Tonga, Samoa and American Samoa, and Fiji tend to experience drought conditions as the SPCZ (with cooler sea temperatures) moves toward the northeast during El Niño (*high confidence*). The opposite is true during La Niña conditions. The consequences of changing rainfall on the countries of the Pacific STG are discussed in greater detail elsewhere (Sections 5.4, 29.3; Table 29-1). Although these changes are due to different phases of long-term variability in the Pacific, they illustrate the ramifications and sensitivity of the Pacific to changes in climate change.

Elevated sea temperatures within the Pacific Ocean have increased the frequency of widespread mass coral bleaching and mortality since the early 1980s (*very high confidence*; Hoegh-Guldberg and Salvat, 1995; Hoegh-Guldberg, 1999; Mumby et al., 2001; Baker et al., 2008; Donner et al., 2010). There are few, if any, scientific records of mass coral bleaching and mortality prior to this period (*high confidence*; Hoegh-Guldberg, 1999). Rates of decline in coral cover on coastal coral reef ecosystems range between 0.5 and 2.0% per year depending on the location within the Indo-Pacific region (*high confidence*; Bruno and Selig, 2007; Hughes et al., 2011; Sweatman et al., 2011; De'ath et al., 2012). The reasons for this decline are complex and involve non-climate change-related factors (e.g., coastal pollution and overfishing) as well as global warming and possibly acidification. A recent comprehensive analysis of the ecological consequences of coral bleaching and mortality concluded that "bleaching episodes have resulted in catastrophic loss of coral reefs in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics" (*high confidence*; Baker et al., 2008, p. 435). Increasing sea levels have also caused changes in seagrass and mangrove systems. Gilman et al. (2007) found a reduction in mangrove area with SLR, with the observed mean landward recession of three mangrove areas over 4 decades being 25, 64, and 72 mm yr^{-1}, 12 to 37 times faster than the observed rate of SLR. Significant interactions exist between climate change and coastal development, where migration shoreward depends on the extent to which coastlines have been modified or barriers to successful migration have been established.

Changes in sea temperature also lead to changes in the distribution of key pelagic fisheries such as skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), big-eye tuna (*T. obesus*), and South Pacific albacore tuna (*T. alalunga*), which make up the majority of key fisheries in the Pacific Ocean. Changes in distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate the close association of pelagic fish stocks and water temperature. The shift in habitat for top predators in the northeast Pacific was examined by Hazen et al. (2012), who used tracking data from 23 marine species and associated environmental variables to predict changes of up to 35% in core habitat for these species within the North Pacific. Potential habitats are predicted to contract for the blue whale, salmon shark, loggerhead turtle, and blue and mako sharks, while potential habitats for the sooty shearwater; black -footed albatross; leatherback turtle; white shark; elephant seal; and albacore, bluefin and yellowfin tuna are predicted to expand (Hazen et al., 2012). However, expansion of OMZs in the Pacific STG is predicted to compress habitat (depth) for hypoxia-intolerant species such as tuna (Stramma et al., 2010, 2012).

Reduction of ocean productivity of the STG (Sarmiento et al., 2004; Signorini and McClain, 2012) reduces the flow of energy to higher trophic levels such as those of pelagic fish (Le Borgne et al., 2011). The distribution and abundance of fisheries stocks such as tuna are also sensitive to changes in sea temperature, and hence long-term variability such as ENSO and PDO. The redistribution of tuna in the western central equatorial region has been related to the position of the oceanic convergence zones, where the warm pool meets the cooler tongue of the Pacific. These changes have been reliably reproduced by population models that use temperature as a driver of the distribution and abundance of tuna (Lehodey et al., 1997, 2006). Projections of big-eye tuna (*T. obesus*) distributions under SRES A2 show an improvement in spawning and feeding habitats by 2100 in the eastern tropical Pacific and declines in the western tropical Pacific, leading to an eastern displacement of tuna stocks (Lehodey et al., 2008, 2010b).

30.5.6.1.2. Indian Ocean Subtropical Gyre

Like the Pacific Ocean, the Indian Ocean plays a crucial role in global weather patterns, with teleconnections throughout Africa, Australasia, Asia, and the Americas (e.g., Clark et al., 2000; Manhique et al., 2011; Meehl and Arblaster, 2011; Nakamura et al., 2011). Increasing sea level, temperature, storm distribution and intensity, and changing seawater chemistry all influence the broad range of physical, chemical, and biological aspects of the Indian Ocean. Coral reef ecosystems in the Indian Ocean gyre system were heavily affected by record positive sea temperature anomalies seen in the Southern Hemisphere between February to April 1998 (*robust evidence*, *high agreement*; *high confidence*; Ateweberhan et al., 2011). Coral cover across the Western Indian Ocean declined by an average of 37.7% after the 1998 heat stress event (Ateweberhan et al., 2011). Responses to the anomalously warm conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases in coral cover directly after the 1998 event (from 40 to 53% coral cover in 1977–1997 to 7% in 1999–2000; *high confidence*; Ateweberhan et al., 2011). Coral reefs lining the islands of southern India and Sri Lanka experienced similar decreases in coral cover (45%, 1977–1997 to 12%, 1999–2000). Corals in the southwestern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, Réunion, and Rodrigues) showed less impact (44%, 1977–1997 to 40%, 1999–2000). Recovery from these increases in mortality has been variable, with sites such as those around the central Indian Ocean islands exhibiting fairly slow recovery (13% by 2001–2005) while those around southern India and Sri Lanka are showing much higher rates (achieving a mean coral cover of 37% by 2001–2005; Ateweberhan et al., 2011). These changes to the population size of key reef-building species will drive major changes in the abundance and composition of fish populations in coastal areas, and affect other ecosystem services that are important for underpinning tourism and coastal protection (*medium confidence*; Box CC-CR).

Fisheries that exploit tuna and other large pelagic species are very valuable to many small island states within the Indian Ocean. As with Pacific fisheries, the distribution and abundance of large pelagic fish in the Indian Ocean is greatly influenced by sea temperature. The anomalously high sea temperatures of 1997–1998 (leading to a deepening of the mixed layer in the west and a shoaling in the east) coincided with anomalously low primary production in the Western Indian Ocean and a major shift in tuna stocks (*high confidence*; Menard et al., 2007; Robinson et al., 2010). Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which was unprecedented for the tuna fishery (*high confidence*). As a result of these changes, many countries throughout the Indian Ocean lost significant tuna-related revenue (Robinson et al., 2010). In 2007, tuna fishing revenue was again reduced by strong surface warming and deepening of the mixed layer, and associated with a modest reduction in primary productivity in the west. These trends highlight the overall vulnerability of tuna fishing countries in the Indian Ocean to climate variability, a situation similar to that in the other major oceans of the world.

30.5.6.1.3. Atlantic Ocean Subtropical Gyres

SST has increased within the two STG of the Atlantic Ocean over the last 2 decades (Belkin, 2009; Signorini and McClain, 2012). Over longer periods of time (1950–2009), trends in average temperature are not significant for the North Atlantic STG (p-value > 0.05) while they remain so for the South Atlantic STG (*very likely*; 0.08°C per decade, p-value $\leq$ 0.05; Table 30-1). In both cases, however, temperatures in the coolest and warmest months increased significantly (Table 30-1). The difference between these studies (i.e., over 10 to 30 years vs. 60 years) emphasizes the importance of long-term patterns of variability in the North Atlantic region. Variability in SST at a period of about 60 to 80 years is associated with the Atlantic Multi-decadal Oscillation (AMO; Trenberth and Shea, 2006). Sea surface temperatures influence hurricane activity (*very likely*) with recent record SST associated with record hurricane activity in 2005 in the Atlantic (Trenberth and Shea, 2006) and mass coral bleaching and mortality in the eastern Caribbean (*high confidence*; Eakin et al., 2010). In the former case, analysis concluded that 0.1°C of the SST anomaly was attributable to the state of the AMO while 0.45°C was due to ocean warming as a result of anthropogenic influences (Trenberth and Shea, 2006).

These changes have influenced the distribution of key fishery species as well the ecology of coral reefs in Bermuda (Wilkinson and Hodgson, 1999; Baker et al., 2008) and in the eastern Caribbean (Eakin et al., 2010). Small island nations such as Bermuda depend on coral reefs for fisheries and tourism and are vulnerable to further increases in sea temperature that cause mass coral bleaching and mortality (*high confidence*; Box CC-CR; Figure 30-10). As with the other STG, phytoplankton communities and pelagic fish stocks are sensitive to temperature changes that have occurred over the past several decades. Observation of these changes has enabled development of models that have a high degree of accuracy in projecting the distribution and abundance of these elements within the Atlantic region in general (Cheung et al., 2011).

30.5.6.2. Key Risks and Vulnerabilities

SSTs of the vast STGs of the Atlantic, Pacific, and Indian Oceans are increasing, which is *very likely* to increase stratification of the water column. In turn, this is *likely* to reduce surface concentrations of nutrients and, consequently, primary productivity (*medium confidence*; Box CC-PP). Warming is projected to continue (Table SM30-4), with substantial increases in the vulnerability and risk associated with systems that have been observed to change so far (*high confidence*; Figure 30-12). Under RCP2.6, the temperatures of the STG are projected to increase by 0.17°C to 0.56°C in the near term (over 2010–2039) and between –0.03°C to 0.90°C in the long term (over 2010–2099) (Table SM30-4). Under RCP8.5, however, surface temperatures of the world's STG are projected to be 0.45°C to 0.91°C warmer in the near term and 1.90°C to 3.44°C warmer in the long term (Table SM30-4). These changes in temperature are *very likely* to increase water column stability, reduce the depth of the mixed layer, and influence key parameters such as nutrient availability and O_2 concentrations. It is not clear as to how longer-term sources of variability such as ENSO and PDO will change (WGI AR5 Sections 14.4, 14.7.6) and ultimately influence these trends.

The world's most oligotrophic ocean sub-regions are *likely* to continue to expand over coming decades, with consequences for ecosystem services such as gas exchange, fisheries, and carbon sequestration. Polovina et al. (2011) explored this question for the North Pacific using a climate model that included a coupled ocean biogeochemical component to investigate potential changes under an SRES A2 scenario (~RCP6.0 to RCP8.5; see also Figure 1.5 from Rogelj et al., 2012). Model projections indicated the STG expanding by approximately 30% by 2100, driven by the northward drift of the mid-latitude westerlies and enhanced stratification of the water column. The expansion of the STG occurred at the expense of the equatorial upwelling and other regions within the North Pacific. In the North Pacific STG, the total primary production is projected to decrease by 10 to 20% and large fish catch by 19 to 29% by 2100 under SRES A2 (Howell et al., 2013; Woodworth-Jefcoats et al., 2013). However, our understanding of how large-scale eddy systems will change in a warming world is incomplete, as are the implications for primary productivity of these large and important systems (Boxes CC-PP, CC-UP).

Understanding how storm frequency and intensity will change represents a key question for many countries and territories within the various STG. Projections of increasing sea temperature are *likely* to change the behavior of tropical cyclones. At the same time, the maximum wind speed and rainfall associated with cyclones is *likely* to increase, although future trends in cyclones and severe storms are *very likely* to vary from region to region (WGI AR5 Section 14.6). Patterns such as "temporal clustering" can have a strong influence on the impact of tropical cyclones on ecosystems such as coral reefs (Mumby et al., 2011), although how these patterns will change within all STG is uncertain at this point. However, an intensifying hydrological cycle is expected to increase precipitation in many areas (*high confidence*; WGI AR5 Sections 2.5, 14.2), although longer droughts are also expected in other STG (*medium confidence*). Changes in the hydrological cycle impact coastal ecosystems, increasing damage through coastal flooding and physical damage from storm waves (Mumby et al., 2011). Improving our understanding of how weather systems associated with features such as the SPCZ (WGI AR5 Section 14.3.1) will vary is critical to climate change adaptation of a large number of nations associated with the STG. Developing an understanding of how ocean temperature, climate systems such as the SPCZ and ITCZ, and climate change and variability (e.g., ENSO, PDO) interact will be essential in this regard. For example, variability in the latitude of the SPCZ is projected to increase, possibly leading to more extreme events in Pacific Island countries (Cai et al., 2012).

The consequences of projected sea temperatures on the frequency of coral bleaching and mortality within key sub-regions of the STG are outlined in Box CC-CR and Figures 30-10 and SM30-3. As with other sub-regions (particularly CBS, STG, and SES) dominated by coral reefs, mass coral bleaching and mortality becomes an annual risk under all scenarios, with mass mortality events beginning to occur every 1 to 2 years by 2100 (*virtually certain*; Box CC-CR; Figures 30-10, SM30-3). Coral-dominated reef ecosystems (areas with more than 30% coral cover) are *very likely* to disappear under these circumstances by the mid part of this century (van Hooidonk et al., 2013). The loss of substantial coral communities has implications for the three-dimensional structure of coral reefs (Box CC-CR) and the role of the latter as habitat for organisms such as fish (Hoegh-Guldberg, 2011; Hoegh-Guldberg et al., 2011a; Pratchett et al., 2011a; Bell et al., 2013b).

The consequences of increasing sea temperature can be exacerbated by increasing ocean acidification, with potential implications for reef calcification (*medium confidence*; Kleypas et al., 1999; Hoegh-Guldberg et al., 2007; Doney et al., 2009), reef metabolism and community calcification (Dove et al., 2013), and other key ecological processes (Pörtner et al., 2001, 2007; Munday et al., 2009). Ocean pH within the STG will continue to decrease as atmospheric CO_2 increases, bringing pH within the STG to 7.9 and 7.7 at atmospheric concentrations of 450 ppm and 800 ppm, respectively (Figure SM30-2a; Box CC-OA). Aragonite saturation states will decrease to around 1.6 (800 ppm) and 3.3 (450 ppm; Figure SM30-2b). Decreasing carbonate ion concentrations and saturation states pose serious risks to other marine calcifiers such as encrusting coralline algae, coccolithophores (phytoplankton), and a range of benthic invertebrates (Doney et al., 2009; Feely et al., 2009).

Increasing sea temperatures and sea level are also *likely* to influence other coastal ecosystems (e.g., mangroves, seagrass meadows) in the Pacific, although significant gaps and uncertainties exist (Section 29.3.1.2; Waycott et al., 2007, 2011). Many of the negative consequences for coral reefs, mangroves, and seagrass meadows are *likely* to have negative consequences for dependent coastal fisheries (through habitat destruction) and tourism industries (*medium confidence*; Bell et al., 2011a, 2013a; Pratchett et al., 2011a,b).

Populations of key large pelagic fish are projected to move many hundreds of kilometers east of where they are today in the Pacific STG (*high confidence*; Lehodey et al., 2008, 2010a, 2011, 2013), with implications for income, industry, and food security across multiple Pacific Island nations (*high confidence*; Cheung et al., 2010; McIlgorm et al., 2010; Bell et al., 2011b, 2013a; Section 7.4.2; Tables 29-2, 29-4). These predictions of species range displacements, contractions, and expansions in response to anticipated changes in the Ocean (Box CC-MB) present both a challenge and an opportunity for the development of large-scale management strategies to preserve these valuable species. Our understanding of the consequences of reduced O_2 for pelagic fish populations is not clear, although there is *high agreement* on the potential physiological outcomes (Section 6.3.3). Those species that are intolerant to hypoxia, such as skipjack and yellowfin tuna (Lehodey et al., 2011), will have their depth range compressed in the Pacific STG, which will increase their vulnerability to fisheries and reduce overall fisheries habitat and productivity (*medium confidence*; Stramma et al., 2010, 2011). Despite the importance of these potential changes, our understanding of the full range of consequences is *limited* at this point.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the Deep Sea (DS) are challenging because of difficulty of access and scarcity of long-term, comprehensive observations (Smith, Jr. et al., 2009). The size of this habitat is also vast, covering well over 54% of the Earth's surface and stretching from the top of the mid-oceanic ridges to the bottom of deep ocean trenches (Smith, Jr. et al., 2009). The fossil record in marine sediments reveals that the DS has undergone large changes in response to climate change in the past (Knoll and Fischer, 2011). The paleo-skeletal record shows that it is the rate, not just the magnitude, of climate change (temperature, O_2, and CO_2) that is critical to marine life in DS. The current rate of change in key parameters *very likely* exceeds that of other major events in Earth history. Two primary time scales are of interest. The first is the slow rate (century-scale) of ocean circulation and mixing, and consequently the slow rate at which DS ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at the surface of the Ocean, which represents a critical food supply to DS animals (Smith, Jr. and Kaufmann, 1999; Smith, Jr. et al., 2009). It can also represent a potential risk in some circumstances where the flux of organic carbon into the deep ocean, coupled with increased sea temperatures, can lead to anoxic areas (dead zones) as metabolism is increased and O_2 decreased (Chan et al., 2008; Stramma et al., 2010).

30.5.7.1. Observed Changes and Potential Impacts

The greatest rate of change of temperature is occurring in the upper 700 m of the Ocean (*very high confidence*; WGI AR5 Section 3.2), although smaller yet significant changes are occurring at depth. The DS environment is typically cold (~–0.5°C to 3°C; Smith et al., 2008), although abyssal temperatures in the SES can be higher (e.g., Mediterranean DS ~12°C; Danovaro et al., 2010). In the latter case, DS organisms can thrive in these environments as well, illustrating the variety of temperature conditions that differing species of abyssal life have adapted to. Individual species, however, are typically constrained within a narrow thermal and O_2-demand window of tolerance (Pörtner, 2010) and therefore it is *likely* that shifts in the distribution of DS species and regional extinctions will occur. Warming over multiple decades has been observed below 700 m (Levitus et al., 2005, 2009), with warming being minimal at mid-range depths (2000 to 3000 m), and increasing toward the sea floor in some sub-regions (e.g., Southern Ocean; WGI AR5 Chapter 3). For the deep Atlantic Ocean, the mean age of deep waters (mean time since last exposure to the atmosphere) is approximately 250 years; the oldest deep waters of the Pacific Ocean are >1000 years old. The patterns of ocean circulation are clearly revealed by the penetration of tracers and the signal of CO_2 released from burning fossil fuel penetrating into the abyss (Sabine et al., 2004). It will take many centuries for full equilibration of deep ocean waters and their ecosystems with recent planetary warming and CO_2 levels (Wunsch and Heimbach, 2008).

Temperature accounts for approximately 86% of the variance in the export of organic matter to the DS (*medium confidence*; Laws et al., 2000). Consequently, upper ocean warming will reduce the export of organic matter to the DS (*medium confidence*), potentially changing the distribution and abundance of DS organisms and associated food webs, and ecosystem processes (Smith, Jr. and Kaufmann, 1999). Most organic matter entering the DS is recycled by microbial systems at relatively shallow depths (Buesseler et al., 2007), and at rates that are temperature dependent. Upper ocean warming will increase the rate of sub-surface decomposition of organic matter (*high confidence*), thus intensifying the intermediate depth OMZs (Stramma et al., 2008, 2010) and reducing food supply to the abyssal ocean.

Particulate organic carbon is exported from the surface to deeper layers of the Ocean (>500 m) with an efficiency of between 20 and 50% (Buesseler et al., 2007), much of it being recycled by microbes before it reaches 1000 m (Smith, Jr. et al., 2009). The export of organic carbon is dependent on surface net primary productivity, which is *likely* to vary (Box CC-PP), influencing the supply of food to DS (Laws et al., 2000; Smith et al., 2008). Warming of intermediate waters will also increase respiration at mid-water depths, reducing the flux of organic carbon. Our understanding of other components of DS ecosystems is also relatively poor. For example, there is *limited evidence* and *limited agreement* as to how ocean warming and acidification are *likely* to affect ecosystems such as those associated with hydrothermal vents (Van Dover, 2012).

Oxygen concentrations are decreasing in the DS (Stramma et al., 2008; Helm et al., 2011a). Although the largest signals occur at intermediate water depths < 1000 m (Nakanowatari et al., 2007; Whitney et al., 2007; Falkowski et al., 2011), some waters >1000 m depth are also experiencing a decline (Jenkins, 2008). The quantity of dissolved O_2

throughout the Ocean will be reduced with warming due to direct effects on solubility (*high confidence*), with these effects being widely distributed (Shaffer et al., 2009). It is also *virtually certain* that metabolic rates of all animals and microbial respiration rates will increase with temperature (Brown et al., 2004). Thus, increased microbial activity and reduced O_2 solubility at higher temperatures will have additive consequences for the decline of O_2 (*high confidence*) even in the DS. The DS waters are relatively well oxygenated owing to the higher solubility of O_2 in colder waters and the low supply rate of organic matter to great depths. The availability of oxygen to marine animals is governed by a combination of concentration, temperature, pressure, and related properties such as diffusivity. Analysis by Hofmann et al. (2013) reveals that the supply potential of oxygen to marine animals in cold deep waters is similar to that at much shallower depths (*very high confidence*).

Anthropogenic CO_2 has penetrated to at least 1000 m in all three ocean basins (particularly the Atlantic; Doney et al., 2009). Further declines of calcite and aragonite in already under-saturated DS water will presumably decrease biological carbonate structure formation and increase dissolution, as has happened many times in Earth's past (*high confidence*; Zeebe and Ridgwell, 2011). Some cold-water corals (reported down to 3500 m) already exist in waters under-saturated with respect to aragonite (Lundsten et al., 2009). Although initial investigations suggested that ocean acidification (reduced by 0.15 and 0.30 pH units) would result in a reduction in the calcification rate of deep water corals (30 and 56%, respectively), accumulating evidence shows that ocean acidification may have far less impact than previously anticipated on the calcification of some deep water corals (*limited evidence*, *medium agreement*; *low confidence*) although it may reduce important habitats given that dead unprotected coral mounds are *likely* to dissolve in under-saturated waters (Thresher et al., 2011; Form and Riebesell, 2012; Maier et al., 2013).

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to DS communities through increasing temperature, decreasing O_2 and pH, and changing carbonate chemistry (*high confidence*; Keeling et al., 2010). Risks associated with the DS have implications for the Ocean and planet given the high degree of inherent dependency and connectivity. The resulting changes to the flow of organic carbon to some parts of the DS (e.g., STG) are *very likely* to affect DS ecosystems (*medium confidence*; Smith et al., 2008). As with the Ocean generally, there is a need to fill in the substantial gaps that exist in our knowledge and understanding of the world's largest habitat and its responses to rapid anthropogenic climate change.

30.5.8. Detection and Attribution of Climate Change Impacts with Confidence Levels

The analysis in this chapter and elsewhere in AR5 has identified a wide range of physical, chemical, and ecological components that have changed over the last century (Box CC-MB). Figure 30-11 summarizes a number of examples from the Ocean as a region together with the degree of confidence in both the detection and attribution steps. For ocean warming and acidification, confidence is *very high* that changes are being detected and that they are due to changes to the atmospheric GHG content. There is considerable confidence in both the detection (*very high confidence*) and attribution (*high confidence*) of mass coral bleaching and mortality, given the well-developed understanding of environmental processes and physiological responses driving these events (Box CC-CR; Section 6.3.1). For other changes, confidence is lower, either because detection of changes has been difficult, or monitoring programs are not long established (e.g., field evidence of declining calcification), or because detection has been possible but models are in conflict (e.g., wind-driven upwelling). The detection and attribution of recent changes is discussed in further detail in Sections 18.3.3-4.

30.6. Sectoral Impacts, Adaptation, and Mitigation Responses

Human welfare is highly dependent on ecosystem services provided by the Ocean. Many of these services are provided by coastal and shelf areas, and are consequently addressed in other chapters (e.g., Sections 5.4.3, 7.3.2.4, 22.3.2.3). Oceans contribute provisioning (e.g., food, raw materials; see Section 30.6.2.1), regulating (e.g., gas exchange, nutrient recycling, carbon storage, climate regulation, water flux), supporting (e.g., habitat, genetic diversity), and cultural (e.g., recreational, religious) services (MEA, 2005; Tallis et al., 2013). The accumulating evidence indicating that fundamental ecosystem services within the Ocean are shifting rapidly should be of major concern, especially with respect to the ability of regulating and supporting ecosystem services to underpin current and future human population demands (Rockström et al., 2009; Ruckelshaus et al., 2013). Discussion here is restricted to environmental, economic, and social sectors that have direct relevance to the Ocean—namely natural ecosystems, fisheries and aquaculture, tourism, shipping, oil and gas, human health, maritime security, and renewable energy. The influences of climate change on Ocean sectors will be mediated through simultaneous changes in multiple environmental and ecological variables (see Figure 30-12), and the extent to which changes can be adapted to and/or risks mitigated (Table 30-3). Both short- and longer-term adaptation is necessary to address impacts arising from warming, even under the lowest stabilization scenarios assessed.

Sectoral approaches dominate resource use and management in the Ocean (e.g., shipping tends to be treated in isolation from fishing within an area), yet cumulative and interactive effects of individual stressors are known to be ubiquitous and substantial (Crain et al., 2008). Climate change consistently emerges as a dominant stressor in regional- to global-scale assessments, although land-based pollution, commercial fishing, invasive species, coastal habitat modification, and commercial activities such as shipping all rank high in many places around the world (e.g., Sections 5.3.4, 30.5.3-4; Halpern et al., 2009, 2010). Such cumulative effects pose challenges to managing for the full suite of stressors to marine systems, but also present opportunities where mitigating a few key stressors can potentially improve overall ecosystem condition (e.g., Halpern et al., 2010; Kelly et al., 2011). The latter has often been seen as a potential strategy for reducing negative consequences of climate impacts on marine ecosystems by boosting ecosystem resilience, thus buying time while the core issue of reducing GHG emissions is tackled (West et al., 2009).

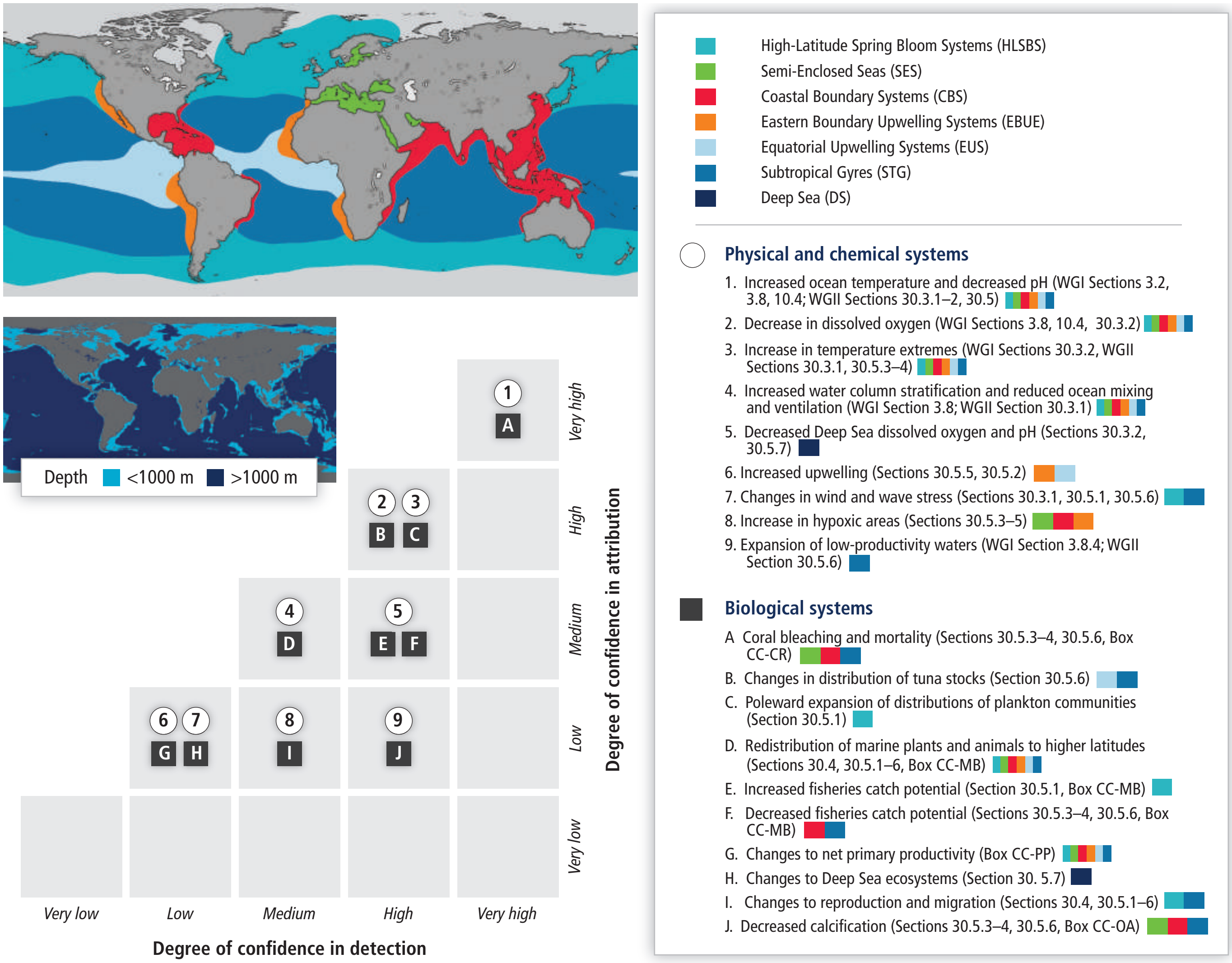


Figure 30-11 | Expert assessment of degree of confidence in detection and attribution of physical and chemical changes (white circles) and ecological changes (dark gray squares) across sub-regions, as designated in Figure 30-1a, and processes in the Ocean (based on evidence explored throughout Chapter 30 and elsewhere in AR5). Further explanation of this figure is given in Sections 18.3.3-4 and 18.6.

30.6.1. Natural Ecosystems

Adaptation in natural ecosystems may occur autonomously, such as tracking shifts in species' composition and distributions (Poloczanska et al., 2013), or engineered by human intervention, such as assisted dispersal (Section 4.4.2.4; Hoegh-Guldberg et al., 2008). Currently, adaptation strategies for marine ecosystems include reducing additional stressors (e.g., maintaining water quality, adapting fisheries management) and maintaining resilience ecosystems (e.g., Marine Protected Areas), and are moving toward whole-of-ecosystem management approaches. Coral reefs, for example, will recover faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained (*medium confidence*; Hughes et al., 2003), indicating that reducing overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of GHGs to stabilize global temperature and ocean chemistry.

Approaches such as providing a formal valuation of ecological services from the Ocean have potential to facilitate adaptation by underpinning more effective governance, regulation, and ocean policy while at the same time potentially improving management of these often vulnerable services through the development of market mechanisms and incentives (Beaudoin and Pendleton, 2012). Supporting, regulating, and cultural ecosystem services tend to transcend the immediate demands placed on provisioning services and are difficult to value in formal economic terms owing to their complexity, problems such as double counting, and the value of non-market goods and services arising from marine ecosystems generally (Fu et al., 2011; Beaudoin and Pendleton, 2012).

"Blue Carbon" is defined as the organic carbon sequestered by marine ecosystems such as phytoplankton, mangrove, seagrass, and salt marsh ecosystems (Laffoley and Grimsditch, 2009; Nellemann et al., 2009). In this respect, Blue Carbon will provide opportunities for both adaptation to, and mitigation of, climate change if key uncertainties in inventories, methodologies, and policies for measuring, valuing, and implementing Blue Carbon strategies are resolved (McLeod et al., 2011). Sediment surface levels in vegetated coastal habitats can rise several meters over thousands of years, building carbon-rich deposits (Brevik and Homburg,

○ Examples of projected impacts and vulnerabilities associated with climate change in Ocean regions

● (1) Expansion of low-productivity areas as a consequence of thermal stratification and changes in wind stress. (*Low*)

● (2) Northward expansion of plankton, invertebrate, and fish communities with warming. Increase in fish biomass at high latitude fringes. (*High*)

● (6) Decline in dissolved oxygen through changes in oxygen solubility (temperature), and ocean ventilation and circulation. (*Medium*)

● (7) Expansion of seasonally hypoxic waters due to thermal stratification and eutrophication. Mass coral bleaching events leading to degradation of coral reefs and loss of associated biodiversity. (*High*)

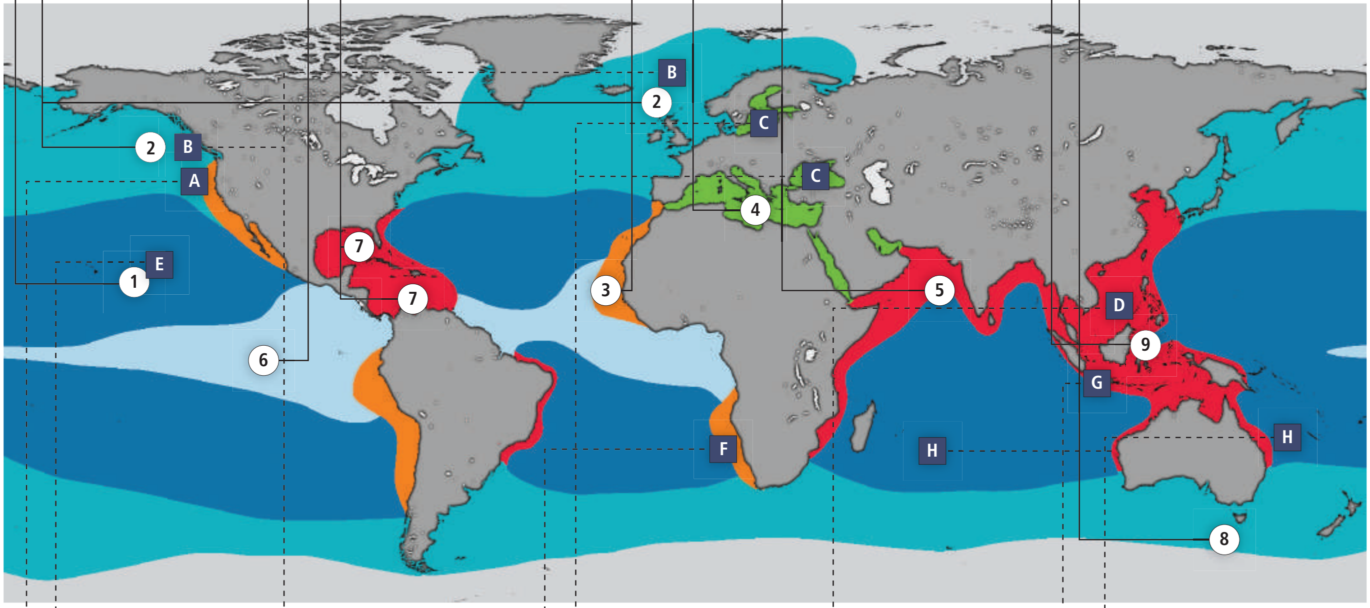
● (3) Upwelling, hence productivity, changes as a result of climate variability, particularly wind stress variability. (*Low*)

● (4) Spread of tropical species originating from Indian and Atlantic Oceans. Increased frequency of mass mortality events of benthic plants and animals linked to extreme temperature events. (*High*)

● (5) Declining dissolved oxygen concentrations and expansion of Oxygen Minimum Zones (OMZ). (*High*)

● (9) Mass coral bleaching and mortality in response to warming as well as temperature-driven decline in growth rates of some corals leading to degradation of coral reefs and loss of associated biodiversity. (*Very high*)

● (8) Shoaling of aragonite saturation horizon reduces biological calcification and alters plankton communities. (*High*)



■ (E) Warming leads to decline in primary production and reductions in fish catch. (*Low*)

■ (A) Acidification of seasonally upwelling waters impacts shellfish aquaculture. (*Medium*)

■ (B) Increased fish catches at high-latitude fringes with economic disruptions and jurisdictional tensions as some fish stocks shift distributions. (*Medium*)

■ (F) Increase in variability of upwelling in some EBUEs adds uncertainty to fisheries management. (*Medium*)

■ (C) Thermal stratification and eutrophication reduces dissolved oxygen with impacts on fish stocks. (*Medium*)

■ (D) Sea level rise modifies coastlines and increases flooding, challenging aquaculture such as shrimp farms. (*Medium*)

■ (H) Temperature-driven shifts in stocks of large pelagic fish create winners and losers among country and island economies. (*High*)

■ (G) Degradation of coral reefs and associated fish stocks as the extent and intensity of mass coral bleaching and mortality increases, increasing risks to regional food security. (*High*)

■ Examples of risks to fisheries from observed and projected impacts

- ■ High-Latitude Spring Bloom Systems
- 🟩 Semi-Enclosed Seas
- 🟥 Coastal Boundary Systems
- 🟧 Eastern Boundary Upwelling Systems
- ■ Equatorial Upwelling Systems
- 🟦 Subtropical Gyres

Figure 30-12 | Top: Examples of projected impacts and vulnerabilities associated with climate change in Ocean sub-regions. Bottom: Examples of risks to fisheries from observed and projected impacts across Ocean sub-regions. Words in parentheses indicate level of confidence. Details of sub-regions are given in Table 30-1a and Section 30.1.1.

2004; Lo Iacono et al., 2008). The degradation of coastal habitats not only liberates much of the carbon associated with vegetation loss, but can also release and oxidize buried organic carbon through erosion of cleared coastlines (*high confidence*; Duarte et al., 2005). Combining data on global area, land use conversion rates, and near-surface carbon stocks for marshes, mangroves, and seagrass meadows, Pendleton et al. (2012) revealed that the CO_2 emissions arising from destruction of these three ecosystems was equivalent to 3 to 19% of the emissions generated by deforestation globally, with economic damages estimated to be US$6 to US$42 billion annually. Similarly, Luisetti et al. (2013) estimate the carbon stock of seagrass and salt marshes in Europe, representing less than 4% of global carbon stocks in coastal vegetation, was valued at US$180 million, at EU Allowance price of €8/tCO_2 in June 2012. A reversal of EU Environmental Protection Directives could result in economic losses of US$1 billion by 2060. Blue Carbon strategies can also be justified in light of the numerous ecosystem services these ecosystems provide, such as protection against coastal erosion and storm damage, and provision of habitats for fisheries species (Section 5.5.7).

30.6.2. Economic Sectors

30.6.2.1. Fisheries and Aquaculture

The Ocean provided 64% of the production supplied by world fisheries (capture and aquaculture) in 2010, amounting to 148.5 million tonnes of fish and shellfish (FAO, 2012). This production, valued at US$217.5 billion, supplied, on average, 18.6 kg of protein-rich food per person to an estimated population of 6.9 billion (FAO, 2012). Marine capture fisheries supplied 77.4 million tonnes with highest production from the northwest Pacific (27%), west-central Pacific (15%), northeast Atlantic (11%), and southeast Pacific (10%) (FAO, 2012). World aquaculture production (59.9 million tonnes in 2010) is dominated by freshwater fishes; nevertheless, marine aquaculture supplied 18.1 million tonnes (30%) (FAO, 2012).

Marine capture fisheries production increased from 16.8 million tonnes in 1950 to a peak of 86.4 million tonnes in 1996, then declined before stabilizing around 80 million tonnes (FAO, 2012). The stagnation of marine capture fisheries production is attributed to full exploitation of around 60% of the world's marine fisheries and overexploitation of 30% (estimates for 2009) (FAO, 2012). Major issues for industrial fisheries include illegal, unreported, and unregulated fishing; ineffective implementation of monitoring, control, and surveillance; and overcapacity in fishing fleets (World Bank and FAO, 2008; FAO, 2012). Such problems are being progressively addressed in several developed and developing countries (Hilborn, 2007; Pitcher et al., 2009; Worm et al., 2009), where investments have been made in stock assessment, strong management, and application of the FAO Code of Conduct for Responsible Fisheries and the FAO Ecosystem Approach to Fisheries Management.

The significance of marine capture fisheries is illustrated powerfully by the number of people engaged in marine small-scale fisheries (SSF) in developing countries. SSF account for around half of the fish harvested from the Ocean, and provide jobs for more than 47 million people—about 12.5 million fishers and another 34.5 million people engaged in post-harvest activities (Mills et al., 2011). SSF are often characterized by large numbers of politically weak fishers operating from decentralized localities, with poor governance and insufficient data to monitor catches effectively (Kurien and Willmann, 2009; Cochrane et al., 2011; Pomeroy and Andrew, 2011). For these SSF, management that aims to avoid further depletion of overfished stocks may be more appropriate in the short-term than management aimed at maximizing sustainable production. These aims are achieved through adaptive management by (1) introduction of harvest controls (e.g., size limits, closed seasons and areas, gear restrictions, and protection of spawning aggregations) to avoid irreversible damage to stocks in the face of uncertainty (Cochrane et al., 2011); (2) flexible modification of these controls through monitoring (Plagányi et al., 2013); and (3) investing in the social capital and institutions needed for communities and governments to manage SSF (Makino et al., 2009; Pomeroy and Andrew, 2011).

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries resulting in loss of coastal and oceanic habitat (Hazen et al., 2012; Stramma et al., 2012), the movement of species (Cheung et al., 2011), the spread and increase of disease and invading species (Ling, 2008; Raitsos et al., 2010; Chan et al., 2011), and changes in primary production (Chassot et al., 2010). There is *medium evidence* and *medium agreement* that these changes will change both the nature of fisheries and their ability to provide food and protein for hundreds of millions of people (Section 7.2.1.2). The risks to ecosystems and fisheries vary from region to region (Section 7.3.2.4). Dynamic bioclimatic envelope models under SRES A1B project potential increases in fisheries production at high latitudes, and potential decreases at lower latitudes by the mid-21st century (Cheung et al., 2010; Section 6.5). Overall, warming temperatures are projected to shift optimal environments for individual species polewards and redistribute production; however, changes will be region specific (Cheung et al., 2010; Merino et al., 2012).

Fisheries, in particular shellfish, are also vulnerable to declining pH and carbonate ion concentrations. As a result, the global production of shellfish fisheries is *likely* to decrease (Cooley and Doney, 2009; Pickering et al., 2011) with further ocean acidification (*medium confidence*; Sections 6.3.2, 6.3.5, 6.4.1.1; Box CC-OA). Impacts may be first observed in EBUE where upwelled water is already relatively low in O_2 and under-saturated with aragonite (Section 30.5.5). Seasonal upwelling of acidified waters onto the continental shelf in the California Current region has recently affected oyster hatcheries along the coast of Washington and Oregon (Barton et al., 2012; Section 30.5.5.1.1). Whether declining pH and aragonite saturation due to climate change played a role is unclear; however, future declines will increase the risk of such events occurring.

Most marine aquaculture species are sensitive to changing ocean temperature (Section 6.3.1.4; exposed through pens, cages, and racks placed directly in the sea, utilization of seawater in land-based tanks, collection of wild spat) and, for molluscs particularly, changes in carbonate chemistry (Turley and Boot, 2011; Barton et al., 2012; Section 6.3.2.4). Environmental changes can therefore impact farm profitability, depending on target species and farm location. For example, a 1°C rise in SST is projected to shift production of Norwegian salmonids further north but may increase production overall (Hermansen and Heen, 2012). Industries for non-food products, which can be important for regional livelihoods such as Black Pearl in Polynesia, are also affected by rising SST. Higher temperatures are known to affect the quality of pearl nacre, and can increase levels of disease in adult oysters (Pickering et al., 2011; Bell et al., 2013b). Aquaculture production is also vulnerable to extreme events such as storms and floods (e.g., Chang et al., 2013). Flooding and inundation by seawater may be a problem to shore facilities on low-lying coasts. For example, shrimp farming operations in the tropics will be challenged by rising sea levels, which will be exacerbated by mangrove encroachment and a reduced ability for thorough-drying of ponds between crops (Della Patrona et al., 2011).

The impacts of climate change on marine fish stocks are expected to affect the economics of fisheries and livelihoods in fishing nations through changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labor markets, and industry re-organization (Sumaila et al., 2011; Section 6.4.1). A study of the potential vulnerabilities of national economies to the effects of climate change on fisheries, in terms of exposure to warming, relative importance of fisheries to national economies and diets, and limited societal capacity to adapt, concluded that a number countries including Malawi, Guinea, Senegal, Uganda, Sierra Leone, Mozambique, Tanzania, Peru, Colombia, Venezuela, Mauritania, Morocco, Bangladesh, Cambodia, Pakistan, Yemen, and Ukraine are most vulnerable (Allison et al., 2009).

Aquaculture production is expanding rapidly (Bostock et al., 2010) and will play an important role in food production and livelihoods as the human demand for protein grows. This may also add pressure on capture fisheries (FAO, 2012; Merino et al., 2012). Two-thirds of farmed food fish production (marine and freshwater) is achieved with the use of feed derived from wild-harvested, small, pelagic fish and shellfish. Fluctuations in the availability and price of fishmeal and fish oil for feeds, as well as their availability, pose challenges for the growth of sustainable aquaculture production, particularly given uncertainties in changes in EBUE upwelling dynamics to climate change (Section 30.5.5). Technological advances and changes in management such as increasing feed efficiencies, using alternatives to fishmeal and fish oil, and farming of herbivorous finfish, coupled with economic and regulatory incentives, will reduce the vulnerability of aquaculture to the impacts of climate change on small, pelagic fish abundance (Naylor et al., 2009; Merino et al., 2010; FAO, 2012).

The challenges of optimizing the economic and social benefits of both industrial fisheries and SSF and aquaculture operations, which often already include strategies to adapt to climatic variability (Salinger et al., 2013), are now made more complex by climate change (Cochrane et al., 2009; Brander, 2010, 2013). Nevertheless, adaptation options include establishment of early warning systems to aid decision making, diversification of enterprises, and development of adaptable management systems (Chang et al., 2013). Vulnerability assessments that link oceanographic, biological, and socioeconomic systems can be applied to identify practical adaptations to assist enterprises, communities, and households to reduce the risks from climate change and capitalize on the opportunities (Pecl et al., 2009; Bell et al., 2013b; Norman-López et al., 2013). The diversity of these adaptation options, and the policies needed to support them, are illustrated by the examples in the following subsections.

30.6.2.1.1. Tropical fisheries based on large pelagic fish

Fisheries for skipjack, yellowfin, big-eye, and albacore tuna provide substantial economic and social benefits to the people of Small Island Developing States (SIDS). For example, tuna fishing license fees contribute substantially (up to 40%) to the government revenue of several Pacific Island nations (Gillett, 2009; Bell et al., 2013b). Tuna fishing and processing operations also contribute up to 25% of gross domestic product in some of these nations and employ more than 12,000 people (Gillett, 2009; Bell et al., 2013b). Considerable economic benefits are also derived from fisheries for top pelagic predators in the Indian and Atlantic Oceans (FAO, 2012; Bell et al., 2013a). Increasing sea temperatures and changing patterns of upwelling are projected to cause shifts in the distribution and abundance of pelagic top predator fish stocks (Sections 30.5.2, 30.5.5-6), with potential to create "winners" and "losers" among island economies as catches of the transboundary tuna stocks change among and within their exclusive economic zones (EEZs; Bell et al., 2013a,b).

A number of practical adaptation options and supporting policies have been identified to minimize the risks and maximize the opportunities associated with the projected changes in distribution of the abundant skipjack tuna in the tropical Pacific (Bell et al., 2011b, 2013a; Lehodey et al., 2011; Table 30-2). These adaptation and policy options include (1) full implementation of the regional "vessel day scheme," designed to distribute the economic benefits from the resource in the face of climatic variability, and other schemes to control fishing effort in subtropical areas; (2) strategies for diversifying the supply of fish for canneries in the west of the region as tuna move progressively east; (3) continued effective fisheries management of all tuna species; (4) energy efficiency programs to assist domestic fleets to cope with increasing fuel costs and the possible need to fish further from port; and (5) the eventual restructuring of regional fisheries management organizations to help coordinate management measures across the entire tropical Pacific. Efforts to ensure provision of operational-level catch and effort data from all industrial fishing operations will improve models for projecting redistribution of tuna stocks and quotas under climate change (Nicol et al., 2013; Salinger et al., 2013). Similar adaptation options and policy responses are expected to be relevant to the challenges faced by tuna fisheries in the tropical and subtropical Indian and Atlantic Oceans.

30.6.2.1.2. Small-scale fisheries

Small-scale fisheries (SSF) account for 56% of catch and 91% of people working in fisheries in developing countries (Mills et al., 2011). SSF are fisheries that tend to operate at family or community level, have low levels of capitalization, and make an important contribution to food security and livelihoods. They are often dependent on coastal ecosystems, such as coral reefs, that provide habitats for a wide range of harvested fish and invertebrate species. Despite their importance to many developing countries, such ecosystems are under serious pressure from human activities including deteriorating coastal water quality, sedimentation, ocean warming, overfishing, and acidification (Sections 7.2.1.2, 30.3, 30.5; Box CC-CR). These pressures are translating into a steady decline in live coral cover, which is *very likely* to continue over the coming decades, even where integrated coastal zone management is in place

Table 30-2 | Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socioeconomic benefits derived from pelagic and coastal fisheries and aquaculture, and to maximize the opportunities. These measures are classified as win–win (W–W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or lose–win (L–W) adaptations, where benefits do not exceed costs in the short term but accrue under longer term climate change (modified from Bell et al., 2013b). WCPFC = Western and Central Pacific Fisheries Commission.

	Adaptation options	Supporting policies
Economic development	• Full implementation of the vessel day scheme to control fishing effort by the Parties to the Nauru Agreement[a] (W–W) • Diversifying sources of fish for canneries in the region and maintaining trade agreements, e.g., an economic partnership agreement with the European Union (W–W) • Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change (W–W) • Energy efficiency programs to assist fleets to cope with oil price rises and minimize CO_2 emissions and reduce costs of fishing further afield as tuna distributions shift east (W–W) • Pan-Pacific tuna management through merger of the WCPFC and Inter-American Tropical Tuna Commission to coordinate management measures across the tropical Pacific (L–W)	• Strengthen national capacity to administer the vessel day scheme. • Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna. • Include implications of climate change in management objectives of the WCPFC. • Apply national management measures to address climate change effects for subregional concentrations of tuna in archipelagic waters beyond the mandate of WCPFC. • Require all industrial tuna vessels to provide operational-level catch and effort data to improve the models for redistribution of tuna stocks during climate change.
Food security	• Manage catchment vegetation to reduce transfer of sediments and nutrients to coasts to reduce damage to adjacent coastal coral reefs, mangroves, and seagrasses that support coastal fisheries (W–W). • Foster the care of coral reefs, mangroves, and seagrasses by preventing pollution, managing waste, and eliminating direct damage to these coastal fish habitats (W–W). • Provide for migration of fish habitats by prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help the plants colonize landward areas as sea level rises (L–W). • Sustain and diversify catches of demersal coastal fish to maintain the replenishment potential of all stocks (L–W). • Increase access to tuna caught by industrial fleets through storing and selling tuna and by-catch landed at major ports to provide inexpensive fish for rapidly growing urban populations (W–W). • Install fish aggregating devices close to the coast to improve access to fish for rural communities as human populations increase and demersal fish decline (W–W). • Develop coastal fisheries for small pelagic fish species, e.g., mackerel, anchovies, pilchards, sardines, and scads (W–W?). • Promote simple post-harvest methods, such as traditional smoking, salting, and drying, to extend the shelf life of fish when abundant catches are landed (W–W).	• Strengthen governance for sustainable use of coastal fish habitats by (1) building national capacity to understand the threats of climate change; (2) empowering communities to manage fish habitats; and (3) changing agriculture, forestry, and mining practices to prevent sedimentation and pollution. • Minimize barriers to landward migration of coastal habitats during development of strategies to assist other sectors to respond to climate change. • Apply "primary fisheries management" to stocks of coastal fish and shellfish to maintain their potential for replenishment. • Allocate the necessary quantities of tuna from total national catches to food security to increase access to fish for both urban and coastal populations. • Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security. • Include anchored inshore fish aggregating devices as part of national infrastructure for food security.
Livelihoods	• Relocate pearl farming operations to deeper water and to sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for good growth and survival of pearl oysters and formation of high-quality pearls (L–W). • Raise the walls and floor of shrimp ponds so that they drain adequately as sea level rises (L–W). • Identify which shrimp ponds may need to be rededicated to producing other commodities (L–W).	• Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be "climate-proofed" and relocated if necessary. • Strengthen environmental impact assessments for coastal aquaculture activities to include the additional risks posed by climate change. • Develop partnerships with regional technical agencies to provide support for development of sustainable aquaculture.

[a] The Parties to the Nauru Agreement are Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, and Tuvalu.

(Sections 30.5.4, 30.5.6). For example, coral losses around Pacific Islands are projected to be as high as 75% by 2050 (Hoegh-Guldberg et al., 2011a). Even under the most optimistic projections (a 50% loss of coral by 2050), changes to state of coral reefs (Box CC-CR; Figures 30-10, 30-12) are *very likely* to reduce the availability of associated fish and invertebrates that support many of the SSF in the tropics (*high confidence*). In the Pacific, the productivity of SSF on coral reefs has been projected to decrease by at least 20% by 2050 (Pratchett et al., 2011b), which is also *likely* to occur in other coral reef areas globally given the similar and growing stresses in these other regions (Table SM30-1; Section 30.5.4).

Adaptation options and policies for building the resilience of coral reef fisheries to climate change suggested for the tropical Pacific include (1) strengthening the management of catchment vegetation to improve water quality along coastlines; (2) reducing direct damage to coral reefs; (3) maintaining connectivity of coral reefs with mangrove and seagrass habitats; (4) sustaining and diversifying the catch of coral reef fish to maintain their replenishment potential; and (5) transferring fishing effort from coral reefs to skipjack and yellowfin tuna resources by installing anchored fish-aggregating devices (FAD) close to shore (Bell et al., 2011b; 2013a,b; Table 30-2). These adaptation options and policies represent a "no regrets" strategy in that they provide benefits for coral reef fisheries and fishers irrespective of climate change and ocean acidification.

30.6.2.1.3. Northern Hemisphere HLSBS fisheries

The high-latitude fisheries in the Northern Hemisphere span from around 30/35°N to 60°N in the North Pacific and 80°N in the North Atlantic, covering a wide range of thermal habitats supporting subtropical/temperate species to boreal/arctic species. The characteristics of these

HLSBS environments, as well as warming trends, are outlined in Section 30.5.1 and Table 30-1. In part, as a result of 30 years of increase in temperature (Belkin, 2009; Sherman et al., 2009), there has been an increase in the size of fish stocks associated with high-latitude fisheries in the Northern Hemisphere. This is particularly the case for the Norwegian spring-spawning herring, which has recovered from near-extinction as a result of overfishing and a cooler climate during the 1960s (Toresen and Østvedt, 2000). The major components of both pelagic and demersal high-latitude fish stocks are boreal species located north of 50°N. Climate change is projected to increase high-latitude plankton production and displace zooplankton and fish species poleward. As a combined result of these future changes, the abundance of fish (particularly boreal species) may increase in the northernmost part of the high-latitude region (Cheung et al., 2011), although increases will only be moderate in some areas.

The changes in distribution and migration of pelagic fish shows considerable spatial and temporal variability, which can increase tensions among fishing nations. In this regard, tension over the Atlantic mackerel fisheries has led to what many consider the first climate change-related conflict between fishing nations (Cheung et al., 2012; Section 30.6.5), and which has emphasized the importance of developing international collaboration and frameworks for decision making (Miller et al., 2013; Sections 15.4.3.3, 30.6.7). The Atlantic mackerel has over the recent decades been a shared stock between the EU and Norway. However, the recent advancement of the Atlantic mackerel into the Icelandic EEZ during summer has resulted in Icelandic fishers operating outside the agreement between the EU and Norway. Earlier records of mackerel from the first half of the 20th and second half of the 19th century show, however, that mackerel was present in Icelandic waters during the earlier warm periods (Astthorsson et al., 2012). In the Barents Sea, the northeast Arctic cod, *Gadus morhua*, reached record-high abundance in 2012 and also reached its northernmost-recorded distribution (82°N) (ICES, 2012). A further northward migration is impossible as this would be into the Deep Sea Polar Basin, beyond the habitat of shelf species. A further advancement eastwards to the Siberian shelf is, however, possible. The northeast Arctic cod stock is shared exclusively by Norway and Russia, and to date there has been a good agreement between those two nations on the management of the stock. These examples highlight the importance of international agreements and cooperation (Table 30-4).

The HLSBS fisheries constitute a large-scale high-tech industry, with large investments in highly mobile fishing vessels, equipment, and land-based industries with capacity for adapting fisheries management and industries for climate change (Frontiers Economics, Ltd., 2013). Knowledge of how climate fluctuations and change affect the growth, recruitment, and distribution of fish stocks is presently not incorporated into fisheries management strategies (Perry et al., 2010). These strategies are vital for fisheries that hope to cope with the challenges of a changing ocean environment, and are centrally important to any attempt to develop ecosystem-based management and sustainable fisheries under climate change. The large pelagic stocks, with their climate-dependent migration pattern, are shared among several nations. Developing equitable sharing of fish quotas through international treaties (Table 30-4) is a necessary adaptation for a sustainable fishery. Factors presently taken into account in determining the shares of quotas are the historical fishery, bilateral exchanges of quotas for various species, and the time that stocks are in the various EEZs.

30.6.2.2. Tourism

Tourism recreation represents one of the world's largest industries, accounting for 9% (>US$6 trillion) of global GDP and employing more than 255 million people. It is expected to grow by an average of 4% annually and reach 10% of global GDP within the next 10 years (WTTC, 2012). As with all tourism, that which is associated with the Ocean is heavily influenced by climate change, global economic and socio-political conditions, and their interactions (Scott et al., 2012b; Section 10.6.1). Climate change, through impacts on ecosystems (e.g., coral reef bleaching), can reduce the appeal of destinations, increase operating costs, and/or increase uncertainty in a highly sensitive business environment (Scott et al., 2012b).

Several facets of the influence of climate change on the Ocean directly impact tourism (Section 10.6). Tourism is susceptible to extreme events such as violent storms, long periods of drought, and/or extreme precipitation events (Sections 5.4.3.4, 10.6.1; IPCC, 2012). SLR, through its influence on coastal erosion and submergence, salinization of water supplies, and changes to storm surge, increases the vulnerability of coastal tourism infrastructure, tourist safety, and iconic ecosystems (*high confidence*; Sections 5.3.3.2, 5.4.3.4, 10.6; Table SPM.1; IPCC, 2012). For example, approximately 29% of resorts in the Caribbean are within 1 m of the high tide mark and 60% are at risk of beach erosion from rapid SLR (Scott et al., 2012a).

Increasing sea temperatures (Section 30.3.1.1) can change attractiveness of locations and the opportunities for tourism through their influence on the movement of organisms and the state of ecosystems such as coral reefs (Section 10.6.2; Box CC-CR; UNWTO and UNEP, 2008). Mass coral bleaching and mortality (triggered by elevated sea temperatures; *high confidence*) can decrease the appeal of destinations for diving-related tourism, although the level of awareness of tourists of impacts (e.g., <50% of tourists were concerned about coral bleaching during a major bleaching year, 1998) and expected economic impacts have been found to be uncertain (Scott et al., 2012b). Some studies, however, have noted reduced tourist satisfaction and identified "dead coral" as one of the reasons for disappointment at the end of the holiday (Westmacott et al., 2000). Tourists respond to changes in factors such as weather and opportunity by expressing different preferences. For example, preferred conditions and hence tourism are projected to shift toward higher latitudes with climate change, or from summer to cooler seasons (Amelung et al., 2007; Section 10.6.1).

Options for adaptation by the marine tourism sector include (1) identifying and responding to inundation risks with current infrastructure, and planning for projected SLR when building new tourism infrastructure (Section 5.5; Scott et al., 2012a); (2) promoting shoreline stability and natural barriers by preserving ecosystems such as mangroves, salt marshes, and coral reefs (Section 5.5; Scott et al., 2012b); (3) deploying forecasting and early-warning systems in order to anticipate challenges to tourism and natural ecosystems (Strong et al., 2011; IPCC, 2012); (4) preparation of risk management and disaster preparation plans in order to respond to extreme events; (5) reducing the effect of other stressors on ecosystems and building resilience in iconic tourism features such as coral reefs and mangroves; and (6) educating tourists to improve understanding of the negative consequences of climate change over those stemming from local stresses (Scott et al., 2012a,b). Adaptation plans for tourism industries need to address specific operators and regions. For example, some operators may have costly infrastructure at risk while others may have few assets but are dependent on the integrity of natural environments and ecosystems (Turton et al., 2010).

30.6.2.3. Shipping

International shipping accounts for more than 80% of world trade by volume (UNCTAD, 2009a,b) and approximately 3% of global CO_2 emissions from fuel combustion although CO_2 emissions are expected to increase two- to threefold by 2050 (Heitmann and Khalilian, 2010; WGIII AR5 Section 8.1). Changes in shipping routes (Borgerson, 2008) and variation in the transport network due to shifts in grain production and global markets, as well as new fuel and weather-monitoring technology, may alter these emission patterns (WGIII AR5 Sections 8.3, 8.5). Extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damaging infrastructure and introducing additional dangers to ships, crews, and the environment (UNCTAD, 2009a,b; Pinnegar et al., 2012; Section 10.4.4). These issues have been assessed by some countries which have raised concerns over the potential for costly delays and cancellation of services, and the implications for insurance premiums as storminess and other factors increase risks (Thornes et al., 2012).

Climate change may benefit maritime transport by reducing Arctic sea ice and consequently shorten travel distances between key ports (Borgerson, 2008), thus also decreasing total GHG emissions from ships (WGIII AR5 Section 8.5.1). Currently, the low level of reliability of this route limits its use (Schøyen and Bråthen, 2011), and the potential full operation of the Northwest Passage and Northern Sea Route would require a transit management regime, regulation (e.g., navigation, environmental, safety, and security issues), and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interest in the Arctic. Further discussion of issues around melting Arctic sea ice and the Northern Sea Route are given in Chapter 28 (Sections 28.2.6, 28.3.4).

30.6.2.4. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry face potential impacts from climate change on its ocean-based activities. More than 100 oil and gas platforms were destroyed in the Gulf of Mexico by the unusually strong Hurricanes Katrina and Rita in 2005. Other consequences for oil pipelines and production facilities ultimately reduced US refining capacity by 20% (IPCC, 2012). The increasing demand for oil and gas has pushed operations to waters 2000 m deep or more, far beyond continental shelves. The very large-scale moored developments required are exposed to greater hazards and higher risks, most of which are not well understood by existing climate/weather projections. Although there is a strong trend toward seafloor well completions with a complex of wells, manifolds, and pipes that are not exposed to surface forcing, these systems face different hazards from instability and scouring of the unconsolidated sediments by DS currents (Randolph et al., 2010). The influence of warming oceans on sea floor stability is widely debated due largely to uncertainties about the effects of methane and methane hydrates (Sultan et al., 2004; Archer et al., 2009; Geresi et al., 2009). Declining sea ice is also opening up the Arctic to further oil and gas extraction. Discussion of potential expansion of oil and mineral production in the Arctic is made in Chapter 28 (Sections 28.2.5-6, 28.3.4).

The principal threat to oil and gas extraction and infrastructure in maritime settings is the impact of extreme weather (Kessler et al., 2011), which is *likely* to increase given that future storm systems are expected to have greater energy (Emanuel, 2005; Trenberth and Shea, 2006; Knutson et al., 2010). Events such as Hurricane Katrina have illustrated challenges which will arise for this industry with projected increases in storm intensity (Cruz and Krausmann, 2008). In this regard, early warning systems and integrated planning offer some potential to reduce the effect of extreme events (IPCC, 2012).

30.6.3. Human Health

Major threats to public health due to climate change include diminished security of water and food supplies, extreme weather events, and changes in the distribution and severity of diseases, including those due to marine biotoxins (Costello et al., 2009; Sections 5.4.3.5, 6.4.2.3, 11.2). The predominantly negative impacts of disease for human communities are expected to be more serious in low-income areas such as Southeast Asia, southern and east Africa, and various sub-regions of South America (Patz et al., 2005), which also have under-resourced health systems (Costello et al., 2009). Many of the influences are directly or indirectly related to basin-scale changes in the Ocean (e.g., temperature, rainfall, plankton populations, SLR, and ocean circulation; McMichael et al., 2006). Climate change in the Ocean may influence the distribution of diseases such as cholera (Section 11.5.2.1), and the distribution and occurrence of HABs. The frequency of cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens are correlated with sea surface temperatures, multi-decadal fluctuations of ENSO, and plankton blooms, which may provide insight into how this disease may change with projected rates of ocean warming (Colwell, 1996; Pascual et al., 2000; Rodó et al., 2002; Patz et al., 2005; Myers and Patz, 2009; Baker-Austin et al., 2012). The incidence of diseases such as ciguatera also shows links to ENSO, with ciguatera becoming more prominent after periods of elevated sea temperature. This indicates that ciguatera may become more frequent in a warmer climate (Llewellyn, 2010), particularly given the higher prevalence of ciguatera in areas with degraded coral reefs (*low confidence*; Pratchett et al., 2011a).

30.6.4. Ocean-Based Mitigation

30.6.4.1. Deep Sea Carbon Sequestration

Carbon dioxide capture and storage into the deep sea and geologic structures are also discussed in WGIII AR5 Chapter 7 (Sections 7.5.5, 7.8.2, 7.12). The economic impact of deliberate CO_2 sequestration beneath the sea floor has previously been reviewed (IPCC, 2005). Active CO_2 sequestration from co-produced CO_2 into sub-sea geologic formations is being instigated in the North Sea and in the Santos Basin offshore from Brazil. These activities will increase as offshore oil and gas production increasingly exploits fields with high CO_2 in the source gas and oil. Significant risks from the injection of high levels of CO_2 into deep ocean waters have been identified for DS organisms and ecosystems although chronic effects have not yet been studied. These risks are similar to those discussed previously with respect to ocean acidification and could further exacerbate declining O_2 levels and changing trophic networks in deep water areas (Seibel and Walsh, 2001; Section 6.4.2.2).

There are significant issues within the decision frameworks regulating these activities. Dumping of any waste or other matter in the sea, including the seabed and its subsoil, is strictly prohibited under the 1996 London Protocol (LP) except for those few materials listed in Annex I. Annex 1 was amended in 2006 to permit storage of CO_2 under the seabed. "Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-Seabed Geological Formations" were adopted by the parties to the LP in 2007. The Guidelines take a precautionary approach to the process, requiring Contracting Parties under whose jurisdiction or control such activities are conducted to issue a permit for the disposal subject to stringent conditions being fulfilled (Rayfuse and Warner, 2012).

30.6.4.2. Offshore Renewable Energy

Renewable energy supply from the Ocean includes ocean energy and offshore wind turbines. The global technical potential for ocean and wind energy is not as high as solar energy although considerable potential still remains. Detailed discussion of the potential of renewable energy sources are given in WGIII AR5 Chapter 7 (Sections 7.4.2, 7.5.3, 7.8.2). There is an increasing trend in the renewable energy sector to offshore wind turbines (Section 10.2.2). At present, there is *high uncertainty* about how changes in wind intensity and patterns, and extreme events (from climate change), will impact the offshore wind energy sector. Given the design and engineering solutions available to combat climate change impacts (Tables 10-1, 10-7), it is *unlikely* that this sector will face insurmountable challenges from climate change.

30.6.5. Maritime Security and Related Operations

Climate change and its influence on the Ocean has become an area of increasing concern in terms of the maintenance of national security and the protection of citizens. These concerns have arisen as nation-states increasingly engage in operations ranging from humanitarian assistance in climate-related disasters to territorial issues exacerbated by changing coastlines, human communities, resource access, and new seaways (Kaye, 2012; Rahman, 2012; Section 12.6). In this regard, increasing sea levels along gently sloping coastlines can have the seemingly perverse outcome that the territorial limits to the maritime jurisdiction of the State might be open to question as the distance from national baselines to the outer limits of the EEZ increases beyond 200 nm over time (Schofield and Arsana, 2012).

Changes in coastal resources may also be coupled with decreasing food security to compound coastal poverty and lead, in some cases, to increased criminal activities such as piracy; IUU fishing; and human, arms, and drug trafficking (Kaye, 2012). While the linkages have not been clearly defined in all cases, it is possible that changes in the Ocean as result of climate change will increase pressure on resources aimed at maintaining maritime security and countering criminal activity, disaster relief operations, and freedom of navigation (Section 12.6.2). National maritime security capacity and infrastructure may also require rethinking as new challenges present themselves as a result of climate change and ocean acidification (Allen and Bergin, 2009; Rahman, 2012; Sections 12.6.1-2).

Opportunities may also arise from changes to international geography such as formation of new ice-free seaways through the Arctic, which may benefit some countries in terms of maintaining maritime security and access (Section 28.2.6). Conversely, such new features may also lead to increasing international tensions as States perceive new vulnerabilities from these changes to geography.

Like commercial shipping (Section 30.6.2.3), naval operations in many countries result in significant GHG emissions (e.g., the US Navy emits around 2% of the national GHG emissions; Mabus, 2010). As a result, there are a number of programs being implemented by navies around the world to try and reduce their carbon footprint and air pollution such as improving engine efficiency, reducing fouling of vessels, increasing the use of biofuels, and using nuclear technology for power generation, among other initiatives.

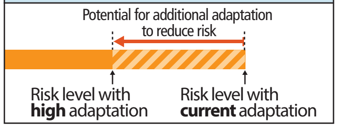
30.7. Synthesis and Conclusions

Evidence that human activities are fundamentally changing the Ocean is *virtually certain*. Sea temperatures have increased rapidly over the past 60 years at the same time as pH has declined, consistent with the expected influence of rising atmospheric concentrations of CO_2 and other GHGs (*very high confidence*). The rapid rate at which these fundamental physical and chemical parameters of the Ocean are changing is unprecedented within the last 65 Ma (*high confidence*) and possibly 300 Ma (*medium confidence*). As the heat content of the Ocean has increased, the Ocean has become more stratified (*very likely*), although there is considerable regional variability. In some cases, changing surface wind has influenced the extent of mixing and upwelling, although our understanding of where and why these differences occur regionally is uncertain. The changing structure and function of the Ocean has led to changes in parameters such as O_2, carbonate ion, and inorganic nutrient concentrations (*high confidence*). Not surprisingly, these fundamental changes have resulted in responses by key marine organisms, ecosystems, and ecological processes, with negative implications for hundreds of millions of people that depend on the ecosystem goods and services provided (*very likely*). Marine organisms are migrating at rapid rates toward higher latitudes, fisheries are transforming, and many organisms are shifting their reproductive and migratory activity in time and in concert with changes in temperature and other parameters. Ecosystems such as coral reefs are declining rapidly (*high confidence*). An extensive discussion of these changes is provided in previous sections and in other chapters of AR5.

Table 30-3 | Key risks to ocean and coastal issues from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer term era of climate options (here, for 2080–2100), for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Climate-related drivers of impacts							
Warming trend	Extreme temperature	Extreme precipitation	Precipitation	Damaging cyclone	Sea level	Ocean acidification	Hypoxia

Level of risk & potential for adaptation



Risks to ecosystems and adaptation options

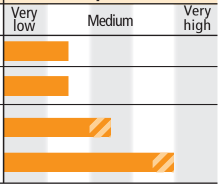
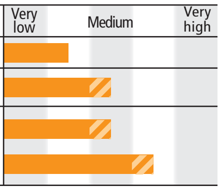
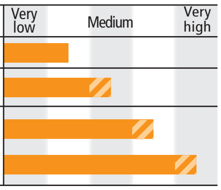
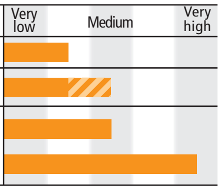
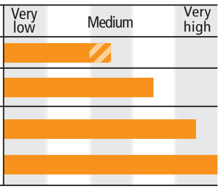
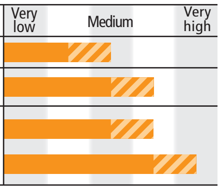
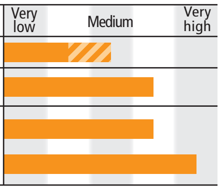
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans. (*medium confidence*) [6.5.1, 6.3.4, Box CC-PP]	Adaptation options are limited to the translocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, or to the expansion of aquaculture.	Warming trend Extreme temperature	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Distributional shift in fish and invertebrate species, fall in fisheries catch potential at low latitudes, e.g., in EUS, CBS, and STG regions. (*high confidence*) [6.3.1, Box CC-MB]	Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well as deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication, the expansion of sustainable aquaculture and development of alternative livelihoods in some regions.	Warming trend Extreme temperature	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects. (*high confidence*) [6.3.3, 30.5.3.2, 30.5.4.1-2]	Human adaptation options involve the large-scale translocation of industrial fishing activities as a consequence of the hypoxia-induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running off of coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.	Warming trend Hypoxia	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae. (*high confidence*) [5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA]	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely limited by the CO_2 concentrations and high temperatures reached; adaptation options shifting to exploit more resilient species or the protection of habitats with low natural CO_2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.	Ocean acidification	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in CBS, SES, and STG regions. (*high confidence*) [5.4.2.4, 6.4.2, 30.3.1.1, 30.3.2.2, 30.5.2, 30.5.3, 30.5.4, 30.5.6, Box CC-CR]	Evidence of rapid evolution by corals is very limited or nonexistent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely given estimates that they need to move at the speed of 10 – 20 km yr^{-1} to keep up with the pace of climate change. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.	Warming trend Damaging cyclone Extreme temperature Ocean acidification	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in CBS and STG subregions. (*medium to high confidence*) [5.5.2, 5.5.4, 30.5.6.1.3, 30.6.2.2, Box CC-CR]	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients. Increased mangrove, coral reef, and seagrass protection and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat.	Warming trend Ocean acidification Sea level Extreme precipitation Damaging cyclone	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Marine biodiversity loss with high rate of climate change. (*medium confidence*) [6.3.1-3, 6.4.1.2-3, Table 30.4, Box CC-MB]	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from tourism and fishing.	Warming trend Extreme temperature Ocean acidification	Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	

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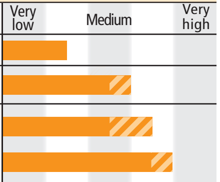
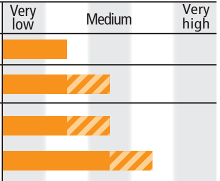
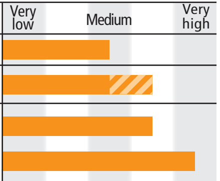
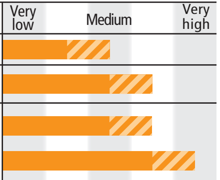
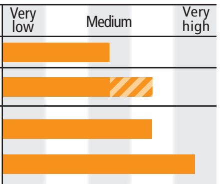
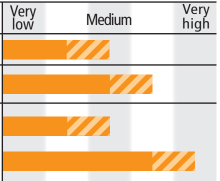
Table 30-3 (continued)

Risks to fisheries				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Decreased production of global shellfish fisheries. (*high confidence*) [6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, Box CC-OA]	Effective shift to alternative livelihoods, changes in food consumption patterns, and adjustment of (global) markets.	🌡 🌡! C	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes. (*medium confidence*) [6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2]	Increasing coastal poverty at low latitudes as fisheries becomes smaller – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts.	🌡	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries. (*high confidence*) [6.3.1, 6.4.3, Table 30.4]	International fisheries agreements and instruments, such as the tuna commissions, may have limited success in establishing sustainable fisheries yields.	🌡	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Variability of small pelagic fishes in EBUEs is becoming more extreme at interannual to multidecadal scales, making industry and management decisions more uncertain. (*medium confidence*) [6.3.2, 6.3.3, 30.5.2, 30.5.5, Box CC-UP]	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.	O_2↓ 🌡 C	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction. (*high confidence*) [6.4.1, 30.5.3-4, 30.5.6, Box CC-CR]	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).	🌡 🌡! C	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Current spatial management units, especially the marine protected areas (MPAs), may fail in the future due to shifts in species distributions and community structure. (*high confidence*) [6.3.1, 6.4.2.1, 30.5.1, Box CC-MB]	Continuous revision and shifts of MPA borders, and of MPA goals and performance.	🌡 O_2↓ 🌡! C	Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

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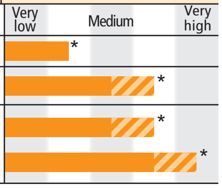
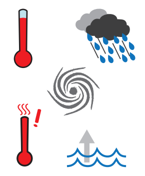
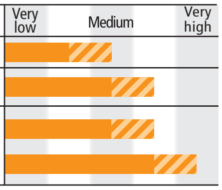
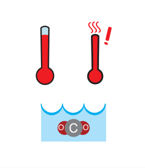
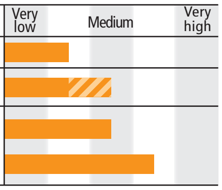
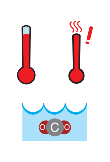
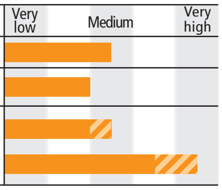
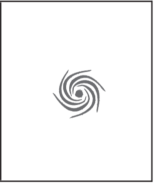
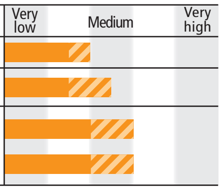
30.7.1. Key Risks and Vulnerabilities

The rapid changes in the physical, chemical, and biological state of the Ocean pose a number of key risks and vulnerabilities for ecosystems, communities, and nations worldwide. Table 30-3 and Figure 30-12 summarize risks and vulnerabilities from climate change and ocean acidification, along with adaptation issues and prospects, and a summary of expert opinion on how these risks will change under further changes in environmental conditions.

Rising ocean temperatures are changing the distribution, abundance, and phenology of many marine species and ecosystems, and consequently represent a key risk to food resources, coastal livelihoods, and industries such as tourism and fishing, especially for HLSBS, CBS, STG, and EBUE (Sections 6.3.1, 6.3.4, 7.3.2.4, 30.5; Figure 30-12; Table 30-3; Box CC-MB). Key risks involve changes in the distribution and abundance of key fishery species (*high confidence*; Section 30.6.2.1; Figure 30-12 A,B,G,H) as well as the spread of disease and invading organisms, each of which has the potential to impact ecosystems as well as aquaculture and fishing (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.4, 7.4.2, 29.5.3-4; Table 30-3). Adaptation to these changes may be possible in the short-term through dynamic fisheries policy and management (i.e., relocation of fishing effort; Table 30-3), as well as monitoring and responding to potential invading species in coastal settings. The increasing frequency of thermal extremes (Box CC-HS) will also increase the risk that the thermal threshold of corals and other organisms is exceeded on a more frequent

Table 30-3 (continued)

Risks to humans and infrastructure (continued)

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Reduced coastal socioeconomic security. (*high confidence*) [5.5.2, 5.5.4, 30.6.5, 30.7.1]	Human adaptation options involve (1) protection using coastal defences (e.g. seawalls where appropriate and economic) and soft measures (e.g., mangrove replanting and enhancing coral growth); (2) accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure; and (3) managed retreat as a last viable option. Vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Reduced livelihoods and increased poverty. (*medium confidence*) [6.4.1-2, 30.6.2, 30.6.5]	Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other species of interest.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Impacts due to increased frequency of harmful algal blooms (*medium confidence*) [6.4.2.3]	Adaptation options include improved monitoring and early warning system, reduction of stresses favoring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*) [IPCC 2012, 30.6.5, 12.4-12.6, 29.3]	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people, and increase humanitarian crises.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*) [IPCC 2012, 30.6.5, 12.4-12.6, 29.3]	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		Present Near term (2030 – 2040) Long term 2°C (2080 – 2100) 4°C	

**High confidence* in existence of adaptation measures, *Low confidence* in magnitude of risk reduction

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwehlling Ecosystems; EUS = Equatorial Upwelling Systems; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Subtropical Gyres.

basis (especially in CBS, STG, SES, HLSBS, and EUS regions; Sections 6.2, 30.5; Box CC-CR). These changes pose a key risk to vulnerable ecosystems such as mangroves and coral reefs, with potential to have a series of serious impacts on fisheries, tourism, and coastal ecosystem services such as coastal protection (Sections 5.4.2.4, 6.3.2, 6.3.5, 6.4.1.3, 7.2.1.2, 29.3.1.2, 30.5; Table 30-3; Box CC-CR). Genetic adaptation of species to increasing levels of stress may not occur fast enough given fairly long generation times of organisms such as reef-building corals and many other invertebrates and fish (Table 30-3). In this case, risks may be reduced by addressing stresses not related to climate change (e.g., pollution, overfishing), although this strategy could have minimal impact if further increases in sea temperature occur (*high confidence*).

Loss of these important coastal ecosystems is associated with emerging risks associated with the collapse of some coastal fisheries along with livelihoods, food, and regional security (*medium confidence*). These changes are *likely* to be exacerbated by other key risks such as coastal inundation and habitat loss due to SLR, as well as intensified precipitation events (*high confidence*; Section 5.4; Box CC-CR). Adaptation options in this case include engineered coastal defenses, reestablishing coastal vegetation such as mangroves, protecting water supplies from salination, and developing strategies for coastal communities to withdraw to less vulnerable locations over time (Section 5.5).

The recent decline in O_2 concentrations has been ascribed to warming through the effect on ocean mixing and ventilation, as well as the solubility of O_2 and its consumption by marine microbes (Sections 6.1.1.3, 6.3.3, 30.3.2.3, 30.5.7). This represents a key risk to ocean ecosystems (*medium confidence*; Figure 30-12 5,6,C). These changes increase the vulnerability of marine communities, especially those below the euphotic zone, to hypoxia and ultimately lead to a restriction of suitable habitat (*high confidence*; Figure 30-12 5). In the more extreme case, often exacerbated by the contribution of organic carbon from land-based sources, "dead zones" may form. Decreasing oxygen, consequently, is *very likely* to increase the vulnerability of fisheries and aquaculture (*medium confidence*; Figure 30-12 C), and consequently puts livelihoods at risk, particularly in EBUE (e.g., California and Humboldt Current ecosystems; Section 30.5.5), SES (e.g., Baltic and Black Seas; Section 30.5.3), and CBS (e.g., Gulf of Mexico, northeast Indian Ocean; Sections 30.3.2.3, 30.5.4). It is *very likely* that the warming of surface waters has also increased the stratification of the upper ocean by about 4% between 0 and 200 m from 1971 to 2010 in all oceans north of about 40°S. In many cases, there is significant adaptation opportunity to reduce hypoxia locally by reducing the flow of organic carbon, hence microbial activity, within these coastal systems (Section 30.5.4). Relocating fishing effort, and modifying procedures associated with industries such as aquaculture, may offer some opportunity to adapt to these changes (*likely*). Declining O_2 concentrations are *likely* to have significant impacts on DS habitats, where organisms are relatively sensitive to environmental changes of this nature owing to the very constant conditions under which they have evolved (Section 30.5.7).

Ocean acidification has increased the vulnerability of ocean ecosystems by affecting key aspects of the physiology and ecology of marine organisms (particularly in CBS, STG, and SES; Section 6.3.2; Table 30-3; Box CC-OA). Decreasing pH and carbonate ion concentrations reduce the ability of marine organisms to produce shells and skeletons, and may interfere with a range of biological processes such as reproduction, gas exchange, metabolism, navigation ability, and neural function in a broad range of marine organisms that show minor to major influences of ocean acidification on their biology (Sections 6.3.2, 30.3.2.2; Box CC-OA). Natural variability in ocean pH can interact with ocean acidification to create damaging periods of extremes (i.e., high CO_2, low O_2 and pH), which can have a strong effect on coastal activities such as aquaculture (*medium confidence*; Section 6.2; Figure 30-12 A; Box CC-UP). There may be opportunity to adapt aquaculture to increasingly acidic conditions by monitoring natural variability and restricting water intake to periods of optimal conditions. Reducing other non-climate change or ocean acidification associated stresses also represents an opportunity to build greater ecological resilience against the impacts of changing ocean carbonate chemistry. Ocean acidification is also an emerging risk for DS habitats as CO_2 continues to penetrate the Ocean, although the impacts and adaptation options are poorly understood and explored. Ocean acidification has heightened importance for some groups of organisms and ecosystems (Box CC-OA). In ecosystems that are heavily dependent on the accumulation of calcium carbonate over time (e.g., coral reefs, *Halimeda* beds), increasing ocean acidification puts at risk ecosystems services that are critical for hundreds of thousands of marine species, plus people and industries, particularly within CBS, STG, and SES (*high confidence*). Further risks may emerge from the non-linear interaction of different factors (e.g., increasing ocean temperature may amplify effects of ocean acidification, and vice versa) and via the interaction of local stressors with climate change (e.g., interacting changes may lead to greater ecosystems disturbances than each impact on its own). There is an urgent need to understand these types of interactions and impacts, especially given the long time it will take to return ocean ecosystems to preindustrial pH and carbonate chemistry (i.e., tens of thousands of years (FAQ 30.1) should CO_2 emissions continue at the current rate).

It is *very likely* that surface warming has increased stratification of the upper ocean, contributing to the decrease in O_2 along with the temperature-related decreases in oxygen solubility (WGI AR5 Section 3.8.3). Changes to wind speed, wave height, and storm intensity influence the location and rate of mixing within the upper layers of the Ocean and hence the concentration of inorganic nutrients (e.g., in EBUE, EUS; Figure 30-12 1,3). These changes to ocean structure increase the risks and vulnerability of food webs within the Ocean. However, our understanding of how primary productivity is going to change in a warming and more acidified ocean is limited, as is our understanding of how upwelling will respond to changing surface wind as the world continues to warm (Boxes CC-PP, CC-UP). As already discussed, these types of changes can have implications for the supply of O_2 into the Ocean and the upward transport of inorganic nutrients to the euphotic zone. Although our understanding is limited, there is significant potential for regional increases in wind speed to result in greater rates of upwelling and the supply of inorganic nutrients to the photic zone. Although this may increase productivity of phytoplankton communities and associated fisheries, greater rates of upwelling can increase the risk of hypoxic conditions developing at depth as excess primary production sinks into the Ocean and stimulates microbial activity at depth (Sections 6.1.1.3, 30.3.2.3, 30.5.5; Table 30-3). Changes in storm intensity may increase the risk of damage to shipping and industrial infrastructure, which increases the risk of accidents and delays to the transport of products between countries, security operations, and the extraction of minerals from coastal and oceanic areas (Section 30.6.2; IPCC, 2012).

Frequently Asked Questions

FAQ 30.5 | How can we use non-climate factors to manage climate change impacts on the oceans?

The Ocean is exposed to a range of stresses that may or may not be related to climate change. Human activities can result in pollution, eutrophication (too many nutrients), habitat destruction, invasive species, destructive fishing, and over-exploitation of marine resources. Sometimes, these activities can increase the impacts of climate change, although they can, in a few circumstances, dampen the effects as well. Understanding how these factors interact with climate change and ocean acidification is important in its own right. However, reducing the impact of these non-climate factors may reduce the overall rate of change within ocean ecosystems. Building ecological resilience through ecosystem-based approaches to the management of the marine environment, for example, may pay dividends in terms of reducing and delaying the effects of climate change (*high confidence*).

The proliferation of key risks and vulnerabilities to the goods and services provided by ocean ecosystems as a result of ocean warming and acidification generate a number of key risks for the citizens of almost every nation. Risks to food security and livelihoods are expected to increase over time, aggravating poverty and inequity (Table 30-3). As these problems increase, regional security is likely to deteriorate as disputes over resources increase, along with increasing insecurity of food and nutrition (Sections 12.4-6, 29.3.3, 30.6.5; Table 30-3; IPCC, 2012).

30.7.2. Global Frameworks for Decision Making

Global frameworks for decision making are central to management of vulnerability and risk at the scale and complexity of the world's oceans. General frameworks and conventions for policy development and decision making within oceanic and coastal regions are important in terms of the management of stressors not directly due to ocean warming or acidification, but that may influence the outcome of these two factors. Tables 30-3 and 30-4 outline a further set of challenges arising from multiple interacting stressors, as well as potential risks and vulnerabilities, ramifications, and adaptation options. In the latter case, examples of potential global frameworks and initiatives for beginning and managing these adaptation options are described. These frameworks represent opportunities for global cooperation and the development of international, regional, and national policy responses to the challenges posed by the changing ocean (Kenchington and Warner, 2012; Tsamenyi and Hanich, 2012; Warner and Schofield, 2012).

The United Nations Convention on the Law of the Sea (UNCLOS) was a major outcome of the third UN Conference on the Law of the Sea (UNCLOS III). The European Union and 164 countries have joined in the

Table 30-4 | Ramifications, adaptation options, and frameworks for decision making for ocean regions. Symbols for primary drivers: IC = ice cover; NU = nutrient concentration; OA = ocean acidification; SLR = sea level rise; SS = storm strength; T = sea temperature (↑ = increased; ↓ = decreased; * = uncertain).

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key references and chapter sections
↑T, ↑OA	Spatial and temporal variation in primary productivity (*medium confidence* at global scales; Box CC-PP)	Reduced fisheries production impacts important sources of income to some countries while others may see increased productivity (e.g., as tuna stocks shift eastwards in the Pacific) (*medium confidence*).	Reduced national income, increased unemployment, plus increase in poverty. Potential increase in disputes over national ownership of key fishery resources (*likely*)	Increased international cooperation over key fisheries. Improved understanding of linkages between ocean productivity, recruitment, and fisheries stock levels. Implementation of the regional "vessel day scheme" provides social and economic incentives to fisheries and fishers for adaptation.	UNCLOS, PEMSEA, CTI, RFMO agreements, UNSFSA	Bell et al. (2011, 2013a); Tsamenyi and Hanich (2012); Sections 6.4.1, 6.5.3, 30.6.2.1, 30.7.2; Box CC-PP
↑T, ↑OA	Ecosystem regime shifts (e.g., coral to algal reefs; structural shifts in phytoplankton communities) (*medium confidence*)	Reduced fisheries production of coastal habitats and ecosystems such as coral reefs (*medium confidence*).	Decreased food and employment security and human migration away from coastal zone (*likely*)	Strengthen coastal zone management to reduce contributing stressors (e.g., coastal pollution, over-harvesting, and physical damage to coastal resources). Promote Blue Carbon[a] initiatives.	PEMSEA, CTI, PACC, MARPOL, UNHCR, CBD, International Organization for Migration, Global Environment Facility, International Labor Organization	Bell et al. (2013a); Sections 5.4.3, 6.3.1–2, 12.4, 29.3.1, 29.3.3, 30.5.2–4, 30.5.6, 30.6.1, 30.6.2.1; Box CC-CR
		Tourist appeal of coastal assets decreases as ecosystems change to less "desirable" state, reducing income to some countries (*low confidence*).	Increased levels of coastal poverty in some countries as tourist income decreases (*likely*)	As above, strengthen coastal zone management and reduce additional stressors on tourist sites; implement education programs and awareness among visitors. Diversify tourism activities.	CBD, PEMSEA, CTI, PACC, UNHCR, MARPOL	Kenchington and Warner (2012); Sections 5.5.4.1, 6.4.1–2, 10.6, 30.6.2.2
		Increased risk of some diseases (e.g., ciguatera, harmful algal blooms) as temperatures increase shift and ecosystems shift away from coral dominance (*low confidence*).	Increased disease and mortality; decreases in coastal food resources and fisheries income (*likely*)	Increase monitoring and education surrounding key risks (e.g., ciguatera); develop alternate fisheries and income for periods when disease incidence increases, and develop or update health response plans.	National policy strategies and regional cooperation needed	Llewellyn (2010); Sections 6.4.2.3, 10.6, 29.3.3.2, 29.5.3, 30.6.3
		Increased poverty and dislocation of coastal people (particularly in the tropics) as coastal resources such as fisheries degrade (*medium confidence*)	Increased population pressure on migration destinations (e.g., large regional cities), and reduced freedom to navigate in some areas (as criminal activity increases) (*likely*)	Develop alternative industries and income for affected coastal people. Strengthen coastal security both nationally and across regions. Increase cooperation over handling of criminal activities.	UNCLOS, PEMSEA, CTI, International Ship and Port Facility Security, IMO, Bali Process, Association of Southeast Asian Nations MLA Treaty and bilateral extradition and MLA agreements	Kaye (2012); Rahman (2012); Sections 12.4–6,29.3.3, 29.6.2, 30.6.5

Continued next page →

[a] Blue Carbon initiatives include conservation and restoration of mangroves, saltmarsh, and seagrass beds as carbon sinks (Section 30.6.1).

Notes: CBD = Convention on Biological Diversity; CTI = Coral Triangle Initiative; IHO = International Hydrographic Organization; IOM = International Organization of Migration; ISPS = International Ship and Port Facility Security; MARPOL = International Convention for the Prevention of Pollution From Ships; MLA = mutual legal assistance; PACC = Pacific Adaptation to Climate Change Project; PEMSEA = Partnerships in Environmental Management for the Seas of East Asia; RFMO = Regional Fisheries Management Organizations; UNCLOS = United Nations Convention on the Law of the Sea; UNHCR = United Nations High Commissioner for Refugees; UNSFSA = United Nations Straddling Fish Stocks Agreement.

Table 30-4 (continued)

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key references and chapter sections
↑T	Migration of organisms and ecosystems to higher latitudes (*high confidence*)	Reorganization of commercial fish stocks and ecological regime shifts (*medium to high confidence*)	Social and economic disruption (*very likely*)	Increase international cooperation and improve understanding of regime changes; implement early-detection monitoring of physical and biological variables and regional seasonal forecasting; include related uncertainties into fisheries management; provide social and economic incentives for industry.	UNCLOS, CBD, RFMO agreements, UNSFSA	Sections 7.4.2, 6.5, 30.5, 30.6.2.1; Box CC-MB
		Increase in abundance, growing season, and distributional extent of pests and fouling species (*medium confidence*)	Increased disease risk to aquaculture and fisheries. Income loss and increased operating and maintenance costs (*very likely*)	Increase environmental monitoring; promote technological advances to deal with pest and fouling organisms; increase vigilance and control related to biosecurity.	IMO, ballast water management, Anti- Fouling Convention	Sections 6.4.1.5, 7.3.2.4, 29.5.3–4, 30.6.2.1; Box CC-MB
		Threats to human health increase due to expansion of pathogen distribution to higher latitudes (*low confidence*)	Increased disease and mortality in some coastal communities (*likely*)	Reduce exposure through increased monitoring and education, adoption, or update of health response plans to outbreaks.	UNICEF, World Health Ogranization, IHOs, and national governments	Myers and Patz (2009); Sections 6.4.3, 10.8.2, 11.7, 29.3.3, 30.6.3; Box CC-MB
↑T, ↑NU, ↑OA*	Increased incidence of harmful algal blooms (*low confidence*)	Increased threats to ecosystems, fisheries, and human health (*medium confidence*)	Reduced supply of marine fish and shellfish and greater incidence of disease among some coastal communities (*likely*)	Provide early-detection monitoring and improve predictive models; provide education and adoption or update of health response plans.	CTI, PEMSEA, World Health Organization, MARPOL	Llewellyn (2010);, Sections 30.6.3, 11.7, 6.4.2.3
↑T	Increased precipitation as a result of intensified hydrological cycle in some coastal areas (*medium confidence*)	Increased freshwater, sediment, and nutrient flow into coastal areas; increase in number and severity of flood events (*medium to high confidence*)	Increasing damage to coastal reef systems with ecological regime shifts in many cases (*very likely*)	Improve management of catchment and coastal processes; expand riparian vegetation along creeks and rivers; improve agricultural retention of soils and nutrients.	CTI, PEMSEA, Secretariat of the Pacific Regional Environment Programme	Sections 3.4, 29.3.1, 30.5.4, 30.6.1
↑T	Changing weather patterns, storm frequency (*medium confidence*)	Increased risk of damage to infrastructure such as that involved in shipping and oil and gas exploration and extraction (*medium to low confidence*)	Increased damage and associated costs (*likely*)	Adjust infrastructure specifications, develop early-warning systems, and update emergency response plans to extreme events.	IMO	IPCC (2012); Sections 10.4.4, 29.3, 30.6.2.3–4
↑SLR, ↑SS	Increased wave exposure of coastal areas and increased sea level (*high confidence*)	Exposure of coastal infrastructure and communities to damage and inundation, increased coastal erosion (*high confidence*)	Increased costs to human towns and settlements, numbers of displaced people, and human migration (*very likely*)	Develop integrated coastal management that considers SLR in planning and decision making; increase understanding of the issues through education.	UNICEF, IHOs, and national governments	Warner (2012); Sections 5.5, 12.4.1, 29.5.1, 30.3.1.2, 30.6.5
		Inundation of coastal aquifers reduces water supplies and decreases coastal agricultural productivity (*high confidence*).	Reduced food and water security leads to increased coastal poverty, reduced food security, and migration (*very likely*).	Assist communities in finding alternatives for food and water, or assist in relocation of populations and agriculture from vulnerable areas.	UNICEF, IHOs, and national governments.	Warner (2012); Sections 5.4.3, 12.4.1, 29.3.2, 30.3.1.2
↑SLR	Risk of inundation and coastal erosion, especially in low-lying countries (*high confidence*)	UNCLOS-defined limits of maritime jurisdiction will contract as national baselines shift inland. Potential uncertainty increases in some areas with respect to the international boundaries to maritime jurisdiction (*high confidence*).	Lack of clarity increases, as do disputes over maritime limits and maritime jurisdiction. Some nations at risk of major losses to their territorial waters (*very likely*)	Seek resolution of "shifting national baselines" issue (retreat and redefinition, stabilization, or fixation of exclusive economic zones and other currently defined maritime jurisdiction limits).	UNCLOS	IPCC (2012); Schofield and Arsana (2012); Warner and Schofield (2012); Sections 5.5, 30.6.5
↑T, ↓IC	Loss of summer sea ice (*high confidence*)	Access to northern coasts of Canada, USA, and Russia increases security concerns (*high confidence*).	Potential for increased tension on different interpretations of access rights and boundaries (*likely to very likely*)	Seek early resolution of areas in dispute currently and in the future.	UNCLOS	Chapter 28
		New resources become available as ice retreats, increasing vulnerability of international borders in some cases (*medium confidence*).	Tensions over maritime claims and ownership of resources (*likely*)	Sort out international agreements.		

Convention. UNCLOS replaced earlier frameworks that were built around the "freedom of the seas" concept and that limited territorial rights to 3 nm off a coastline. UNCLOS provides a comprehensive framework for the legitimate use of the Ocean and its resources, including maritime zones, navigational rights, protection and preservation of the marine environment, fishing activities, marine scientific research, and mineral resource extraction from the seabed beyond national jurisdiction. The relationship between climate change and UNCLOS is not clear and depends on interpretation of key elements within the UNFCCC (United Nations Framework Convention for Climate Change) and Kyoto Protocol (Boyle, 2012). However, UNCLOS provides mechanisms to help structural adaptation in response to challenges posed by climate change. In a similar way, there is a wide range of other policy and legal frameworks that structure and enable responses to the outcomes of rapid anthropogenic climate change in the Ocean.

There are many existing international conventions and agreements that explicitly recognize climate change (Table 30-4). The UN Straddling Fish Stocks Agreement (UNSFSA) aims at enhancing international cooperation of fisheries resources, with an explicit understanding under Article 6 that management needs to take account "existing and predicted oceanic, environmental and socio-economic conditions" and to undertake "relevant research, including surveys of abundance, biomass surveys, hydro-acoustic surveys, research on environmental factors affecting stock abundance, and oceanographic and ecological studies" (UNSFSA, Annex 1, Article 3). International conventions such as these will become increasingly important as changes to the distribution and abundance of fisheries are modified by climate change and ocean acidification.

Global frameworks for decision making are increasingly important in the case of the Ocean, most of which falls outside national boundaries (Oude Elferink, 2012; Warner, 2012). Approximately 64% of the Ocean (40% of the Earth's surface) is outside EEZs and continental shelves of the world's nations (high seas and seabed beyond national jurisdiction). With rapidly increasing levels of exploitation, there are increasing calls for more effective decision frameworks aimed at regulating fishing and other activities (e.g., bio-prospecting) within these ocean "commons." These international frameworks will become increasingly valuable as nations respond to impacts on fisheries resources that stretch across national boundaries. One such example is the multilateral cooperation that was driven by President Yudhoyono of Indonesia in August 2007 and led to the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI), which involves region-wide (involving 6.8 million km^2 including 132,800 km of coastline) cooperation between the governments of Indonesia, Philippines, Malaysia, Papua New Guinea, the Solomon Islands, and Timor Leste on reversing the decline in coastal ecosystems such as coral reefs (Clifton, 2009; Hoegh-Guldberg et al., 2009; Veron et al., 2009). Partnerships, such as CTI, have the potential to provide key frameworks to address issues such as interaction between the over-exploitation of coastal fishing resources and the recovery of reefs from mass coral bleaching and mortality, and the implications of the movement of valuable fishery stocks beyond waters under national jurisdiction.

An initiative called the Global Partnership for Oceans set out to establish a global framework with which to share experience, resources, and expertise, as well as to engage governments, industry, civil, and public sector interests in both understanding and finding solutions to key issues such as overfishing, pollution, and habitat destruction (Hoegh-Guldberg et al., 2013). Similarly, the Areas Beyond National Jurisdiction (ABNJ, Global Environment Facility) Initiative has been established to promote the efficient, collaborative, and sustainable management of fisheries resources and biodiversity conservation across the Ocean.

Global partnerships are also essential for providing support to the many nations that often do not have the scientific or financial resources to solve the challenges that lie ahead (Busby, 2009; Mertz et al., 2009). In this regard, international networks and partnerships are particularly significant in terms of assisting nations in developing local adaptation solutions to their ocean resources. By sharing common experiences and strategies through global networks, nations have the chance to tap into a vast array of options with respect to responding to the negative consequences of climate change and ocean acidification on the world's ocean and coastal resources.

30.7.3. Emerging Issues, Data Gaps, and Research Needs

Although there has been an increase in the number of studies being undertaken to understand the physical, chemical, and biological changes within the Ocean in response to climate change and ocean acidification, the number of marine studies of ecological impacts and risks still lag behind terrestrial studies (Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013). Rectifying this gap should be a major international objective given the importance of the Ocean in terms of understanding and responding to future changes and consequences of ocean warming and acidification.

30.7.3.1. Changing Variability and Marine Impacts

Understanding the long-term variability of the Ocean is critically important in terms of the detection and attribution of changes to climate change (Sections 30.3, 30.5.8), but also in terms of the interaction between variability and anthropogenic climate change. Developing instrument systems that expand the spatial and temporal coverage of the Ocean and key processes will be critical to documenting and understanding its behavior under further increases in average global temperature and changes in the atmospheric concentration of CO_2. International collaborations such as the Argo network of oceanographic floats illustrate how international cooperation can rapidly improve our understanding of the physical behavior of the Ocean and will provide important insight into its long-term subsurface variability (Schofield et al., 2013).

30.7.3.2. Surface Wind, Storms, and Upwelling

Improving our understanding of the potential behavior of surface wind in a warming world is centrally important to our understanding of how upwelling will change in key regions (e.g., EUS, EBUE; Box CC-UP). Understanding these changes will provide important information for future fisheries management but will also illuminate the potential risks of intensified upwelling leading to hypoxia at depth and the potential expansion of "dead zones" (Sections 30.3.2, 30.5.2-4). Understanding surface wind in a warming climate will also yield important information on surface mixing as well as how surface wave height might also vary, improving our understanding of potential interactions in coastal areas between wind, waves, and SLR (Section 30.3.1). Given the importance of mixing and upwelling to the supply of inorganic nutrients to the surface layers of the ocean, understanding these important phenomena at the ocean-atmosphere interface will provide important insight into how ocean warming and acidification are likely to impact ecosystems, food webs, and ultimately important fisheries such as those found along the west coasts of Africa and the Americas.

30.7.3.3. Declining Oxygen Concentrations

The declining level of O_2 in the Ocean is an emerging issue of major importance (Section 30.3.2). Developing a better understanding of the role and temperature sensitivity of microbial systems in determining O_2 concentrations will enable a more coherent understanding of the changes and potential risks to marine ecosystems. Given the importance of microbial systems to the physical, chemical, and biological characteristics of the Ocean, it is extremely important that these systems receive greater focus, especially with regard to their response to ocean warming and acidification. This is particularly important for the DS (>1000 m), which is the most extensive habitat on the planet. In this respect, increasing our understanding of DS habitats and how they may be changing under the influence of climate change and ocean acidification is of great importance. Linkages between changes occurring in the surface layers and those associated with the DS are particularly important in light of our need to understand how rapidly changes are occurring and what the implications are for the metabolic activity and O_2 content of DS habitats.

30.7.3.4. Ocean Acidification

The rapid and largely unprecedented changes to ocean acidification represent an emerging issue given the central importance of pH and the concentration of ions such as carbonate in the biology of marine organisms (Box CC-OA). Despite the relatively short history of research on this issue, there are already a large number of laboratory and field studies that demonstrate a large range of effects across organisms, processes, and ecosystems. Key gaps (Gattuso et al., 2011) remain in our understanding of how ocean acidification will interact with other changes in the Ocean, and whether or not biological responses to ocean acidification are necessarily linear. The vulnerability of fishery species (e.g., molluscs) to ocean acidification represents an emerging issue, with a need for research to understand and develop strategies for fishery and aquaculture industries to minimize the impacts. Understanding of how carbonate structures such as coral reefs and *Halimeda* beds will respond to a rapidly acidifying ocean represents a key gap and research need, especially in understanding the rate at which consolidated carbonate structures and related habitats are likely to erode and dissolve. Interactions between ocean acidification, upwelling, and decreasing O_2 represent additional areas of concern and research. There is also a need to improve our understanding of the socioeconomic ramifications of ocean acidification (Turley and Boot, 2011; Hilmi et al., 2013).

30.7.3.5. Net Primary Productivity

Oceanic phytoplankton are responsible for approximately 50% of global net primary productivity. However, our understanding of how oceanic primary production is likely to change in a warmer and more acidified ocean is uncertain (Boxes CC-PP, CC-UP). Changes in net primary productivity will resonate through food webs and ultimately affect fisheries production. Given the central role that primary producers and their associated ecological processes play in ocean ecosystem functioning, the understanding of how net primary productivity is likely to vary at global and regional levels is improved (Sections 30.5.2, 30.5.5). At the same time, understanding how plankton communities will vary spatially and temporarily will be important in any attempt to understand how fish populations will fare in a warmer and more acidified ocean. The research challenge is to determine when and where net primary production is expected to change, coupled with research on adaptation strategies for coping with the changes to the global distribution of seafood procurement, management, and food security.

30.7.3.6. Movement of Marine Organisms and Ecosystems

Marine organisms are moving generally toward higher latitudes or deeper waters consistent with the expectation of a warming ocean. Our current understanding of which organisms and ecosystems are moving, ramifications for reorganization of ecosystems and communities, and the implications for nations is uncertain at best. Given the implications for fisheries, invasive species, and the spread of disease, it is imperative that our understanding of the movement of ecosystems is improved. Documentation of species' responses and a deeper understanding of the processes that lead to persistent range shifts, and a focus on the ecosystem, social, and economic implications of range shifts is an important research need.

30.7.3.7. Understanding Cumulative and Synergistic Impacts

Understanding cumulative and synergistic impacts is poorly developed for ocean systems. Much of our understanding has been built on experimental approaches that are focused on single stressors that respond gradually without interaction or impacts that accumulate over time (Table 30-3). Multifactorial experiments exploring the impact of combined variables (e.g., elevated temperature and acidification at the same time) will enable more realistic projections of the future to be established. Equally, developing a better understanding of how biological and ecological responses change in relation to key environmental variables should also be a goal of future research. In this regard, assumptions that responses are likely to be gradual and linear over time ultimately have little basis, yet are widespread within the scientific literature.

30.7.3.8. Reorganization of Ecosystems and Food Webs

The pervasive influence of ocean warming and acidification on the distribution, abundance, and function of organisms and processes has and will continue to drive the reorganization of ecosystems and food webs (*virtually certain*; Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013; Box CC-MB). One of the inevitable outcomes of differing tolerances and responses to climate change and ocean acidification is the development of novel assemblages of organisms in the near future. Such communities are likely to have no past or contemporary counterparts, and will consequently require new strategies for managing coastal areas and fisheries. Changes to a wide array of factors related or not related to climate change have the potential to drive extremely complex changes in community structure and, consequently, food web dynamics. Developing a greater capability for detecting and understanding these changes will be critical for future management of ocean and coastal resources.

30.7.3.9. Socio-ecological Resilience

Many communities depend on marine ecosystems for food and income yet our understanding of the consequences of environmental degradation is poor. For example, although there is *high confidence* that coral reefs will continue to deteriorate at current rates of climate change and ocean acidification (Gardner et al., 2003; Bruno and Selig, 2007; De'ath et al., 2012), there is relatively poor understanding of the implications for the hundreds of millions of people who depend on these important coastal ecosystems for food and livelihoods. Improving our understanding of how to reinforce socio-ecological resilience in communities affected by the deterioration of key coastal and oceanic ecosystems is central to developing effective adaptation responses to these growing challenges (Section 30.6, Tables 30-3, 30-4).

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Annexes

ANNEX I

Authors and Expert Reviewers

Algeria

Houria Djoudi, Center for International Forestry Research (CIFOR)

Argentina

Susana Beatriz Adamo, Columbia University
Osvaldo Canziani, Academia Argentina de Ciencias Ambientales
Anibal Eduardo Carbajo, Universidad Nacional de San Martín
Hector Ginzo, Academia Argentina de Ciencias Ambientales
Leonidas Osvaldo Girardin, Fundación Bariloche
Graciela Magrin, Instituto Nacional de Tecnología Agropecuaria
Juan Jose Neiff, National Scientific and Technical Research Council (CONICET) / Universidad Nacional del Nordeste
Olga Clorinda Penalba, Universidad de Buenos Aires
Rubén Piacentini, Institute of Physics, National University of Rosario / National Scientific and Technical Research Council (CONICET)
Miguel Angel Taboada, Instituto Nacional Tecnología Agropecuaria
Elda Tancredi, National University of Luján / International Human Dimensions Programme
María Isabel Travasso, Instituto Nacional de Tecnología Agropecuaria
Ernesto Viglizzo, National Institute for Agricultural Technology (INTA) / National Scientific and Technical Research Council (CONICET)
Alejandra Volpedo, University of Buenos Aires / National Scientific and Technical Research Council (CONICET)

Australia

Carolina Adler, Swiss Federal Institute of Technology (ETH) Zurich
Adrian Barnett, Queensland University of Technology
Jonathon Barnett, University of Melbourne
Paul Beggs, Macquarie University
Jensen Benedikte, Department of the Environment
Helen Berry, University of Canberra
Nick Bond, Griffith University
Sarah Boulter, National Climate Change Adaptation Research Facility, Griffith University
Kathryn Bowen, Australian National University
Cassandra Brooke, World Wildlife Fund International
Christopher J. Brown, University of Queensland
Stuart Bunn, Griffith University
Colin Butler, University of Canberra / National Centre for Epidemiology and Population Health, Australian National University
Andrew Campbell, Charles Darwin University
Lynda Chambers, Australian Bureau of Meteorology
Francis Chiew, Commonwealth Scientific and Industrial Research Organization
Hamish Clarke, The University of South Wales
Andrew Constable, Australian Antarctic Division
Carlos Corvalan, Pan America Health Organization / World Health Organization
Lisa Cowan, Department of Primary Industries
Jocelyn Davies, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Tom Davies, Edge Environment
Adam Davis, Manidis Roberts Pty Ltd
Keith Dear, Australian National University
Nega Debela, University of Tasmania
Stephen Dovers, Australian National University
Carlos M. Duarte, University of Western Australia / Spanish National Research Council
Kyla Finlay, Department of Primary Industries, Victoria
Elizabeth A. Fulton, Commonwealth Scientific and Industrial Research Organisation
Kirsty Galloway McLean, United Nations University-Institute of Advanced Studies
David George, Griffith University
Habiba Gitay, The World Bank
Sonia Graham, University of Melbourne
Donna Green, University of New South Wales
Don Gunasekera, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
John Handmer, Centre for Risk and Community Safety, RMIT University
Kevin Hennessy, Commonwealth Scientific and Industrial Research Organization
Beverley Henry, Queensland University of Technology
Bradley Hiller, The World Bank
Alistair Hobday, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Ove Hoegh-Guldberg, University of Queensland
Neil Holbrook, University of Tasmania
Mark Howden, Commonwealth Scientific and Industrial Research Organization (CSIRO)
Lesley Hughes, Macquarie University
Graeme Hugo, University of Adelaide
Sue Jackson, Griffith University
Benedikte Jensen, Department of Industry, Innovation, Climate Change, Science, Research and Tertiary Education
David Jones, Bureau of Meteorology
Roger N. Jones, Victoria University
David Karoly, University of Melbourne
Robert Kay, Adaptive Futures
Marie Keatley, University of Melbourne
Stuart Kent, University of Melbourne
Roger Kitching, Griffith University
Natasha Kuruppu, Institute for Sustainable Futures
Constance Lever-Tracy, Flinders University of South Australia
Stephan Lewandowsky, University of Western Australia
Janice Lough, Australian Institute of Marine Science
Margaret Loughnan, Monash University
Jo Luck, Plant Biosecurity Cooperative Research Centre
Cate Macinnis-Ng, University of Auckland
Thilak Mallawaarachchi, University of Queensland
Yiheyis Maru, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Jan McDonald, University of Tasmania
Melodie McGeoch, Monash University
Kathleen McInnes, Commonwealth Scientific and Industrial Research Organization Marine and Atmospheric Research
Roger McLean, University of New South Wales
Anthony McMichael, Australian National University, Professor Emeritus
Celia McMichael, La Trobe University
Judith McNeill, University of New England
Thomas Measham, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Ecosystem Sciences
Shahbaz Mehmood, Global Change Impact Studies Centre
Gary Meyers, Commonwealth Scientific and Industrial Research Organisation (CSIRO) Marine and Atmospheric Research
Kimberley Millers, University of Melbourne
Michael Miloshis, Charles Darwin University
Andrew Moore, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Colette Mortreux, University of Melbourne
Sharif Ahmed Mukul, The University of Queensland
Shahbaz Mushtaq, University of Southern Queensland
Steve Nicol, Australian Antarctic Division / Antarctic Climate and Ecosystems Cooperative Research Centre
Ian Noble, Consultant
Barbara Norman, University of Canberra / Australian National University
Robert Norton, International Plant Nutrition Institute
Mark Ooi, University of Wollongong
Jean Palutikof, Griffith University
Graeme Pearman, Monash University
Jonathan Pickering, Australian National University
Bob Pokrant, Curtin University
Elvira Poloczanska, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Marine and Atmospheric Research
Scott Power, Bureau of Meteorology
Joseph Reser, Griffith University
Thomas Reuter, University of Melbourne
Penny Reyenga, Department of Environment / Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Anthony J. Richardson, Commonwealth Scientific and Industrial Research Organization / University of Queensland
Lauren Rickards, University of Melbourne
David Rissik, Griffith University

Kevin Ronan, Central Queensland University
Helen Ross, University of Queensland
Neil Saintilan, Office of Environment and Heritage
David S. Schoeman, University of the Sunshine Coast
Sandra Schuster, Disaster Resilience and Climate Risk Consultant
Neville Smith, Bureau of Meteorology (Retired)
Timothy F. Smith, University of the Sunshine Coast
Leon Soste, Department of Primary Industries
Mark Stafford Smith, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Will Steffen, Australian National University
Roger Stone, University of Southern Queensland
Shilu Tong, Queensland University of Technology
Stephen Turton, James Cook University
Xiaoming Wang, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Elissa Waters, University of Melbourne
Bob Webb, Australian National University
Leanne Webb, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Barbara Weinecke, Australian Antarctic Division / Antarctic Climate and Ecosystems Cooperative Research Centre
Tony Weir, University of the South Pacific
Seth Westra, University of Adelaide
Penny Whetton, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Marine and Atmospheric Research
Nadine Elizabeth White, Southern Cross University
Russell Wise, Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Eric Woehler, University of Tasmania
Colin Woodroffe, University of Wollongong
Paul Woods, World Vision
Celeste Young, Victoria Institute of Strategic Economic Studies (VISES), Victoria University
Md Younus, School of the Environment, Flinders University / Adelaide University

Austria

Susanne Hanger, International Institute for Applied Systems Analysis
Stefan Kienberger, University of Salzburg
Reinhard Mechler, International Institute for Applied Systems Analysis / Vienna University of Economics
Anthony Patt, Swiss Federal Institute of Technology
Harald Pauli, Austrian Academy of Sciences
Klaus Radunsky, Umweltbundesamt GmbH
Peter Rauch, University of Natural Resources and Life Sciences, Vienna
Bernhard Riegl, Nova Southeastern University
Andreas Scheba, University of Manchester
Vegard Skirbekk, International Institute for Applied Systems Analysis (IIASA)

Bahamas

Adelle Thomas, College of the Bahamas

Bangladesh

Atiq Kainan Ahmed, Asian Disaster Preparedness Center (ADPC)
Ahsan Uddin Ahmed, Centre for Global Change (CGC)
Mozaharul Alam, United Nations Environment Programme
Rawshan Ara Begum, University Kebangsaan Malaysia (UKM)
Saleemul Huq, International Institute for Environment and Development (IIED) / International Centre for Climate Change and Development (ICCCAD)
Haseeb Irfanullah, Practical Action
A K M Saiful Islam, Bangladesh University of Engineering and Technology
Sharmind Neelormi, GenderCC-Women for Climate Justice
M. Monirul Qader Mirza, Environment Canada
Golam Sarwar, Bangladesh Unnayan Parishad (BUP)

Barbados

Leonard Nurse, University of the West Indies
Leisa Perch, United Nations Development Programme / World Centre for Sustainable Development (Centro Rio +)

Belgium

Johan Bogaert, Nature and Energy Policy Division, Flemish Government
Wouter Buytaert, Imperial College London
Collin Claire, Direction Generale de l'environnement
Joann de Zegher, Stanford University
Drieu Godefridi, Cogito
Rafiq Hamdi, Royal Meteorological Institute of Belgium
Jean Hugé, Ghent University
Pol Knops, Katholieke Universiteit Leuven
Suzanne Leroy, Brunei University
Philippe Marbaix, Université catholique de Louvain
Andrea Tilche, European Commission Directorate
Rafael Tuts, United Nations Human Settlements Programme (UN Habitat)
Jean-Pascal van Ypersele, Université catholique de Louvain (TECLIM)
Martine Vanderstraeten, Belgian Federal Science Policy Office
Eline Vanuytrecht, Katholieke Universiteit Leuven
Dirk Verschuren, Ghent University
Romain Weikmans, Universite Libre de Bruxelles
Patrick Willems, Katholieke Universiteit Leuven

Bolivia

Juan Hoffmaister, Ministry of Foreign Affairs

Botswana

Pauline Dube, University of Botswana
Wame Lucretia Hambira, University of Botswana

Brazil

Paulo Brando, Instituto de Pesquisa Ambiental da Amazônia (IPAM)
Marcos S. Buckeridge, University of Sao Paulo
Ulisses E. C. Confalonieri, Laboratório de Educação em Saúde e Ambiente / Centro de Pesquisas Rene Rachou / Oswaldo Cruz Foundation
Christiano de Campos, Petroleo Brasileiro SA
Amanda Pereira, de Souza,
Carolina Dubeux, Federal University of Rio de Janeiro-COPPE
Jose Gustavo Feres, Institute of Applied Economic Research
Felipe Ferreira, Ministry of External Relations, Brazil
José Marengo, Centro de Ciências do Sistema Terrestre (CCST) / Instituto Nacional de Pesquisas Espaciais (INPE)
Maria Muylaert de Araujo, Federal University of Rio de Janeiro
Carlos Nobre, Ministry of Science and Technology
Milton Nogueira da Silva, Climate Change Forum of Minas Gerais
Jean Pierre Ometto, National Institute for Space Research
Marcia Real, Universidade Federal Fluminense
Paulo Saldiva
Fabio R. Scarano, Conservation International / Universidade Federal do Rio de Janeiro
Maria Assunção Faus da Silva Dias, University of Sao Paulo
Roberto Teixeira Luz, Brazilian Geography and Statistics Institute (IBGE)
Andrea Young, State University of Campinas (UNICAMP)

Bulgaria

Emilia Pramova, Center for International Forestry Research (CIFOR)

Burkina Faso

Leopold Some, Centre National de la Recherche Scientifique Technologique
Dieudonné Pascal Yaka, Burkina Meteorological Authority / University of Ouagadougou

Cameroon

Calvin Atewamba, National Agency for Information and Communication
Michael Balinga, Center for International Forestry Research
Beckline Mukete, University of Buea
Johnson Ndi Nkem, United Nations Development Programme Cambodia
Precillia Ijang Tata epouse Ngome, Institute of Agricultural Research for Development

Canada

Robert Arnot, Natural Resources Canada
David Atkinson, University of Victoria

Fikret Berkes, University of Manitoba Natural Resources Institute
Pierre Bernier, Natural Resources Canada
Peter Berry, Health Canada
Mike Brklacich, Carleton University
Ross Brown, Environment Canada
Ian Burton, University of Toronto
Elizabeth Bush, Environment Canada
Christine Callihoo, Canadian Institute of Planners (CIP)
Campbell Campbell, Natural Resources Canada
Diane Chaumont, Ouranos
William Cheung, University of British Columbia
James Christian, Government of Canada
Ian Church, Canadian Foundation for Climate and Atmospheric Sciences / International Polar Year (IPY) Canada
J. Graham Cogley, Trent University
Stewart Cohen, Adaptation and Impacts Research, Environment Canada
Ashlee Cunsolo Willox, McGill University
Debra Davidson, University of Alberta
Ramon de Elia, Ouranos Consortium
Rob de Loë, University of Waterloo
Tom Deligiannis, University of Western Ontario
Andrew Derocher, University of Alberta
Narayan Dhital, Laval University
Antony Diamond, University of New Brunswick
Thea Dickinson, University of Toronto
Karen Dodds, Environment Canada
Simon Donner, University of British Columbia
Victoria Edge, Public Health Agency of Canada
Jason Edwards, Natural Resources Canada
Susan Evans, World Wildlife Fund-Canada
Richard Fernandes, Natural Resources Canada
Richard Arthur Fleming, Canadian Forest Service
Sean Fleming, Meteorological Service of Canada
Evan Fraser, University of Guelph / University of Leeds
Martin Gauthier, Natural Resources Canada
Martin Girardin, Natural Resources Canada
Blane Harvey, International Development Research Centre
Erica Head, Fisheries and Oceans Canada
Regine Hock, University of Alaska Fairbanks
Darwin Horning, University of British Columbia Okanagan
Carol Hunsberger, Institute of Social Studies
Craig Johnson, University of Guelph
Sanjay Khanna, Massey College in the University of Toronto
Paul Kovacs, Institute for Catastrophic Loss Reduction
Tajula Kulkarni, Aboriginal Affairs and Northern Development Canada
Caroline Larrivée, Ouranos
Liza Leclerc, Ouranos Consortium Incorporated
Donald Lemmen, Natural Resources Canada
Gita L. Ljubicic, Carleton University
Connie Lovejoy, Université Laval
Katie Lundy, Environment Canada
Nick Macaluso, Environment Canada
James MacLellan, University of New Brunswick
Bob Manteaw, Government of Alberta
Bonita McFarlane, Natural Resources Canada
Stewart M. McKinnell, North Pacific Marine Science Organization
Carrie Mitchell, International Development Research Centre (IDRC)
Pat Roy Mooney, Action Group on Erosion, Technology and Concentration (ETC Group)
Kathryn Moran, Ocean Networks Canada
Hugues Morand, Agriculture and Agri-Food Canada
Veronique Morin, Asian Institute of Technology
Linda Mortsch, Environment Canada
Trevor Murdock, Pacific Climate Impacts Consortium
Douglas Nakashima, United Nations Educational, Scientific and Cultural Organization (UNESCO)
Mary I. O'Connor, University of British Columbia
Nicholas Ogden, Public Health Agency of Canada
Dan F. Orcherton, Pacific Centre for Envionment and Sustainable Development (PaCE-SD)
Greg Oulahen, Institute for Catastrophic Loss Reduction
Stephen Parker, Public Health Agency of Canada
David Pearson, Laurentian University
R. Ian Perry, Fisheries and Oceans Canada
Ian Perry, University of British Columbia
David Price, Natural Resources Canada
Terry Prowse, Environment Canada / University of Victoria
Marie Raphoz, Ouranos, Consortium on Regional Climatology and Adaptation to Climate Change
Graham Reeder, College of the Atlantic
James D. Reist, Fisheries and Oceans Canada
Christian Reuten, RWDI Air Incorporated
David Sauchyn, University of Regina
Daniel Scott, University of Waterloo
Karin Simonson, Natural Resources Canada
Elizabeth Smalley, Transport Canada
Sharon Smith, Geological Survey of Canada
Carolyn Smyth, Natural Resources Canada
Dave Spittlehouse, Ministry of Forests, Lands and Natural Resource Operations, British Columbia
Dáithí Stone, University of Cape Town / Lawrence Berkeley National Laboratory
John Stone, Carleton University
Roger B. Street, United Kingdom Climate Impacts Programme
Liette Vasseur, Brock University
Elizabeth Walsh, Natural Resources Canada
Fiona Warren, Natural Resources Canada
Frank Whitney, Institute of Ocean Sciences
Andrew Wong, University of Waterloo
David Wright, University of Ottawa
Fred Wrona, Environment Canada
Kristina Yuzva, United Nations University Institute for Environment and Human Security (UNU-EHS)
Francis Zwiers, Pacific Climate Impacts Consortium / University of Victoria

Chile

Paulina Aldunce, University of Chile
Daniel Barrera, Ministry of Agriculture
Rene Garreaud
Maritza Jadrijevic, Ministry of Environment
Francisco Meza, Pontificia Universidad Catolica de Chile
Sebastian Vicuña, Pontificia Universidad Catolica de Chile

China

Rongshuo Cai, Third Institute of Oceanography, Chinese State Oceanic Administration
Yi Cai, National Marine Environmental Forecasting Center
Long Cao, Zhejiang University
Liqi Chen, The Third Institute of Oceanography, State Oceanic Administration
Minpeng Chen, Institution of Environment and Sustainable Development in Agriculture
Richard T. Corlett, Chinese Academy of Sciences
Xuefeng Cui, Beijing Normal University
Yongiian Ding, Cold and Arid Regions Environmental and Engineering Research Institute
Juqi Duan, National Climate Center, Chinese Meteorological Administration
David Dudgeon, University of Hong Kong
Ge Gao, National Climate Center, China Meteorological Administration
Qingxian Gao, Chinese Research Academy of Environmental Sciences
Qingzhu Gao, Institute of Environment and Sustainable Development in Agriculture
Jie Guo, China Academy of Transportation Sciences
Shiyi Guo, China Center for Information Industry Development
He Qing Huang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences
Jikun Huang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences
Tong Jiang, China Meteorological Administration
Zhongcheng Jiang, Institute of Karst Geology, Chinese Academy of Geological Sciences
Cao Jianting, General Institute of Water Resources and Hydropower Planning (GIWP), Ministry of Water Resources

Yinhong Jin, Chinese Center for Disease Control and Prevention
Yinlong Jin, Institute of Environmental Health and Related Products Safety, Chinese Center for Disease Control and Prevention
Sai-ming Lee, Hong Kong Observatory
Bingrui Li, Polar Research Institute of China, State Oceanic Administration
Chaolun Li, Institute of Oceanology, Chinese Academy of Sciences
Maosong Li, Chinese Academy of Agricultural Sciences
Ning Li, Academy of Disaster Reduction and Emergency Management, Beijing Normal University
Tiantian Li, Chinese Center for Disease Control and Prevention
Wenjun Li, Beijing University
Xiucang Li, National Climate Center, China Meteorological Adiministration
Ying Li, National Climate Center, China Meteorological Adiministration
Yu'e Li, Chinese Academy of Agricultural Sciences
Erda Lin, Chinese Academy of Agricultural Sciences
Bo Liu, National Climate Center,China Meteorological Adiministration
Chunzen Liu, Ministry of Water Resources
Luliu Liu, National Climate Center,China Meteorological Adiministration
Qiyong Liu, National Institute for Communicable Disease Control and Prevention, Chinese Center for Disease Control and Prevention
Hualou Long, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS)
Qi Lu, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS)
Xianfu Lu, Asian Development Bank
Yong Luo, Qinghua University
Shiming Ma, Institute of Environment and Sustainable Development in Agriculture
Shiguang Miao, Institute of Urban Meteorology, China Meteorological Administration
Xingguo Mo, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS)
Lin Mou, State Oceanic Administration of China, National Marine Data and Information Service
Genxing Pan, Nanjing Agricultural University
Jiahua Pan, Chinese Academy of Social Sciences
Xiaosheng Qin, Nanyang Technological University
Jiansheng Qu, Data Center for Resources and Environmental Sciences, Chinese Academy of Science (CAS)
Chao Ren, The Chinese University of Hong Kong
Guoyu Ren, National Climate Center
Lianchun Song, National Climate Center, China Meteorological Administration
Yanling Song, China Meteorological Administration
Buda Su, China Meteorological Administration
Jianguo Tan, Shanghai Meteorological Institute
Fulu Tao, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS)
Chunfeng Wang, State Forestry Administration
Chunsheng Wang, Second Institute of Oceanography, Chinese State Oceanic Administration
Guoqing Wang, Nanjing Hydraulic Research Institute
Jinxia Wang, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS)
Xiao-Ling Wang, National Climate Center, China Meteorological Administration
Jian Guo Wu, Chinese Academy of Environmental Sciences
Shaohong Wu, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences
Chaozong Xia, Academy of Forest Inventory and Planning
Jun Xia, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Science (CAS)
Liyong Xie, Shenyang Agricultural University
He Xu, College of Environmental Science and Engineering, Nankai University
Hongmei Xu, National Climate Center, China Meteorological Administration
Yinlong Xu, Institute of Environment and Sustainable Development in Agriculture (IEDA), Chinese Academy of Agricultural Sciences (CAAS)
Denghua Yan, China Institute of Water Resources and Hydropower Research
Luhui Yan, Tanzuji
Xiangjun Yao, Food and Agriculture Organization of the United Nations (FAO)
Siyuan Ye, Qingdao Institute of Marine Geology
Songcai You, Chinese Academy of Agricultural Sciences
Rita Yu, Tyndall Centre for Climate Change Research, University of East Anglia
Tianshan Zha, Beijing Forestry University
Feng Zhang, Ministry of Housing and Urban-Rural Development
Fengchun Zhang, Foreign Economic Cooperation Office, Ministry of Environmental Protection
Guobin Zhang, State Forestry Administration
Jianyun Zhang, Nanjing Institute of Water Resources and Hydropower Research
Jinliang Zhang, Chinese Research Academy of Environmental Sciences
Rui Zhang, Xiamen University
Xiaochun Zhang, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences
Yingnan Zhang, National Center for Food Safety Risk Assessment
Zhibin Zhang, Institute of Zoology, Chinese Academy of Sciences
Zong-Ci Zhao, National Climate Center
Dawei Zheng, China Agricultural University
Yan Zheng, Chinese Academy of Social Sciences (CASS)
Xiaonong Zhou, National Institute of Parasitic Diseases, Chinese Center for Disease Control and Prevention
Liucai Zhu, Ministry of Environmental Protection
Xiaojin Zhu, National Climate Center
Juncheng Zuo, Hohai University

Colombia

Angela Andrade, Conservation International
Omar-Dario Cardona, Universidad Nacional de Colombia, Instituto de Estudios Ambientales (IDEA)
Jason Garcia-Portilla, University of Sussex
Juanita Gonzalez Lamus, Institute of Hydrology Meteorology and Environmental Studies of Colombia (IDEAM)
Juan David Gutiérrez, Universidad de Santander
José Daniel Pabón-Caicedo, Universidad Nacional de Colombia
Germán Poveda, Department of Geosciences and Environment, Universidad Nacional de Colombia
Carmenza Robledo Abad, HELVETAS Swiss Intercooperation
Marcela Tarazona, Oxford Policy Management
Jorge Julian Velez, Universidad Nacional de Colombia Sede Manizales
Walter Vergara, Inter-American Development Bank (IDB)

Costa Rica

Eric Alfaro
Oscar Calvo-Solano, Center for Geophysical Research
Maximiliano Campos, Organization of American States
Hugo Hidalgo, Universidad de Costa Rica
Juan Hoffmaister, Third World Network
Sergio Mora Castro, Independent Consultant

Cuba

Cristobal Diaz Morejon, Ministry of Science, Technology and the Environment
Avelino G. Suarez, Institute of Ecology and Systematic, Cuban Environmental Agency

Cyprus

Polyxeni Loizidou, AKTI Project and Research Centre

Czech Republic

Sarka Blazkova, T.G. Masaryk Water Research Institute
Radim Tolasz, Czech Hydrometeorological Institute

Democratic Republic of the Congo

A. K. Sanga-Ngoie, Ritsumeikan Asia Pacific University

Denmark

Niels Aagaard, Danish Building Research Institute
Claus Beier, Technical University of Denmark
Keith Brander, Technical University of Denmark
Tina Christensen, Danish Meteorological Institute
Denisa Cupi, Technical University of Denmark
Ole Faergeman, Aarhus University Hospital
Louise Grøndahl, Danish Nature Agency

Teunis Jansen, National Institute of Aquatic Resources, Technical University of Denmark
Anne Mette Jørgensen, Centre Danish Meteorological
Jonas Nielsen, Copenhagen University
Anne Olhoff, UNEP Risø Centre on Energy, Climate and Sustainable Development
Morten S. Olsen, Danish Energy Agency
John R. Porter, University of Copenhagen
Bent Sorensen, Roskilde University
Per Sørensen, Danish Coastal Authority
Hans Dencker Thulstrup, United Nations Educational, Scientific and Cultural Organization (UNESCO)

Ecuador
Maria Jose Galarza, Ministerio del Ambiente del Ecuador

Egypt
Sherif Abdelrahim, IPCC National Focal Point
Mohamed Abdrabo, Institute of Graduate Studies and Research, University of Alexandria
Tamer Afifi, United Nations University Institute for Environment and Human Security
Ibrahim Elshinnawy, National Water Research Center
Mounir Wahba Labib, Third National Communication (TNC) Project
Amal Saad-Hussein, National Research Center
Mohamed Tawfic Ahmed, Suez Canal University

Ethiopia
Girmaw Bogale, United Nations Economic Commission for Africa
Berhane Grum, Mekelle University
Hussen Seid, University of Cape Town

Fiji
Anirudh Singh, University of the South Pacific
Arthur Webb, Ocean and Islands Programme, SOPAC Division / Secretariat of the Pacific Community (SPC)

Finland
Miimu Airaksinen, VTT Technical Research Centre of Finland
Timothy R. Carter, Finnish Environment Institute
Majella Clarke, Forestry and Climate Change, Indufor
Linda Ekholm, Ministry for Foreign Affairs
Bruce C. Forbes, Arctic Centre, University of Lapland
Simo Haanpää , Aalto University
Kaija Hakala, MTT Agrifood Research Finland
Mikko Halonen, Gaia Consulting Oy
Antti Hannukkala, Agrifood Research Finland
Asko Hannukkala, MTT Agrifood Research Finland
Pirkko Heikinheimo, Ministry of the Environment
Jani Heino, Finnish Environment Institute
Anni Huhtala, Government Institute for Economic Research
Kari Hyytiäinen, MTT Agrifood Research Finland
Jatta Jämsén, Ministry for Foreign Affairs
Sirkku Juhola, Aalto University
Helena Kahiluoto, MTT Agrifood Research Finland
Jaana Kaipainen, Ministry of Agriculture and Forestry
Susanna Kankaanpää, Helsinki Region Environmental Services Authority (HSY)
Anne Kasurinen, University of Eastern Finland
Marjut Kaukolehto, University of Helsinki
Pekka Lauri, International Institute for Applied Systems Analysis
Heikki Lehtonen, MTT Agrifood Research
Markus Lindner, European Forest Institute
Sanna Luhtala, Finnish Meteorological Institute
Johanna Mustelin, Griffith University
Matti Nummelin, Ministry for Foreign Affairs
Jouni Paavola, University of Leeds
Juha Pekkanen, National Institute for Health
Paula Perälä, Ministry of the Environment
Nina Pirttioja, Finnish Environment Institute
Jouni Räisänen, University of Helsinki
Katri Rankinen, Finnish Environment Institute
Hannu Rintamäki, Finnish Institute of Occupational Health
Philipp Schmidt-Thomé, Geological Survey of Finland
Hanne Siikavirta, The Ministry of Employment and the Economy
Kimmo Silvo, Finnish Environment Institute
John Sumelius, University of Helsinki, Faculty of Agriculture and Forestry
Monica Tennberg, University of Lapland
Heikki Tuomenvirta, Finnish Meteorological Institute
Anne Vehviläinen, Ministry of Agriculture and Forestry

France
Fabien Anthelme
Audrey Baills, Bureau of Geological and Mining Research (BRGM)
Pierre Batteau, Aix Marseille Université
Gregory Beaugrand, Centre National de la Recherche Scientifique
Celine Bellard, Université Paris-Sud
Nicolas Beriot, Ministry of Ecology and Sustainable Development
Etienne Berthier, Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS)
Arnaud Bertrand
Anne Blondlot, Ouranos
Olivier Boucher, Laboratoire de Météorologie Dynamique / National Centre for Scientific Research (CNRS)
Jean-Philipe Boulanger, Institut de Recherche pour le Développement
Chris Bowler, École normale supérieure
Nathalie Breda, French National Institute for Agricultural Research (INRA)
Cyril Caminade, University of Liverpool
Hélène Connor Lajambe, HELIO International
Franck Courchamp, Université Paris-Sud
Christophe Cudennec, Agrocampus Ouest
Philippe Cury
Nicolas Desramaut, Bureau of Geological and Mining Research (BRGM)
Patrice Dumas, Centre International de Recherche sur l'Environnement et le Développement (CIRED)
Virginie Duvat-Magnan, University of la Rochelle / National Centre for Scientific Research (CNRS)
Samuel Etienne, École pratique des hautes études (EPHE)
Evelyne Foerster, Bureau of Geological and Mining Research (BRGM)
Bernard Francou, Institut de Recherche pour le Développement (IRD) / Laboratoire d'étude des Transferts en Hydrologie et Environnement (LTHE)
JC Gaillard, The University of Auckland
Simon Gascoin, Centre National de la Recherche Scientifique (CNRS)
Jean-Pierre Gattuso, Centre National de la Recherche Scientifique (CNRS)
Joel Guiot, Centre National de la Recherche Scientifique (CNRS)
Stephane Hallegatte, The World Bank
Deborah Idier, Bureau of Geological and Mining Research (BRGM)
Stephanie Jenouvrier, Woods Hole Oceanographic Institution
Sylvie Joussaume, Laboratoire des Sciences du Climat et de l'Environnement
Zaneta Kubik, Paris Sorbonne University
Benoit Laignel, Université de Rouen
Annamaria Lammel, Université Paris 8
Mariene Laruelle, George Washington University
Goneri Le Cozannet, Bureau de Recherches Géologiques et Minières
Olivier Le Pape, Agrocampus Quest
Hervé Le Treut, Laboratoire de Météorologie Dynamique/ Institut Pierre Simon Laplace
Paul Leadley, Université Paris
Antoine Leblois, Centre International de Recherche sur l'Environnement et le Développement (CIRED)
Alexia Leseur, CDC Climat Research
Bruno Locatelli, Agricultural Research for Development (CIRAD) / Center for International Forestry Research (CIFOR)
Denis Loustau, French National Institute for Agricultural Research (INRA)
Philippe MacClenahan, Synergies Environnement
Eric Martin, Meteo-France Centre National de Recherches Meteorologiques
Timothee Ourbak, Ministere des Affaires Etrangeres
Chantal Pacteau, Groupement d'Interet Scientifique GIS-Climat
Martin Pecheux, Institut des Foraminifères Symbiotiques
Michel Petit, Conseil General de L'industrie, de L'energie et des Technologies (CGIET)

Josyane Ronchail, Laboratory of Oceanography and Climate
Bernard Seguin, Institut National de la Recherche Agronomique
Guillaume Simioni, French National Institute for Agricultural Research (INRA)
Jean-Francois Soussana, French National Institute for Agriculture, Food and Environment Research
Benjamin Sultan, Laboratoire LOCEAN
Jean-Philippe Vidal, Irstea
Vincent Viguié, Centre International de Recherche sur l'Environnement et le Développement

Germany

Rita Adrian, Leibniz-Institute of Freshwater Ecology and Inland Fisheries
Mariam Akhtar-Schuster, German Aerospace Center
Jürgen Alheit, University of Rostock
Jens Arle, German Federal Environment Agency
Claudia Bach, United Nations University Institute for Environment and Human Security
Ruth Badeberg, German Aerospace Center
Christoph Bals, Germanwatch
Armineh Barkhordarian, Institute of Coastal Research, Helmholtz-Zentrum Geesthacht
Roland Barthel, Helmholtz Centre for Environmental Research (UFZ)
Anne-Christine Becker, German Federal Agency for Nature Conservation
Nina Becker, Helmholtz Centre for Environmental Research (UFZ) / Overseas Development Institute (ODI)
Till Below, Competence Centre for Climate Change (GIZ)
Joern Birkmann, United Nations University, Institute for Environment and Human Security
Gisela Böhm, University of Bergen
Andreas Bolte, Johann Heinrich von Thuenen-Institute (vTI)
Angelika Brandt, University of Hamburg
Hans Gunter Brauch , Free University of Berlin
Michael Brzoska, University of Hamburg
Dim Coumou, Potsdam Institute for Climate Impact Research
Wolfgang Cramer, Potsdam Institute for Climate Impact Research (PIK) / Institut Méditerranéen de Biodiversité et d'Ecologie marine et continentale (IMBE)
Achim Daschkeit, German Federal Environment Agency
Petra Döll, Goethe University Frankfurt
Klaus Elsenack, Carl von Ossietzky University Oldenburg
Nilson Enno, German Federal Institute of Hydrology
Raffael Ernst, Senckenberg Natural History Collections Dresden
Rita Fabris, German Federal Environment Agency
Eberhard Faust, Munich Reinsurance Company
Simone Ruiz Fernandez, Allianz Climate Solutions
Annelie Fincke, Project Management Agency, German Aerospace Center
Wiltrud Fischer, German Aerospace Center
Thomas Fischer, University of Tuebingen
Martina Flörke, University of Kassel
Johannes Förster, Helmholtz Centre for Environmental Research (UFZ)
Joerg Friedrichs, University of Oxford
Stefan Fronzek, Finnish Environment Institute
Barbara Früh, German Weather Service
Hartmut Fuenfgeld, RMIT University
Ursula Fuentes-Hutfilter, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Hans-Martin Füssel, European Environment Agency
Ruhi Gandhi, Humboldt University
Matthias Garschagen, Institute for Environment and Human Security, United Nations University
Sebastian Gerland, Norwegian Polar Institute
Dieter Gerten, Potsdam Institute for Climate Impact Research
Nicole Glanemann, University of Hamburg
Inka Gnittke, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Stefan Greiving, Technical University of Dortmund
Hans-Peter Grossart, Leibniz Institute of Freshwater Ecology and Inland Fisheries
Torsten Grothmann, Carl von Ossietzky University of Oldenburg
Gerrit Hansen, Potsdam Institute for Climate Impact Research
Köthe Harald, Federal Ministry of Transport, Building and Urban Development
William Hare, Climate Analytics GmbH
Sven Harmeling, Germanwatch
Jochen Harnisch, KfW
Marek Harsdorff, International Labour Office (ILO)
Florian Hartig, Helmholtz Centre for Environmental Research (UFZ)
Clemens Haße, Federal Environment Agency
Heike Hebbinghaus, North-Rhine Westphalian State Agency for Nature, Environment and Consumer Protection
Gabriele C. Hegerl, University of Edinburgh
Hartmut Heinrich, Federal Maritime and Hydrographic Agency
Hermann Held, University of Hamburg
Andreas Hemp, University of Bayreuth
Susanne Hempen, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Clemens Heuson, Helmholtz Centre for Environmental Research (UFZ)
Thomas Hickler, Goethe University, Frankfurt
Jacquelinie Hilbert, Federal Environment Agency
Jochen Hinkel, Global Climate Forum (GCF)
Dirk Hoffmann, Bolivian Mountain Institute (BMI)
Dirk Hölscher, University of Göttingen
Anne Holsten, Potsdam Institute of Climate Impact Research
Britta Horstmann, German Development Institute
Wulf Hülsmann, Federal Environment Agency
Tobias Ide, Research Group Climate Change and Security
Björn Ingendahl, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Venugopalan Ittekkot, University of Bremen (Retired)
Daniela Jacob, Climate Service Center, Hamburg
Annelie Janz Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Andreas Kaeaeb, University of Oslo
Leonhard Kaehler, Carl von Ossietzky Universitat of Oldenburg
Uwe Kaminski, German Weather Service
Marcus Kaplan, German Development Institute
Karin Kartschall, Federal Environment Agency
Kur Christian Kersebaum, Leibniz Centre for Agricultural Landscape Research
Christina Koppe, German Meteorological Service
Meinolf Koßmann, German Weather Service
Werner Krauss, Institute for Coastal Research, Helmholtz Zentrum Geesthacht
Frank Kreienkamp, Climate and Environment Consulting Potsdam GmbH
Birgit Kuna, German Aerospace Center
Oliver Lah, Wuppertal Institute for Climate, Environment and Energy
Phan Thanh Lan, Humboldt University
Tracy Lane, International Hydropower Association (IHA)
Marcel Langner, Federal Environment Agency
Walter Leal, Hamburg University of Applied Sciences
Anja Mager, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Petra Mahrenholz, Federal Environment Agency
Cornelia Maier, Laboratoire de Océanographie de Villefranche sur Mer
Regina Maltry, Federal Ministry of Transport, Building and Urban Development
Cindy Mathan, Federal Environment Agency
Eva Franziska Matthies, Consultant
Wilhelm May, Danish Meteorological Institute
Bettina Menne, World Health Organization, Regional Office for Europe
Lena Menzel, Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research
Annette Menzel, Technical University of Munich
Andreas Meyer-Aurich, Leibniz-Institute for Agricultural Engineering Potsdam-Bornim
Jan Minx, WGIII Technical Support Unit
Fausto Mirabile, VDI Technologiezentrum GmbH
Lutz Morgenstern, Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Claudia Müller, German Aerospace Center
Jens Mundhenke, Federal Ministry of Economics and Technology
Christoph Oberlack, University of Freiburg
Daniel Osberghaus, Centre for European Economic Research (ZEW)
Frank Oskamp, Federal Ministry of Finance

Papasozomenou Ourania, Humboldt University
Claudia Pahl-Wostl, University of Osnabruck
Frank Paul, University of Zurich
Anna Pechan, University of Oldenburg
Juliane Petersen, Climate Service Centre, Helmholtz-Zentrum Geesthacht
Hans-O. Pörtner, Alfred-Wegener-Institute for Polar and Marine Research
Marco Puetz, Swiss Federal Institute for Forest, Snow and Landscape Research WSL
Christoph Rau, Federal Environment Agency
Christopher Reyer, Potsdam Institute for Climate Impact Research
Joachim Rock, Johann Heinrich von Thuenen-Institute, Federal Research Institute for Rural Areas, Forestry and Fisheries
Björn Rost, Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research
Reimund Rötter, MTT Agrifood Research Finland
Armin Sandhoevel, Allianz Climate Solutions
M. Satyanarayan, Ministry of Water Resources
Inke Schauser, Federal Environment Agency
Jürgen Scheffran, University of Hamburg
Torsten Schlurmann, Franzius-Institut for Hydraulic, Waterways and Coastal Engineering
Stefan Schneiderbauer, EURAC (European Academy)
Benjamin Schraven, German Development Institute
Hartmut Schug, VDI Technologiezentrum GmbH
Lena Schulte-Uebbing, Wageningen University and Research Centre
Sven Schulze, Hamburgisches WeltWirtschaftsInstitut (HWWI)
Susanne Schwan, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)
Reimund Schwarze, Helmholtz Leipzig
Luitgard Schwendenmann, University of Auckland
Josef Settele, Helmholtz Centre for Environmental Research
Diana Sietz, Wageningen University
Kreft Sönke, United Nations University Institute for Environmental and Human Security
Horst Steg, German Aerospace Center
Daniela Storch, Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research
Swenja Surminski, Grantham Research Institute on Climate Change and the Environment / London School of Economics and Political Science
Andreas Täuber, Federal Ministry of Food, Agriculture and Consumer Protection
Christiane Textor, German Aerospace Center
Klement Tockner, Leibniz Institute of Freshwater Ecology and Inland Fisheries
Petra van Rüth, Federal Environment Agency
Andreas Vetter, Federal Environment Agency
Thomaa Voigt, Federal Environment Agency
Gottfried von Gemmingen, Federal Ministry for Economic Cooperation and Development
Christoph von Stechow, WGIII Technical Support Unit
Hans von Storch, Helmholtz-Zentrum Geesthacht
Koko Warner, United Nations University Institute for Environment and Human Security
Christian Webersik, University of Agder
Juergen Weichselgartner, University of Kiel
Christian Wiencke, Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research
Florian Wieneke, KfW Development Bank
Marten Winter, Helmholtz Centre for Environmental Research (UFZ) / German Centre for Integrative Biodiversity Research (iDiv)
Astrid Wittmann, Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research
Tanja Wolf, World Health Organization Regional Office for Europe
Sabine Wurzler, North Rhine Westphalia State Environment Agency
Shelby Yamamoto, Heidelberg University
Winfried Zacher, Germanwatch
Peter Zeil, Center for Geoinformatics- Z_GIS, Salzburg University
Michael Zissener, United Nations University Institute for Environment and Human Security (UNU-EHS)
Johanna Wolf, Royal Roads University

Ghana

Ama Essel, Korle-Bu Teaching Hospital, University of Ghana Medical School

Greece

Kostas Balaras, Institute for Environmental Research and Sustainable Development, National Observatory of Athens
Constantinos Cartalis, University of Athens
Dimitri Damigos National Technical University of Athens
Danae Diakoulaki, National Technical University of Athens
Elena Georgopoulou, National Observatory of Athens
Klea Katsouyanni, University of Athens Medical School
Anastasios Kentarchos, European Commission DG-Research
Denia Kolokotsa, Technical University of Crete
Vally Koubi, University of Bern
Aristeidis Koutroulis, Technical University of Crete
Demetris Koutsoyiannis, National Technical University of Athens
Anastasios Legakis, University of Athens
Athanasios Loukas, University of Thessaly
Andreas Matzarakis, University of Freiburg
Dimitrios Melas, Aristotle University of Thessaloniki
Nikolaos Nikolaidis, Technical University of Crete
Matheos Santamouris, National University Athens
Yannis Sarafidis, National Observatory of Athens, Institute for Environmental Research and Sustainable Development
Dimitris Stathakis, University of Thessaly
Nikolaos Stilianakis, European Commission
Athanasios Vafeidis, University of Kiel
Despoina Vokou, Aristotle University of Thessaloniki
Prodromos Zanis, Aristotle University of Thessaloniki

Guatemala

Edwin Castellanos, Universidad del Valle de Guatemala

Hungary

Lukács Ákos, Ministry of National Development
Ferenc L. Tóth, International Atomic Energy Agency / Corvinus University

Iceland

Olafur S. Ástþórsson, Marine Research Institute
Halldor Bjornsson, Icelandic Meteorological Office
Tomas Jóhannessson, Icelandic Meteorological Office
Joan Nymand Larsen, Stefansson Arctic Institute
Jon Ólafsson, University of Iceland
Bjarni Sigurðsson, Agricultural University of Iceland

India

P.C. Abhilash, Banaras Hindu University
Pramod Aggarwal, CGIAR Research Program on Climate Change, Agriculture, and Food Security
Ashish Aggarwal, University of Manchester
Rais Akhtar, Aligarh Muslim University
Archis Ambulkar, Brinjac Engineering Incorporated
S. Attri, Indian Meteorological Department
Govindasamy Bala, Indian Institute of Science
Suruchi Bhadwal, The Energy and Resources Institute
Alka Bharat, M.A. National Institute of Technology
Shelley Bhattacharya, Visva Bharati University
Rita Chauhan, Jawaharial Nehru University
Purnamita Dasgupta, Institute of Economic Growth, University of Delhi Enclave
Susmita Dasgupta, The World Bank
Jitendra Desai, Reliance Industries Limited
Ramesh C. Dhiman, National Institute of Malaria Research (ICMR)
Navroz Dubash, Centre for Policy Research
Amit Garg, Indian Institute of Management, Ahmedabad
Himangana Gupta, Panjab University
Ahmad Hussain, Bihar State Electricity Board (Retired)
Manmohan Kapshe, Maulana Azad National Institute of Technology
Sanjiv Kumar, Center for Ocean-Land-Atmosphere Studies
B. Mohan Kumar, Indian Council of Agricultural Research
Surender Kumar, University of Delhi
Salvador Lyngdoh, Wildlife Institute of India
Ather Masoodi, Aligarh Muslim University

Manju Mohan, Indian Institute of Technology Delhi
Pradeep Mujumdar, Indian Institute of Science
Rupa Mukerji, HELVETAS Swiss Intercooperation
Indu Murthy, Indian Institute of Social Sciences
Malini Nair, Indiana Institute of Science
Sreeja Nair, Lee Kuan School of Public Policy, National University of Singapore
A.W. Naqvi, National Institute of Oceanography
Nandan Nawn, West Bengal National University of Juridical Sciences
Amrutasri Nori-Sarma, Indian Institute of Public Health
Sumetee Pahwa Gajjar, Indian Institute for Human Settlements (IIHS)
L.M.S. Palini, G.B. Institute of Himilayan Geology
Anand Patwardhan, Indian Institute of Technology Bombay
Zahoor Ahmad Pir, Government Girls Post Graduate College, Moti Tabela
S.V.R.K. Prabhakar, Institute of Global Environmental Studies (IGES), Tokyo
N.H. Ravindranath, Indian Institute of Social Sciences
Rajasree Ray, Department of Economic Affairs
Aromar Revi, Indian Institute for Human Settlements
S. Satapathy, Ministry of Environment and Forests
B.N. Satapathy, Planning Commission
Subodh Kumar Sharma, Ministry of Environment and Forests
C. Sharma, National Physical Laboratory
Aakash Shrivastava, National Centre for Disease Control, Ministry of Health and Family Welfare
Balwinder Singh, Pacific Northwest National Laboratory
Naresh Soora, Indian Institute of Agriculture Research
Akhilesh Surjan, Kyoto University
Renoj Thayyen, National Institute of Hydrology
A. Unnikrishnan, National Institute of Oceanography
B. Venkateshwarlu, Central Research Institute for Dryland Agriculture

Indonesia

Pramaditya Wicaksono, Universitas Gadjah Mada

Iran

Ali Reza Gohari, Isfahan University of Technology

Ireland

Margaret Desmond, Environmental Protection Agency
Alison Donnelly, Trinity College Dublin
Paul Egan, Trinity College Dublin
Patrick Goodman, Dublin Institute of Technology
Fion O'Connor, Met Office Hadley Centre
Clionadh Raleigh, Trinity College Dublin
John Sweeney, National University of Ireland Maynooth

Italy

Giovanni Bettini, Lund University
Andrea Bigano, Fondazione Eni Enrico Mattei
Marco Bindi, University of Florence
Laura Bonzanigo, Ca' Foscari University of Venice
Marco Borga, University of Padova
Francesco Bosello, University of Milan / Fondazione Eni Enrico Mattei
Lorenzo Carrera, Ca' Foscari University of Venice
Claudio Cassardo, University of Torino
Sergio Castellari, Centro Euro-Mediterraneo sui Cambiamenti Climatici / Istituto Nazionale di Geofisica e Vulcanologia (INGV)
Maria Vincenza Chiriacò, University of Tuscia
Paolo Ciavola, University of Ferrara
Luisa Cristini, University of Hawaii
Fabio Eboli, Fondazione Eni Enrico Mattei
Andre Filpa, Universita Roma Tre
Domenico Gaudioso, Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)
Valentina Giannini, Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
Francesca Giordano, Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)
Filippo Giorgi, Abdus Salam International Centre for Theoretical Physics
Carlo Giupponi, Università Ca' Foscari Venezia / Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
Georg Kaser, University of Innsbruck
Leslie Lipper, Food and Agriculture Organization of the United Nations
Andrea Milan, United Nations University Institute for Environment and Human Security
Luca Montanarella, European Commission-Joint Research Centre, Institute for Environment and Sustainability
Antonio Navarra, Centro Euro-Mediterranean Center for Climate Change
Simone Ombuen, Universita Roma Tre
Stefania Proietti, University of Perugia
Lorenzo Quaglietta, University of Rome
Carlo Rondinini, University of Rome
Cristina Sabbioni, Institute of Atmospheric Sciences and Climate, Italian National Research Council
Gianluca Sara, University of Palermo
Carlo Scaramella, World Food Programme (WFP)
Luciana Sinisi, Institute for Environmental Protection and Research
Donatella Spano, University of Sassari
Chiara Trabacchi, Ca' Foscari University of Venice
Riccardo Valentini, University of Tuscia and Euro-Mediterranean Center for Climate Change
Sara Venturini, Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)
Federico Viscarra, Ca' Foscari University of Venice
Marianne Zeyringer, European Commission, Joint Research Centre

Jamaica

David Dodman, International Institute for Environment and Development (IIED) / University College London
Clifford Mahlung, Meteorological Service

Japan

Sachiho Adachi, Japan Argency for Marine-Earth Science and Technology
Keigo Akimoto, Research Institute of Innovative Technology for the Earth (RITE)
Kenshi Baba, Center for Regional Research, Hosei University
Sanae Chiba, Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Mariko Fujimori, Pacific Consultants Company Ltd.
Kazuhiko Fukami, National Institute for Land and Infrastructure Management (NILIM) / Ministry of Land, Infrastructure, Transport and Tourism (MLIT)
Masayuki Hara, Japan Agency for Marine-Earth Science and Technology
Naomi Harada, Japan Agency for Marine-Earth Science and Technology
Masahiro Hashizume, Institute of Tropical Medicine, Nagasaki University
Ayami Hayashi, Research Institute of Innovative Technology for the Earth (RITE)
Yasuaki Hijioka, National Institute for Environmental Studies
Yukiko Hirabayashi, University of Tokyo
Yasushi Honda, University of Tsukuba
Toshichika Iizumi, National Institute for Agro-Environmental Sciences
Masahiko Isobe, University of Tokyo
Shin-ichi Ito, Fisheries Research Agency, Tohoku National Fisheries Research Institute
Shinjiro Kanae, Tokyo Institute of Technology
Hiromitsu Kanno, National Agricultural Research Center for Tohoku Region
Hiroyasu Kawai, Port and Airport Research Institute
Hajime Kayanne, University of Tokyo
So Kazama, Tohoku University
Akio Kitoh, University of Tsukuba
Yoshiyuki Kiyono, Forestry and Forest Products Research Institute (FFPRI)
Hiroaki Kondo, National Institute of Advanced Industrial Science and Technology (AIST)
Toshichika Lizumi, National Institute for Agro-Environmental Sciences
Toshihiko Masui, National Institute for Environmental Studies
Tetsuya Matsui, Forestry and Forest Products Research Institute
Nobuo Mimura, Ibaraki University
Tsuneyoshi Mochizuki, Japan River Association
Akihiko Murata, Japan Agency for Marine-Earth Science and Technology
Toshiyuki Nakaegawa, Meteorological Research Institute, Japan Meteorological Agency
Motoki Nishimori, National Institute for Agro-Environmental Sciences
Yukihiro Nojiri, Nationall Institute for Environmental Studies
Junichiro Oda, Research Institute of Innovative Technology for the Earth (RITE)
Taikan Oki, University of Tokyo
Norio Saito, Graduate School of Science and Engineering, Ibaraki University

Yoshiki Saito, National Institute of Advanced Industrial Science and Technology
Rajib Shaw, Kyoto University
Yoshiyuki Shimoda, Osaka University
Masato Sugi, Research Institute for Global Change (RIGC) / Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
Toshihiko Sugiura, National Agriculture and Food Research Organization
Taishi Sugiyama, Central Research Institute of Electric Power Industry
Kiyoshi Takahashi, National Institute for Environmental Studies
Kuniyoshi Takeuchi, International Centre for Water Hazard and Risk Management (ICHARM)
Kazuhiko Takeuchi, United Nations University
Masami Tamura, Ministry of Foreign Affairs of Japan
Tetsuji Tanaka, Towett Institute of Nutrition and Health, University of Aberdeen
Hasegawa Toshihiro, National Institute for Agro-Environmental Sciences
Ikutaro Tsuyama, Forestry and Forest Products Research Institute
Mitsutsune Yamaguchi, The University of Tokyo
Kazuya Yasuhara, Ibaraki University
Hiromune Yokoki, Ibaraki University

Kenya

Richard Anyah, University of Connecticut
Samwel Marigi, Kenya Meteorological Department
Margaret Mwangi, Pennsylvania State University
Maggie Opondo, University of Nairobi

Luxembourg

Andrew Ferrone, Public Research Centre-Gabriel Lippmann

Madagascar

Tatiana Arivelo, United Nations Economic Commission for Africa
Nimbol Raelinera, National Meteorological Office
Nirivololona Raholijao, National Meteorological Service
Marie-Louise Rakotondrafara, Madagascar National Weather Service

Malaysia

Hoy Yen Chan, National University of Malaysia
Joy Jacqueline Pereira, Universiti Kebangsaan Malaysia
Jennifer Rubis, United Nations Educational, Scientific and Cultural Organization (UNESCO)

Maldives

Amjad Abdulla, Ministry of Housing, Environment, and Energy
Mr./Ms. Zahid, Maldives Meteorological Service

Malta

Lino Pascal Briguglio, Islands and Small States Institute, University of Malta

Mauritania

Guéladio Cissé, Swiss Tropical and Public Health Institute

Mauritius

Premchand Coolaup, Mauritius Meteorological Services

Mexico

Fernando Aragón-Durand, Researcher and Independent Consultant
Clara Aranda, University of Cambridge
Marylin Bejarano, National Autonomous University of Mexico
Julio Campo Alves, Universidad Nacional Autónoma de México
Cecilia Conde, Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México
Pablo Del Monte-Luna, National Polytechnic Institute
Ana Elisa Peña del Valle Isla, Programa de Investigaciòn en Cambio Climático, Universidad Nacional Autónoma de México
Francisco Estrada Porrua, Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México
Ricardo Fuentes-Nieva, Oxfam Great Britain
Blanca E. Jiménez Cisneros, Universidad Nacional Autónoma de México / United Nations Educational, Scientific and Cultural Organization (UNESCO)
Salvador E. Lluch-Cota, Centro de Investigaciones Biológicas del Noroeste, S.C.
Alejandro Monterroso, Universidad Autonoma Chapingo
Ana Rosa Moreno, School of Medicine, Universidad Nacional Autónoma de México
Úrsula Oswald Spring, Universidad Nacional Autónoma de México
Ameyali Ramos Castillo, United Nations University Institute of Advanced Studies
Patricia Romero-Lankao, National Center for Atmospheric Research
Joseluis Samaniego, United Nations Economic Commission for Latin America and the Caribbean (ECLAC)
Landy Sánchez Peña, El Colegio de Mexico
Roberto A. Sanchez Rodriguez, El Colegio de la Frontera Norte
Ana Solorzano-Sanchez, Institute of Development Studies
Fabiola S. Sosa-Rodriguez, University of Waterloo
Lourdes Villers-Ruiz, Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México
Maria Eugenia Ibarraran Viniegra, Universidad Iberoamericana Puebla

Morocco

Karim Hilmi, Institut National de Recherche Halieutique
Abdellatif Khattabi, Ecole Nationale Forestiere d'Ingénieurs
Abdalah Mokssit, Direction de la Météorologie Nationale (DMN)

Namibia

Oliver C. Ruppel, University of Stellenbosch

Nepal

Tek Gurung, Consultant

New Caledonia

Johann Bell, Secretariat of the Pacific Community

New Zealand

Susanne Becken, Griffith University / Lincoln University
Robert Bell, National Institute of Water and Atmospheric Research (NIWA)
Paula Blackett, AgResearch
Chris Cameron, Wellington City Council
John Richard Campbell, University of Waikato
Louise Parsons Chini, University of Maryland
Daniel Collins, National Institute of Water and Atmospheric Research (NIWA)
Brad Field, GNS Science
Blair Fitzharris, University of Otago
Olia Glade, Ministry for the Environment
Bruce Glavovic, Massey University
Frances Graham, Ministry of Health
Vincent Gray, Climate Consultant
Simon Hales, University of Otago, Wellington
Garth Harmsworth, Landcare Research
John Hay, University of the South Pacific
Kate Hodgkinson, Ministry for the Environment
Sam Holmes, Ministry for the Environment
Darren King, National Institute of Water and Atmospheric Research (NIWA)
Miko Kirschbaum, Landcare Research
Tord Kjellstrom, Centre for Global Health Research, Umea University
Julie Knauf, Ministry for the Environment
Cliff Law, National Institute of Water and Atmospheric Research (NIWA)
Judy Lawrence, PS Consulting
Amanda Leathers, Ministry of Māori Development
Graeme Lindsay, School of Population Health, University of Auckland
Mary Livingston, Ministry for Primary Industries
Martin Richard Manning, Victoria University of Wellington
Henrik Moller, University of Otago
Paul Newton, AgResearch
Eric Pawson, University of Canterbury
Grant Pearce, Scion
Susan Peoples, AgResearch
Helen Plume, Ministry for the Environment
Andy Reisinger, New Zealand Agricultural Greenhouse Gas Research Centre
Alice Ryan, Ministry for the Environment
Bruce Harris Small, AgResearch Ltd
Inga Smith, University of Otago
Wayne Stephenson, University of Otago

Adolf Stroombergen, Infometrics
Frances Sullivan, Local Government New Zealand
Andrew Tait, National Institute of Water and Atmosphere
Ian Turney, Ministry of Business, Innovation and Employment
Alistair Woodward, University of Auckland
David Wratt, National Institute of Water and Atmospheric Research
Dan Zwartz, Ministry for the Environment
Philip W. Boyd, Institute of Marine and Antractic Studies (IMAS)

Nicaragua

Juanita Jergenal, Ministry of the Environment and Natural Resources

Niger

Dieudonne Goudou, High Commission of Niger Valley Development

Nigeria

Ibidun Adelekan, University of Ibadan
Julius Adewopo, University of Florida
Chineke Theo Chidiezie
Etim Essien, University of Uyo
Elochukwu Ezenekwe, Nnamdi Azikiwe University
Emiola Gbobaniyi, Centre for Atmospheric Research
Maruf Sanni, National Centre for Technology Management
Okoro Ugochukwu
Michael Uwagbae, Ambrose Alli University
Dike Victor

Norway

Maja Stade Aaronaes, Norwegian Directorate for Nature Management
Dag Lorents Aksnes, University of Bergen
Helene Amundsen, Centre for International Climate and Environmental Research (CICERO)
Claire Armstrong, Arctic University of Norway
Torgrim Asphjell, Climate and Pollution Agency
Tor A. Benjaminsen, Norwegian University of Life Sciences
Halvard Buhaug, Peace Research Institute Oslo
Anne Chapuis, Norwegian Environment Agency
Oyvind Christophersen, Norwegian Environment Agency
Linda Dalen, Norwegian Environment Agency
Halvor Dannevig, Western Norway Research Institute
Kenneth Drinkwater, Institute of Marine Research
Arne Eide, Norwegian College of Fishery Science, University of Tromsø
Siri Eriksen, Norwegian University of Life Sciences
Per Fjeldal, Climate and Pollution Agency
Jan Fuglestvedt, Centre for International Climate and
Alice Gaustad, Climate and Pollution Agency
Solveig Glomsrød, Centre for International Climate and Environmental Research (CICERO)
Håvard Haarstad, University of Bergen
Susanne Hanssen, Norwegian Directorate for Nature Management
Dag Hessen, University of Oslo
Hege Hisdal, Norwegian Water Resources and Energy Directorate
Grete K. Hovelsrud, Nordland Research Institute
Randi Ingvaldsen, Institute of Marine Research
Ketil Isaksen, Norwegian Meteorological Institute
Environmental Research (CICERO)
Vikram Kolmannskog, Norwegian Refugee Council
Kit Kovacs, Norwegian Polar Institute
Maria Malene Kvalevåg, Norwegian Environment Agency
Ole-Kristian Kvissel, Norwegian Environment Agency
Herdis Laupsa, Norwegian Environment Agency
Harold Leffertstra, Norwegian Environment Agency
Else Marie Løbersli, Norwegian Directorate for Nature Management
Harald Loeng, Institute of Marine Research / University of Tromsø
Torleif Markussen Lunde, University of Bergen
Andrei Marin, Norwegian University of Life Sciences
Svein Disch Mathiesen, International Centre for Reindeer Husbandry
Philip Mortensen, Norwegian Environment Agency
Lars Otto Naess, Institute of Development, University of Sussex
Stale Navrud, Norwegian University of Life Sciences
Robert Amos Ngwira, Norwegian University of Life Sciences
Birgit Njåstad, Norwegian Polar Institute
Karen O'Brien, University of Oslo
Ellen Øseth , Norwegian Polar Institute
Anders Oskal, International Centre for Reindeer Husbandry
Geir Ottersen, Institute of Marine Research
Åsa Pedersen, Norwegian Environment Agency
Riccardo Pravettoni, GRID-Arendal
Pål Prestrud, Centre for International Climate and Environmental Research (CICERO)
Gunnar Skotte, Norwegian Environment Agency
Birger Solberg, Norwegian University of Life Sciences
Asuncion Lera St. Clair, Centre for International Climate and Environmental Research (CICERO)
Svein Sundby, Institute of Marine Research
Linda Sygna, University of Oslo
Vigdis Vestreng, Climate and Pollution Agency
Amanda Villaruel, Norwegian Water Directorate
Cecilie von Quillfeldt, Norwegian Polar Institute
Anna von Streng Velken, Norwegian Environment Agency
Dag Vongraven, Norwegian Polar Institute

Pakistan

Muhammad Adnan, Ministry of Climate Change
Ghazanfar Ali, Global Change Impact Studies Centre (GCISC)
Muhammad Amjad, Global Change Impact Studies Centre (GCISC)
Javeria Ashraf, Global Change Impact Studies Centre (GCISC)
Sobiah Becker, Munich Climate Insurance Initiative, United Nations University
Qamar uz Zaman Chaudhry, Ministry of Climate Change Government of Pakistan
Arif Goheer, Global Change Impact Studies Centre (GCISC)
Muhammad Zia ur Rahman Hashmi, Global Change Impact Studies Centre (GCISC)
Muhammad Mohsin Iqbal, Global Change Impact Studies Centre (GCISC)
Naeem Manzoor, Global Change Impact Studies Centre (GCISC)
Muhammad Munir Sheikh, Global Change Impact Studies Centre (GCISC)

Panama

José Fábrega, Universidad Tecnológica de Panamá
Emilio Messina, Panama Canal Authority
Casilda Saavedra, Technological University of Panama

Peru

Wilfredo Bulege-Gutiérrez, Universidad Continental
Eduardo Calvo, Universidad Nacional Mayor de San Marcos
Jhan Caro Espinoza, Instituto Geofísico del Perú (IGP)
Catherine Mariela Coronado Leon, Universidad Cientifica del Sur
Ken Takahashi, Instituto Geofísico del Perú

Philippines

Felino P. Lansigan, University of the Philippines Los Baños
Rodel Lasco, World Agroforestry Centre (ICRAF)
Manuel F. Montes, South Centre Global Governance for Development
Rosa Perez, Manila Observatory
Juan Pulhin, University of the Philippine Los Baños
Lourdes Tibig, Manila Observatory
Reiner Wassman, International Rice Research Institute (IRRI)

Poland

Krzysztof Błażejczyk, University of Warsaw
Janusz Filipiak, Institute of Meteorology and Water Management National Research Institute
Janusz Kindler, Warsaw University of Technology
Zbigniew Kundzewicz, Polish Academy of Sciences
Krzysztof Olendrzynski, United Nations Economic Commission for Europe
Grzegorz Różyński, Institute of Hydroengineering of the Polish Academy of Sciences
Maciej Sadowski, Institute of Environmental Protection National Research Institute
Tomasz Walczykiewicz, Institute of Meteorology and Water Management National Research Institute
Jan Marcin Węsławski, Institute of Oceanology of the Polish Academy of Sciences
Thomasz Zylicz, University of Warsaw

Portugal

Sofia Bettencourt, The World Bank
Luciana das Neves, University of Porto-Faculty of Engineering
Diogo de Gusmao, Met Office Hadley Centre
Oscar Ferreira, University of Algarve
Teresa Fidalgo Fonseca, Universidade de Trás-os-Montes e Alto Douro
Bruno Moreira, Centre for Functional Ecology, University of Coimbra
Maria Manuela Portela, Instituto Superior Tecnico (IST)
Filipe Santos, University of Lisbon
Carla Andreia Silva Mora, University of Lisbon
Celine Verissimo, University College London
Goncalo Vieira, University of London

Republic of Korea

Tae Sung Cheong, National Disaster Management Institute
So-Min Cheong, University of Kansas
Youngeun Choi, Konkuk University
JinYong Choi, Seoul National University
Jae-Youn Jang, Ajou University
Sukgeun Jung, Jeju National University
Suam Kim, Pukyong National University
Won-Tae Kwon, National Institute of Meteorological Research
Seung-Ki Min, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Marine and Atmospheric Research
Soojeong Myeong, Korea Environment Institute
Seung-Kyun Park, Korea Meteorological Administration

Republic of Moldova

Alexei Andreev, BIOTICA Ecological Society
Roman Corobov, Independent Researcher
Ilya Trombitsky, Eco-TIRAS International Environmental Association of River Keepers

Romania

Cosmin Corendea, United Nations University Institute for Environment and Human Security
Valentina Mara, Columbia University
Elena Mateescu, National Meteorological Administration of Romania

Russian Federation

Maria Ananicheva, Institute of Geography, Russian Academy of Sciences
Oleg A. Anisimov, State Hydrological Institute
Yuri Anokhin, Institute of Global Climate and Ecology of the Federal Service on Hydrometeorology and Environmental Monitoring, and Russian Academy of Sciences
Vsevolod Belkovich, P.P. Shirshov Institute of Oceanology
Alexey V. Eliseev, A.M.Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences
Mikhail Flint, P.P. Shirshov Institute of Oceanology
Gregory Insarov, Institute of Geography, Russian Academy of Sciences
Yury Izrael, Institute of Global Climate and Ecology of the Federal Service on Hydrometeorology and Environmental Monitoring, and Russian Academy of Sciences
Andrey G. Kostianoy, P.P. Shirshov Institute of Oceanology, Russian Academy of Sciences
Anna Kukhta, Institute of Global Climate and Ecology of the Federal Service on Hydrometeorology and Environmental Monitoring, and Russian Academy of Sciences
Dmitry L. Musolin, Saint Petersburg State Forest Technical University
Vera Pavlova, Federal State Institution of Agricultural Meteorology
Boris Revich, Institute of Forecasting, Russian Academy of Science
Alexey Ryaboshapko, Institute of Global Climate and Ecology of the Federal Service on Hydrometeorology and Environmental Monitoring, and Russian Academy of Sciences
Sergey Semenov, Institute of Global Climate and Ecology of the Federal Service on Hydrometeorology and Environmental Monitoring, and Russian Academy of Sciences
Kristina Trusilova, Deutscher Wetterdienst
Peter Zavialov, P.P. Shirshov Institute of Oceanology

Rwanda

Didace Musoni, Rwanda Meteorological Agency

Saint Lucia

Keith Nichols, Caribbean Community Climate Change Centre

Saudi Arabia

Khalid Abuleif, IPCC Focal Point
Faisal Al Zawad, Presidency of Meteorology and Environment

Senegal

Salif Diop, United Nations Environment Programme / Scientific Assessment Branch (SAB) of the Division of Early Warning and Assessment (DEWA)
Aliou Diouf, ENDA Energie-Environnement-Développement
Papa Demba Fall, University Cheikh Anta Diop of Dakar, Institut fondamental d'Afrique Noire
Omar Ly, Environment and Fisheries Department / INGESAHEL-sa
Aminata Ndiaye, University Cheikh Anta Diop of Dakar
Jacques Andre Ndione, Centre de Suivi Ecologique
Isabelle Niang, University Cheikh Anta Diop
Aissa Toure Sarr, International Fund for Agricultural Development (IFAD)

Serbia

Andjelka Mihajlov, University of Novi Sad / Environmental Ambassadors for Sustainable Development

Seychelles

Rolph Payet, University of Seychelles

Sierra Leone

Abdulai Jalloh, West and Central African Council for Agricultural Research and Development (CORAF/WECARD)
Osman Sankoh, INDEPTH Network/University of the Witwatersrand/Hanoi Medical University

Singapore

Winston Chow, National University of Singapore
Li Ding, Nanyang Technological University (NTU)
Xixi Lu, University of Singapore
Andreas Schaffer, Nanyang Technological University (NTU)
Poh Poh Wong, National University of Singapore (Retired)

Slovakia

Jaroslav Mysiak, Fondazione Eni Enrico Mattei; and Euro-Mediteranean Center for Climate Change
Jan Szolgay, Slovak University of Technology

Slovenia

Lucka Kajfez Bogataj, University of Ljubljana

South Africa

Emma Archer van Garderen, Council for Scientific and Industrial Research (CSIR)
Sally Archibald, Natural Resources and the Environment, Council for Scientific and Industrial Research / University of the Witwatersrand
Jane Battersby, African Centre for Cities, University of Cape Town
Kevern Cochrane, Rhodes University
Tracy Cull, Kulima Integrated Development Solutions (Pty) Ltd.
Wendy Foden, University of the Witwatersrand
Rebecca Garland, Natural Resources and the Environment Unit, Council for Scientific and Industrial Research
Bruce Hewitson, University of Cape Town
Nicholas King, Consultant
Christopher Lennard, Climate Systems Analysis Group, University of Cape Town
Andrew Mather, eThekwini Municipality
Alexio Mbereko, University of Kwazulu-Natal
Guy F. Midgley, South African National Biodiversity Institute
Coleen Moloney, Marine Research Institute
Jane Mukarugwiza Olwoch, South African National Space Agency (SANSA)
Pierre Mukheibir, University of Technology Sydney

Debra Roberts, eThekwini Municipality
Michael Henry Schleyer, Oceanographic Research Institute
Robert Scholes, Council for Scientific and Industrial Research (CSIR), Natural Resources and the Environment (NRE)
Roland Schulze, University of KwaZulu-Natal
Sarshen Scorgie, Conservation South Africa
Sheona Shackleton, Rhodes University
Mxolisi Shongwe, South African Weather Service
James Thurlow, United Nations University's World Institute for Development Economics Research
Rabelani Tshikalanke, International Climate Change Mitigation, Environmental Affairs
Penny Urquhart, Independent Consultant
Claire van Wyk, University of Cape Town
Katharine Vincent, Kulima Integrated Development Solutions / University Witwatersrand Johannesburg
Coleen Vogel, University of Pretoria
Caradee Wright, Council for Scientific and Industrial Research

Spain

X. Anton Alvarez-Salgado, CSIC Instituto de Investigaciones Marinas
Ricardo Anadon, University of Oviedo
Javier Aristegui, Universidad de Las Palmas de Gran Canaria
Gerardo Benito, Spanish Council for Scientific Research
Antonio Bode, Instituto Espanol de Oceanografia
Ibáñez Carles, Institute for Food Research and Technology (IRTA)
Juan-Carlos Ciscar, European Commission
Jordi Cortina, University of Alicante
Roger Cremades, University of Hamburg
Carlos de Miguel, United Nations Economic Commission for Latin America and the Caribbean
Cristina Garcia-Diaz, Spanish Climate Change Office
Raquel Garza Garrido, Spanish Climate Change Office
M. Dolores Garza-Gil, University of Vigo
Jonathan Gómez Cantero, Universidad de Alicante
Ana Iglesias, Universidad Politecnica de Madrid
Julio Diaaz Jimenez, Carlos III Institute of Health, National School of Public Health
Olcina Jorge, University of Alicante
Carmen Lacambra Segura, Grupo La era
Cristina Linares Gil, Instituto de Salud Carlos III
Maria-Carmen Llasat, University of Barcelona
Josep Lloret, University of Girona
Feliu López-i-Gelats, Center for Agro-food Economy and Development (CREDA-UPC-IRTA)
Iñigo J. Losada, Universidad de Cantabria, Environmental Hydraulics Institute IH Cantabria
Anil Markandya, Basque Centre for Climate Change
Jorge Martínez Chamorro, Gobierno de Canarias
Juan Carlos Montero, Health Sciences Institute
José M. Moreno, University of Castilla-La Mancha
Lino Naranjo, MeteoGalicia
Francisco José Pascual Pérez, Spanish Climate Change Office
Carle Pelejero Institució Catalana de Recerca i Estudis Avançats (ICREA) / Institut de Ciències del Mar, CSIC
Josep Penuelas, Centre for Ecological Research and forestry Applications (CREAF) / Consejo Superior de Investigaciones Cientificas (CSIC)
José Ramón Picatoste Ruggeroni, Spanish Climate Change Office
Salvador Pueyo, Institut Català de Ciències del Clima (IC3)
Sonia Quiroga, Universidad de Alcala
Victor Resco de Dios, University of Western Sydney
Marta G. Rivera-Ferre, University of Vic-Central University of Catalonia
Dionisio Rodriguez Alvarez, Xunta de Galicia
Beatriz Rodriguez-Labajos, Autonomous University of Barcelona
Bruno Sanchez Andrade Nuno, gain.org
Ethemcan Turhan, Universitat Autonoma de Barcelona
Ramón Vallejo, Universidad de Barcelona
David Velázquez, Universidad Autónoma de Madrid
Montserrat Vila, Estación Biólogica de Doñana - Consejo Superior de Investigaciones Científicas (EBD-CSIC)

Sri Lanka

Achala Chandani Abeysinghe, International Institute for Environment and Development
Amithirigala Jayawardena, International Centre for Water Hazard and Risk Management (ICHARM)

State of Palestine

Nedal Katbeh-Bader, Ministry of Environmental Affairs Environment Quality Authority (EQA)
Imad Khatib, Palestine Academy for Science and Technology

Sudan

Balgis Osman-Elasha, African Development Bank
Sumaya Zakieldeen, University of Khartoum

Sweden

Lotta Andersson, Swedish Meteorological and Hydrological Institute
Lars Bärring, Swedish Meteorological and Hydrological Institute
Kristina Blennow, Swedish University of Agricultural
Anna Bratt, County Administrative Board
Annika Carlsson-Kanyama, Swedish Defense Research Agency
Charlotte Cederbom, Swedish Geotechnical Institute
Goran Duus-Otterstrom, University of Gothenburg
Adam Felton, Swedish University of Agricultural Sciences
Carina Keskitalo, Umea University
Richard J.T. Klein, Stockholm Environment Institute
Elisabet Lindgren, Karolinska Institutet
Ulf Molau, University of Gothenburg
Lennart Olsson, Lund University
Markku Rummukainen, Lund University / Swedish Meteorological and Hydrological Institute
Rainer Sauerborn, Umeå University
E. Lisa F. Schipper, Stockholm Environment Institute
Åsa Sjöström, Swedish Meteorological and Hydrological Institute
Sofie Storbjork, Linkoping University

Switzerland

Simon K. Allen, IPCC Working Group I Technical Support Unit
Martin Beniston, Institute for Environmental Sciences University of Geneva
Thomas Bernauer, Swiss Federal Institute of Technology (ETH) Zurich
David Bresch, Swiss Reinsurance Company
Nicole Clot, HELVETAS Swiss Intercooperation
Johann Dupuis, Swiss Graduate School of Public Administration (IDHEAP)
Urs Feller, University of Bern
Andreas Fischlin, Swiss Federal Institute of Technology (ETH) Zurich, Systems Ecology
Thomas Frölicher, Institute of Biogeochemistry and Pollutant Dynamics, Swiss Federal Institute of Technology (ETH) Zurich
Yuka Nathalie Greiler, Swiss Federal Agency for Development and Cooperation
Wilfried Haeberli, University of Zurich
Christian Huggel, University of Zurich
Christian Körner, University of Basel
Herbert Lang, Swiss Federal Institute of Technology (ETH) Zurich
Heike Lischke, Swiss Federal Institute for Forest, Snow and Landscape Research
Juerg Luterbacher, Justus Liebig University
Axel Michaelowa, University of Zurich
Lea Mueller, Swiss Reinsurance Company Ltd.
Ulrike Mueller-Boeker, University of Zurich
Adrian Muller, Research Institute of Organic Agriculture FiBL
Alexander Nauels, IPCC Working Group I Technical Support Unit
Etienne Piguet, University of Neuchâtel
Gian-Kasper Plattner, IPCC Working Group I Technical Support Unit
Ana Maria Priceputu, United Nations Environment Programme
Dominik Reusser, Potsdam Institute for Climate Impact Research
José Romero, Federal Office for the Environment
Dominic Roser, University of Zurich / University of Graz
This Rutishauser, University of Bern
Jan Sedlacek, Institute for Atmospheric and Climate Science, Swiss Federal Institute of Technology (ETH) Zurich
Thomas F. Stocker, IPCC Working Group I Technical Support Unit

Yu Xia, IPCC Working Group I Technical Support Unit
Hong Yang, Swiss Federal Institute for Aquatic Science and Technology

Tanzania
Joseph P. Hella, Sokoine University of Agriculture
Shadrack S. Mwakalila, University of Dar es Salaam

Thailand
Bundit Limmeechokchai, Sirindhorn International Institute of Technology, THAMMASAT University

The former Yugoslav Republic of Macedonia
Vladimir Kendrovski, World Health Organization Regional Office for Europe

The Gambia
Fatima Denton, African Climate Policy Centre, United Nations Economic Commission for Africa
Fatou Ndey Gaye, Ministry of Forestry and Environment
Sirra Njai
Sidat Yaffa, University of The Gambia

The Netherlands
Fernanda Minikowski Achete, UNESCO Institute for Water Education
Valeria Agamennone, Vrije University Amsterdam
Farhana Ahmed, UNESCO Institute for Water Education
Julito Aligaen, UNESCO Institute for Water Education
Wondmyibza Tsegaye Bayou, Wageningen University
Frans G.H. Berkhout, King's College London
Pieter Bloemen, Ministry of Infrastructure and the Environment
Andrew Bollinger, Delft University of Technology
Christiaan Both, University of Groningen
Wouter Botzen, Vrije Universiteit Amsterdam
Laurens M. Bouwer, Deltares
Anne Sjoerd Brouwer, Utrecht University
Bas Clabbers, Ministry of Economic Affairs, Department of Nature and Biodiversity
Sjoerd Croqué, Ministry of Economic Affairs, European Agricultural Policy and Food Security
Maarten de Jong, Wageningen University
Roos M. den Uyl, Utrecht University
Katrien Descheemaeker, Plant Production Systems, Wageningen University
Peter P.J. Driessen, Utrecht University
Mario Duarte Duque, UNESCO Institute for Water Education
Giema Ebrahim, UNESCO Institute for Water Education
David Eitelberg, Vrije University Amsterdam
Kai Fang, Leiden University
Ronald Flipphi, Ministry of Infrastructure and Environment
Hayo Haanstra, Ministry of Economic Affairs
Linh Hoang, UNESCO Institute for Water Education
Andries Hof, Netherlands Environmental Assessment Agency
Rumana Hossain, Wageningen University
Rohan Jain, UNESCO Institute for Water Education
Rob Jongman, Wageningen University
Olaf Jonkeren, PBL Netherlands Environmental Assessment Agency
Jeanelle Joseph, Wageningen University
Pavel Kabat, International Institute for Applied Systems Analysis (IIASA)
Mark Koetse, Vrije University Amsterdam
Elco Koks, Vrije University Amsterdam
Hans Komakech, UNESCO Institute for Water Education
Rik Leemans, Wageningen University
Chris Manyamba, Wageningen University
Belinda McFadgen, Vrije University Amsterdam
Heleen Mees, Utrecht University
Lieke Melsen, Wageningen University
Jack Middelburg, Utrecht University
Erik Min, Royal Netherlands Meteorological Institute (KNMI)
Iris Monnereau, University of the West Indies
Francesc Montserrat, Netherlands Institute for Sea Research
Piero Morseletto, Vrije University Amsterdam
Micah Mukungu Mukolwe, UNESCO Institute for Water Education
Aidin Niamir, University of Twente
Pedi Obani, UNESCO Institute for Water Education
Abby Onencan, Vrije University Amsterdam
Astra Ooms, Vrije University Amsterdam
Amandine Pastor, Wageningen University
Pieter Pauw, German Development Institute
Adriaan Perrels, Finnish Meteorological Institute
Arthur Petersen, PBL Netherlands Environmental Assessment Agency
Catharina Philippart, Royal Netherlands Institute for Sea Research
Mirjam Poppe, Ministry of Economic Affairs, Department of Nature and Biodiversity
Piet Rietveld, Vrije University Amsterdam
Johanna Schild, Vrije University Amsterdam
Arina Schrier, Wetlands International
Pita Spruijt, Vrije University Amsterdam
Marcel Stive, Delft University of Technology (DUT)
Wouter Suring, Vrije University Amsterdam
Behnam Taebi, Delft University of Technology
Caroline Uittenbroek, Utrecht University
Maarten van Aalst, Red Cross / Red Crescent Climate Centre
Vincent van den Bergen, Ministry of Infrastructure and the Environment
B. van den Hurk, Royal Netherlands Meteorological Institute
Kees van der Geest, United National University
Klaas Van der Hoek, National Institute for Public Health and the Environment (RIVM)
Merel van der Wal, Open University
Anne van Loon, Wageningen University
Jelle van Minnen, PBL Netherlands Environmental Assessment Agency
Geert Jan van Oldenborgh, The Royal Netherlands Meteorological Institute
Detlef van Vuuren, PBL Netherlands Environmental Assessment Agency / Utrecht University
Ted Veldkamp, Vrije University Amsterdam
Jan E. Vermaat, Vrije University Amsterdam
Lucie Vermeulen, Wageningen University
Marcel Visser, Netherlands Institute of Ecology
Philip Ward, Vrije University Institute for Environmental Studies
Gijsbert Werner, Vrije University Amsterdam
Liang Xiong, Delft University of Technology
Mark Zandvoort, Wageningen University
Yijian Zeng, University of Twente

Tonga
Netatua Pelesikoti, Pacific Regional Environment Programme
Malia Talakai, Alliance of Small Island States (AOSIS)

Trinidad and Tobago
John Agard, University of the West Indies
Dave Chadee, University of the West Indies
Ainka Granderson, University of Melbourne
Shobha Maharaj, University of the West Indies
Maurice Rawlins, University of the West Indies
Bhawan Singh, University of Montreal
Joan Sutherland, University of the West Indies, St. Augustine Campus

Tunisia
Mohammed Chahed

Turkey
H. Resit Akcakaya, Stony Brook University
Ercan Gulay, Ministry of Environment and Urbanization of Turkey
Serhat Sensoy, Turkish State Meteorological Service
Barış Karapinar, Boğaziçi University

Ukraine
Alexander Polonsky, Marine Hydrophysical Institute of National Academy of Sciences

United Kingdom
Helen Adams, University of Exeter
W. Neil Adger, University of Exeter
Nigel W. Arnell, University of Reading Walker Institute
Jessica Ayers, Department of Energy and Climate Change

Caroline Bain, Met Office Hadley Centre
Rosa Barciela, Met Office Hadley Centre
Jonathan Barton
Laura Bates, Department of Energy and Climate Change
Pam Berry, Oxford University
Richard A. Betts, Met Office Hadley Centre
Yvan Biot, Department for International Development
Clare Blencowe, Environment Agency
Ian Boyd, Department for Environment, Food and Rural Affairs
Emily Boyd, University of Reading
Barbara Brown, University of Newcastle
Sally Brown, University of Southampton
Matthew Bunce, Institute of Marine Engineering, Science and Technology
Mark Burnett, Foreign and Commonwealth Office
Michael T. Burrows, The Scottish Association for Marine Science
Peter Burt, University of Greenwich
John Caesar, Met Office Hadley Centre
Tiege Cahill, Department for International Development
Terry V. Callaghan, Department of Animal and Plant Sciences, University of Sheffield
Diarmid Campbell-Lendrum, World Health Organization
Gillian Cambers, Secretariat of the Pacific Community
Karen Carr, Department for Environment Food and Rural Affairs
John Carstensen, Department for International Development
Robin Chadwick, Met Office Hadley Centre
Teige Chaill, Department for International Development
Paula Chalinder, Department for International Development
Andrew Challinor, University of Leeds
Andrew Chalmers, Department of Energy and Climate Change
Lee Chapman, University of Birmingham
Amanda Charles, Government Office for Science
Mark Charlesworth, Keele University
Katie Chesover, Department of Energy and Climate Change
Samuel Clemmens, Welsh Government Chief Scientific Advisors Division
Peter Convey, British Antarctic Survey
Alison Cook, Swansea University
Sarah Cornell, Stockholm Resilience Centre
Michael James Crabbe, University of Bedfordshire
Robert Craig, Department for Environment Food and Rural Affairs
Jo da Silva, Arup International Development
Alan Dangour, London School of Hygiene and Tropical Medicine
Rutger Dankers, Met Office Hadley Centre
Stephen Darby, University of Southampton
Geoff Darch, Atkins Consultants / University of East Anglia
Radhika Dave, University of Southampton
Michael Davies, University College London
Suraje Dessai, University of Leeds
Tyrone Dunbar, Met Office Hadley Centre, Department of Energy and Climate Change
John Duncan, University of Southampton
Martin Edwards, Sir Alister Hardy Foundation for Ocean Science
Peter Falloon, Met Office Hadley Centre
Samuel Fankhauser, London School of Economics
Lucy Faulkner, International Centre for Climate Change and Development (ICCCAD)
David Flint, Cass Business School
Paul Freeman, Department of Energy and Climate Change
Jon French, University College London
Peter T. Fretwell, British Antarctic Survey
Andrew Friend, University of Cambridge
Nicola Golding, Met Office Hadley Centre
Peter Good, Met Office Hadley Centre
Clare Goodess, University of East Anglia Climatic Research Unit
Simon Gosling, University of Nottingham
Peter Gregory, University of Reading
David J. Griggs, Monash University
Jeremy Haggar, Natural Resources Institute, University of Greenwich
Andrew Haines, London School of Hygiene and Tropical Medicine
Shakoor Hajat, London School of Hygiene and Tropical Medicine
Kate Halladay, Met Office Hadley Centre
Jacqueline M. Hamilton, Hamburg University
Genevra Harker, HarmonicQuay Ltd
Paula Harrison, Environmental Change Institute, University of Oxford
Andrew Hartley, Met Office Hadley Centre
Sharon Harvey, Department for International Development
Blane Harvey, Institute of Development Studies, University of Sussex
Ed Hawkins, University of Reading
Stephen Hawkins, University of Southampton
Adrian Hayes, Australian National University
Lucy Hayes, Department of Energy and Climate Change
Rachel Hemingway, Department for International Development
Chris Hewitt, Met Office Hadley Centre
Jennifer Hodbod, Global Institute of Sustainability, Arizona State University
Dominic Hodgson, British Antarctic Survey
David Hole, Conservation International
Joanna I. House, University of Bristol, QUEST
Guy Howard, Department for International Development
Candice Howarth, Department of Energy and Climate Change
Kathryn Humphrey, Parliament Committee on Climate Change
Alistair Hunt, University of Bath
George Hutchinson, Queen's University, Belfast
Christopher Ilori, University of Greenwich
John Ingram, Environmental Change Institute, University of Oxford
William Ingram, Hadley Centre for Climate Change
Tamara Janes, Met Office Hadley Centre
Guy Jobbins, Overseas Development Institute
Catherine Johnson, Department of Energy and Climate Change
Richard G. Jones, Met Office Hadley Centre
Chris Jones, Met Office Hadley Centre
Gareth S. Jones, Met Office Hadley Centre
Lindsey Jones, Overseas Development Institute
Daniel Kingston, University of Otago
Robert Kitchen, Department for Environment, Food and Rural Affairs
Sari Kovats, London School of Hygiene and Tropical Medicine
Eva Ludi, Overseas Development Institute
Georgina M. Mace, University College London
Chris Mack, Department of Energy and Climate Change
John Magrath, Oxfam GB
Andrew Maskrey, United Nations Office for Disaster Risk Reduction (UNISDR)
Barry McAuley, Northern Ireland Department of Environment
Michael McCallion, Northern Ireland Department of Environment
Mark McCarthy, Met Office Hadley Centre
Doug McNeall, Met Office Hadley Centre
Carol McSweeney, Met Office Hadley Centre
Marc Metzger, University of Edinburgh School of GeoSciences
Alistair Montgomery, Scottish Government
Michael Morecroft, Natural England
John Morton, Natural Resources Institute, University of Greenwich
Alessandro Moscuzza, Department for International Development
Robert Muir-Wood, Risk Management Solutions
Eugene Murphy, British Antarctic Survey
Tom Murray, Department for Environment Food and Rural Affairs
Virginia Murray, Public Health London
Zebedee Naate, Department for Environment, Food and Rural Affairs
Louise Newport, Department of Health
Andrew Newsham, School of Oriental and African Studies (SOAS), University of London
Robert Nicholls, University of Southampton
Gordon Nichols, European Centre for Disease Prevention and Control
Raquel Nunes, University of East Anglia
Patrick Nunn, University of New England
Tom Oliver, Centre for Ecology and Hydrology
Annika Olsson, Department for International Development
Julian Orford, Queen's University, Belfast
Fiona Page, Scottish Government
Andrew Parker, Harvard Kennedy School
David Parker, Met Office Hadley Centre
Martin Parry, Imperial College London
Richard Pearson, University College London

Mark Pelling, King's College London
Edmund Penning-Rowsell, Middlesex University
Carlos Peres, University of East Anglia
Chris Perry, University of Exeter
John K. Pinnegar, Centre for Environment, Fisheries and Aquaculture Science
Edward Pope, Met Office Hadley Centre
Martin Price, Perth College / University of the Highlands and Islands
Jeff Price, Tyndall Centre
Nicola Ranger, Department for International Development
Tim Rayner, University of East Anglia, Tyndall Centre for Climate Change Research
Grace Redmond, Met Office Hadley Centre
Hannah Reid, International Institute for Environment and Development
Paul Reiter, Institut Pasteur
Jeff Ridley, Met Office Hadley Centre
J. Murray Roberts, Heriot-Watt University
Mark Rounsevell, University of Edinburgh
David Rowell, Met Office Hadley Centre
David Santillo, Greenpeace Research Laboratories
David Satterthwaite, International Institute for Environment and Development
Daniela Schmidt, University of Bristol
Chris Sear, Department of Energy and Climate Change
Simon Sharpe, Foreign and Commonwealth Office
Jonathan Silvertown, The Open University
Chandhi Singh, University of Reading
Stephen Sitch, University of Exeter
Malcolm Smart, Department for International Development
Daniel Smith, School of Biosciences, University of Nottingham
Christopher Smith, United Nations University
Thomas Spencer, University of Cambridge
Peter A. Stott, Met Office Hadley Centre
Lindsay Stringer, University of Leeds
Andy Sumner, Institute of Development Studies
Chris Taylor, Department of Energy and Climate Change
Richard Taylor, University College London
David Thomas, School of Geography and the Environment, University of Oxford
Chris D. Thomas, University of York
Philip Thornton, CGIAR Research Program on Climate Change, Agriculture and Food Security Program (CCAFS)
Richard S.J. Tol, University of Sussex
Emma Tompkins, University of Southampton Highfield Campus
Natalie Trapp, University of Hamburg / International Max Planck Research School on Earth System Modelling
Phil Trathan, British Antarctic Survey
Carol Turley, Plymouth Marine Laboratory
Sotiris Vardoulakis, Health Protection Agency
David Vaughan, British Antarctic Survey
Daniele Viappiani, Department of Energy and Climate Change
David Viner
Piero Visconti, Microsoft Research
Chris Vivian, Institute of Marine Engineering, Science and Technology (IMarEST)
Andrew Wade, University of Reading
Rachel Warren, University of East Anglia, Tyndall Centre
David Warrilow, Department of Energy and Climate Change
Paul Watkiss, Paul Watkiss Associates
James Watson, University of Leeds
Ivy Wellman, Department for Environment, Food and Rural Affairs
Tim Wheeler, Department for International Development
Meriwether Wilson, University of Edinburgh, School of GeoSciences
Narumon Withers-Harvey, Department for Environment Food and Rural Affairs
Yolande Wright, Department for International Development
Kenneth Wright, Department of Energy and Climate Change
Helena Wright, Imperial College London
Ruby Yau, Foreign and Commonwealth Office
Adrienne Yuen, Foreign and Commonwealth Office

United Republic of Tanzania

Ladislaus Chang'a, Tanzania Meteorological Agency
Robert B. R. Kiunsi, Disaster Management Training Centre, Ardhi University
Emmanuel Mpeta, Tanzania Meteorological Agency

United States of America

Nicholas Adams, O-I
Jeffery Adkins, National Oceanic and Atmospheric Administration, Coastal Services Center
Liwayway Adkins, U.S. Department of Energy
Arun Agrawal, University of Michigan
Gloria Aguilar, Famine Early Warning Systems Network
David Ainley, H.T. Harvey & Associates Ecological Consultants
Elena Aizen, College of Science, University of Idaho
Vladimir B. Aizen, College of Science, University of Idaho
Farhan Akhtar, U.S. Department of State
Stacy Alboher, Millennium Challenge Corporation
Joseph Alcamo, United Nations Environment Programme
Catherine Allen, U.S. Environmental Protection Agency
Craig Allen, U.S. Geological Survey
David Allen, U.S. Global Change Research Program
John Allen, International Research Institute for Climate and Society, Columbia University
William Anderegg, Princeton University
Glen Anderson, International Resources Group / Engility
Kacky Andrews, The Nature Conservancy
Yanna Antypas, U.S. Department of Energy, Energy Information Administration
Alex Apotsos, U.S. Agency for International Development
Douglas Arent, National Renewable Energy Laboratory
Tom Armstrong, White House Office of Science and Technology Policy
Channing Arndt, University of Copenhagen
Jeffrey Arnold, U.S. Army Corps of Engineers
Kevin Arrigo, Stanford University
Maximilian Auffhammer, University of California, Berkeley
Bilal Ayyub, University of Maryland
Amanda Babson, U.S. Department of the Interior, National Park Service
Dominique Bachelet, Conservation Biology Institute
George Backus, Sandia National Laboratories
Hans Baer, University of Melbourne
Walter Baethgen, International Research Institute for Climate and Society, Columbia University
Laura Bailey, Royal Wind Turbines
Noel Bakhtian, United States Senate
John Balbus, National Institute of Environmental Health Sciences, National Institutes of Health
Charles Barber, U.S. Department of State
Curtis Barrett, U.S. Agency for International Development, Office of Foreign Disaster Assistance
Ko Barrett, U.S. Department of Commerce / National Oceanic and Atmospheric Administration
Ben Beard, U.S. Department of Health and Human Services, Centers for Disease Control
Natalie Beckman, U.S. Department of State
Katherine Beggs, U.S. Agency for International Development
Robin Bell, Lamont-Doherty Earth Observatory of Columbia University
Vatsal Bhatt, U.S. Department of Energy, Brookhaven National Laboratory
Abhoyjit Bhown, Electric Power Research Institute
Rosina Bierbaum, University of Michigan
Anthony Bigio, The World Bank
Eren Bilir, IPCC WGII Technical Support Unit
Tegan Blaine, U.S. Agency for International Development
Gentry Blake, Gente de I'itoi A.C / University of Arizona College of Public Health
Geoffrey Blate, World Wildlife Fund
Marlon Boarnet, University of Southern California
Jean Bogner, University of Illinois at Chicago (UIC)
Paula Bontempi, National Aeronautic and Space Administration
Daniel Botkin, University of California, Santa Barbara
Doug Boucher, Union of Concerned Scientists
Travis Bradford, Columbia University
Cynthia Brady, U.S. Agency for International Development
Charles Brandt, U.S. Department of Energy, Pacific Northwest National Laboratory
Anthony Brazel, Arizona State University
Levi Brekke, U.S. Department of of the Interior, Bureau of Reclamation
John Brennan, U.S. Naval Postgraduate School

Michael Brewer, National Oceanic and Atmospheric Administration
Peter G. Brewer, Monterey Bay Aquarium Research Institute
Robin Bronen, University of Alaska
Austin Brown, U.S. Department of Energy, National Renewable Energy Laboratory
David Brown, National Oceanic and Atmospheric Administration
Jessica Brown, U.S. Department of State
Molly Brown, National Aeronautic and Space Administration
Robert Brulle, Drexel University
Beth Brumbaugh, National Aeronautic and Space Administration, DEVELOP Program
Joan Brunkard, U.S. Department of Health and Human Services, Centers for Disease Control
Benjamin Bryant, Millennium Challenge Corporation
Shelley Buonajuto, OMNI350 / Citizen's Climate Lobby
Marshall Burke, University of California, Berkeley
Virginia Burkett, U.S. Geological Survey
Elizabeth Burleson, Pace University School of Law
Joshua Busby, University of Texas-Austin
Kent Butts, Pennsylvania State University Harrisburg, Center for Naval Analysis
Karl W. Butzer, University of Texas at Austin
Maria Cafrey, U.S. National Park Service / University of Colorado, Boulder
Ken Caldeira, Carnegie Institution
Thomas Calloway, U.S. Department of Energy, Savannah River National Laboratory
Mark Carey, University of Oregon
Christopher Carlson, U.S. Department of Agriculture Forest Service
JoAnn Carmin, Massachusetts Institute of Technology
Edward R. Carr, University of South Carolina
Jessie Carr, University of Pittsburgh School of Health
Peter Carter, Climate Emergency Institute
Shawn Carter, U.S. Geological Survey
Joe Casola, Center for Climate and Energy Solutions (C2ES)
A. Peter Castro, Maxwell School, Syracuse University
Pietro Ceccato, International Research Institute for Climate and Society
Zoë Chafe, University of California, Berkeley
Adam Chambers, U.S. Department of Agriculture, Natural Resources Conservation Service
Christina Chan, U.S. Department of State
Steven Chan, Newcastle University
F. Stuart Chapin III, Institute of Arctic Biology, University of Alaska Fairbanks
Monalisa Chatterjee, IPCC WGII Technical Support Unit
Muthuvel Chelliah, National Oceanic and Atmospheric Administration
Anthony Cheng
Netra Chhetri, Arizona State University
Paul S. Chinowsky, Mortenson Center in Engineering for Developing Communities, University of Colorado
Ben Chou, Natural Resources Defense Council
Matthew Church, University of Hawaii
Corrie Clark, U.S. Department of Energy, Argonne National Laboratory
Erika Clesceri, U.S. Agency for International Development
Nell Codner, U.S. Department of Commerce / National Oceanic and Atmospheric Administration
Marlene Cole, U.S. Environmental Protection Agency
Robert K. Colwell, University of Connecticut
Josefino Comiso, National Aeronautics and Space Administration (NASA) Goddard Space Flight Center
Ken Conca, American University
Jonathan Cook, U.S. Agency for International Development (USAID)
Heather Cooley, Pacific Institute
Sarah Cooley, Woods Hole Oceanographic Institute
Jan Corfee-Morlot, Organisation for Economic Co-operation and Development
Joel Corona, U.S. Environmental Protection Agency
Tyler Corson-Rikert, U.S. Department of Homeland Security, Federal Emergency Management Agency
Daniel Costa, University of California Santa Cruz
Erin Coughlan, Red Cross / Red Crescent Climate Centre
Catherine Courtney, Tetra Tech Incorporated
Michael Craghan, U.S. Environmental Protection Agency
Jim Crawford, Trane Ingersoll-Rand
Jared Creason, U.S. Environmental Protection Agency
Kelley Crews, National Science Foundation
Michael Crimmins, University of Arizona
John Crocker, Metropolitan Atlanta Rapid Transit Authority
Thomas Cronin, U.S. Geological Survey
Molly Cross, Wildlife Conservation Society
Mark Crowell, U.S. Department of Homeland Security, Federal Emergency Management Agency
Thomas Cuddy, U.S. Department of Transportation, Federal Aviation Administration
Mary Culver, National Oceanic and Atmospheric Administration, Coastal Services Center
Lara Cushing, University of California, Berkeley
Elizabeth Cushion, U.S. Agency for International Development
Susan Cutter, University of South Carolina
Christopher D'Elia, Louisiana State University, School of the Coast and Environment
Shereen D'Souza, U.S. Department of State
Geoffrey D. Dabelko, Ohio University, Voinovich School of Leadership and Public Affairs
Jan Dash, Climate Initiative Chair, UU United Nations Office
Margaret Davidson, U.S. Department of Commerce / National Oceanic and Atmospheric Administration
John Davies, U.S. Department of Transportation, Federal Highway Administration
Jonathan Davis, Science Applications International Corporation
Steve Davis, University of California, Irvine
Benjamin DeAngelo, U.S. Environmental Protection Agency
Douglas DeMaster, National Oceanic and Atmospheric Administration, Fisheries
Curtis Deutsch, University of California, Los Angeles
Ernesto Diaz, Puerto Rico Coastal Zone Management Program
Noah Diffenbaugh, Stanford University
Joseph Donahue, Stratus Consulting
Michael Donovan, U.S. Agency for International Development
Ellen Douglas, University of Massachusetts
Kirstin Dow, University of South Carolina
Thomas Downing, Global Climate Adaptation Partnership
Christine Dragisic, U.S. Department of State
John Drake, University of Tennessee, Knoxville
Richard Driscoll, U.S. Department of State
Kea Duckenfield, U.S. Department of Defense
Phil Duffy, Lawrence Livermore National Laboratory
Hari Dulal, The World Bank
John Dunne, National Oceanic and Atmospheric Administration
Elizabeth Dutrow, U.S. Environmental Protection Agency
Betsy Eagin, MDB, Incorporated
C. Mark Eakin, National Oceanic and Atmospheric Administration, Coral Reef Watch
Hallie Eakin, Arizona State University
Shane Easter, Carnegie Institution of Washington
Kristie L. Ebi, ClimAdapt, LLC
Natalie Elwell, U.S. Agency for International Development, GenDev
William Elwood, National Institutes of Health
Steve Emmett-Mattox, Restore America's Estuaries
Nathan L. Engle, AAAS Science and Technology Policy Fellow
Carolyn Enquist, USA National Phenology Network
Yuka Estrada, IPCC WGII Technical Support Unit
David Evans, U.S. Environmental Protection Agency
Geoffrey Evans, Humane Society International
Marien Eve, U.S. Department of Agriculture
Victoria J. Fabry, California State University, San Marcos
Kelly Falkner, National Science Foundation
Daniel Farber, University of California, Berkeley
Philip M. Fearnside, National Institute for Research in Amazonia (INPA)
Richard Feely, National Oceanic and Atmospheric Administration, Pacific Marine Environmental Laboratory
Sergio Feld, Millennium Challenge Corporation
Tyler Felgenhauer, U.S. Environmental Protection Agency, Office of Research and Development
Francesco Femia, The Center for Climate and Security
Zach Ferdana, The Nature Conservancy
Nora Ferm, U.S. Agency for International Development
Tye Ferrell, U.S. Agency for International Development, East Africa
Christopher Field, Carnegie Institution, IPCC WGII Co-chair

Cash Fitzpatrick, U.S. Department of Energy
James Rodger Fleming, Colby College
Mick Follows, Massachusetts Institute of Technology
Jennifer Francis, Rutgers University
Guido Franco, California Energy Commission
Jenny Frankel-Reed, U.S. Administration for International Development
J. Randall Freed, ICF International
Howard Frumkin, University of Washington
Chris Funk, U.S. Department of Interior / U.S. Geological Survey
John Furlow, U.S. Agency for International Development
Murielle Gamache-Morris, National Oceanic and Atmospheric Administration
Janet Gamble, U.S. Environmental Protection Agency
Luis E. Garcia, The World Bank
Philip Garone, California State University, Stanislaus
Karen Garrett, Kansas State University
Christian Giardina, U.S. Department of Agriculture, Forest Service
Maribeth Gidley, University of Miami Cooperative Institute for Marine and Atmospheric Studies (CIMAS) / National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory
Stephen Gill, National Oceanic and Atmospheric Administration
Kristin Gilroy, U.S. Army Corps of Engineers
Evan Girvetz, The Nature Conservancy
Michael Glantz, University of Colorado
Paul Glaser, University of Minnesota
Peter Gleick, Pacific Institute
Daniel M. Gnatz, Nova Southeastern University
Scott Goetz, Woods Hole Research Center
Indur Goklany, Independent
Gilberto Gonzales
Otto Gonzales, U.S. Department of Agriculture, Foreign Agricultural Service
Patrick Gonzalez, U.S. National Park Service
James Goodrich, U.S. Environmental Protection Agency
Edward Gorecki, National Oceanic and Atmospheric Administration
Vivien Gornitz, Columbia University
Derrick Gough, United States Army
Anne Grambsch, U.S. Environmental Protection Agency
Timothy Grant, U.S. Department of Energy, National Energy Technology Laboratory
Clark Gray, University of North Carolina at Chapel Hill
Timothy Green, U.S. Department of Agriculture, Agricultural Research Service
Rachel Gregg, EcoAdapt
Noel Gurwick, Smithsonian Environmental Research Center
Jessica Gutknecht, Helmholtz Centre for Environmental Research-UFZ
Stanton Hadley, U.S. Department of Energy, Oak Ridge National Laboratory
Clarissa Hageman, U.S. Agency for International Development
Robert Hall, U.S. Department of Health and Human Services, National Institute of Allergy and Infectious Diseases
Benjamin Halpern, University of California Santa Barbara / Imperial College London
Lara Hansen, EcoAdapt
Paul J. Hanson, Oak Ridge National Laboratory
Karen Hardee, Futures Group
Christopher Harley, University of British Columbia
Betsy Hartmann, Hampshire College
Ashley Haugo, BlueGreen Alliance
Petr Havlik, International Institute for Applied Systems Analysis
Maria Haws, University of Hawaii Hilo
Mary Hayden, National Center for Atmospheric Research
Jack Hayes, National Oceanic and Atmospheric Administration (Retired)
Elliott Hazen, National Oceanic and Atmospheric Association
Geoffrey Heal, Columbia Business School
Sean Hecht, University of California Los Angeles
Mark Heil, U.S. Department of the Treasury
Robert Heilmayr, Stanford University
Nicole Heller, Duke University
Rebecca R. Hernandez, Stanford University / Carnegie Institution for Science
Carl Hershner, Virginia Institute of Marine Science
Joseph Hewitt, U.S. Agency for International Development
Kathy Hibbard, U.S. Department of Energy / Pacific Northwest National Laboratory
Margaret Hiza Redsteer, U.S. Geological Survey
Tina Hodges, U.S. Department of Transportation, Federal Highway Administration
Elke Hodson, U.S. Department of Energy
Ron Hoffer, U.S. Environmental Protection Agency
Jennifer Hoffman, EcoAdapt
Eileen Hofmann, Center for Coastal Physical Oceanography, Old Dominion University
William Hohenstein, U.S. Department of Agriculture
Brian Holland, International Council for Local Environmental Initiatives (ICLEI) USA
Anne Hollowed, National Oceanic and Atmospheric Administration, National Marine Fisheries Service
Heather Holsinger, U.S. Department of Transportation, Federal Highway Administration
Robert Horner, U.S. Department of Energy, Argonne National Laboratory
Tamara Houston, National Oceanic and Atmospheric Administration, NESDIS/NCDC
Solomon Hsiang, Princeton University, Woodrow Wilson School of Public and International Affairs
Brian Huberty, U.S. Fish and Wildlife Service, National Wetland Inventory
George Hunt, University of Washington
David Hurlbut, U.S. Department of Energy, National Renewable Energy Laboratory
George Hurtt, University of Maryland
Dana Hyland, U.S. Environmental Protection Agency
Eric Hyman, U.S. Agency for International Development
Robert Hyman, U.S. Department of Transportation, Federal Highway Administration
Danielle Ignace, Smith College
Ana Iju Fukushima, Inter-American Development Bank
Micah Ingalls, Cornell University
Louis Iverson, U.S. Department of Agriculture Forest Service
Patricia Jacobberger-Jellison, National Aeronautics and Space Administration
Jenna Jadin, U.S. Department of Agriculture
Catherine Jampel, Pennsylvania State University
Anthony C. Janetos, Frederick S. Pardee Center for the Study of the Longer-Range Future, Boston University
James Jarvie, Mercy Corps
Anne Jensen, UIC Science LLC
Christine Jessup, U.S. Department of Health and Human Services, National Institutes of Health
Michael Johnsen, U.S. Department of Transportation, Federal Motor Carrier Safety Administration
Jennifer Johnson, Stanford University / Carnegie Institution
Kristen Johnson, U.S. Department of Energy, Bioenergy Technologies Office
Randy Johnson, U.S. Department of Agriculture, Forest Service
Matt Johnston, University of Minnesota
Kyle Joly, U.S. National Park Service
Carol Jones, U.S. Department of Agriculture, ERS
Lawrence Jones
Susan Julius, U.S. Environmental Protection Agency
Tamara Kadir, California Environmental Protection Agency
Robert Kafalenos, U.S. Department of Transportation, Federal Highway Administration
David Kahler, U.S. Agency for International Development
Adam Kalkstein, U.S. Military Academy
Richard Kanner, University of Utah School of Medicine
Carrie Kappel, University of California, Santa Barbara, National Center for Ecological Analysis and Synthesis
David Karl, University of Hawaii
George Kasali
Victoria Keener, East-West Center, Pacific RISA
Klaus Keller, Pennsylvania State University
Martin Kellogg, University of California, Santa Barbara
Brendan Kelly, White House Office of Science and Technology Policy
Thomas Kenkin, U.S. Department of Energy, National Renewable Energy Laboratory
Melissa A. Kenney, Johns Hopkins University / National Oceanic and Atmospheric Administration
Haroon Kheshgi, ExxonMobil Research and Engineering Company
Charles Kilstad, Stanford University
Yoon Hui Kim, International Resources Group/IRG
Marcus King, George Washington University
Patrick Kinney, Mailman School of Public Health of Columbia University
Paul Kirshen, University of New Hampshire
Eric Kissel, IPCC WGII Technical Support Unit
Kristian Kiuru, Energetics Incorporated
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Walter Knausenberger, U.S. Agency for International Development

Andrew Knoll, Harvard University
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William Landuyt, ExxonMobil Research and Engineering
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Claudia Langford, University of Georgia / U.S. National Climate Assessment Health Chapter Author Team
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Chrisopher Miller
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Frances Moore, Stanford University
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Max Moritz, University of California, Berkeley
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Sheila Moynihan, U.S. Department of Energy
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Brian Nelson, National Oceanic and Atmospheric Administration, NESDIS/NCDC

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Juli Trtanj, U.S. Department of Commerce / National Oceanic and Atmospheric Administration
Petra Tschakert, Pennsylvania State University
Michael Tubman, Center for Climate and Energy Solutions
Walt Tunnessen, U.S. Environmental Protection Agency, ENERGY
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Ruben van Hooidonk, National Oceanic and Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory / Rosenstiel School of Marine and Atmospheric Science, University of Miami
Valeri Vasquez, U.S. Department of State
Lisa Vaughan, National Oceanic and Atmospheric Administration, Climate Program Office
John Verdieck, U.S. Department of State
Hassan Virji, International START Secretariat
Eric Vugrin, U.S. Department of Energy, Sandia National Laboratories
Duane Waliser, National Aeronautic and Space Administration, Jet Propulsion Laboratory Caltech University
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STAR Industrial Program
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Kate Weinberger, Mailman School of Public Health at Columbia University
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Thomas Wilbanks, Oak Ridge National Laboratory
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Elizabeth Wolkovich, University of British Columbia
Eva (Lini) Wollenberg, CGIAR Research Theme on Pro-Poor Climate Change Mitigation / University of Vermont
Michael Wolosin, Climate Advisers
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Zinta Zommers, United Nations Environment Programme

Venezuela

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Vietnam

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Hong Ha Tran, Ministry of Natural Resources and Environment

Zimbabwe

Muyeye Chambwera, United Nations Development Programme
Mzime R. Ndebele-Murisa, Chinhoyi University of Technology

ANNEX II

Glossary

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Abrupt climate change
A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems.

Access to food
One of the three components underpinning food security, the other two being availability and utilization. Access to food is dependent on (1) the affordability of food (i.e., people have income or other resources to exchange for food); (2) satisfactory allocation within the household or society; and (3) preference (i.e., it is what people want to eat, influenced by socio-cultural norms). See also Food security.

Acclimatization
A change in functional or morphological traits occurring once or repeatedly (e.g., seasonally) during the lifetime of an individual organism in its natural environment. Through acclimatization the individual maintains performance across a range of environmental conditions. For a clear differentiation between findings in laboratory and field studies, the term *acclimation* is used in ecophysiology for the respective phenomena when observed in well-defined experimental settings. The term *(adaptive) plasticity* characterizes the generally limited scope of changes in phenotype that an individual can reach through the process of acclimatization.

Adaptability
See Adaptive capacity.

Adaptation[1]
The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects.

> ***Incremental adaptation*** Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.[2]
>
> ***Transformational adaptation*** Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

See also Autonomous adaptation, Evolutionary adaptation, and Transformation.

Adaptation assessment
The practice of identifying options to adapt to climate change and evaluating them in terms of criteria such as availability, benefits, costs, effectiveness, efficiency, and feasibility.

Adaptation constraint
Factors that make it harder to plan and implement adaptation actions or that restrict options.

Adaptation deficit
The gap between the current state of a system and a state that minimizes adverse impacts from existing climate conditions and variability.

Adaptation limit
The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

> ***Hard adaptation limit*** No adaptive actions are possible to avoid intolerable risks.
>
> ***Soft adaptation limit*** Options are currently not available to avoid intolerable risks through adaptive action.

Adaptation needs
The circumstances requiring action to ensure safety of populations and security of assets in response to climate impacts.

Adaptation opportunity
Factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.

Adaptation options
The array of strategies and measures that are available and appropriate for addressing adaptation needs. They include a wide range of actions that can be categorized as structural, institutional, or social.

Adaptive capacity
The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences.[3]

Adaptive management
A process of iteratively planning, implementing, and modifying strategies for managing resources in the face of uncertainty and change. Adaptive management involves adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables.

Aggregate impacts
Total impacts integrated across sectors and/or regions. The aggregation of impacts requires knowledge of (or assumptions about) the relative importance of different impacts. Measures of aggregate impacts include, for example, the total number of people affected, or the total economic costs, and are usually bound by time, place, and/or sector.

Ancillary benefits
See Co-benefits.

Anomaly
The deviation of a variable from its value averaged over a reference period.

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[1] Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

[2] This definition builds from the definition used in Park et al. (2012).

[3] This glossary entry builds from definitions used in previous IPCC reports and the Millennium Ecosystem Assessment (MEA, 2005).

Anthropogenic
Resulting from or produced by human activities.

Anthropogenic emissions
Emissions of greenhouse gases, greenhouse gas precursors, and aerosols caused by human activities. These activities include the burning of fossil fuels, deforestation, land use changes, livestock production, fertilization, waste management, and industrial processes.

Arid zone
Areas where vegetation growth is severely constrained due to limited water availability. For the most part, the native vegetation of arid zones is sparse. There is high rainfall variability, with annual averages below 300 mm. Crop farming in arid zones requires irrigation.

Atlantic Multi-decadal Oscillation/Variability (AMO/AMV)
A multi-decadal (65- to 75-year) fluctuation in the North Atlantic, in which sea surface temperatures showed warm phases during roughly 1860 to 1880 and 1930 to 1960 and cool phases during 1905 to 1925 and 1970 to 1990 with a range of approximately 0.4°C. See AMO Index in WGI AR5 Box 2.5.

Atmosphere-Ocean General Circulation Model (AOGCM)
See Climate model.

Attribution
See Detection and attribution.

Autonomous adaptation
Adaptation in response to experienced climate and its effects, without planning explicitly or consciously focused on addressing climate change. Also referred to as spontaneous adaptation.

Baseline/reference
The baseline (or reference) is the state against which change is measured. A baseline period is the period relative to which anomalies are computed. The baseline concentration of a trace gas is that measured at a location not influenced by local anthropogenic emissions.

Biodiversity
The variability among living organisms from terrestrial, marine, and other ecosystems. Biodiversity includes variability at the genetic, species, and ecosystem levels.[4]

Bioenergy
Energy derived from any form of biomass such as recently living organisms or their metabolic by-products.

Biofuel
A fuel, generally in liquid form, developed from organic matter or combustible oils produced by living or recently living plants. Examples of biofuel include alcohol (bioethanol), black liquor from the paper-manufacturing process, and soybean oil.

> ***First-generation manufactured biofuel*** First-generation manufactured biofuel is derived from grains, oilseeds, animal fats, and waste vegetable oils with mature conversion technologies.
>
> ***Second-generation biofuel*** Second-generation biofuel uses non-traditional biochemical and thermochemical conversion processes and feedstock mostly derived from the lignocellulosic fractions of, for example, agricultural and forestry residues, municipal solid waste, etc.
>
> ***Third-generation biofuel*** Third-generation biofuel would be derived from feedstocks such as algae and energy crops by advanced processes still under development.

These second- and third-generation biofuels produced through new processes are also referred to as next-generation or advanced biofuels, or advanced biofuel technologies.

Biomass
The total mass of living organisms in a given area or volume; dead plant material can be included as dead biomass. Biomass burning is the burning of living and dead vegetation.

Biome
A biome is a major and distinct regional element of the biosphere, typically consisting of several ecosystems (e.g., forests, rivers, ponds, swamps within a region). Biomes are characterized by typical communities of plants and animals.

Biosphere
The part of the Earth system comprising all ecosystems and living organisms, in the atmosphere, on land (terrestrial biosphere), or in the oceans (marine biosphere), including derived dead organic matter, such as litter, soil organic matter, and oceanic detritus.

Boundary organization
A bridging institution, social arrangement, or network that acts as an intermediary between science and policy.

Business As Usual (BAU)
Business as usual projections are based on the assumption that operating practices and policies remain as they are at present. Although baseline scenarios could incorporate some specific features of BAU scenarios (e.g., a ban on a specific technology), BAU scenarios imply that no practices or policies other than the current ones are in place. See also Baseline/reference, Climate scenario, Emission scenario, Representative Concentration Pathways, Scenario, Socioeconomic scenario, and SRES scenarios.

Capacity building
The practice of enhancing the strengths and attributes of, and resources available to, an individual, community, society, or organization to respond to change.

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[4] This glossary entry builds from definitions used in the Global Biodiversity Assessment (Heywood, 1995) and the Millennium Ecosystem Assessment (MEA, 2005).

Carbon cycle

The term used to describe the flow of carbon (in various forms, e.g., as carbon dioxide) through the atmosphere, ocean, terrestrial and marine biosphere, and lithosphere. In this report, the reference unit for the global carbon cycle is GtC or equivalently PgC (10^{15}g).

Carbon dioxide (CO_2)

A naturally occurring gas, also a by-product of burning fossil fuels from fossil carbon deposits, such as oil, gas, and coal, of burning biomass, of land use changes, and of industrial processes (e.g., cement production). It is the principal anthropogenic greenhouse gas that affects the Earth's radiative balance. It is the reference gas against which other greenhouse gases are measured and therefore has a Global Warming Potential of 1.

Carbon dioxide (CO_2) fertilization

The enhancement of the growth of plants as a result of increased atmospheric carbon dioxide (CO_2) concentration.

Carbon sequestration

See Uptake.

Clean Development Mechanism (CDM)

A mechanism defined under Article 12 of the Kyoto Protocol through which investors (governments or companies) from developed (Annex B) countries may finance greenhouse gas emission reduction or removal projects in developing (Non-Annex B) countries, and receive Certified Emission Reduction Units for doing so, which can be credited towards the commitments of the respective developed countries. The CDM is intended to facilitate the two objectives of promoting sustainable development in developing countries and of helping industrialized countries to reach their emissions commitments in a cost-effective way.

Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate-altering pollutants (CAPs)

Gases and particles released from human activities that affect the climate either directly, through mechanisms such as radiative forcing from changes in greenhouse gas concentrations, or indirectly, by, for example, affecting cloud formation or the lifetime of greenhouse gases in the atmosphere. CAPs include both those pollutants that have a warming effect on the atmosphere, such as CO_2, and those with cooling effects, such as sulfates.

Climate change

Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. See also Climate change commitment and Detection and Attribution.

Climate change commitment

Due to the thermal inertia of the ocean and slow processes in the cryosphere and land surfaces, the climate would continue to change even if the atmospheric composition were held fixed at today's values. Past change in atmospheric composition leads to a committed climate change, which continues for as long as a radiative imbalance persists and until all components of the climate system have adjusted to a new state. The further change in temperature after the composition of the atmosphere is held constant is referred to as the constant composition temperature commitment or simply committed warming or warming commitment. Climate change commitment includes other future changes, for example, in the hydrological cycle, in extreme weather events, in extreme climate events, and in sea level change. The constant emission commitment is the committed climate change that would result from keeping anthropogenic emissions constant and the zero emission commitment is the climate change commitment when emissions are set to zero. See also Climate change.

Climate extreme (Extreme weather or climate event)

See Extreme weather event.

Climate feedback

An interaction in which a perturbation in one climate quantity causes a change in a second, and the change in the second quantity ultimately leads to an additional change in the first. A negative feedback is one in which the initial perturbation is weakened by the changes it causes; a positive feedback is one in which the initial perturbation is enhanced. In this Assessment Report, a somewhat narrower definition is often used in which the climate quantity that is perturbed is the global mean surface temperature, which in turn causes changes in the global radiation budget. In either case, the initial perturbation can either be externally forced or arise as part of internal variability.

Climate governance

Purposeful mechanisms and measures aimed at steering social systems towards preventing, mitigating, or adapting to the risks posed by climate change (Jagers and Stripple, 2003).

Climate model (spectrum or hierarchy)

A numerical representation of the climate system based on the physical, chemical, and biological properties of its components, their interactions, and feedback processes, and accounting for some of its known properties. The climate system can be represented by models of varying complexity; that is, for any one component or combination of components, a spectrum or hierarchy of models can be identified, differing in such aspects as the number of spatial dimensions, the extent to which physical, chemical, or biological processes are explicitly represented, or the level at which empirical parameterizations are involved. Coupled Atmosphere-Ocean General Circulation Models (AOGCMs) provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available. There is an evolution towards more complex models with interactive chemistry and biology. Climate models are applied as a research tool to study and simulate the climate, and for operational purposes, including monthly, seasonal, and interannual climate predictions. See also Earth System Model.

Climate prediction

A climate prediction or climate forecast is the result of an attempt to produce (starting from a particular state of the climate system) an estimate of the actual evolution of the climate in the future, for example, at seasonal, interannual, or decadal time scales. Because the future evolution of the climate system may be highly sensitive to initial conditions, such predictions are usually probabilistic in nature. See also Climate projection, Climate scenario, and Predictability.

Climate projection

A climate projection is the simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission/concentration/radiative-forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized. See also Climate scenario.

Climate-resilient pathways

Iterative processes for managing change within complex systems in order to reduce disruptions and enhance opportunities associated with climate change.

Climate scenario

A plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships that has been constructed for explicit use in investigating the potential consequences of anthropogenic climate change, often serving as input to impact models. Climate projections often serve as the raw material for constructing climate scenarios, but climate scenarios usually require additional information such as the observed current climate. See also Emission scenario and Scenario.

Climate sensitivity

In IPCC reports, equilibrium climate sensitivity (units: °C) refers to the equilibrium (steady state) change in the annual global mean surface temperature following a doubling of the atmospheric equivalent carbon dioxide concentration. Owing to computational constraints, the equilibrium climate sensitivity in a climate model is sometimes estimated by running an atmospheric general circulation model coupled to a mixed-layer ocean model, because equilibrium climate sensitivity is largely determined by atmospheric processes. Efficient models can be run to equilibrium with a dynamic ocean. The climate sensitivity parameter (units: $°C\ (W\ m^{-2})^{-1}$) refers to the equilibrium change in the annual global mean surface temperature following a unit change in radiative forcing.

The effective climate sensitivity (units: °C) is an estimate of the global mean surface temperature response to doubled carbon dioxide concentration that is evaluated from model output or observations for evolving non-equilibrium conditions. It is a measure of the strengths of the climate feedbacks at a particular time and may vary with forcing history and climate state, and therefore may differ from equilibrium climate sensitivity.

The transient climate response (units: °C) is the change in the global mean surface temperature, averaged over a 20-year period, centered at the time of atmospheric carbon dioxide doubling, in a climate model simulation in which CO_2 increases at 1% yr^{-1}. It is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing.

Climate system

The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere, and the biosphere, and the interactions among them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations, and anthropogenic forcings such as the changing composition of the atmosphere and land use change.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also Climate change.

Climate velocity

The speed at which isolines of a specified climate variable travel across landscapes or seascapes due to changing climate. For example, climate velocity for temperature is the speed at which isotherms move due to changing climate ($km\ yr^{-1}$) and is calculated as the temporal change in temperature ($°C\ yr^{-1}$) divided by the current spatial gradient in temperature ($°C\ km^{-1}$). It can be calculated using additional climate variables such as precipitation or can be based on the climatic niche of organisms.

Climatic driver (Climate driver)

A changing aspect of the climate system that influences a component of a human or natural system.

CMIP3 and CMIP5

Phases three and five of the Coupled Model Intercomparison Project (CMIP3 and CMIP5), coordinating and archiving climate model simulations based on shared model inputs by modeling groups from around the world. The CMIP3 multi-model data set includes projections using SRES scenarios. The CMIP5 data set includes projections using the Representative Concentration Pathways.

Coastal squeeze

A narrowing of coastal ecosystems and amenities (e.g., beaches, salt marshes, mangroves, and mud and sand flats) confined between landward-retreating shorelines (from sea level rise and/or erosion) and naturally or artificially fixed shorelines including engineering defenses (e.g., seawalls), potentially making the ecosystems or amenities vanish.

Co-benefits

The positive effects that a policy or measure aimed at one objective might have on other objectives, irrespective of the net effect on overall social welfare. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Co-benefits are also referred to as ancillary benefits.

Community-based adaptation

Local, community-driven adaptation. Community-based adaptation focuses attention on empowering and promoting the adaptive capacity of communities. It is an approach that takes context, culture, knowledge, agency, and preferences of communities as strengths.

Confidence

The validity of a finding based on the type, amount, quality, and consistency of evidence (e.g., mechanistic understanding, theory, data, models, expert judgment) and on the degree of agreement. Confidence is expressed qualitatively (Mastrandrea et al., 2010). See Box 1-1. See also Uncertainty.

Contextual vulnerability (Starting-point vulnerability)

A present inability to cope with external pressures or changes, such as changing climate conditions. Contextual vulnerability is a characteristic of social and ecological systems generated by multiple factors and processes (O'Brien et al., 2007).

Convection

Vertical motion driven by buoyancy forces arising from static instability, usually caused by near-surface cooling or increases in salinity in the case of the ocean and near-surface warming or cloud-top radiative cooling in the case of the atmosphere. In the atmosphere, convection gives rise to cumulus clouds and precipitation and is effective at both scavenging and vertically transporting chemical species. In the ocean, convection can carry surface waters to deep within the ocean.

Coping

The use of available skills, resources, and opportunities to address, manage, and overcome adverse conditions, with the aim of achieving basic functioning of people, institutions, organizations, and systems in the short to medium term.[5]

Coping capacity

The ability of people, institutions, organizations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term.[6]

Coral bleaching

Loss of coral pigmentation through the loss of intracellular symbiotic algae (known as zooxanthellae) and/or loss of their pigments.

Cryosphere

All regions on and beneath the surface of the Earth and ocean where water is in solid form, including sea ice, lake ice, river ice, snow cover, glaciers and ice sheets, and frozen ground (which includes permafrost).

Cultural impacts

Impacts on material and ecological aspects of culture and the lived experience of culture, including dimensions such as identity, community cohesion and belonging, sense of place, worldview, values, perceptions, and tradition. Cultural impacts are closely related to ecological impacts, especially for iconic and representational dimensions of species and landscapes. Culture and cultural practices frame the importance and value of the impacts of change, shape the feasibility and acceptability of adaptation options, and provide the skills and practices that enable adaptation.

Dead zones

Extremely hypoxic (i.e., low-oxygen) areas in oceans and lakes, caused by excessive nutrient input from human activities coupled with other factors that deplete the oxygen required to support many marine organisms in bottom and near-bottom water. See also Eutrophication and Hypoxic events.

Decarbonization

The process by which countries or other entities aim to achieve a low-carbon economy, or by which individuals aim to reduce their consumption of carbon.

Deforestation

Conversion of forest to non-forest. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and *deforestation* see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). See also the report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Desertification

Land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities. Land degradation in arid, semi-arid, and dry sub-humid areas is reduction or loss of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest, and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns, such as (1) soil erosion caused by wind and/or water; (2) deterioration of the physical, chemical, biological, or economic properties of soil; and (3) long-term loss of natural vegetation (UNCCD, 1994).

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[5] This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).

[6] This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).

Detection and attribution

Detection of change is defined as the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense, without providing a reason for that change. An identified change is detected in observations if its likelihood of occurrence by chance due to internal variability alone is determined to be small, for example, <10%. Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence (Hegerl et al., 2010).

Detection of impacts of climate change

For a natural, human, or managed system, identification of a change from a specified baseline. The baseline characterizes behavior in the absence of climate change and may be stationary or non-stationary (e.g., due to land use change).

Disadvantaged populations

Sectors of a society that are marginalized, often because of low socioeconomic status, low income, lack of access to basic services such as health or education, lack of power, race, gender, religion, or poor access to communication technologies.

Disaster

Severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery.

Disaster management

Social processes for designing, implementing, and evaluating strategies, policies, and measures that promote and improve disaster preparedness, response, and recovery practices at different organizational and societal levels.

Disaster risk

The likelihood within a specific time period of disaster. See Disaster.

Disaster Risk Management (DRM)

Processes for designing, implementing, and evaluating strategies, policies, and measures to improve the understanding of disaster risk, foster disaster risk reduction and transfer, and promote continuous improvement in disaster preparedness, response, and recovery practices, with the explicit purpose of increasing human security, well-being, quality of life, and sustainable development.

Disaster Risk Reduction (DRR)

Denotes both a policy goal or objective, and the strategic and instrumental measures employed for anticipating future disaster risk; reducing existing exposure, hazard, or vulnerability; and improving resilience.

Discounting

A mathematical operation making monetary (or other) amounts received or expended at different times (years) comparable across time. The discounter uses a fixed or possibly time-varying discount rate (>0) from year to year that makes future value worth less today.

Disturbance regime

Frequency, intensity, and types of disturbances of ecological systems, such as fires, insect or pest outbreaks, floods, and droughts.

Diurnal temperature range

The difference between the maximum and minimum temperature during a 24-hour period.

Downscaling

Downscaling is a method that derives local- to regional-scale (10 to 100 km) information from larger-scale models or data analyses. Two main methods exist: dynamical downscaling and empirical/statistical downscaling. The dynamical method uses the output of regional climate models, global models with variable spatial resolution, or high-resolution global models. The empirical/statistical methods develop statistical relationships that link the large-scale atmospheric variables with local/regional climate variables. In all cases, the quality of the driving model remains an important limitation on quality of the downscaled information.

Drought

A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term; therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, shortage of precipitation during the growing season impinges on crop production or ecosystem function in general (due to soil moisture drought, also termed agricultural drought), and during the runoff and percolation season primarily affects water supplies (hydrological drought). Storage changes in soil moisture and groundwater are also affected by increases in actual evapotranspiration in addition to reductions in precipitation. A period with an abnormal precipitation deficit is defined as a meteorological drought. A megadrought is a very lengthy and pervasive drought, lasting much longer than normal, usually a decade or more. For the corresponding indices, see WGI AR5 Box 2.4.

Dynamic Global Vegetation Model (DGVM)

A model that simulates vegetation development and dynamics through space and time, as driven by climate and other environmental changes.

Early warning system

The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities, and organizations threatened by a hazard to prepare to act promptly and appropriately to reduce the possibility of harm or loss.[7]

Earth System Model (ESM)

A coupled atmosphere-ocean general circulation model in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric CO_2 or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included. See also Climate model.

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[7] This glossary entry builds from the definition used in UNISDR (2009) and IPCC (2012a).

Ecophysiological process

Processes in which individual organisms respond continuously to environmental variability or change, such as climate change, generally at a microscopic or sub-organ scale. Ecophysiological mechanisms underpin individual organisms' tolerance to environmental stress, and comprise a broad range of responses defining the absolute tolerances by individuals of environmental conditions. Ecophysiological responses may scale up to control species' geographic ranges.

Ecosystem

A functional unit consisting of living organisms, their non-living environment, and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key organisms, or are influenced by the effects of human activities in their environment.

Ecosystem approach

A strategy for the integrated management of land, water, and living resources that promotes conservation and sustainable use in an equitable way. An ecosystem approach is based on the application of scientific methodologies focused on levels of biological organization, which encompass the essential structure, processes, functions, and interactions of organisms and their environment. It recognizes that humans, with their cultural diversity, are an integral component of many ecosystems. The ecosystem approach requires adaptive management to deal with the complex and dynamic nature of ecosystems and the absence of complete knowledge or understanding of their functioning. Priority targets are conservation of biodiversity and of the ecosystem structure and functioning, in order to maintain ecosystem services.[8]

Ecosystem-based adaptation

The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change. Ecosystem-based adaptation uses the range of opportunities for the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. It aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change. Ecosystem-based adaptation is most appropriately integrated into broader adaptation and development strategies (CBD, 2009).

Ecosystem services

Ecological processes or functions having monetary or non-monetary value to individuals or society at large. These are frequently classified as (1) supporting services such as productivity or biodiversity maintenance, (2) provisioning services such as food, fiber, or fish, (3) regulating services such as climate regulation or carbon sequestration, and (4) cultural services such as tourism or spiritual and aesthetic appreciation.

El Niño-Southern Oscillation (ENSO)

The term El Niño was initially used to describe a warm-water current that periodically flows along the coast of Ecuador and Peru, disrupting the local fishery. It has since become identified with a basin-wide warming of the tropical Pacific Ocean east of the dateline. This oceanic event is associated with a fluctuation of a global-scale tropical and subtropical surface pressure pattern called the Southern Oscillation. This coupled atmosphere-ocean phenomenon, with preferred time scales of 2 to about 7 years, is known as the El Niño-Southern Oscillation (ENSO). It is often measured by the surface pressure anomaly difference between Tahiti and Darwin or the sea surface temperatures in the central and eastern equatorial Pacific. During an ENSO event, the prevailing trade winds weaken, reducing upwelling and altering ocean currents such that the sea surface temperatures warm, further weakening the trade winds. This event has a great impact on the wind, sea surface temperature, and precipitation patterns in the tropical Pacific. It has climatic effects throughout the Pacific region and in many other parts of the world, through global teleconnections. The cold phase of ENSO is called La Niña. For the corresponding indices, see WGI AR5 Box 2.5.

Emergent risk

A risk that arises from the interaction of phenomena in a complex system, for example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region.

Emission scenario

A plausible representation of the future development of emissions of substances that are potentially radiatively active (e.g., greenhouse gases, aerosols) based on a coherent and internally consistent set of assumptions about driving forces (such as demographic and socioeconomic development, technological change) and their key relationships. Concentration scenarios, derived from emission scenarios, are used as input to a climate model to compute climate projections. In IPCC (1992) a set of emission scenarios was presented, which were used as a basis for the climate projections in IPCC (1996). These emission scenarios are referred to as the IS92 scenarios. In the IPCC Special Report on Emissions Scenarios (Nakićenović and Swart, 2000) emission scenarios, the so-called SRES scenarios, were published, some of which were used, among others, as a basis for the climate projections presented in Chapters 9 to 11 of IPCC (2001) and Chapters 10 and 11 of IPCC (2007). New emission scenarios for climate change, the four Representative Concentration Pathways, were developed for, but independently of, the present IPCC assessment. See also Climate scenario and Scenario.

Ensemble

A collection of model simulations characterizing a climate prediction or projection. Differences in initial conditions and model formulation result in different evolutions of the modeled system and may give information on uncertainty associated with model error and error in initial conditions in the case of climate forecasts and on uncertainty associated with model error and with internally generated climate variability in the case of climate projections.

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[8] This glossary entry builds from definitions used in CBD (2000), MEA (2005), and the Fourth Assessment Report.

Environmental migration

Human migration involves movement over a significant distance and duration. Environmental migration refers to human migration where environmental risks or environmental change plays a significant role in influencing the migration decision and destination. Migration may involve distinct categories such as direct, involuntary, and temporary displacement due to weather-related disasters; voluntary relocation as settlements and economies become less viable; or planned resettlement encouraged by government actions or incentives. All migration decisions are multi-causal, and hence it is not meaningful to describe any migrant flow as being solely for environmental reasons.

Environmental services

See Ecosystem services.

Eutrophication

Over-enrichment of water by nutrients such as nitrogen and phosphorus. It is one of the leading causes of water quality impairment. The two most acute symptoms of eutrophication are hypoxia (or oxygen depletion) and harmful algal blooms. See also Dead zones.

Evolutionary adaptation

For a population or species, change in functional characteristics as a result of selection acting on heritable traits. The rate of evolutionary adaptation depends on factors such as strength of selection, generation turnover time, and degree of outcrossing (as opposed to inbreeding). See also Adaptation.

Exposure

The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

External forcing

External forcing refers to a forcing agent outside the climate system causing a change in the climate system. Volcanic eruptions, solar variations, and anthropogenic changes in the composition of the atmosphere and land use change are external forcings. Orbital forcing is also an external forcing as the insolation changes with orbital parameters eccentricity, tilt, and precession of the equinox.

Externalities/external costs/external benefits

Externalities arise from a human activity when agents responsible for the activity do not take full account of the activity's impacts on others' production and consumption possibilities, and no compensation exists for such impacts. When the impacts are negative, they are external costs. When the impacts are positive, they are external benefits.

Extratropical cyclone

A large-scale (of order 1000 km) storm in the middle or high latitudes having low central pressure and fronts with strong horizontal gradients in temperature and humidity. A major cause of extreme wind speeds and heavy precipitation especially in wintertime.

Extreme climate event

See Extreme weather event.

Extreme sea level

See Storm surge.

Extreme weather event

An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

Famine

Scarcity of food over an extended period and over a large geographical area, such as a country, or lack of access to food for socioeconomic, political, or cultural reasons. Famines may be caused by climate-related extreme events such as droughts or floods and by disease, war, or other factors.

Feedback

See Climate feedback.

Fire weather

Weather conditions conducive to triggering and sustaining wild fires, usually based on a set of indicators and combinations of indicators including temperature, soil moisture, humidity, and wind. Fire weather does not include the presence or absence of fuel load.

Fitness (Darwinian)

Fitness is the relative capacity of an individual or genotype to both survive and reproduce, quantified as the average contribution of the genotype to the gene pool of the next generations. During evolution, natural selection favors functions providing greater fitness such that the functions become more common over generations.

Flood

The overflowing of the normal confines of a stream or other body of water, or the accumulation of water over areas not normally submerged. Floods include river (fluvial) floods, flash floods, urban floods, pluvial floods, sewer floods, coastal floods, and glacial lake outburst floods.

Food security

A state that prevails when people have secure access to sufficient amounts of safe and nutritious food for normal growth, development, and an active and healthy life.[9] See also Access to food.

Food system

A food system includes the suite of activities and actors in the food chain (i.e., producing, processing and packaging, storing and transporting, trading and retailing, and preparing and consuming food); and the outcome of these activities relating to the three components underpinning food security (i.e., access to food, utilization of food, and food availability), all of which need to be stable over time. Food security is therefore

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[9] This glossary entry builds from definitions used in FAO (2000) and previous IPCC reports.

underpinned by food systems, and is an emergent property of the behavior of the whole food system. Food insecurity arises when any aspect of the food system is stressed.

Forecast

See Climate prediction and Climate projection.

General Circulation Model (GCM)

See Climate model.

Geoengineering

Geoengineering refers to a broad set of methods and technologies that aim to deliberately alter the climate system in order to alleviate the impacts of climate change. Most, but not all, methods seek to either (1) reduce the amount of absorbed solar energy in the climate system (Solar Radiation Management) or (2) increase net carbon sinks from the atmosphere at a scale sufficiently large to alter climate (Carbon Dioxide Removal). Scale and intent are of central importance. Two key characteristics of geoengineering methods of particular concern are that they use or affect the climate system (e.g., atmosphere, land, or ocean) globally or regionally and/or could have substantive unintended effects that cross national boundaries. Geoengineering is different from weather modification and ecological engineering, but the boundary can be fuzzy (IPCC, 2012b, p. 2).

Global change

A generic term to describe global scale changes in systems, including the climate system, ecosystems, and social-ecological systems.

Global Climate Model (also referred to as General Circulation Model, both abbreviated as GCM)

See Climate model.

Global mean surface temperature

An estimate of the global mean surface air temperature. However, for changes over time, only anomalies, as departures from a climatology, are used, most commonly based on the area-weighted global average of the sea surface temperature anomaly and land surface air temperature anomaly.

Greenhouse effect

The infrared radiative effect of all infrared-absorbing constituents in the atmosphere. Greenhouse gases, clouds, and (to a small extent) aerosols absorb terrestrial radiation emitted by the Earth's surface and elsewhere in the atmosphere. These substances emit infrared radiation in all directions, but, everything else being equal, the net amount emitted to space is normally less than would have been emitted in the absence of these absorbers because of the decline of temperature with altitude in the troposphere and the consequent weakening of emission. An increase in the concentration of greenhouse gases increases the magnitude of this effect; the difference is sometimes called the enhanced greenhouse effect. The change in a greenhouse gas concentration because of anthropogenic emissions contributes to an instantaneous radiative forcing. Surface temperature and troposphere warm in response to this forcing, gradually restoring the radiative balance at the top of the atmosphere.

Greenhouse gas (GHG)

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself, and clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human-made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O, and CH_4, the Kyoto Protocol deals with the greenhouse gases sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). For a list of well-mixed greenhouse gases, see WGI AR5 Table 2.SM.1.

Ground-level ozone

Atmospheric ozone formed naturally or from human-emitted precursors near Earth's surface, thus affecting human health, agriculture, and ecosystems. Ozone is a greenhouse gas, but ground-level ozone, unlike stratospheric ozone, also directly affects organisms at the surface. Ground-level ozone is sometimes referred to as tropospheric ozone, although much of the troposphere is well above the surface and thus does not directly expose organisms at the surface. See also Ozone.

Groundwater recharge

The process by which external water is added to the zone of saturation of an aquifer, either directly into a geologic formation that traps the water or indirectly by way of another formation.

Hazard

The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.

Heat wave

A period of abnormally and uncomfortably hot weather.

Hotspot

A geographical area characterized by high vulnerability and exposure to climate change.

Human security

A condition that is met when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In the context of climate change, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests and to live with dignity.

Human system

Any system in which human organizations and institutions play a major role. Often, but not always, the term is synonymous with society or social system. Systems such as agricultural systems, political systems, technological systems, and economic systems are all human systems in the sense applied in this report.

Hydrological cycle

The cycle in which water evaporates from the oceans and the land surface, is carried over the Earth in atmospheric circulation as water vapor, condenses to form clouds, precipitates over ocean and land as rain or snow, which on land can be intercepted by trees and vegetation, provides runoff on the land surface, infiltrates into soils, recharges groundwater, discharges into streams, and ultimately, flows out into the oceans, from which it will eventually evaporate again. The various systems involved in the hydrological cycle are usually referred to as hydrological systems.

Hypoxic events

Events that lead to deficiencies of oxygen in water bodies. See also Dead zones and Eutrophication.

Ice cap

A dome-shaped ice mass that is considerably smaller in extent than an ice sheet.

Ice sheet

A mass of land ice of continental size that is sufficiently thick to cover most of the underlying bed, so that its shape is mainly determined by its dynamics (the flow of the ice as it deforms internally and/or slides at its base). An ice sheet flows outward from a high central ice plateau with a small average surface slope. The margins usually slope more steeply, and most ice is discharged through fast flowing ice streams or outlet glaciers, in some cases into the sea or into ice shelves floating on the sea. There are only two ice sheets in the modern world, one on Greenland and one on Antarctica. During glacial periods there were others.

Ice shelf

A floating slab of ice of considerable thickness extending from the coast (usually of great horizontal extent with a very gently sloping surface), often filling embayments in the coastline of an ice sheet. Nearly all ice shelves are in Antarctica, where most of the ice discharged into the ocean flows via ice shelves.

(climate change) Impact assessment

The practice of identifying and evaluating, in monetary and/or non-monetary terms, the effects of climate change on natural and human systems.

Impacts (Consequences, Outcomes)[10]

Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Income

The maximum amount that a household, or other unit, can consume without reducing its real net worth. Total income is the broadest measure of income and refers to regular receipts such as wages and salaries, income from self-employment, interest and dividends from invested funds, pensions or other benefits from social insurance, and other current transfers receivable.[11]

Indian Ocean Dipole (IOD)

Large-scale mode of interannual variability of sea surface temperature in the Indian Ocean. This pattern manifests through a zonal gradient of tropical sea surface temperature, which in one extreme phase in boreal autumn shows cooling off Sumatra and warming off Somalia in the west, combined with anomalous easterlies along the equator.

Indigenous peoples

Indigenous peoples and nations are those that, having a historical continuity with pre-invasion and pre-colonial societies that developed on their territories, consider themselves distinct from other sectors of the societies now prevailing on those territories, or parts of them. They form at present principally non-dominant sectors of society and are often determined to preserve, develop, and transmit to future generations their ancestral territories, and their ethnic identity, as the basis of their continued existence as peoples, in accordance with their own cultural patterns, social institutions, and common law system.[12]

Industrial Revolution

A period of rapid industrial growth with far-reaching social and economic consequences, beginning in Britain during the second half of the 18th century and spreading to Europe and later to other countries including the United States. The invention of the steam engine was an important trigger of this development. The industrial revolution marks the beginning of a strong increase in the use of fossil fuels and emission of, in particular, fossil carbon dioxide. In this report the terms *preindustrial* and *industrial* refer, somewhat arbitrarily, to the periods before and after 1750, respectively.

Industrialized/developed/developing countries

There are a diversity of approaches for categorizing countries on the basis of their level of development, and for defining terms such as industrialized, developed, or developing. Several categorizations are used in this report. In the United Nations system, there is no established convention for the designation of developed and developing countries or areas. The United Nations Statistics Division specifies developed and developing regions based on common practice. In addition, specific countries are designated as least developed countries, landlocked

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[10] Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

[11] This glossary entry builds from the definition used in OECD (2003).

[12] This glossary entry builds from the definitions used in Cobo (1987) and previous IPCC reports.

developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. The World Bank uses income as the main criterion for classifying countries as low, lower middle, upper middle, and high income. The UNDP aggregates indicators for life expectancy, educational attainment, and income into a single composite human development index (HDI) to classify countries as low, medium, high, or very high human development. See Box 1-2.

Informal sector

Commercial enterprises (mostly small) that are not registered or that otherwise fall outside official rules and regulations. Among the businesses that make up the informal sector, there is great diversity in the value of the goods or services produced, the numbers employed, the extent of illegality, and the connection to the formal sector. Many informal enterprises have some characteristics of formal-sector enterprises, and some people are in informal employment in the formal sector as they lack legal protection or employment benefits.

Informal settlement

A term given to settlements or residential areas that by at least one criterion fall outside official rules and regulations. Most informal settlements have poor housing (with widespread use of temporary materials) and are developed on land that is occupied illegally with high levels of overcrowding. In most such settlements, provision for safe water, sanitation, drainage, paved roads, and basic services is inadequate or lacking. The term *slum* is often used for informal settlements, although it is misleading as many informal settlements develop into good quality residential areas, especially where governments support such development.

Institutions

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction. Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations—such as parliaments, regulatory agencies, private firms, and community bodies—develop and act in response to institutional frameworks and the incentives they frame. Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization.

Insurance/reinsurance

A family of financial instruments for sharing and transferring risk among a pool of at-risk households, businesses, and/or governments. See also Risk transfer.

Integrated assessment

A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions among these components, in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

Integrated Coastal Zone Management (ICZM)

An integrated approach for sustainably managing coastal areas, taking into account all coastal habitats and uses.

Invasive species/Invasive Alien Species (IAS)

A species introduced outside its natural past or present distribution (i.e., an alien species) that becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity (IUCN, 2000; CBD, 2002).

Key vulnerability, Key risk, Key impact

A vulnerability, risk, or impact relevant to the definition and elaboration of "dangerous anthropogenic interference (DAI) with the climate system," in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policy makers in that context.

Key risks are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered "key" due to high hazard or high vulnerability of societies and systems exposed, or both.

Vulnerabilities are considered "key" if they have the potential to combine with hazardous events or trends to result in key risks. Vulnerabilities that have little influence on climate-related risk, for instance, due to lack of exposure to hazards, would not be considered key.

Key impacts are severe consequences for humans and social-ecological systems.

Land grabbing

Large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities.

Land surface air temperature

The surface air temperature as measured in well-ventilated screens over land at 1.5 m above the ground.

Land use and Land use change

Land use refers to the total of arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions). The term *land use* is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). Land use change refers to a change in the use or management of land by humans, which may lead to a change in land cover. Land cover and land use change may have an impact on the surface albedo, evapotranspiration, sources and sinks of greenhouse gases, or other properties of the climate system and may thus give rise to radiative forcing and/or other impacts on climate, locally or globally. See also the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000).

La Niña

See El Niño-Southern Oscillation.

Last Glacial Maximum (LGM)

The period during the last ice age when the glaciers and ice sheets reached their maximum extent, approximately 21 ka ago. This period has been widely studied because the radiative forcings and boundary conditions are relatively well known.

Likelihood

The chance of a specific outcome occurring, where this might be estimated probabilistically. Likelihood is expressed in this report using a standard terminology (Mastrandrea et al., 2010), defined in Box 1-1. See also Confidence and Uncertainty.

Livelihood

The resources used and the activities undertaken in order to live. Livelihoods are usually determined by the entitlements and assets to which people have access. Such assets can be categorized as human, social, natural, physical, or financial.

Low regrets policy

A policy that would generate net social and/or economic benefits under current climate and a range of future climate change scenarios.

Maladaptive actions (Maladaptation)

Actions that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future.

Mean sea level

The surface level of the ocean at a particular point averaged over an extended period of time such as a month or year. Mean sea level is often used as a national datum to which heights on land are referred.

Meridional Overturning Circulation (MOC)

Meridional (north-south) overturning circulation in the ocean quantified by zonal (east-west) sums of mass transports in depth or density layers. In the North Atlantic, away from the subpolar regions, the MOC (which is in principle an observable quantity) is often identified with the thermohaline circulation (THC), which is a conceptual and incomplete interpretation. It must be borne in mind that the MOC is also driven by wind, and can also include shallower overturning cells such as occur in the upper ocean in the tropics and subtropics, in which warm (light) waters moving poleward are transformed to slightly denser waters and subducted equatorward at deeper levels. See also Thermohaline circulation.

Microclimate

Local climate at or near the Earth's surface. See also Climate.

Mitigation (of climate change)

A human intervention to reduce the sources or enhance the sinks of greenhouse gases.

Mitigation (of disaster risk and disaster)

The lessening of the potential adverse impacts of physical hazards (including those that are human-induced) through actions that reduce hazard, exposure, and vulnerability.

Mode of climate variability

Underlying space-time structure with preferred spatial pattern and temporal variation that helps account for the gross features in variance and for teleconnections. A mode of variability is often considered to be the product of a spatial climate pattern and an associated climate index time series.

Monsoon

A monsoon is a tropical and subtropical seasonal reversal in both the surface winds and associated precipitation, caused by differential heating between a continental-scale land mass and the adjacent ocean. Monsoon rains occur mainly over land in summer.

Non-climatic driver (Non-climate driver)

An agent or process outside the climate system that influences a human or natural system.

Nonlinearity

A process is called nonlinear when there is no simple proportional relation between cause and effect. The climate system contains many such nonlinear processes, resulting in a system with potentially very complex behavior. Such complexity may lead to abrupt climate change. See also Predictability.

North Atlantic Oscillation (NAO)

The North Atlantic Oscillation consists of opposing variations of surface pressure near Iceland and near the Azores. It therefore corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded extratropical cyclones with their associated frontal systems. See NAO Index in WGI AR5 Box 2.5.

Ocean acidification

Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011, p. 37).

Opportunity costs

The benefits of an activity forgone through the choice of another activity.

Outcome vulnerability (End-point vulnerability)

Vulnerability as the end point of a sequence of analyses beginning with projections of future emission trends, moving on to the development of climate scenarios, and concluding with biophysical impact studies and the identification of adaptive options. Any residual consequences that remain after adaptation has taken place define the levels of vulnerability (Kelly and Adger, 2000; O'Brien et al., 2007).

Oxygen Minimum Zone (OMZ)

The midwater layer (200 to 1000 m) in the open ocean in which oxygen saturation is the lowest in the ocean. The degree of oxygen depletion depends on the largely bacterial consumption of organic matter, and the distribution of the OMZs is influenced by large-scale ocean circulation. In coastal oceans, OMZs extend to the shelves and may also affect benthic ecosystems.

Ozone

Ozone, the triatomic form of oxygen (O_3), is a gaseous atmospheric constituent. In the troposphere, it is created both naturally and by photochemical reactions involving gases resulting from human activities (smog). Tropospheric ozone acts as a greenhouse gas. In the stratosphere, it is created by the interaction between solar ultraviolet radiation and molecular oxygen (O_2). Stratospheric ozone plays a dominant role in the stratospheric radiative balance. Its concentration is highest in the ozone layer.

Pacific Decadal Oscillation (PDO)

The pattern and time series of the first empirical orthogonal function of sea surface temperature over the North Pacific north of 20°N. The PDO broadened to cover the whole Pacific Basin is known as the Interdecadal Pacific Oscillation (IPO). The PDO and IPO exhibit similar temporal evolution.

Parameterization

In climate models, this term refers to the technique of representing processes that cannot be explicitly resolved at the spatial or temporal resolution of the model (sub-grid scale processes) by relationships between model-resolved larger-scale variables and the area- or time-averaged effect of such sub-grid scale processes.

Particulates

Very small solid particles emitted during the combustion of fossil and biomass fuels. Particulates may consist of a wide variety of substances. Of greatest concern for health are particulates of diameter less than or equal to 10 nm, usually designated as PM_{10}.

Pastoralism

A livelihood strategy based on moving livestock to seasonal pastures primarily in order to convert grasses, forbs, tree leaves, or crop residues into human food. The search for feed is however not the only reason for mobility; people and livestock may move to avoid various natural and/or social hazards, to avoid competition with others, or to seek more favorable conditions. Pastoralism can also be thought of as a strategy that is shaped by both social and ecological factors concerning uncertainty and variability of precipitation, and low and unpredictable productivity of terrestrial ecosystems.

Path dependence

The generic situation where decisions, events, or outcomes at one point in time constrain adaptation, mitigation, or other actions or options at a later point in time.

Permafrost

Ground (soil or rock and included ice and organic material) that remains at or below 0°C for at least 2 consecutive years.

Persistent Organic Pollutants (POPs)

Toxic organic chemical substances that persist in the environment for long periods of time, are transported and deposited in locations distant from their sources of release, bioaccumulate, and can have adverse effects on human health and ecosystems.[13]

Phenology

The relationship between biological phenomena that recur periodically (e.g., development stages, migration) and climate and seasonal changes.

Photochemical smog

A mix of oxidizing air pollutants produced by the reaction of sunlight with primary air pollutants, especially hydrocarbons.

Poverty

Poverty is a complex concept with several definitions stemming from different schools of thought. It can refer to material circumstances (such as need, pattern of deprivation, or limited resources), economic conditions (such as standard of living, inequality, or economic position), and/or social relationships (such as social class, dependency, exclusion, lack of basic security, or lack of entitlement).

Poverty trap

Poverty trap is understood differently across disciplines. In the social sciences, the concept, primarily employed at the individual, household, or community level, describes a situation in which escaping poverty becomes impossible due to unproductive or inflexible resources. A poverty trap can also be seen as a critical minimum asset threshold, below which families are unable to successfully educate their children, build up their productive assets, and get out of poverty. Extreme poverty is itself a poverty trap, since poor persons lack the means to participate meaningfully in society. In economics, the term *poverty trap* is often used at national scales, referring to a self-perpetuating condition where an economy, caught in a vicious cycle, suffers from persistent underdevelopment (Matsuyama, 2008). Many proposed models of poverty traps are found in the literature.

Predictability

The extent to which future states of a system may be predicted based on knowledge of current and past states of the system. Because knowledge of the climate system's past and current states is generally imperfect, as are the models that utilize this knowledge to produce a climate prediction, and because the climate system is inherently nonlinear and chaotic, predictability of the climate system is inherently limited. Even with arbitrarily accurate models and observations, there may still be limits to the predictability of such a nonlinear system (AMS, 2000).

Preindustrial

See Industrial Revolution.

Probability Density Function (PDF)

A probability density function is a function that indicates the relative chances of occurrence of different outcomes of a variable. The function integrates to unity over the domain for which it is defined and has the property that the integral over a sub-domain equals the probability that the outcome of the variable lies within that sub-domain. For example, the probability that a temperature anomaly defined in a particular way is greater than zero is obtained from its PDF by integrating the PDF over all possible temperature anomalies greater than zero. Probability density functions that describe two or more variables simultaneously are similarly defined.

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[13] This glossary entry builds from the definition in the Stockholm Convention on Persistent Organic Pollutants (Secretariat of the Stockholm Convention, 2001).

Projection
A projection is a potential future evolution of a quantity or set of quantities, often computed with the aid of a model. Unlike predictions, projections are conditional on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized. See also Climate prediction and Climate projection.

Proxy
A proxy climate indicator is a record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time. Climate-related data derived in this way are referred to as proxy data. Examples of proxies include pollen analysis, tree ring records, speleothems, characteristics of corals, and various data derived from marine sediments and ice cores. Proxy data can be calibrated to provide quantitative climate information.

Public good
A good that is both non-excludable and non-rivalrous in that individuals cannot be effectively excluded from use and where use by one individual does not reduce availability to others.

Radiative forcing
Radiative forcing is the change in the net, downward minus upward, radiative flux (expressed in W m^{-2}) at the tropopause or top of atmosphere due to a change in an external driver of climate change, such as a change in the concentration of carbon dioxide or the output of the Sun. Sometimes internal drivers are still treated as forcings even though they result from the alteration in climate, for example aerosol or greenhouse gas changes in paleoclimates. The traditional radiative forcing is computed with all tropospheric properties held fixed at their unperturbed values, and after allowing for stratospheric temperatures, if perturbed, to readjust to radiative-dynamical equilibrium. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. The radiative forcing once rapid adjustments are accounted for is termed the effective radiative forcing. For the purposes of this report, radiative forcing is further defined as the change relative to the year 1750 and, unless otherwise noted, refers to a global and annual average value. Radiative forcing is not to be confused with cloud radiative forcing, which describes an unrelated measure of the impact of clouds on the radiative flux at the top of the atmosphere.

Reanalysis
Reanalyses are estimates of historical atmospheric temperature and wind or oceanographic temperature and current, and other quantities, created by processing past meteorological or oceanographic data using fixed state-of-the-art weather forecasting or ocean circulation models with data assimilation techniques. Using fixed data assimilation avoids effects from the changing analysis system that occur in operational analyses. Although continuity is improved, global reanalyses still suffer from changing coverage and biases in the observing systems.

Reasons for concern
Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be "dangerous" (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

Reference scenario
See Baseline/reference.

Reflexivity
A system attribute where cause and effect form a feedback loop, in which the effect changes the system itself. Self-adapting systems such as societies are inherently reflexive, as are planned changes in complex systems. Reflexive decision making in a social system has the potential to change the underpinning values that led to those decisions. Reflexivity is also an important aspect of adaptive management.

Reforestation
Planting of forests on lands that have previously contained forests but that have been converted to some other use. For a discussion of the term *forest* and related terms such as *afforestation*, *reforestation*, and *deforestation*, see the IPCC Special Report on Land Use, Land-Use Change, and Forestry (IPCC, 2000). See also the Report on Definitions and Methodological Options to Inventory Emissions from Direct Human-induced Degradation of Forests and Devegetation of Other Vegetation Types (IPCC, 2003).

Relative sea level
Sea level measured by a tide gauge with respect to the land upon which it is situated. See also Mean sea level and Sea level change.

Representative Concentration Pathways (RCPs)
Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word *representative* signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. The term *pathway* emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome (Moss et al., 2010).

RCPs usually refer to the portion of the concentration pathway extending up to 2100, for which Integrated Assessment Models produced corresponding emission scenarios. Extended Concentration Pathways (ECPs) describe extensions of the RCPs from 2100 to 2500 that were calculated using simple rules generated by stakeholder consultations, and do not represent fully consistent scenarios.

Four RCPs produced from Integrated Assessment Models were selected from the published literature and are used in the present IPCC Assessment as a basis for the climate predictions and projections in WGI AR5 Chapters 11 to 14:

> ***RCP2.6*** One pathway where radiative forcing peaks at approximately 3 W m^{-2} before 2100 and then declines (the corresponding ECP assuming constant emissions after 2100).
>
> ***RCP4.5 and RCP6.0*** Two intermediate stabilization pathways in which radiative forcing is stabilized at approximately 4.5 W m^{-2} and 6.0 W m^{-2} after 2100 (the corresponding ECPs assuming constant concentrations after 2150).

RCP8.5 One high pathway for which radiative forcing reaches greater than 8.5 W m^{-2} by 2100 and continues to rise for some amount of time (the corresponding ECP assuming constant emissions after 2100 and constant concentrations after 2250).

For further description of future scenarios, see WGI AR5 Box 1.1.

Resilience

The capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.[14]

Return period

An estimate of the average time interval between occurrences of an event (e.g., flood or extreme rainfall) of (or below/above) a defined size or intensity. See also Return value.

Return value

The highest (or, alternatively, lowest) value of a given variable, on average occurring once in a given period of time (e.g., in 10 years). See also Return period.

Risk

The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values.[15] Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Risk assessment

The qualitative and/or quantitative scientific estimation of risks.

Risk management

Plans, actions, or policies to reduce the likelihood and/or consequences of risks or to respond to consequences.

Risk perception

The subjective judgment that people make about the characteristics and severity of a risk.

Risk transfer

The practice of formally or informally shifting the risk of financial consequences for particular negative events from one party to another.

Runoff

That part of precipitation that does not evaporate and is not transpired, but flows through the ground or over the ground surface and returns to bodies of water. See also Hydrological cycle.

Salt-water intrusion/encroachment

Displacement of fresh surface water or groundwater by the advance of salt water due to its greater density. This usually occurs in coastal and estuarine areas due to decreasing land-based influence (e.g., from reduced runoff or groundwater recharge, or from excessive water withdrawals from aquifers) or increasing marine influence (e.g., relative sea level rise).

Scenario

A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (e.g., rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions. See also Climate scenario, Emission scenario, Representative Concentration Pathways, and SRES scenarios.

Sea level change

Sea level can change, both globally and locally due to (1) changes in the shape of the ocean basins, (2) a change in ocean volume as a result of a change in the mass of water in the ocean, and (3) changes in ocean volume as a result of changes in ocean water density. Global mean sea level change resulting from change in the mass of the ocean is called barystatic. The amount of barystatic sea level change due to the addition or removal of a mass of water is called its sea level equivalent (SLE). Sea level changes, both globally and locally, resulting from changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric. Barystatic and steric sea level changes do not include the effect of changes in the shape of ocean basins induced by the change in the ocean mass and its distribution. See also Relative sea level and Thermal expansion.

Sea Surface Temperature (SST)

The sea surface temperature is the subsurface bulk temperature in the top few meters of the ocean, measured by ships, buoys, and drifters. From ships, measurements of water samples in buckets were mostly switched in the 1940s to samples from engine intake water. Satellite measurements of skin temperature (uppermost layer; a fraction of a millimeter thick) in the infrared or the top centimeter or so in the microwave are also used, but must be adjusted to be compatible with the bulk temperature.

Semi-arid zone

Areas where vegetation growth is constrained by limited water availability, often with short growing seasons and high interannual variation in primary production. Annual precipitation ranges from 300 to 800 mm, depending on the occurrence of summer and winter rains.

Sensitivity

The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range,

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[14] This definition builds from the definition used in Arctic Council (2013).

[15] This definition builds from the definitions used in Rosa (1998) and Rosa (2003).

or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Significant wave height
The average trough-to-crest height of the highest one-third of the wave heights (sea and swell) occurring in a particular time period.

Sink
Any process, activity, or mechanism that removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas or aerosol from the atmosphere.

Social Cost of Carbon (SCC)
The net present value of climate damages (with harmful damages expressed as a positive number) from one more tonne of carbon in the form of CO_2, conditional on a global emissions trajectory over time.

Social protection
In the context of development aid and climate policy, social protection usually describes public and private initiatives that provide income or consumption transfers to the poor, protect the vulnerable against livelihood risks, and enhance the social status and rights of the marginalized, with the overall objective of reducing the economic and social vulnerability of poor, vulnerable, and marginalized groups (Devereux and Sabates-Wheeler, 2004). In other contexts, social protection may be used synonymously with social policy and can be described as all public and private initiatives that provide access to services, such as health, education, or housing, or income and consumption transfers to people. Social protection policies protect the poor and vulnerable against livelihood risks and enhance the social status and rights of the marginalized, as well as prevent vulnerable people from falling into poverty.

Socioeconomic scenario
A scenario that describes a possible future in terms of population, gross domestic product, and other socioeconomic factors relevant to understanding the implications of climate change.

Southern Annular Mode (SAM)
The leading mode of variability of Southern Hemisphere geopotential height, which is associated with shifts in the latitude of the midlatitude jet. See SAM Index in WGI AR5 Box 2.5.

Species distribution modeling
Simulation of ecological effects of climate change. Species distribution modeling uses statistically or theoretically derived response surfaces to relate observations of species occurrence or known tolerance limits to environmental predictor variables, thereby predicting a species' range as the manifestation of habitat characteristics that limit or support its presence at a particular location. Species distribution models are also referred to as environmental niche models. Bioclimate envelope models can be considered as a subset of species distribution models that predict species occurrence or habitat suitability based on climatic variables only.

SRES scenarios
SRES scenarios are emission scenarios developed by Nakićenović and Swart (2000) and used, among others, as a basis for some of the climate projections shown in Chapters 9 to 11 of IPCC (2001) and Chapters 10 and 11 of IPCC (2007). The following terms are relevant for a better understanding of the structure and use of the set of SRES scenarios:

> ***Scenario family*** Scenarios that have a similar demographic, societal, economic, and technical change storyline. Four scenario families comprise the SRES scenario set: A1, A2, B1, and B2.
>
> ***Illustrative scenario*** A scenario that is illustrative for each of the six scenario groups reflected in the Summary for Policymakers of Nakićenović and Swart (2000). They include four revised marker scenarios for the scenario groups A1B, A2, B1, and B2, and two additional scenarios for the A1FI and A1T groups. All scenario groups are equally sound.
>
> ***Marker scenario*** A scenario that was originally posted in draft form on the SRES web site to represent a given scenario family. The choice of markers was based on which of the initial quantifications best reflected the storyline, and the features of specific models. Markers are no more likely than other scenarios, but are considered by the SRES writing team as illustrative of a particular storyline. They are included in revised form in Nakićenović and Swart (2000). These scenarios received the closest scrutiny of the entire writing team and via the SRES open process. Scenarios were also selected to illustrate the other two scenario groups.
>
> ***Storyline*** A narrative description of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces, and the dynamics of their evolution.

Storm surge
The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place.

Storm tracks
Originally, a term referring to the tracks of individual cyclonic weather systems, but now often generalized to refer to the main regions where the tracks of extratropical disturbances occur as sequences of low (cyclonic) and high (anticyclonic) pressure systems.

Stratosphere
The highly stratified region of the atmosphere above the troposphere extending from about 10 km (ranging from 9 km at high latitudes to 16 km in the tropics on average) to about 50 km altitude.

Stressors
Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate-related risk.

Subsistence agriculture
Farming and associated activities that together form a livelihood strategy in which most output is consumed directly but some may be sold at market. Subsistence agriculture can be one of several livelihood activities.

Surface temperature
See Global mean surface temperature, Land surface air temperature, and Sea Surface Temperature.

Sustainability
A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

Sustainable development
Development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

Thermal expansion
In connection with sea level, this refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level. See also Sea level change.

Thermocline
The layer of maximum vertical temperature gradient in the ocean, lying between the surface ocean and the abyssal ocean. In subtropical regions, its source waters are typically surface waters at higher latitudes that have subducted and moved equatorward. At high latitudes, it is sometimes absent, replaced by a halocline, which is a layer of maximum vertical salinity gradient.

Thermohaline circulation (THC)
Large-scale circulation in the ocean that transforms low-density upper ocean waters to higher-density intermediate and deep waters and returns those waters back to the upper ocean. The circulation is asymmetric, with conversion to dense waters in restricted regions at high latitudes and the return to the surface involving slow upwelling and diffusive processes over much larger geographic regions. The THC is driven by high densities at or near the surface, caused by cold temperatures and/or high salinities, but despite its suggestive though common name, is also driven by mechanical forces such as wind and tides. Frequently, the name THC has been used synonymously with Meridional Overturning Circulation. See also Meridional Overturning Circulation.

Tipping point
A level of change in system properties beyond which a system reorganizes, often abruptly, and does not return to the initial state even if the drivers of the change are abated.[16]

Traditional knowledge
The knowledge, innovations, and practices of both indigenous and local communities around the world that are deeply grounded in history and experience. Traditional knowledge is dynamic and adapts to cultural and environmental change, and also incorporates other forms of knowledge and viewpoints. Traditional knowledge is generally transmitted orally from generation to generation. It is often used as a synonym for indigenous knowledge, local knowledge, or traditional ecological knowledge.

Transformation
A change in the fundamental attributes of natural and human systems.

Tree line
The upper limit of tree growth in mountains or at high latitudes. It is more elevated or more poleward than the forest line.

Tropical cyclone
A strong, cyclonic-scale disturbance that originates over tropical oceans. Distinguished from weaker systems (often named tropical disturbances or depressions) by exceeding a threshold wind speed. A tropical storm is a tropical cyclone with 1-minute average surface winds between 18 and 32 $m\ s^{-1}$. Beyond 32 $m\ s^{-1}$, a tropical cyclone is called a hurricane, typhoon, or cyclone, depending on geographic location.

Troposphere
The lowest part of the atmosphere, from the surface to about 10 km in altitude at mid-latitudes (ranging from 9 km at high latitudes to 16 km in the tropics on average), where clouds and weather phenomena occur. In the troposphere, temperatures generally decrease with height. See also Stratosphere.

Tsunami
A wave, or train of waves, produced by a disturbance such as a submarine earthquake displacing the sea floor, a landslide, a volcanic eruption, or an asteroid impact.

Tundra
A treeless biome characteristic of polar and alpine regions.

Uncertainty
A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behavior. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts) (see Moss and Schneider, 2000; Manning et al., 2004; Mastrandrea et al., 2010). See also Confidence and Likelihood.

United Nations Framework Convention on Climate Change (UNFCCC)
The Convention was adopted on 9 May 1992 in New York and signed at the 1992 Earth Summit in Rio de Janeiro by more than 150 countries and the European Community. Its ultimate objective is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." It contains commitments for all Parties. Under the Convention, Parties included in Annex I (all OECD countries and countries with economies in transition) aim to return greenhouse gas emissions not controlled by the Montreal Protocol to 1990 levels by the year 2000. The convention entered in force in March 1994. In 1997, the UNFCCC adopted the Kyoto Protocol.

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[16] The glossary for the Working Group I contribution to the Fifth Assessment Report defines tipping point in the context of climate: "In climate, a hypothesized critical threshold when global or regional climate changes from one stable state to another stable state. The tipping point event may be irreversible."

Uptake

The addition of a substance of concern to a reservoir. The uptake of carbon containing substances, in particular carbon dioxide, is often called (carbon) sequestration.

Upwelling region

A region of an ocean where cold, typically nutrient-rich waters well up from the deep ocean.

Urban heat island

The relative warmth of a city compared with surrounding rural areas, associated with changes in runoff, effects on heat retention, and changes in surface albedo.

Volatile Organic Compounds (VOCs)

Important class of organic chemical air pollutants that are volatile at ambient air conditions. Other terms used to represent VOCs are *hydrocarbons* (HCs), *reactive organic gases* (ROGs), and *non-methane volatile organic compounds* (NMVOCs). NMVOCs are major contributors (together with NO_X and CO) to the formation of photochemical oxidants such as ozone.

Vulnerability[17]

The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. See also Contextual vulnerability and Outcome vulnerability.

Vulnerability index

A metric characterizing the vulnerability of a system. A climate vulnerability index is typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability.

Water cycle

See Hydrological cycle.

Water-use efficiency

Carbon gain by photosynthesis per unit of water lost by evapotranspiration. It can be expressed on a short-term basis as the ratio of photosynthetic carbon gain per unit transpirational water loss, or on a seasonal basis as the ratio of net primary production or agricultural yield to the amount of water used.

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[17] Reflecting progress in science, this glossary entry differs in breadth and focus from the entry used in the Fourth Assessment Report and other IPCC reports.

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ANNEX III

Acronyms

20CR	20th Century Reanalysis
AAL	average annual loss
ABNJ	Areas Beyond National Jurisdiction
ACC	Antarctic Circumpolar Current
ACCCA	Advancing Capacity for Climate Change Adaptation
ACRE	Atmospheric Circulation Reconstructions over the Earth
AF	Adaptation Fund
AFTA	ASEAN Free Trade Agreement
AGCM	Atmosphere General Circulation Models
AgMIP	Agricultural Model Intercomparison and Improvement Project
AGWA	Alliance for Global Water Adaptation
AIM	Asia-Pacific Integrated Model
AMMA	African Monsoon Multidisciplinary Analysis
AMO	Atlantic Multi-decadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
AMU	Arab Maghreb Union
AOC	Appellation d'Origine Controlee
AOGCMs	Atmosphere-Ocean General Circulation Model
AOSIS	Alliance Of Small Island States
APHRODITE	Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
ARPEGE	Action de Recherche Petite Echelle Grande Echelle
ASEAN	Association of Southeast Asian Nations
ASH	Aragonite Saturation Horizon
ASP	adaptive social protection
AVHRR	Advanced Very High Resolution Radiometer
BATS	Bermuda Atlantic Time-series Study
BAU	business as usual
BFIs	Bilateral Finance Institutions
C^{4}MIP	Carbon Cycle Model Intercomparison Project
CAADP	Comprehensive Africa Agriculture Development Program
CaCO$_3$	calcium carbonate
CAF	Cancun Adaptation Framework
CAP	Common Agricultural Policy
CAPS	climate-altering pollutants
CARLA	Climate Adaptation for Rural Livelihoods and Agriculture
CBA	community-based adaptation
CBAA	Community-Based Adaptation in Africa
CBD	Convention on Biological Diversity
CBDRR	community-based disaster risk reduction
CBNRM	community-based natural resource management
CBS	Coastal Boundary Systems
CC	community composition
CCA	climate change adaptation
CCAD	Central American Commission for Environment and Development
CCAFS	Climate Change Agriculture and Food Security
CCAMLR	Commission for the Conservation of Antarctic Marine Living Resources
CCM	carbon-concentrating mechanism
CCRA	Climate Change Risk Assessment
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CCS	carbon capture and storage
CCSM	Community Climate System Model
CDM	Clean Development Mechanism
CDR	carbon dioxide removal
CEN-SAD	Community of Sahel-Saharan States
CER	certified emissions reduction
CFP	Ciguatera fish poisoning
CFP	Common Fisheries Policy
CFSR	Climate Forecast System Reanalysis
CGCM	Coupled General Circulation Model
CGE	Computable General Equilibrium
CGIAR	Consultative Group on International Agricultural Research
CH$_4$	methane
CIAV	climate impact, adaptation, and vulnerability
CIL	Cold Intermediate Layer
CILSS	Permanent Inter-States Committee for Drought Control in the Sahel
CLARIS	Europe-South America Network for Climate Change Assessment and Impact Studies
Climate-ADAPT	Climate Adaptation Platform
CLIVAR	Climate Variability and Predictability Programme
CLLJ	Caribbean Low Level Jet
CLRTAP	Convention on Long-range Transboundary Air Pollution
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM	Centre National de Recherches Météorologiques
CO$_2$	carbon dioxide
COADS	Comprehensive Ocean-Atmosphere Data Set
COMESA	Common Market for Eastern and Southern Africa
COMIFAC	Commission of Central African Forests
CORDEX	Coordinated Regional Downscaling Experiment
CPIA	Country Policy and Institutional Assessment
CPP	Cyclone Preparedness Program
CRED	Centre for Research on the Epidemiology of Disasters
CRiSTAL	Community-based Risk Screening Tool-Adaptation and Livelihoods
CRUTEM4	Climatic Research Unit/Hadley Centre gridded land-surface air temperature version 4
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	concentrating solar power
CTI	Coral Triangle Initiative
CTM	Chemical Transport Model
CTP	carbon from thawed permafrost
DAI	dangerous anthropogenic interference
DALYs	disability-adjusted life years
Defra	Department for Environment Food and Rural Affairs
DGVM	Dynamic Global Vegetation Model
DHMs	degree heating months
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DIVA	Dynamic Interactive Vulnerability Assessment
DJF	December-January-February
DMS	dimethylsulfide

DNCs	dark needle conifers
DO	Dansgaard-Oeschger
DOC	Denominazione di Origine Controllata
DOCG	Denominazione di Origine Controllata e Garantita
DOM	dissolved organic matter
DRM	disaster risk management
DRR	disaster risk reduction
DS	Deep Sea
E&V	exposure and vulnerability
EAC	East African Community
EAC	East Australian Current
EAM	East Asian Monsoon
EbA	Ecosystem-based Adaptation
EBUE	Eastern Boundary Upwelling Ecosystems
ECCAS	Economic Community of Central African States
ECHAM4	European Centre for Medium Range Weather Forecasts and Hamburg 4
ECLAC	Economic Commission for Latin America and the Caribbean
ECO	European Climate Change Oscillation
ECOWAS	Economic Community of West African States
ECP	Extended Concentration Pathway
EEZs	exclusive economic zones
EIs	economic instruments
ENM	Ecological Niche Model
ENSO	El Niño-Southern Oscillation
ERA	European Centre for Medium Range Weather Forecasts Reanalyses
ERSST	Extended Reconstructed SST
ESCI	Emerging and Sustainable Cities Initiative
ESCOs	Energy Service Companies
ESM	Earth System Model
ESPACE	European Spatial Planning Adapting to Climate Events Project
ETCCDI	Expert Team on Climate Change Detection and Indices
ETCs	extratropical cyclones
EU	European Union
EUS	Equatorial Upwelling System
EWS	early warning systems
EWS	Eelpout in the Wadden Sea
FACE	Free Air CO_2 Enrichment
FACE	free atmosphere carbon exchange
FADs	fish-aggregating devices
FAO	Food and Agriculture Organization
FAR	First Assessment Report
FCP	Fisheries Catch Potential
FDIs	foreign direct investments
FEWS NET	Famine Early Warning Systems Network
FFDI	Forest Fire Danger Index
FONDEN	Fondo de Desastres Naturales
FUND	Framework for Uncertainty, Negotiation and Distribution
GAIN	Global Adaptation Alliance
GANs	Global Action Networks
GCAM	Global Change Assessment Model
GCM	General Circulation Model
GCMs	Global Climate Models
GDIs	gross domestic investments
GDP	gross domestic product
GEF	Global Environmental Facility
GENIE	Grid Enabled Integrated Earth System Model
GFDL-CM2	Geophysical Fluid Dynamics Laboratory Coupled Model version 2
GHG	greenhouse gas
GHM	Global Hydrological Model
GIS	Geographic Information System
GISS	Goddard Institute of Space Studies
GISTEMP	Goddard Institute for Space Studies Surface Temperature Analysis
GLADA	Global Land Degradation Assessment and Improvement
GLISA	Great Lakes Integrated Sciences and Assessments
GLOF	glacier lake outburst flood
GMOs	genetically modified organisms
GMSL	global mean sea level
GMSLR	global mean sea level rise
GMST	global mean surface temperature
GMT	global mean temperature
GNP	Gross National Product
gNPP	global NPP
GPCC	Global Precipitation Climatology Centre
GPP	Gross Primary Productivity
GS	governance structures
HABs	harmful algal blooms
HadCM3	Hadley Centre climate prediction model 3
HadCRUT4	Hadley Centre/climatic research unit gridded surface temperature data set 4
HadCRUT4.2	Hadley Centre/climatic research unit gridded surface temperature data set 4.2
HadGEM2-ES	Hadley Centre new Global Environmental Model version 2 Earth System
HadRM3	Hadley Centre Regional Model 3
HARITA	Horn of Africa Risk Transfer for Adaptation
HDI	Human Development Index
HE	hypoxia effect
HIC	high-income country
HIRHAM	HIgh-Resolution HAMburg climate Model
HLSBS	High-Latitude Spring Bloom Systems
HNLC	high-nutrient low-chlorophyll
HOT	Hawaii Ocean Time series
HY-INT	hydroclimatic intensity
I&FF	investment and financial flows
IAM	Integrated Assessment Model
IAS	invasive alien species
IAV	impacts, adaptation, and vulnerability
ICLEI	International Council for Local Environmental Initiatives
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
ICPAC	International Climate Prediction and Applications Centre
ICTs	information and communication technologies
ICZM	Integrated Coastal Zone Management

IDB	Inter-American Development Bank
IEA	International Energy Agency
IGAD	Intergovernmental Authority on Development
IHO	International Hydrographic Organization
IJEPA	Indonesia-Japan Economic Partnership Agreement
ILO	International Labor Organization
iLUC	indirect land use change
IMAGE	Integrated Model to Assess the Global Environment
IMF	International Monetary Fund
IMO	International Maritime Organization
IOD	Indian Ocean Dipole
IOM	International Organization of Migration
IPO	Inter-decadal Pacific Oscillation
IPY	International Polar Year
ISFS	Invasive Species Forecasting System
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
ISPS	International Ship and Port Facility Security
ITCZ	Intertropical Convergence Zone
ITF	Indonesian Throughflow
IUCN	International Union for Conservation of Nature
IUPA	Index of Usefulness of Practices for Adaptation
IUU	illegal, unreported, and unregulated
IWRM	Integrated Water Resource Management
JGOFS	Joint Global Ocean Flux Study
JI	Joint Implementation
JJA	June-July-August
JMA	Japan Meteorological Agency
KOE	Kuroshio-Oyashio Extension
KVs	Key Vulnerabilities
LAPA	Local Adaptation Plans of Action
LDCF	Least Developed Countries Fund
LDCs	Least Developed Countries
LECZ	low-elevation coastal zone
LGM	Last Glacial Maximum
LIC	low-income country
LiDAR	Light Detection And Ranging
LMB	Lower Mekong River Basin
LMICs	lower middle-income countries
LP	London Protocol
LPB	La Plata Basin
LSLA	large-scale land acquisitions
LUCC	land use and cover change
M&A	mitigation and adaptation
MAB	Marine Air Breathers
MAGICC	Model for the Assessment of Greenhouse gas Induced Climate Change
MAM	March-April-May
MAP	mean annual precipitation
MARPOL	International Convention for the Prevention of Pollution From Ships
MBIs	market-based instruments
MCA	multi-criteria analysis
MCDA	multi-criteria decision analysis
MDB	Marine Data Bank
MDB	Multilateral Development Bank
MDBA	Murray-Darling Basin Authority
MDGs	Millennium Development Goals

MEA	Millennium Ecosystem Assessment
MERCOSUR	Mercado Común del Sur
MERRA	Modern Era Reanalysis for Research and Applications
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MFIs	Multilateral Financial Institutions
MICs	medium-income country
MIROC	Model for Interdisciplinary Research On Climate
MLD	mixed layer depth
MLOST	Merged Land-Ocean Surface Temperature
MME	Multi-Model Ensemble
MMM	Maximum Monthly Mean
MOC	Meridional Overturning Circulation
MODIS	Moderate Resolution Imaging Spectrometer
MOSE	MOdulo Sperimentale Elettromeccanico
MPAs	marine protected areas
MPI	Max Planck Institute
MRC	Mekong River Commission
MRI-AGCMS	Meteorological Research Institute of Japan Meteorological Agency
MRSP	Metropolitan Region of São Paulo
MSL	mean sea level
MWF	mid-water fishes
NAFTA	North American Free Trade Agreement
NAMS	North American Monsoon System
NAO	North Atlantic Oscillation
NAP	National Adaptation Plan
NAPA	National Adaptation Programme of Action
NARCCAP	North American Regional Climate Change Assessment Program
NARR	North American Regional Reanalysis
NCAR	National Center for Atmospheric Research
NCCARF	National Climate Change Adaptation Research Facility
NCCRS	National Climate Change Response Strategies
NCDC	National Climate Data Center
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEB	northeast Brazil
NEPAD	New Partnership for Africa's Development
NGO	non-governmental organization
NH	Northern Hemisphere
NIES	National Institute for Environmental Studies
NNR	NCEP-NCAR Reanalyses
NOAA	National Oceanic and Atmospheric Administration
NPGO	North Pacific Gyre Oscillation
NPP	Net Primary Productivity
NRM	Natural Resource Management
NSR	Northern Sea Route
NWP	Northwest Passage
O_{2crit}	critical O_2 concentration
O_3	ozone
OA	ocean acidification
OAE	ocean acidification effect
OC	organic carbon
OCLTT	Oxygen and Capacity Limited Thermal Tolerance
ODA	Official Development Assistance

OECD	Organisation for Economic Co-operation and Development
OMZ	Oxygen Minimum Zone
OND	October-November-December
OPEC	Organization of the Petroleum Exporting Countries
PACC	Pacific Adaptation to Climate Change Project
$p\mathrm{CO}_2$	CO_2 partial pressures
PDF	Probability Density Function
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PEMSEA	Partnerships in Environmental Management for the Seas of East Asia
PES	Payment for Environmental Services
PESETA	Projections of Economic impacts of climate change in Sectors of Europe based on bottom-up analysis
PETM	Paleocene-Eocene Thermal Maximum
PFEL	Pacific Fisheries Environmental Laboratory,
PIACC	Ibero-American Programme on Adaptation to Climate Change
$\mathrm{PM}_{2.5}$	particulate matter with aerodynamic diameter <2.5 µm
PM_5	particulate matter with aerodynamic diameter <5 µm
PNA	Pacific North America
POM	particulate organic matter
POPs	persistent organic pollutants
PP	Plankton Phenology
PPCR	Pilot Program for Climate Resilience
PRECIS	Providing REgional Climates for Impact Studies
PROVIA	Programme of Research on Climate Change Vulnerability, Impacts and Adaptation
PSS78	Practical Salinity Scale 1978
PV	photovoltaic
PVA	participatory vulnerability assessment
PWC	Pacific Walker Circulation
RAC	Regional Adaptation Collaborative
RCA 3	Rossby Centre regional Atmospheric model 3
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RDM	robust decision making
RECs	Regional Economic Communities
REDD+	Reduction of Emissions from Deforestation and Forest Degradation
RFC	Reasons for Concern
RFMO	Regional Fisheries Management Organization
RICE	Regional dynamic Integrated model of Climate and the Economy
RISAs	Regional Integrated Sciences and Assessments
ROI	return on investment
RSLR	relative sea level rise
RWCs	reef-building warm-water corals
SADC	Southern African Development Community
SAM	Southern Annular Mode
SAMS	South American Monsoon System
SAR	synthetic aperture radar
SAR	Second Assessment Report
SAS	Southeast Asian Seas
SCC	social cost of carbon
SCS	South China Sea
SDGs	Sustainable Development Goals
SDM	species distribution modeling
SE	synergistic effects
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SED	socioeconomic development
SEI	Stockholm Environment Institute
SES	Semi-Enclosed Seas
SICA	Sistema de la Integración Centroamericana
SIDS	Small Island Developing States
SLP	sea level pressure
SLR	sea level rise
SMEs	small to medium enterprises
SO_2	sulfur dioxide
SP	social protection
SPAs	Shared Policy Assumptions
SPCRs	Strategic Programmes for Climate Resilience
SPCZ	South Pacific Convergence Zone
SPM	Summary for Policymakers
SPREP	South Pacific Regional Environmental Programme
SR	Species Richness
SRC	short rotation coppice
SRES	Special Report on Emission Scenarios
SREX	Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SRM	Solar Radiation Management
SRREN	Special Report on Renewable Energy Sources and Climate Change Mitigation
SSFs	small-scale fisheries
SSP	Shared Socioeconomic Pathway
SST	sea surface temperature
STF	subtropical front
STG	subtropical gyre
SWH	significant wave height
TAR	Third Assessment Report
TBE	tick-borne encephalitis
TC	tropical cyclone
TE	temperature effect
TEK	traditional ecological knowledge
TEP	transparent exopolymer particle
TH	thermal heating
THC	thermohaline circulation
THI	Temperature-Humidity Index
TRMM	Tropical Rainfall Measuring Mission
UCL	urban canopy layer
UHI	urban heat island
UKCIP	UK Climate Impacts Program
UMIC	upper middle income country
UNCLOS	United Nations Convention on the Law of the Sea
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNHCR	United Nations High Commissioner for Refugees
UNSFSA	United Nations Straddling Fish Stocks Agreement
UV	ultraviolet

VCO	voluntary carbon offset
VOCs	volatile organic compounds
WAP	western Antarctic Peninsula
WASWind	Wave- and Anemometer-based Sea Surface Wind
WaterMIP	Water Model Intercomparison Project
WB	World Bank
WCRP	World Climate Research Programme
WHO	World Health Organization
WIPO	World Intellectual Property Organization
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WTO	World Trade Organization
WUCA	Water Utilities Climate Alliance
WUE	water use efficiency

ANNEX IV

List of Major IPCC Reports

Climate Change: The IPCC Scientific Assessment
Report of the IPCC Scientific Assessment Working Group
1990

Climate Change: The IPCC Impacts Assessment
Report of the IPCC Impacts Assessment Working Group
1990

Climate Change: The IPCC Response Strategies
Report of the IPCC Response Strategies Working Group
1990

Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment
Report of the IPCC Scientific Assessment Working Group
1992

Climate Change 1992: The Supplementary Report to the IPCC Impacts Assessment
Report of the IPCC Impacts Assessment Working Group
1992

Climate Change: The IPCC 1990 and 1992 Assessments – IPCC First Assessment Report Overview and Policymaker Summaries, and 1992 IPCC Supplement
1992

Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios
IPCC Special Report
1994

IPCC Guidelines for National Greenhouse Gas Inventories
1994

Climate Change 1995: The Science of Climate Change
Contribution of Working Group I
to the IPCC Second Assessment Report
1996

Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses
Contribution of Working Group II
to the IPCC Second Assessment Report
1996

Climate Change 1995: Economic and Social Dimensions of Climate Change
Contribution of Working Group III
to the IPCC Second Assessment Report
1996

Climate Change 1995: IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change
1996

Technologies, Policies, and Measures for Mitigating Climate Change
IPCC Technical Paper I
1996

Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories
1996

An Introduction to Simple Climate Models used in the IPCC Second Assessment Report
IPCC Technical Paper II
1997

Stabilization of Atmospheric Greenhouse Gases: Physical, Biological, and Socio-Economic Implications
IPCC Technical Paper III
1997

Implications of Proposed CO_2 Emissions Limitations
IPCC Technical Paper IV
1997

The Regional Impacts of Climate Change
IPCC Special Report
1998

Aviation and the Global Atmosphere
IPCC Special Report
1999

Methodological and Technological Issues in Technology Transfer
IPCC Special Report
2000

Land Use, Land-Use Change, and Forestry
IPCC Special Report
2000

Emissions Scenarios
IPCC Special Report
2000

Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories
2000

Climate Change 2001: The Scientific Basis
Contribution of Working Group I
to the IPCC Third Assessment Report
2001

Climate Change 2001: Impacts, Adaptation, and Vulnerability
Contribution of Working Group II
to the IPCC Third Assessment Report
2001

Climate Change 2001: Mitigation
Contribution of Working Group III
to the IPCC Third Assessment Report
2001

Climate Change 2001: IPCC Third Assessment Synthesis Report
2001

Climate Change and Biodiversity
IPCC Technical Paper V
2002

Good Practice Guidance for Land Use, Land-Use Change, and Forestry
2003

Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons
IPCC Special Report
2005

Carbon Dioxide Capture and Storage
IPCC Special Report
2005

2006 IPCC Guidelines for National Greenhouse Gas Inventories
2006

Climate Change 2007: The Physical Science Basis
Contribution of Working Group I
to the IPCC Fourth Assessment Report
2007

Climate Change 2007: Impacts, Adaptation, and Vulnerability
Contribution of Working Group II
to the IPCC Fourth Assessment Report
2007

Climate Change 2007: Mitigation of Climate Change
Contribution of Working Group III
to the IPCC Fourth Assessment Report
2007

Climate Change 2007: Synthesis Report
2008

Climate Change and Water
IPCC Technical Paper VI
2008

Renewable Energy Sources and Climate Change Mitigation
IPCC Special Report
2011

Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
IPCC Special Report
2012

Climate Change 2013: The Physical Science Basis
Contribution of Working Group I
to the IPCC Fifth Assessment Report
2013

2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol
2014

2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands
2014

Climate Change 2014: Impacts, Adaptation, and Vulnerability
Contribution of Working Group II
to the IPCC Fifth Assessment Report
2014

Climate Change 2014: Mitigation of Climate Change
Contribution of Working Group III
to the IPCC Fifth Assessment Report
2014

Climate Change 2014: Synthesis Report
2014

Enquiries: IPCC Secretariat, c/o World Meteorological Organization, 7 bis, Avenue de la Paix, Case Postale 2300, CH - 1211 Geneva 2, Switzerland

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