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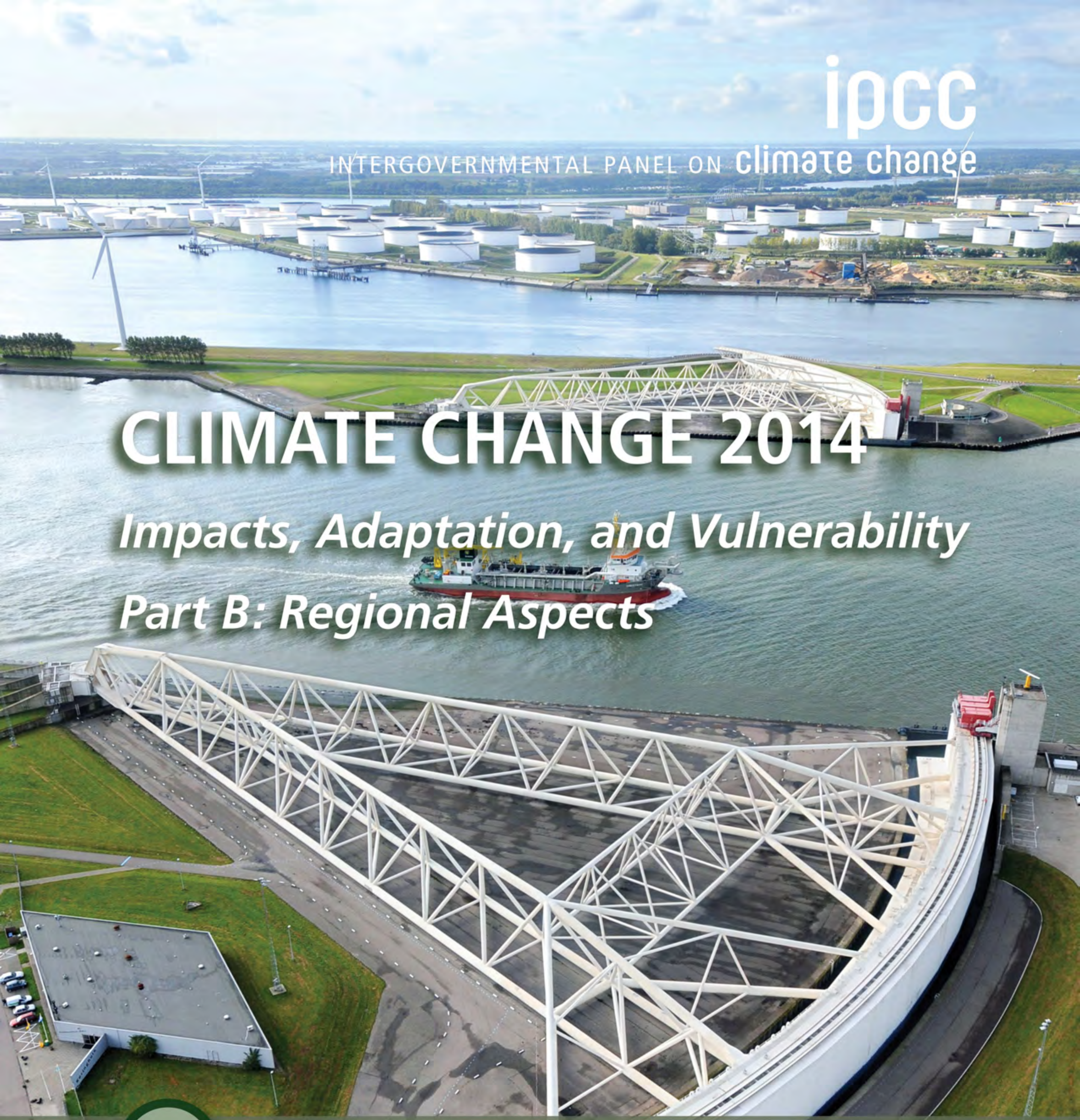

CLIMATE CHANGE 2014

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

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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.

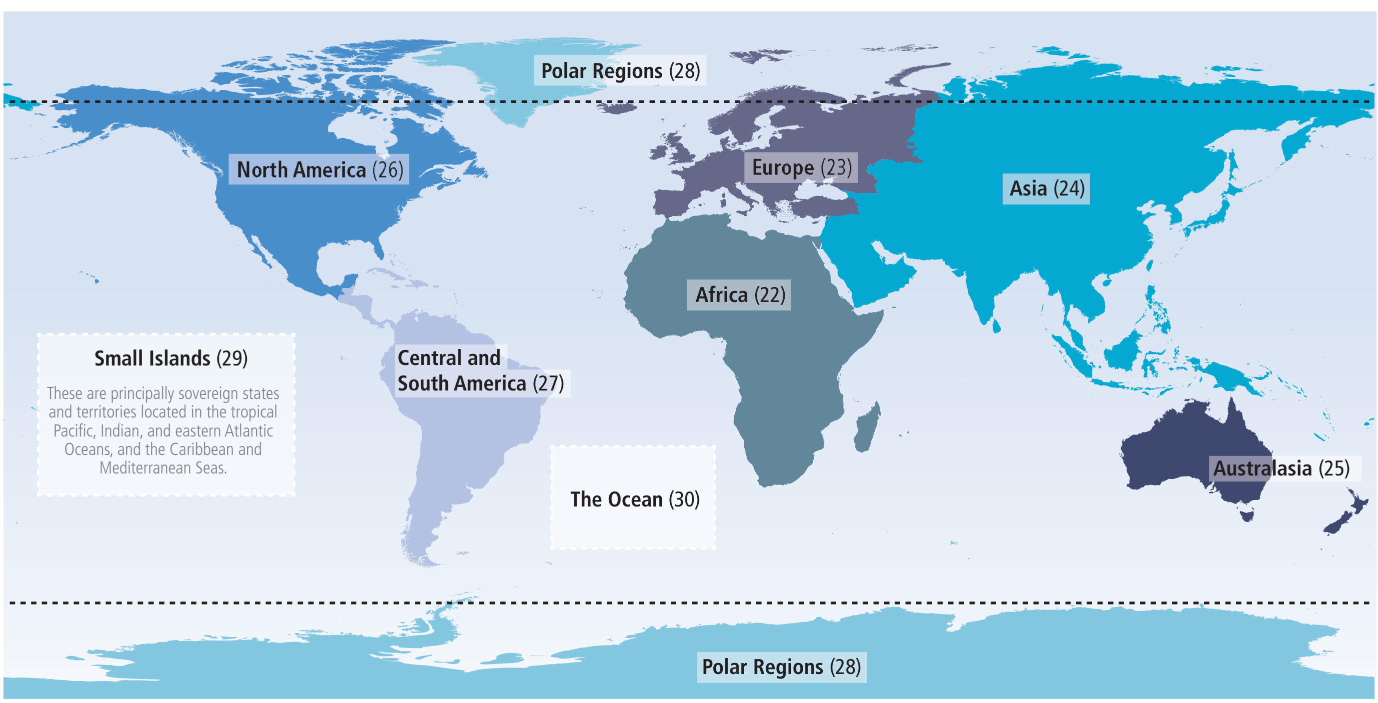

Figure 21-1 | Specification of the world regions described in Chapters 22 to 30 of this volume. Chapter numbers are given in parentheses after each region's name.

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]

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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]

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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.

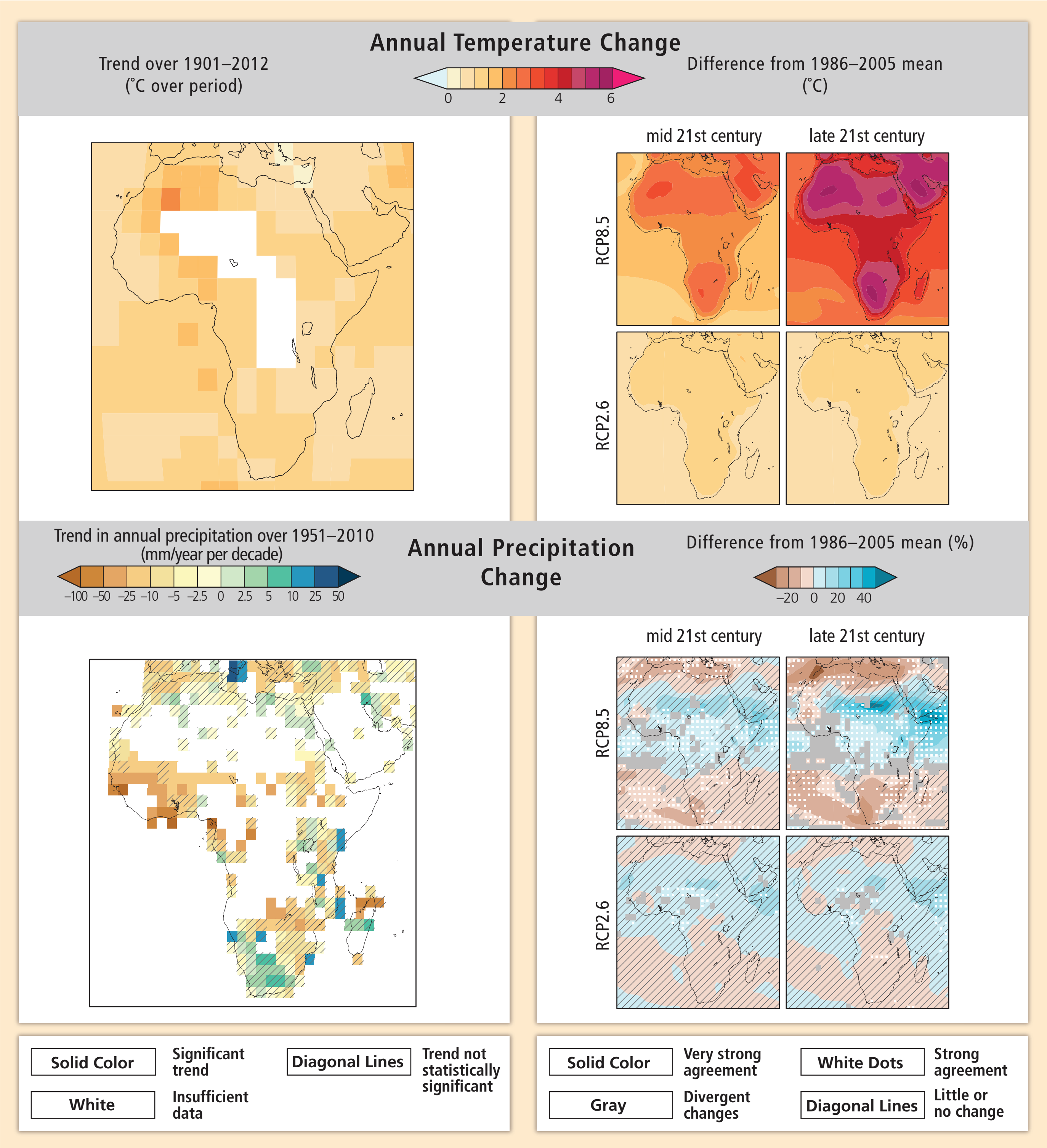

Figure 21-2 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change 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]

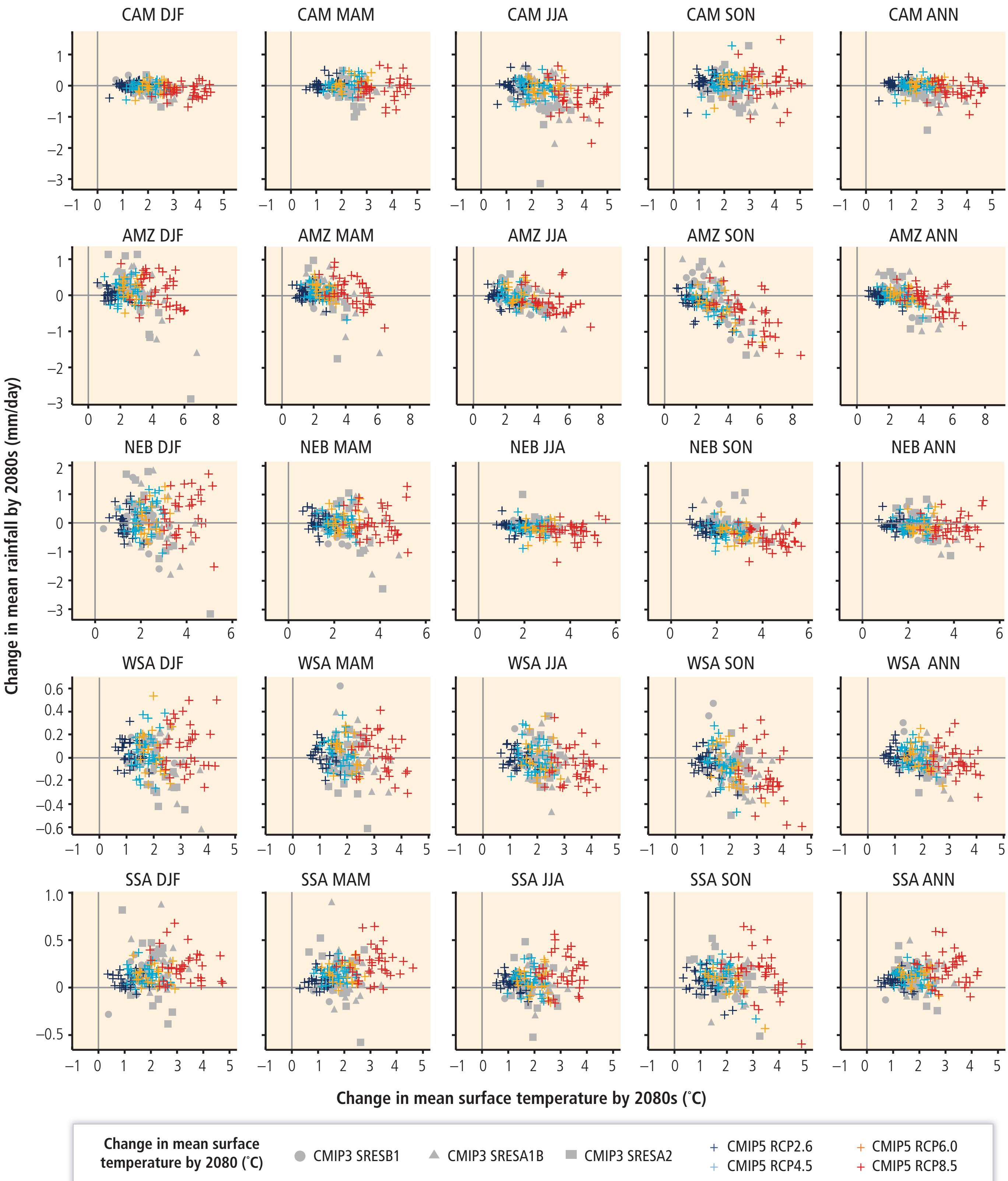

Figure 21-3 | Regional average change in seasonal and annual mean temperature and precipitation over five sub-regions covering South and Central America for the period 2071–2100 relative to 1961–1990 in General Circulation Model (GCM) projections from 35 Coupled Model Intercomparison Project Phase 5 (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

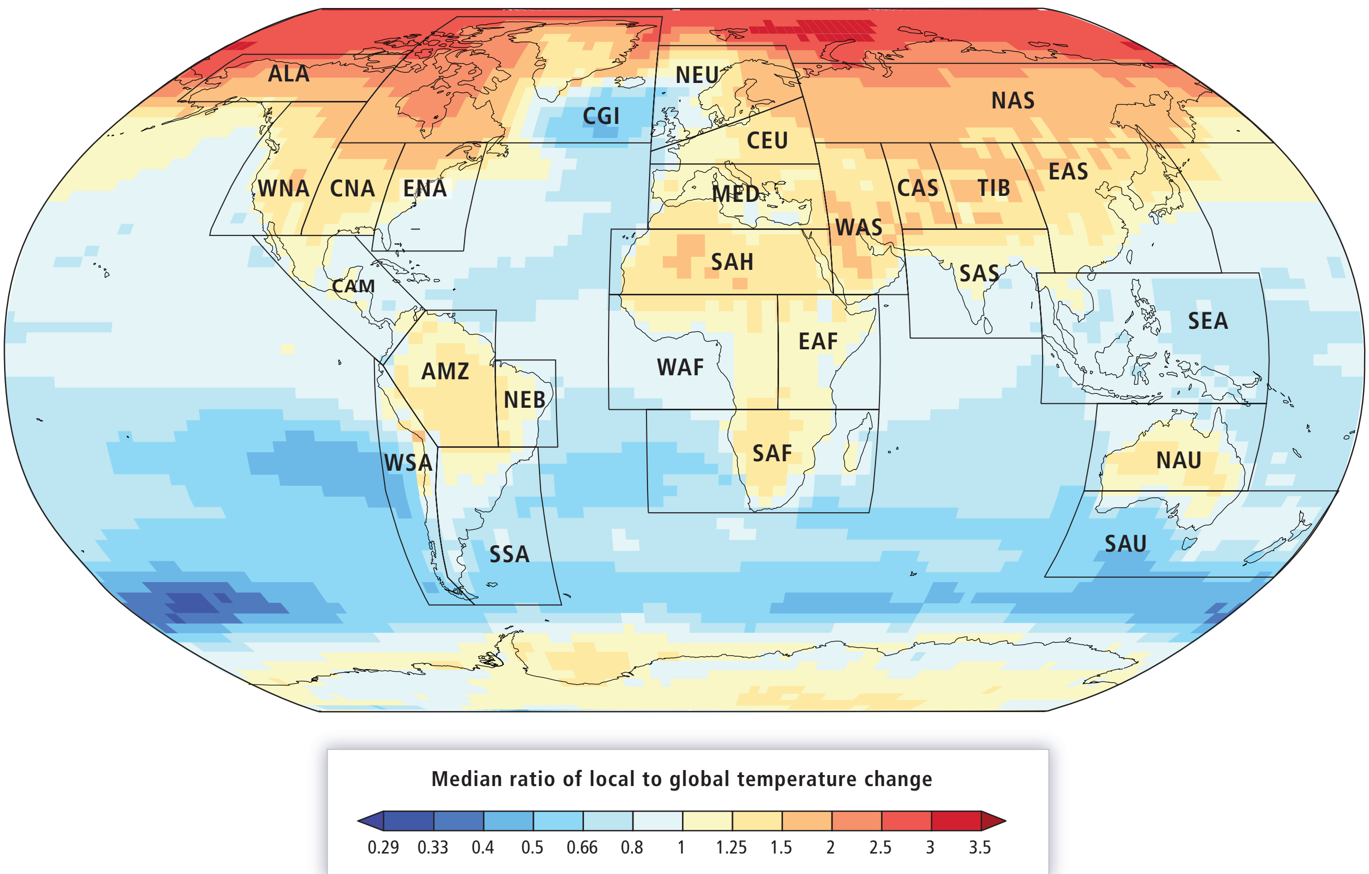

Figure 21-4 | Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble median ratio of local to global average temperature change in the period 2071–2100 relative to 1961–1990 under the Representative Concentration Pathway 8.5 (RCP8.5) emissions/concentrations scenario. The values are displayed 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.

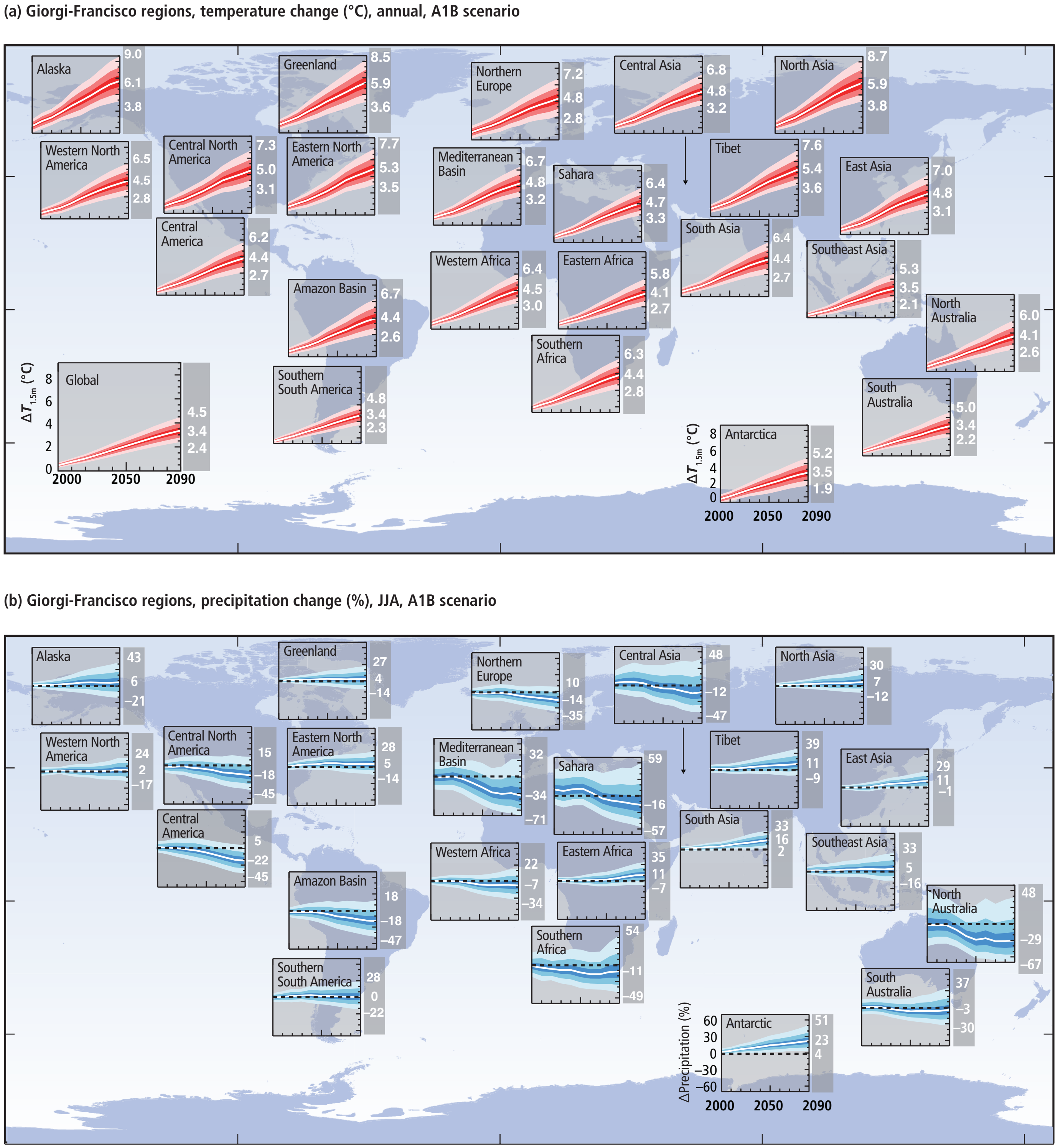

Figure 21-5 | Evolution of the 5%, 17%, 33%, 50%, 67%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (panel a) and JJA percentage precipitation changes (panel b) for the Giorgi-Francisco (2000) regions and the globe with the SRES A1B forcing scenario (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

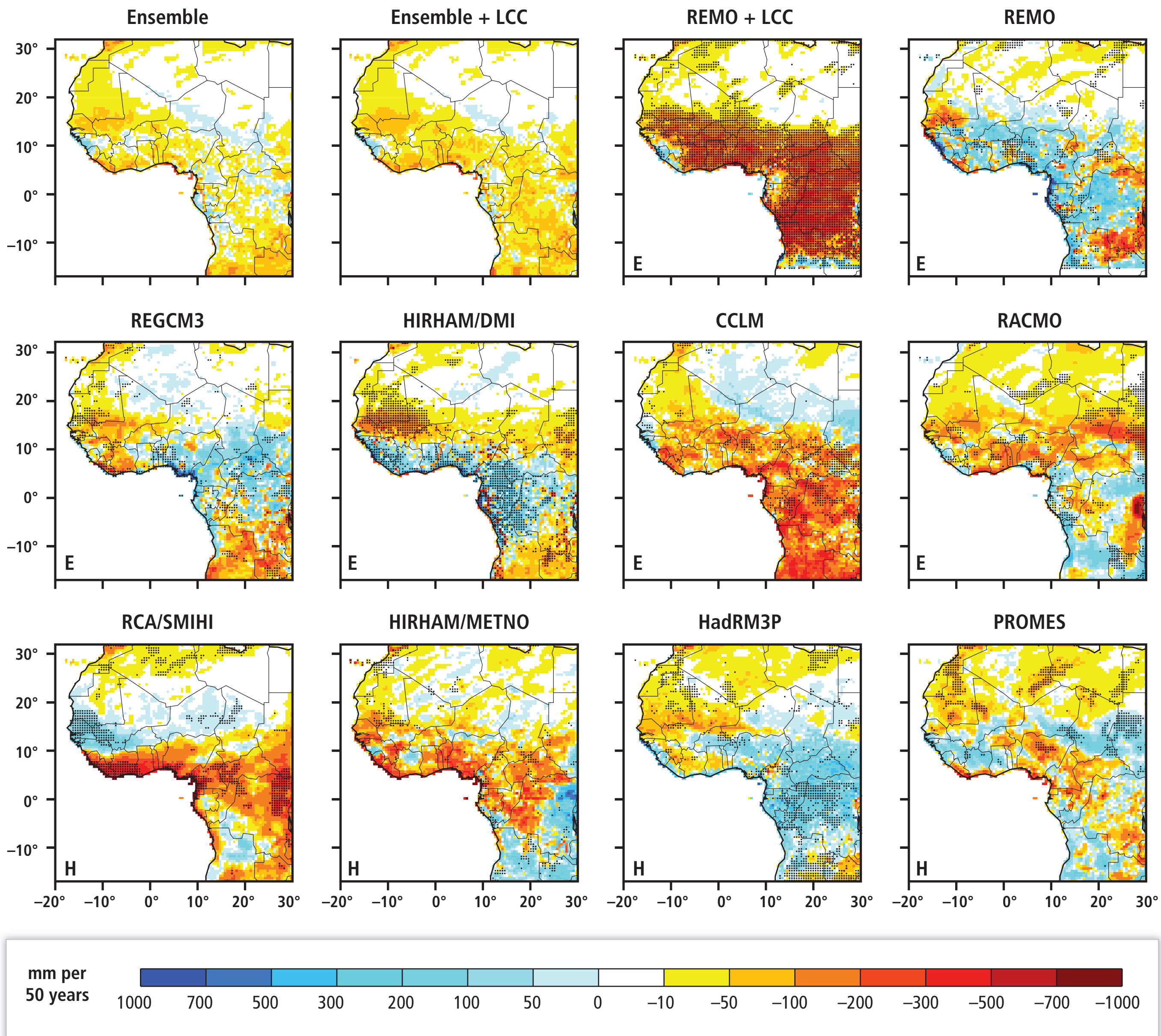

Figure 21-6 | Linear changes (i.e., changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001–2050 period from 10 individual Regional Climate Model (RCM) experiments and the Multi-Model Ensemble (MME) mean under the A1B emission scenario. 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.

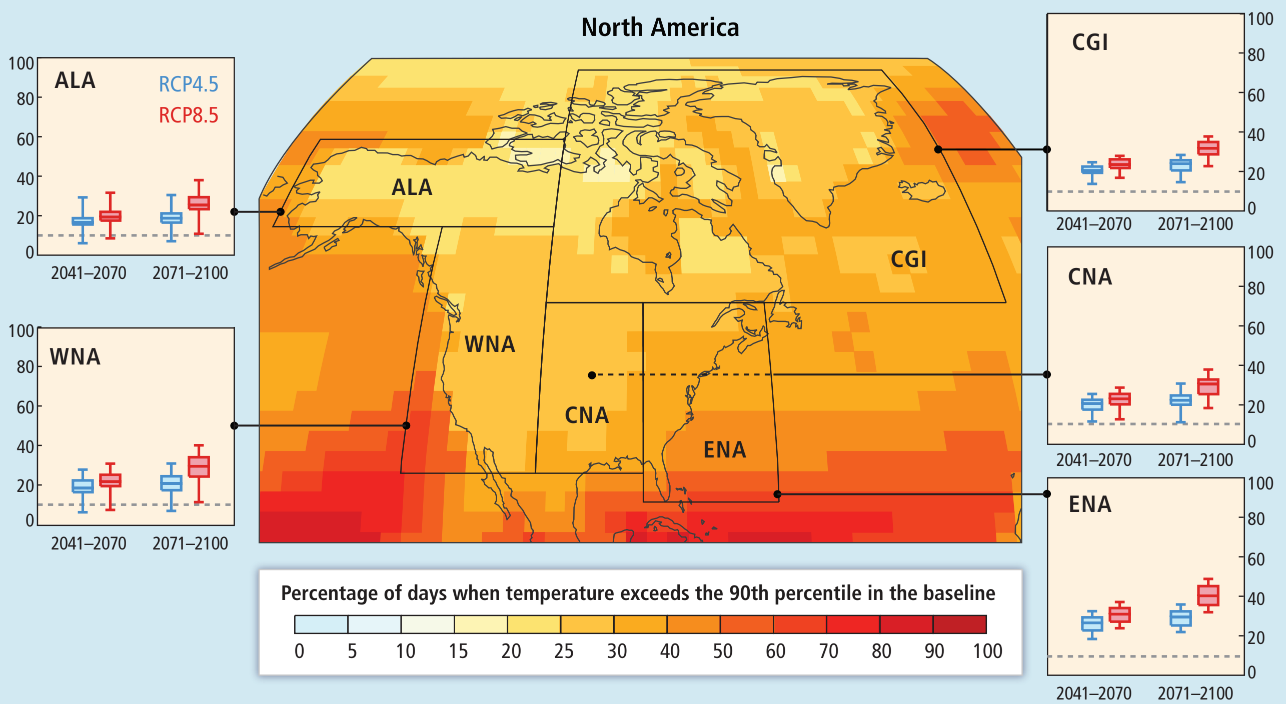

Figure 21-7 | The frequency of "warm days" (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961–1990) projected for the 2071–2100 period by 26 Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs) for North America. Map: Ensemble 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.

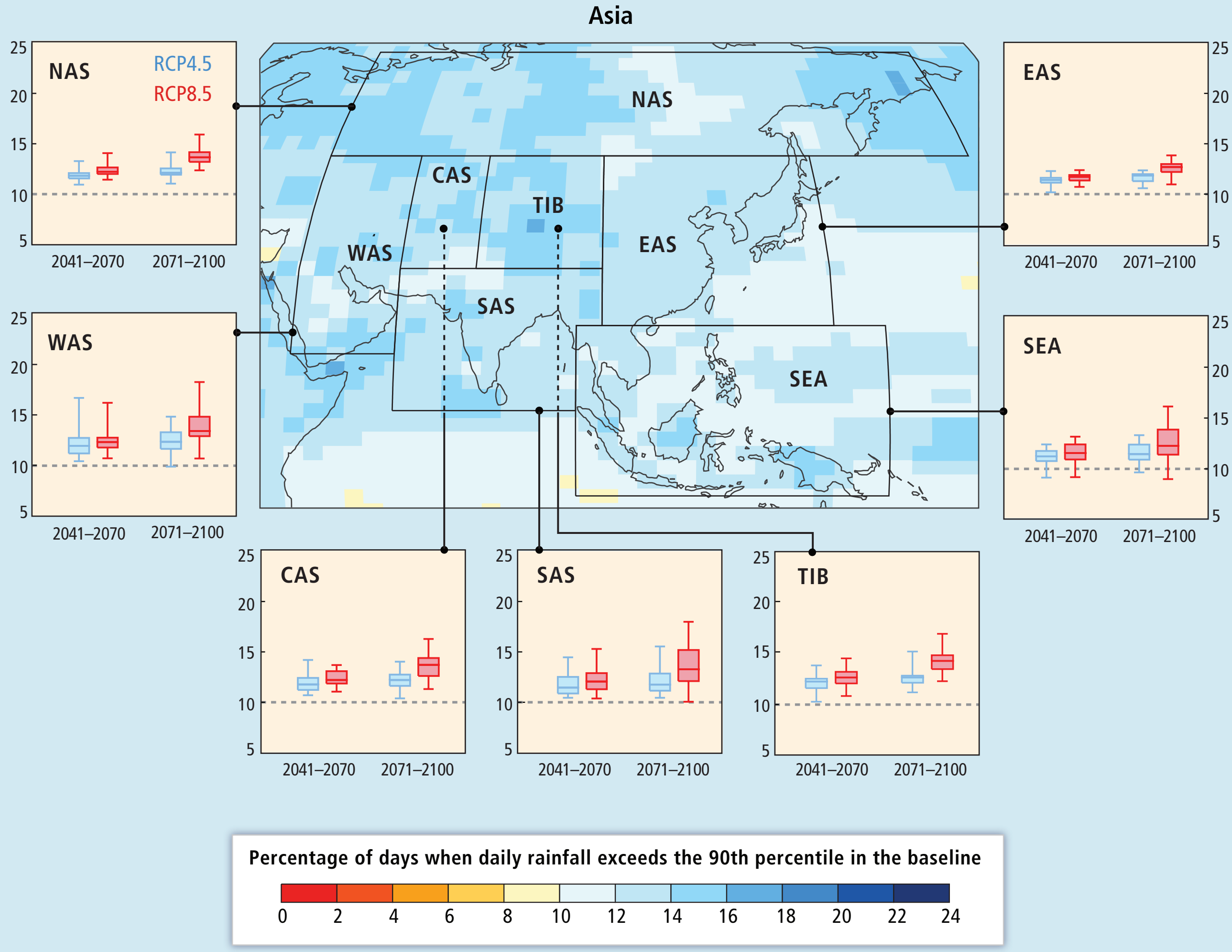

Figure 21-8 | The frequency of "very wet days" (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961–1990 with wet days defined as days with 1 mm of precipitation or more) projected for the 2071–2100 period by 26 Coupled Model Intercomparison Project 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]	Insufficent 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]

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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
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)

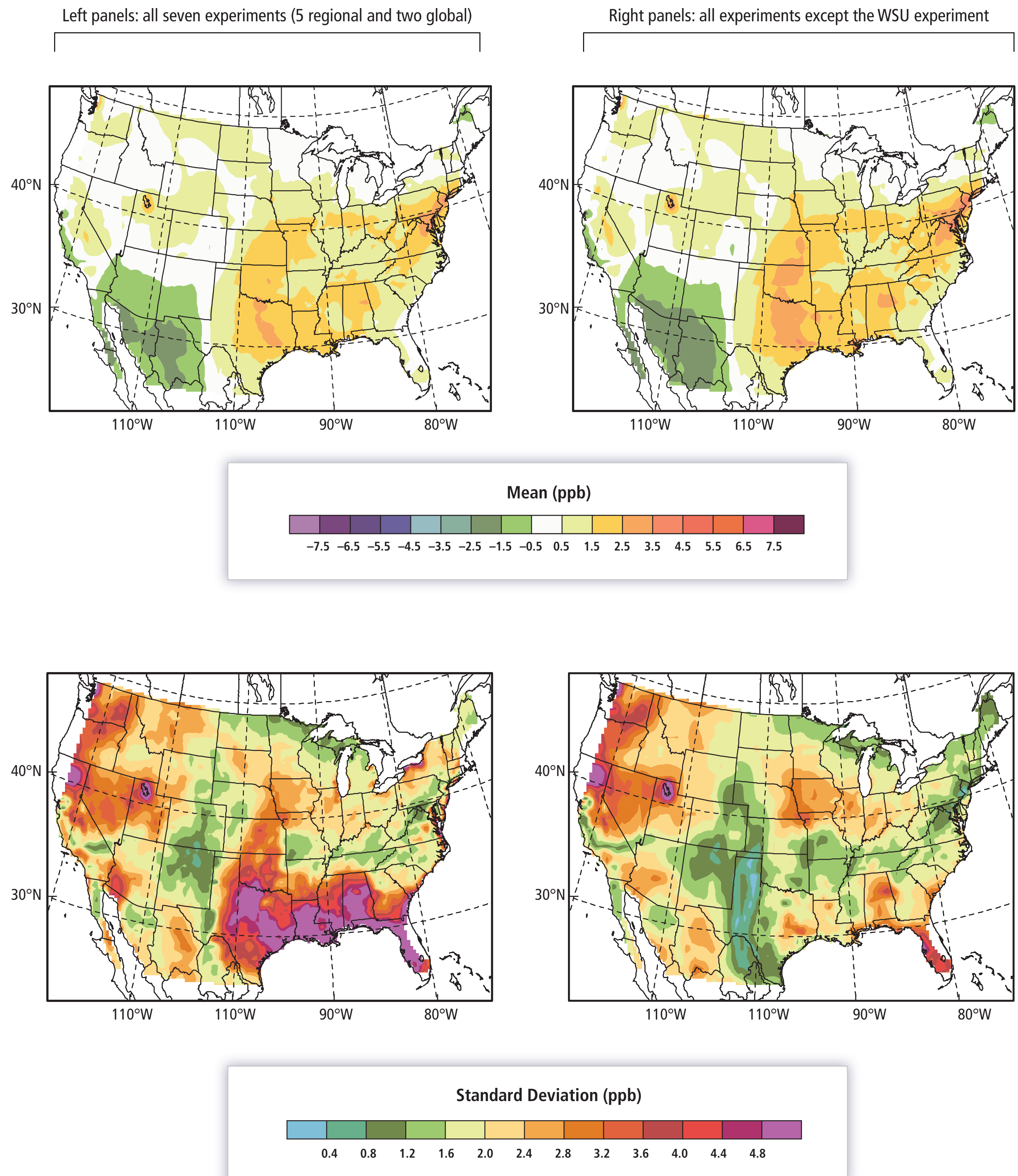

Figure 21-9 | Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2050s minus 1990s) MDA8 summer ozone concentrations across (lefthand panels) all seven experiments (five regional and two global) and for comparison purposes (righthand panels), not including the WSU experiment (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).

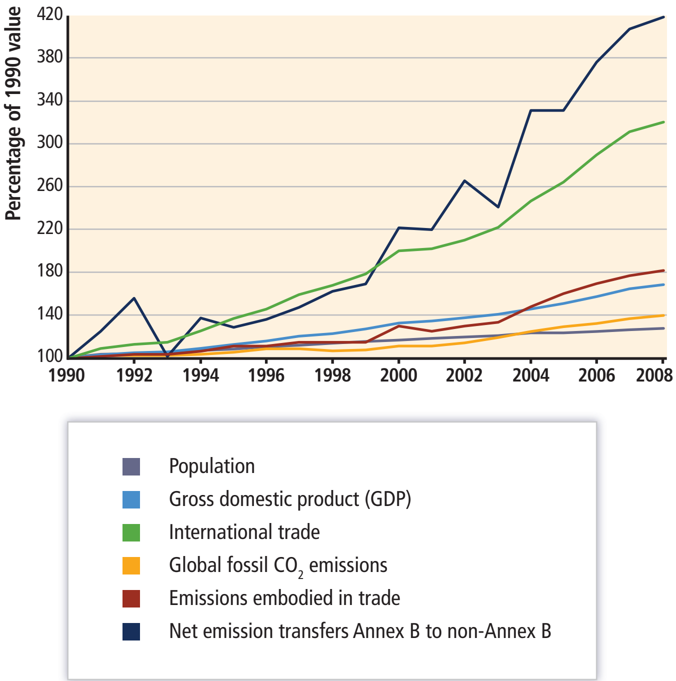

Figure 21-10 | Growth rates from 1990–2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macro-variables, all indexed to 1990 (Peters et al., 2011). Annex B and non-Annex B Parties to the United Nations 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.

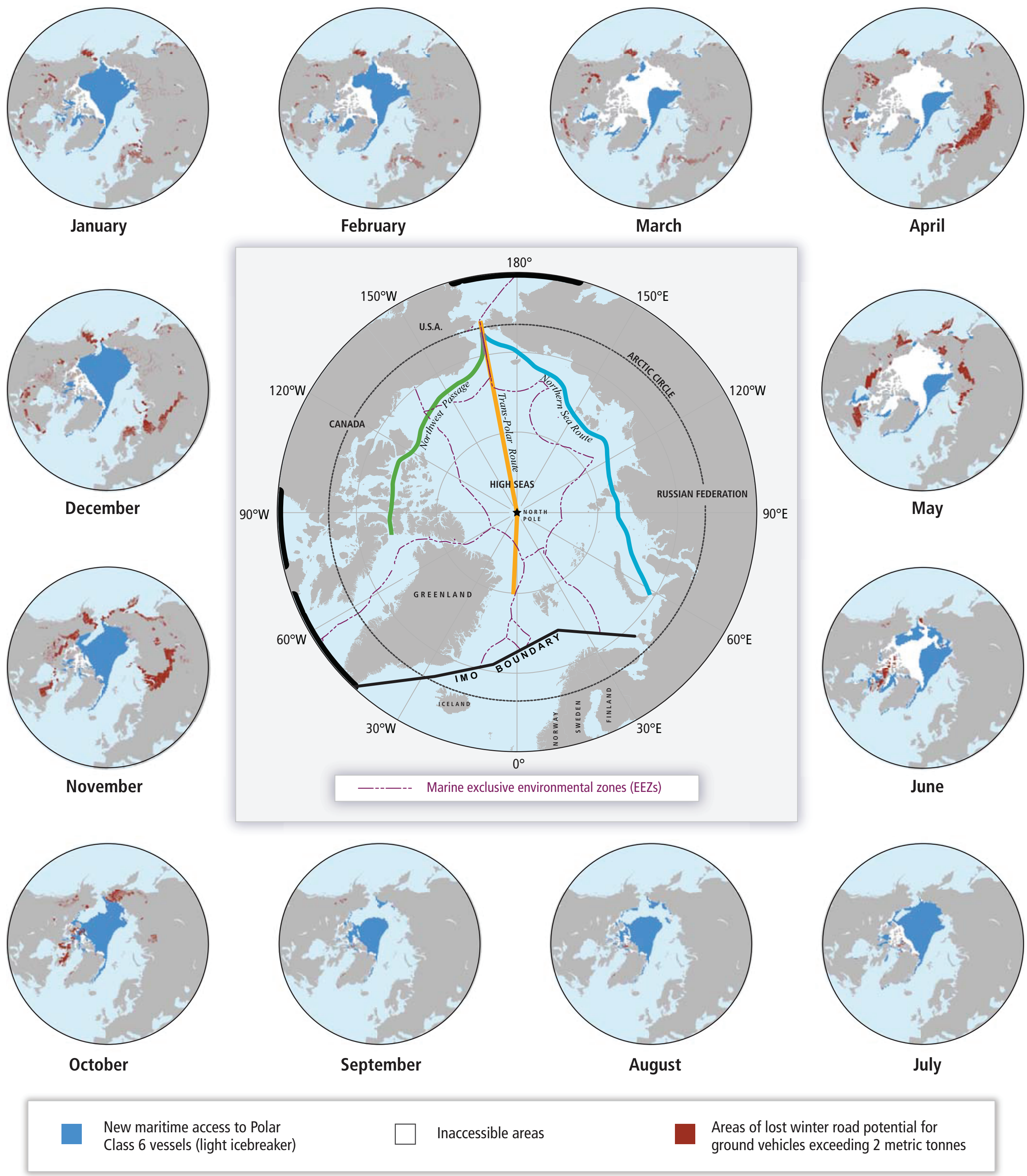

Figure 21-11 | Central map: Marine exclusive environmental zones (EEZs, dashed lines) of Canada, Greenland/Denmark, Norway, Russian Federation, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the International Maritime Organization (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

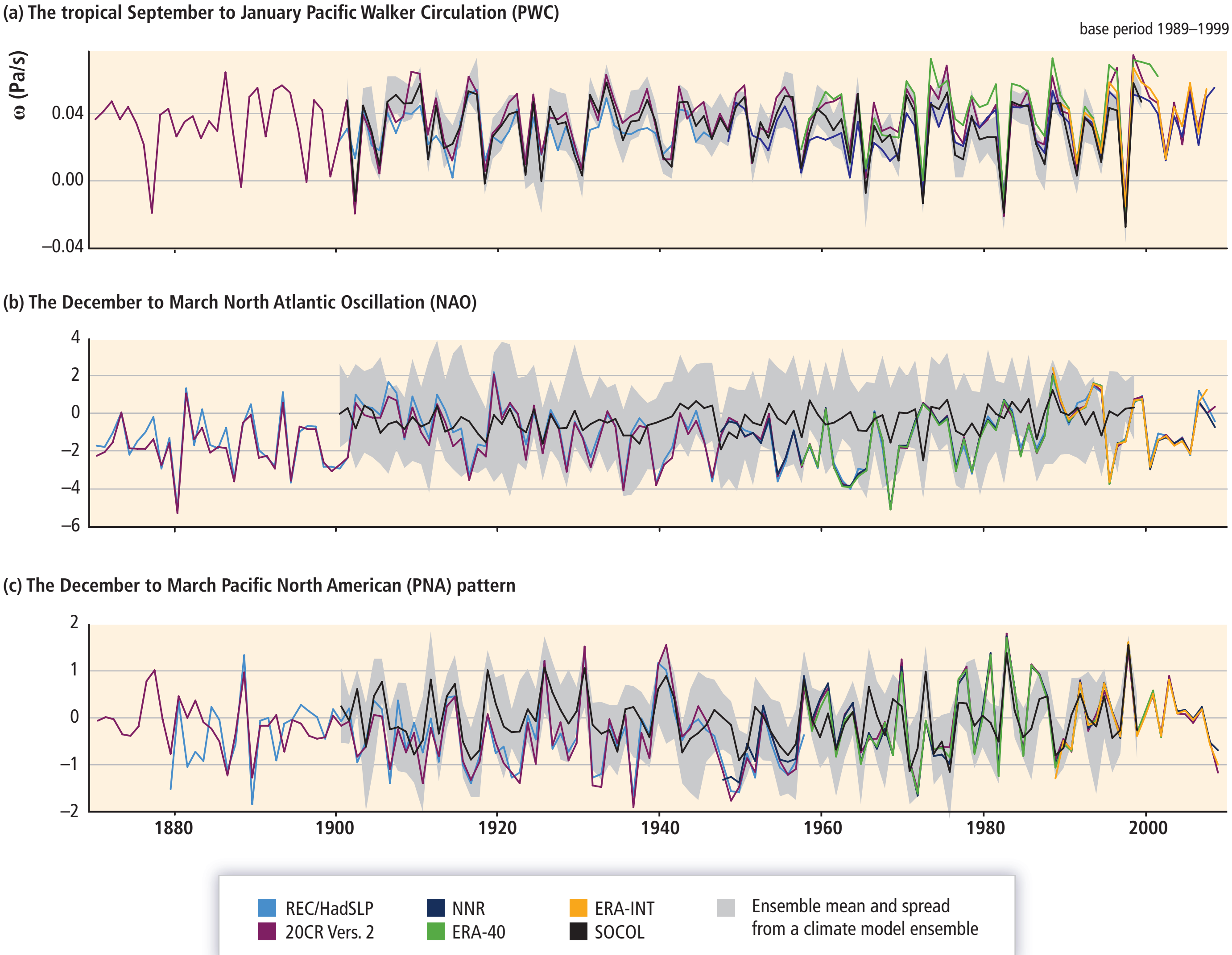

Figure 21-12 | Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); and (c) the December to March Pacific North 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

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Frequently Asked Questions

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)

[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)

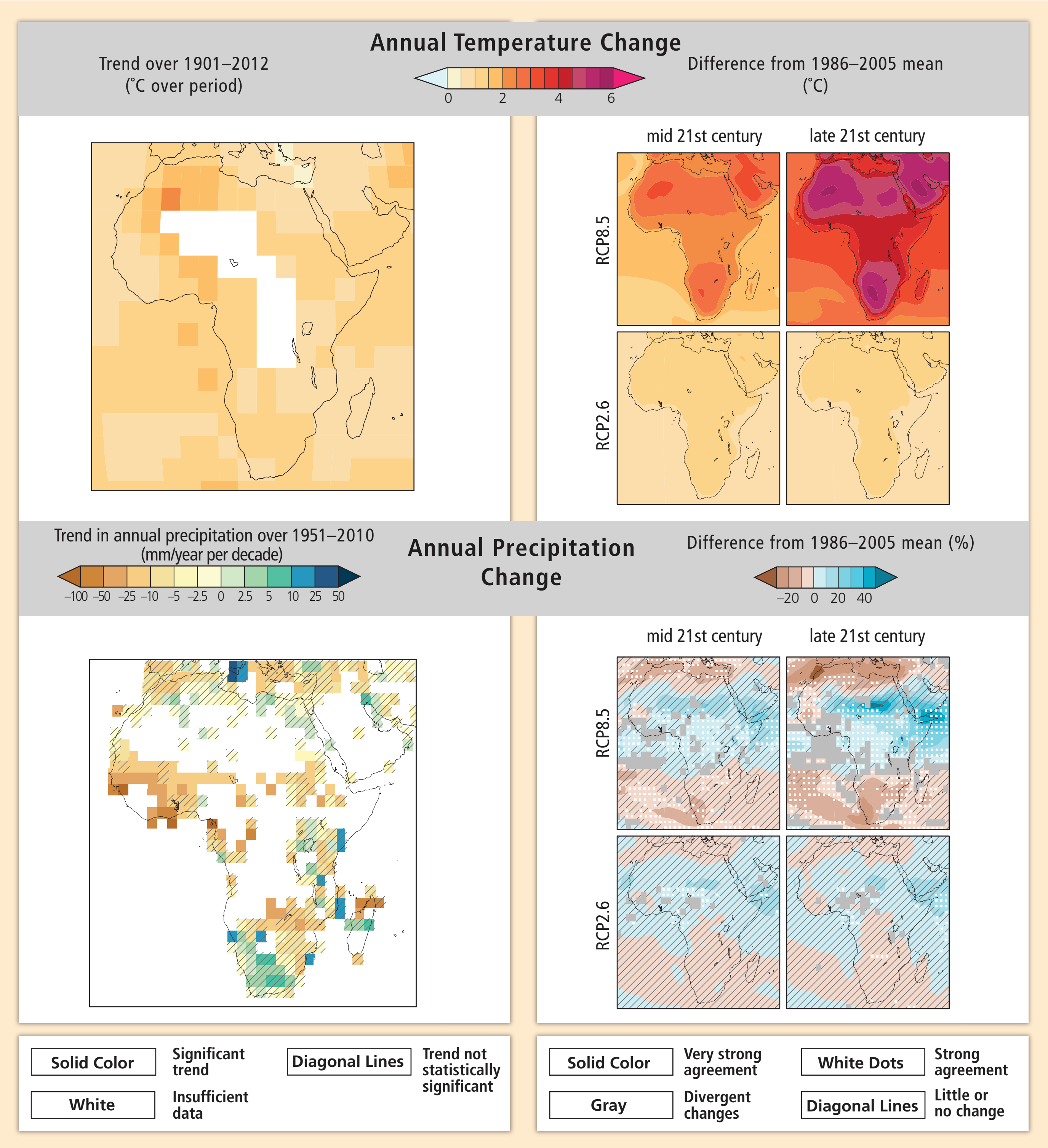

Figure 22-1 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change 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]

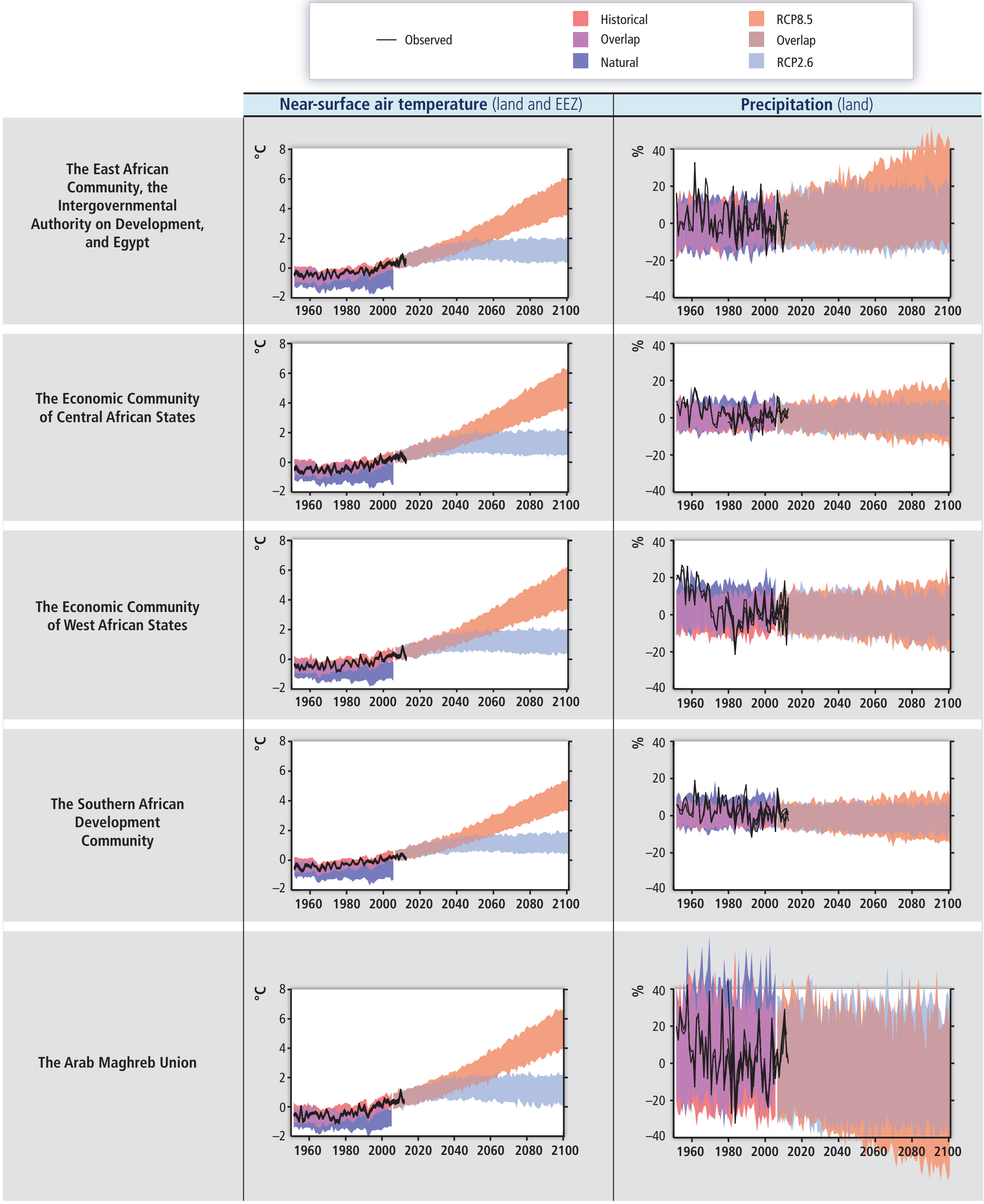

Figure 22-2 | Observed and simulated variations in past and projected future annual average temperature over East African Community–Intergovernmental Authority on Development–Egypt (EAC–IGAD–Egypt), Economic Community of Central African States (ECCAS), Economic Community of West African States (ECOWAS), 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

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

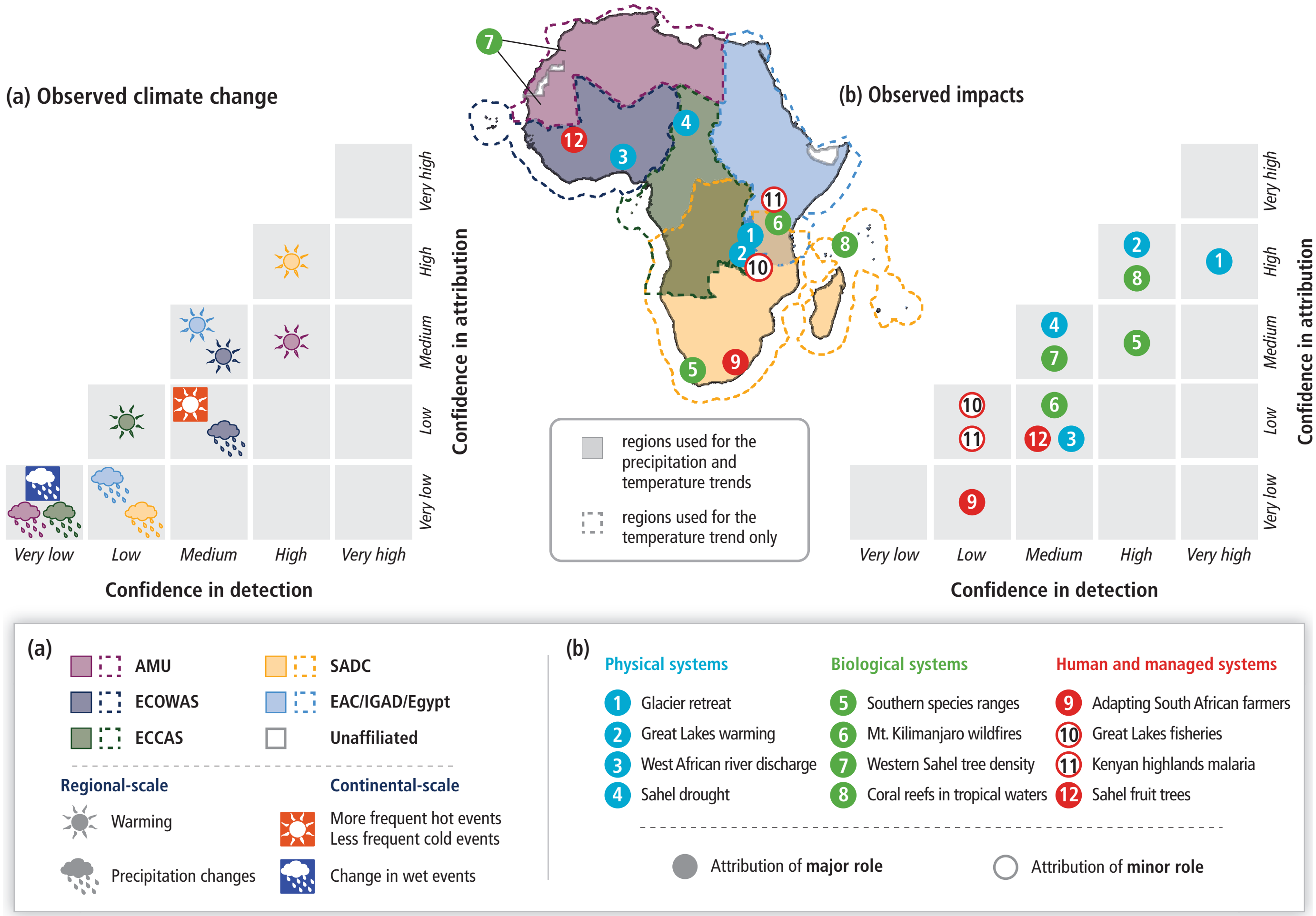

Figure 22-3 | (a) Confidence in detection and in attribution of observed climate change over Africa to anthropogenic emissions. All detection assessments are against a reference of no change, while all attribution assessments concern a major role of anthropogenic emissions in the observed changes. See 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).

[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

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 Mg C ha^{-1} 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)

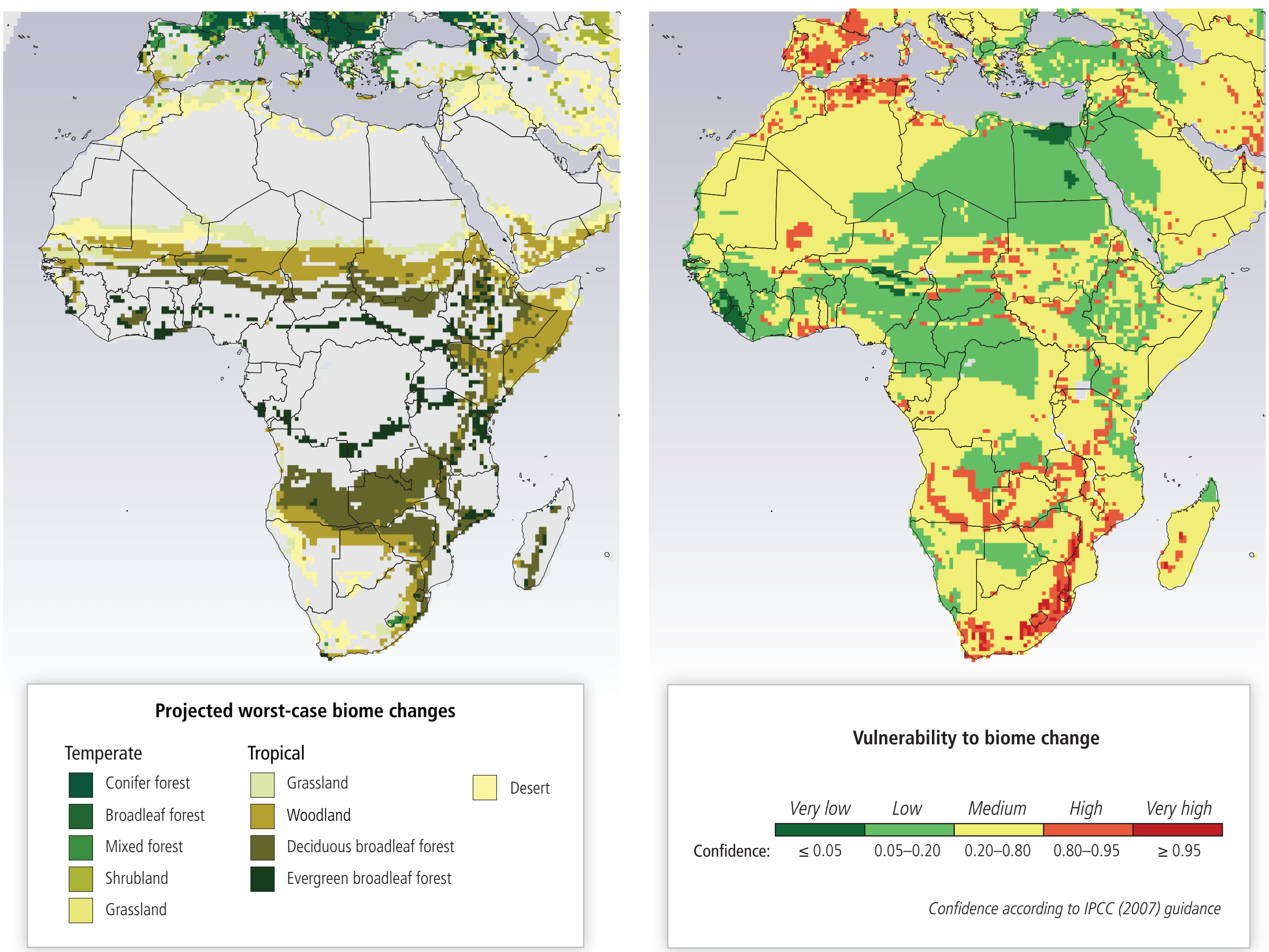

Figure 22-4 | (a) Projected biome change from the periods 1961–1990 to 2071–2100 using the MC1 Dynamic Vegetation Model. Change is indicated if any of nine combinations of three General Circulation Models (GCMs: Commonwealth Scientific and Industrial Research Organisation (CSIRO Mk3), Met Office Hadley 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

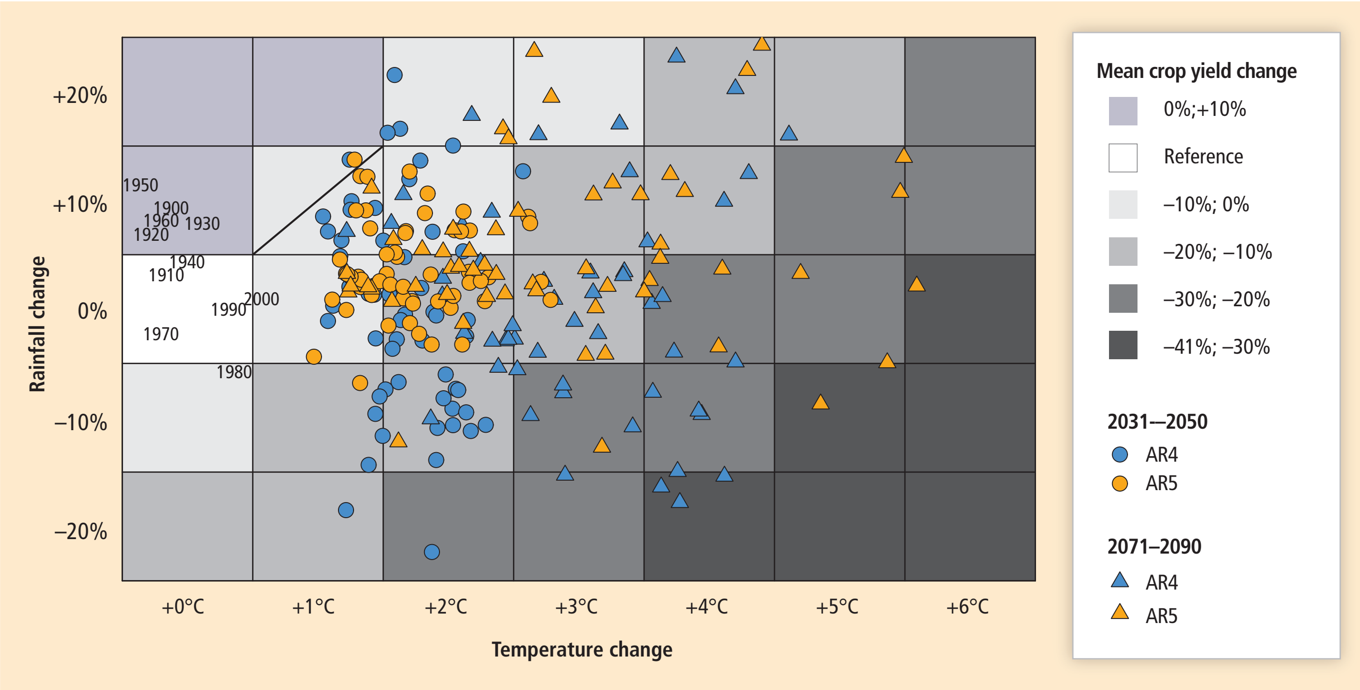

Figure 22-5 | The effect of rainfall and temperature changes on mean crop yield. Mean crop yield change (%) relative to the 1961–1990 baseline for 7 temperatures (x-axis) and 5 rainfall (y-axis) scenarios. Results are shown as the average over the 35 stations across West Africa and the 6 cultivars of 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),

[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 (Vermuelen 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 effectivess 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

[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,

[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

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).

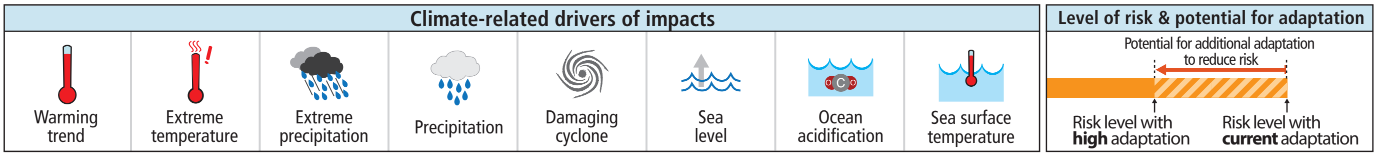
Recognition is increasing that understanding psychological factors such as mindsets and risk perceptions is crucial for supporting adaptation (Grothmann and Patt, 2005; Patt and Schröter, 2008; Jones, 2012). Cognitive barriers to adaptation include alternative explanations of extreme events and weather 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

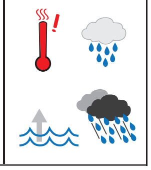
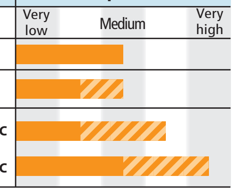
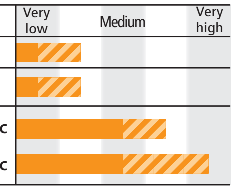
Table 22-6 | Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Africa. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and 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	Very low – Medium – Very high
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	Very low – Medium – Very high
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	Very low – Medium – Very high
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	Very low – Medium – Very high
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	Very low – Medium – Very high
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	Very low – Medium – Very high
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	Very low – Medium – Very high

Continued next page →

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

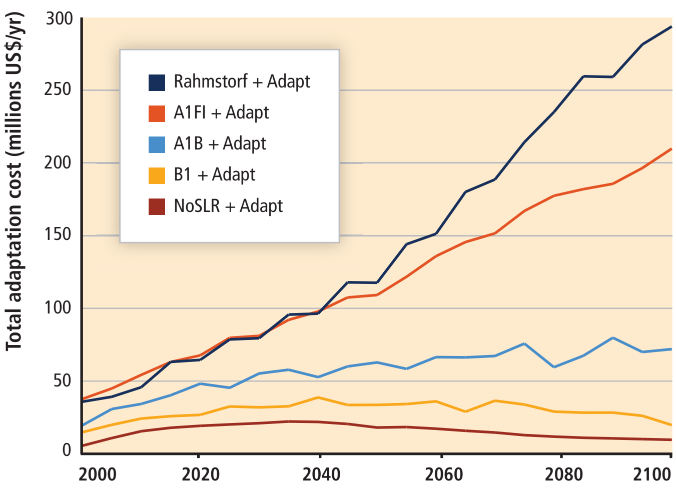


Figure 22-6 | Total additional costs of adaptation per year from 2000 to 2100 for Tanzania (including beach nourishment and sea and river dikes). The values do not consider the existing adaptation deficit (values in US$ 2005, without discounting). Source: Kebede et al., 2010.

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.

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).

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 (Nakhooda 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

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Frequently Asked Questions

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}

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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.

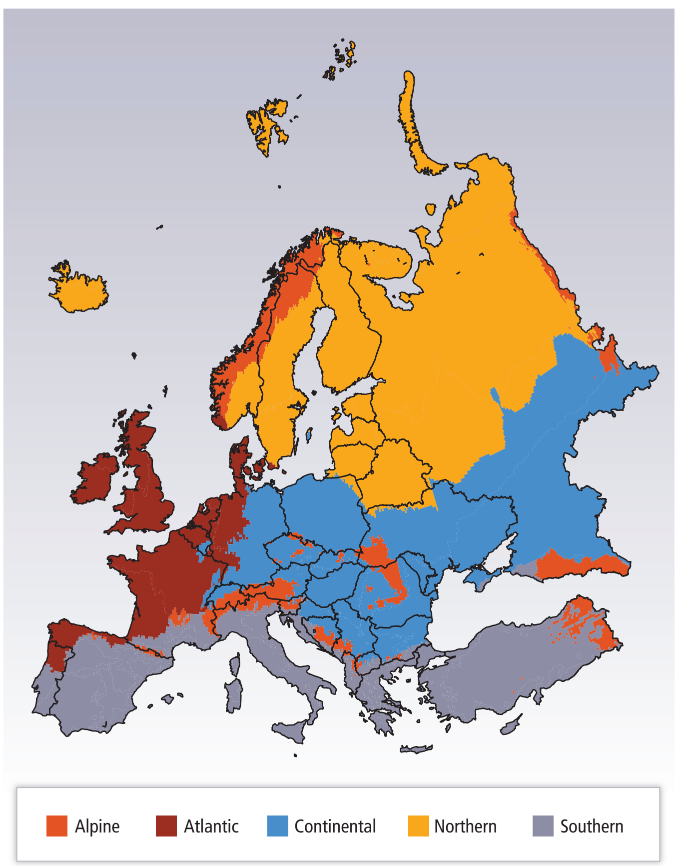


Figure 23-1 | Sub-regional classification of the IPCC Europe region. Based on Metzger et al., 2005.

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

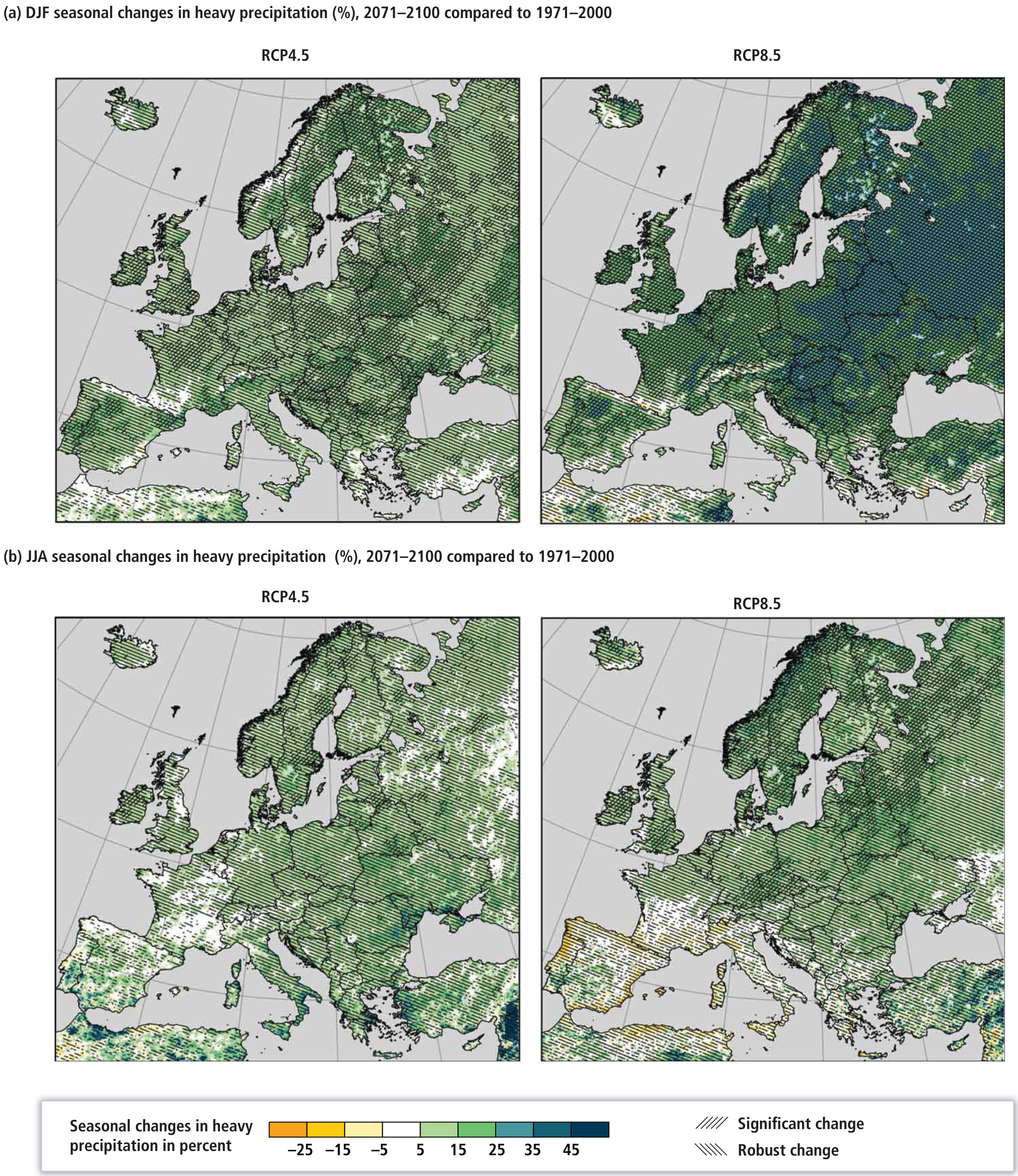
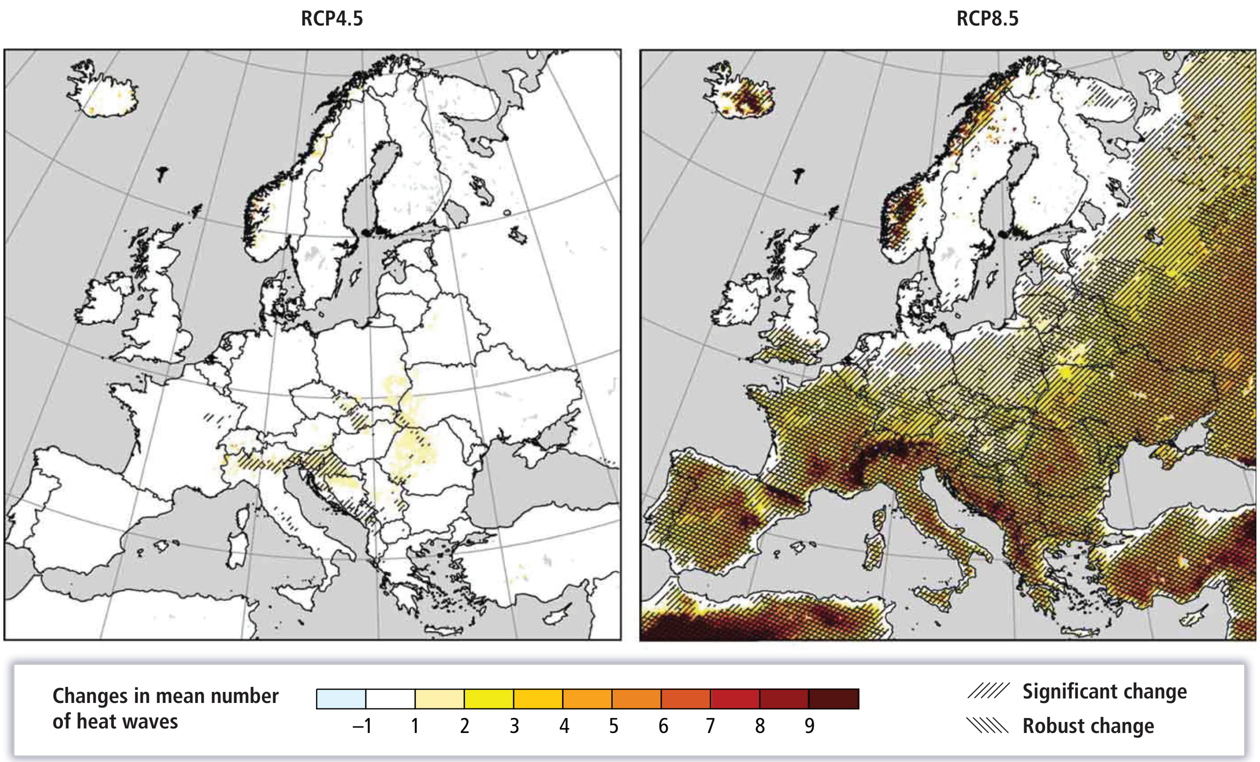


Figure 23-2 | (a) and (b): Projected seasonal changes in heavy precipitation defined as the 95th percentile of daily precipitation (only days with precipitation >1 mm day^{-1} are considered) for the period 2071–2100 compared to 1971–2000 (in %) in the months December to February (DJF) and June to August (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.

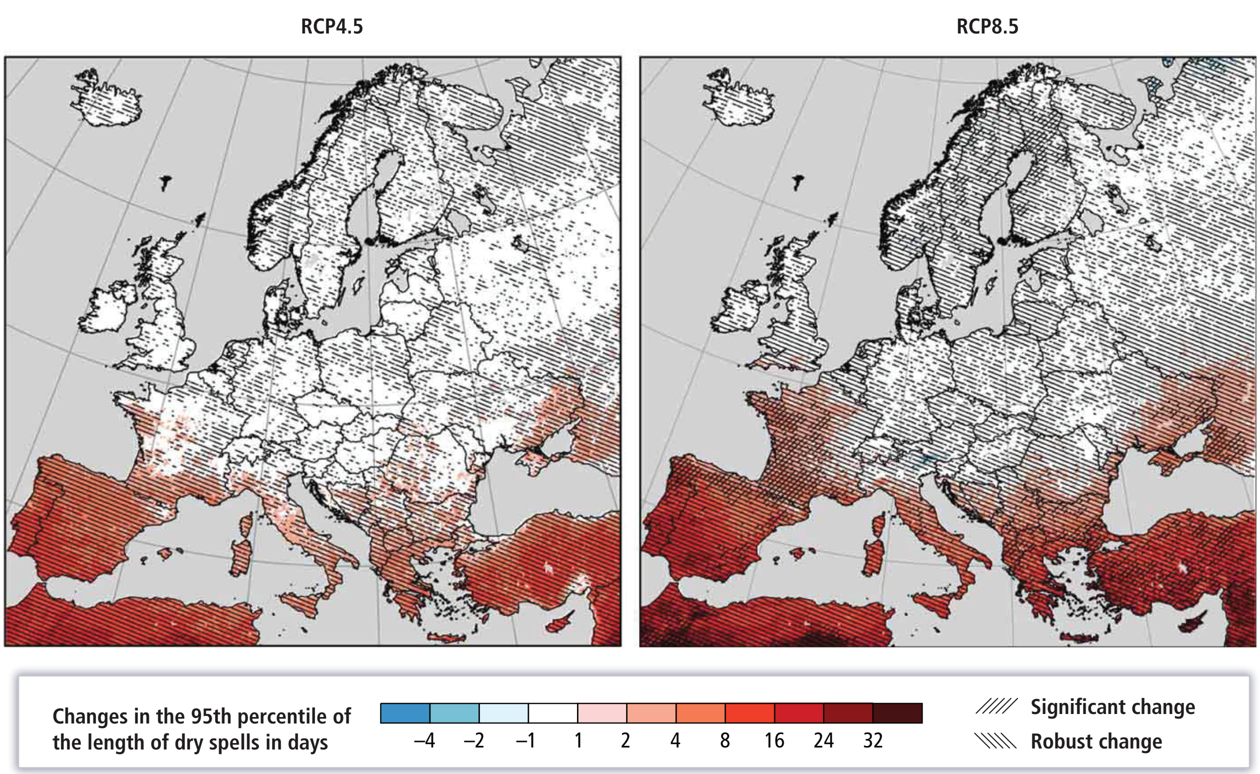
Continued next page →

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

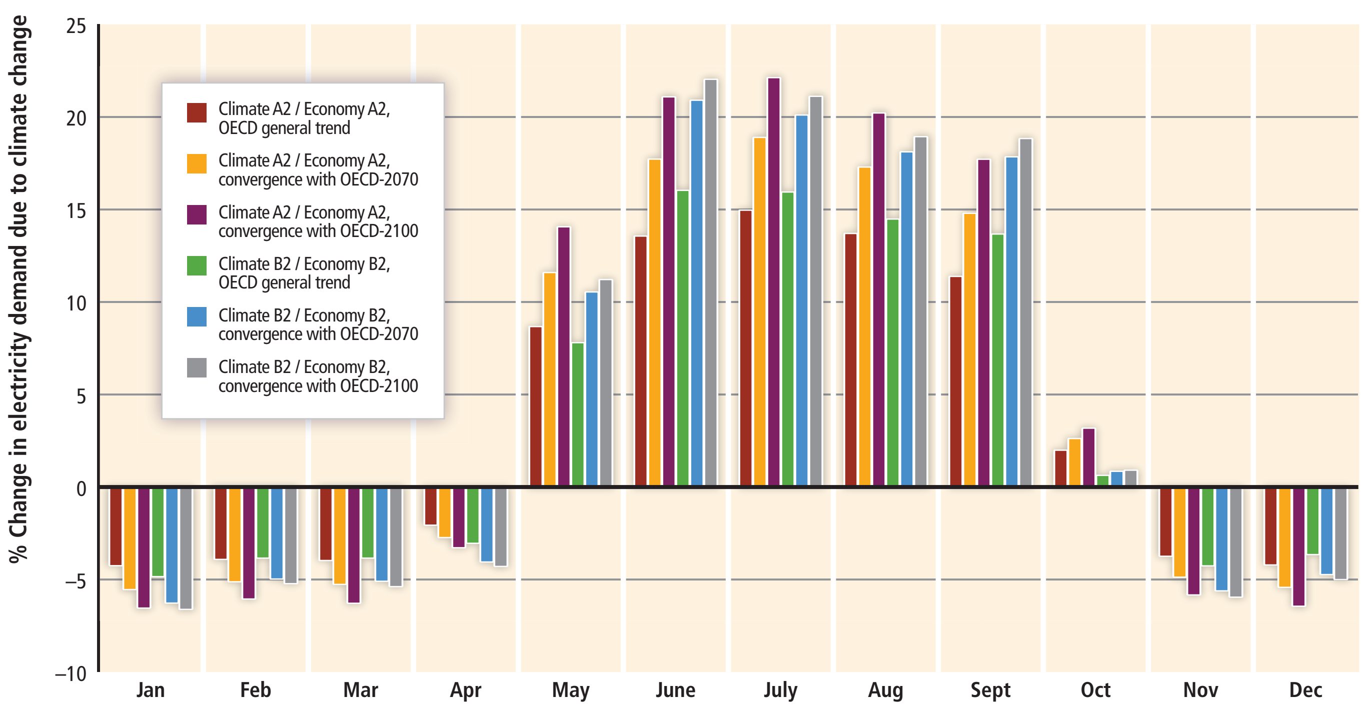


Figure 23-3 | Percentage change in electricity demand in Greece attributable to climate change, under a range of climate scenarios and economic assumptions. Source: Mirasgedis et al., 2007.

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

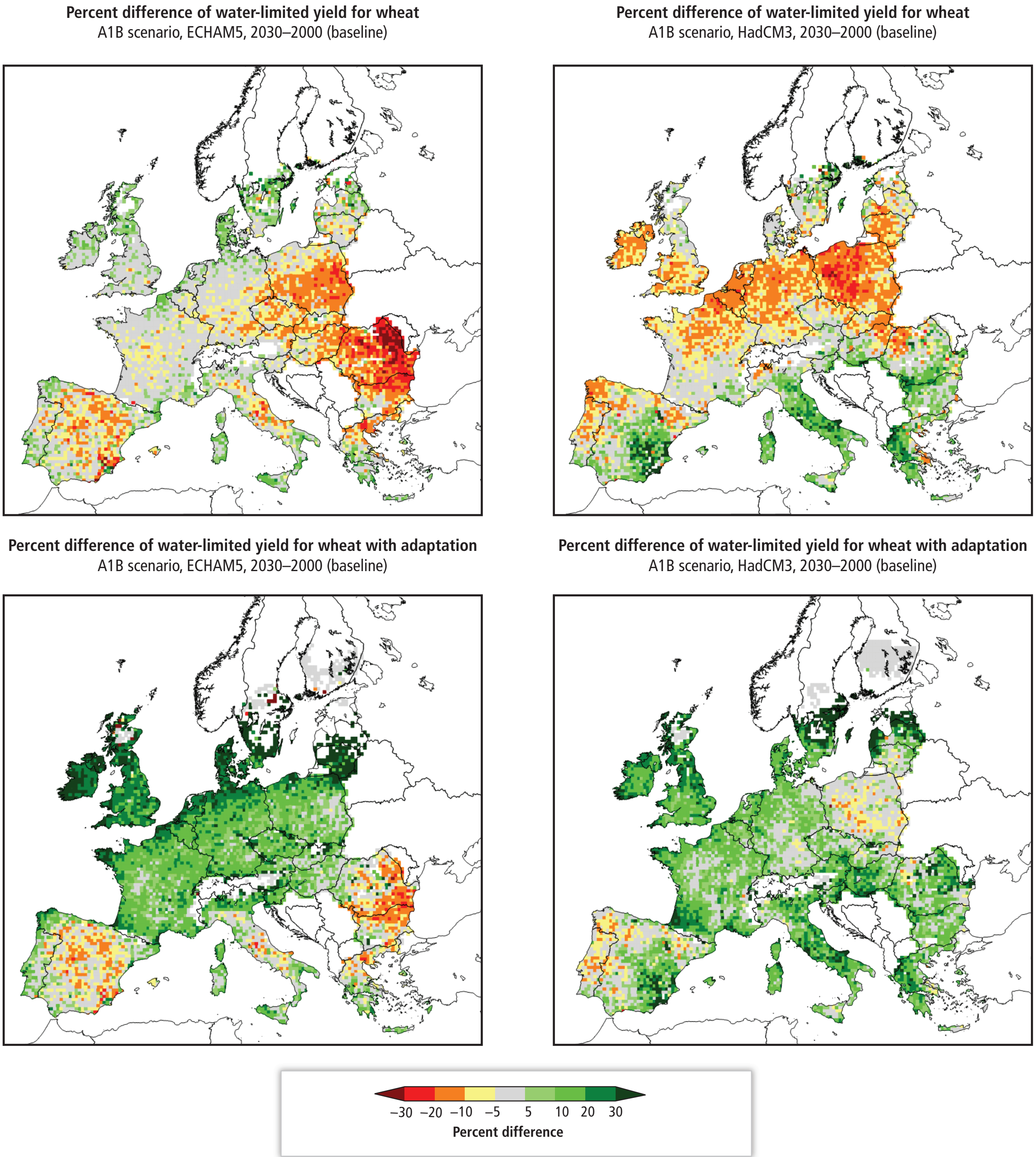


Figure 23-4 | Percentage change in simulated water-limited yield for winter wheat in 2030 with respect to the 2000 baseline for the A1B scenario using European Centre for Medium Range Weather Forecasts and Hamburg 5 (ECHAM5; left column) and Hadley Centre Coupled Model version 3 (HadCM3; right) General 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)**

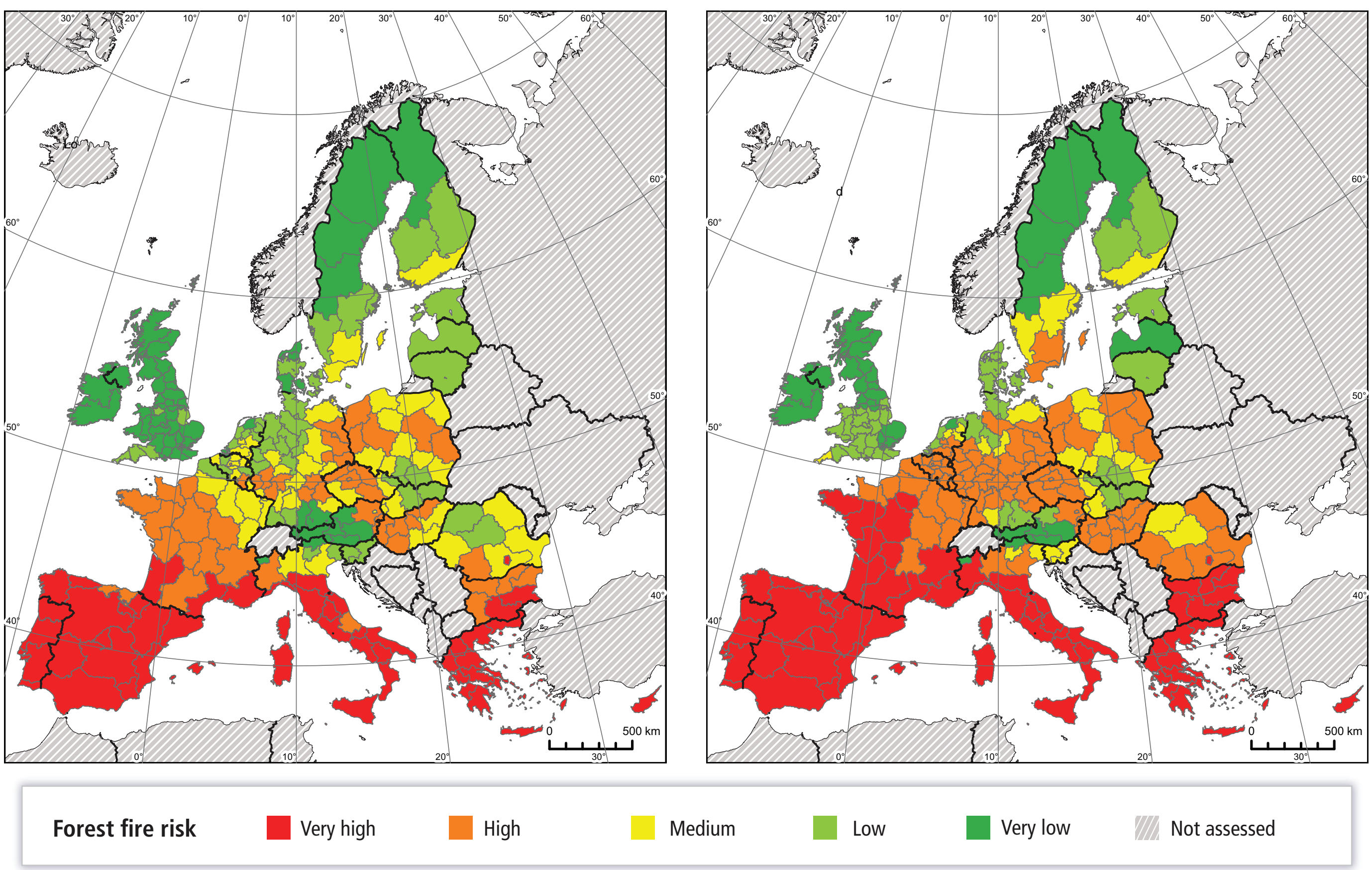


Figure 23-5 | Forest fire risk in Europe for two time periods: baseline (left) and 2041–2070 (right), based on high-resolution regional climate models and the Special Report on Emission Scenarios (SRES) A1B emission scenario. Forest fire risk indicator is based on climate and non-climate factors (e.g.,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

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(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

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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 inter-tidal 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	

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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.

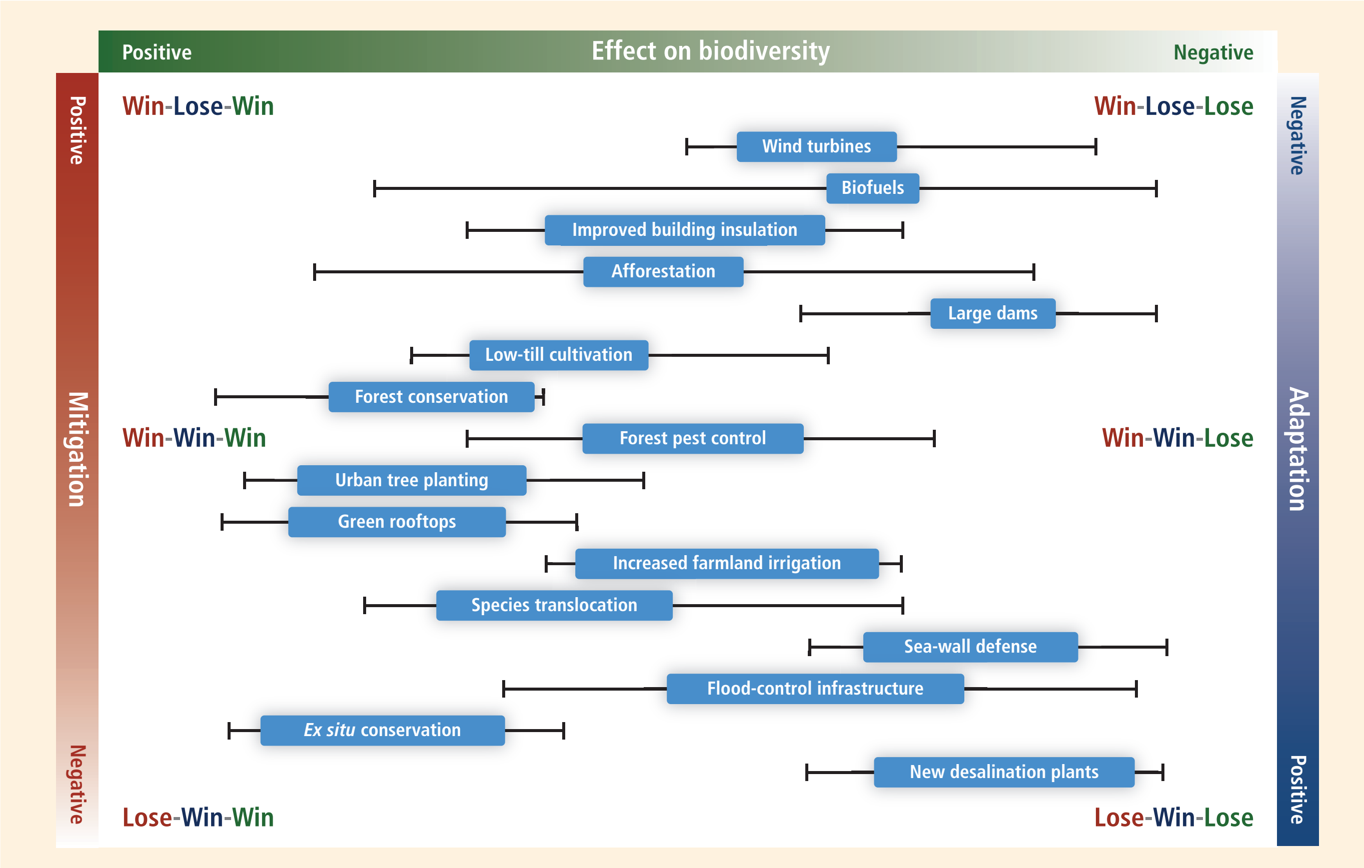


Figure 23-6 | Adaptation and mitigation options and their effects on biodiversity. The horizontal axis ranges from positive effects on biodiversity (lefthand side) to negative effects (righthand side). Each mitigation/adaptation option is located on the biodiversity effect axis (solid bars), including 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	↗ (green) / → / ↘ (red) [a]	↗ (green) / → / ↘ (red)	→	→	→ / ↗ (green)	23.3.4
	Hydropower generation	↘ (red)	↘ (red)	↘ (red)	↗ (green) / ↘ (red) [b]	→ / ↗ (green)	
	Thermal power production	→ / ↘ (red)	→ / ↘ (red)	→ / ↘ (red)	→ / ↘ (red)	→	23.3.4, 8.2.3.2
	Energy consumption (net annual change)	↗ (red)	↘ (green)	↘ (green)	↘ (green)	↘ (green)	23.3.4, 23.8.1
Transport	Road accidents[c]	↘ (green)	→ / ↘ (green)	→ / ↘ (green)	→ / ↘ (green)	→ / ↘ (green)	23.3.3
	Rail delays (weather-related)	?	↗ (red) / ↘ (green) [d]	?	?	↗ (red)	23.3.3, 8.3.3.6
	Load factor of inland ships	?	→ / ↘ (red)	→ / ↘ (red)	?	?	23.3.3
	Transport time and cost in ocean routes	?	?	↘ (green)	?	↘ (green)	23.3.3, 18.3.3.3.5
Settlements	River flood damages	→	↗ (red) / ↘ (green)	↗ (red) / ↘ (green)	→	→	23.3.1
	Coastal flood damages	→ / ↗ (red)	→ / ↗ (red)	→ / ↗ (red)	N/A	→ / ↗ (red)	
Tourism	Length of ski season	?	?	↘ (red)	→ / ↘ (red)	↘ (red)	23.3.6, 3.5.7
Human health	Heat wave mortality and morbidity[e]	↗ (red)	↗ (red)	↗ (red)	→	↗ (red)	23.5.1
	Food-borne disease[e]	↗ (red)	↗ (red)	↗ (red)	→	↗ (red)	
Social and cultural impacts	Social costs of floods	→ / ↗ (red)	↗ (red) / ↘ (green)	↗ (red) / ↘ (green)	→	→ / ↗ (red)	23.5.3
	Damage to cultural buildings	↗ (red) / ↘ (green)	↗ (red)	↗ (red)	↗ (red)	↗ (red)	23.5.4
	Loss of cultural landscapes	?	↗ (red)	↗ (red)	↗ (red)	↗ (red)	
Environmental quality	Air quality (ozone background levels)	↗ (red) / ↘ (green)	↗ (red) / ↘ (green)	↗ (red) / ↘ (green)	?	↗ (red) / ↘ (green)	23.6.1
	Air quality (particulates)	↗ (red) / ↘ (green)	↗ (red) / ↘ (green)	↗ (red) / ↘ (green)	?	↗ (red) / ↘ (green)	
	Water quality	↘ (red)	↘ (red)	→	→	→	23.6.3

Increasing ↗

No change →

Decreasing ↘

A range from no change to increasing → / ↗

A range from no change to decreasing → / ↘

A range from increasing to decreasing ↗ / ↘

Green arrows mean a "beneficial change"

Red arrows means a "harmful change"

? 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).

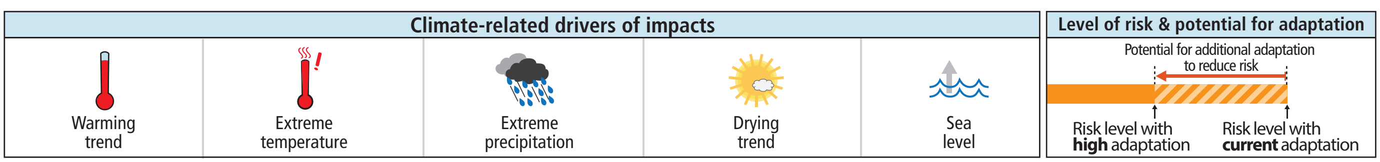
Climate change will have a range of impacts in different European sub-regions. The adaptive capacity of populations is likely to vary significantly within Europe. Adaptive capacity indicators have been developed based on future changes in socioeconomic indicators and projections (Metzger et al., 2008; 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:

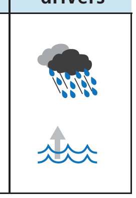
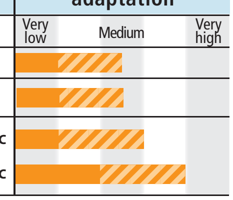
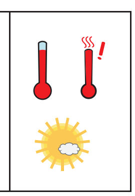
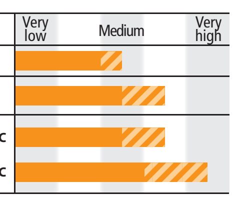
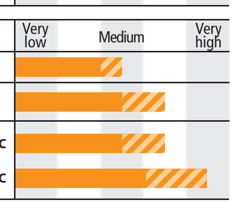
- Populations and infrastructure in coastal regions are likely to be adversely affected by sea level rise, particularly after mid-century (Sections 23.3.1, 23.5.3).
- Urban areas are also vulnerable to weather extremes owing to high density of people and built infrastructure (Sections 23.3, 23.5.1).
- 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.



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		Present Near term (2030–2040) Long term (2080-2100) 2°C / 4°C	
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		Present Near term (2030–2040) Long-term (2080–2100) 2°C / 4°C	
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		Present Near term (2030-2040) Long term (2080–2100) 2°C / 4°C	

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

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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).

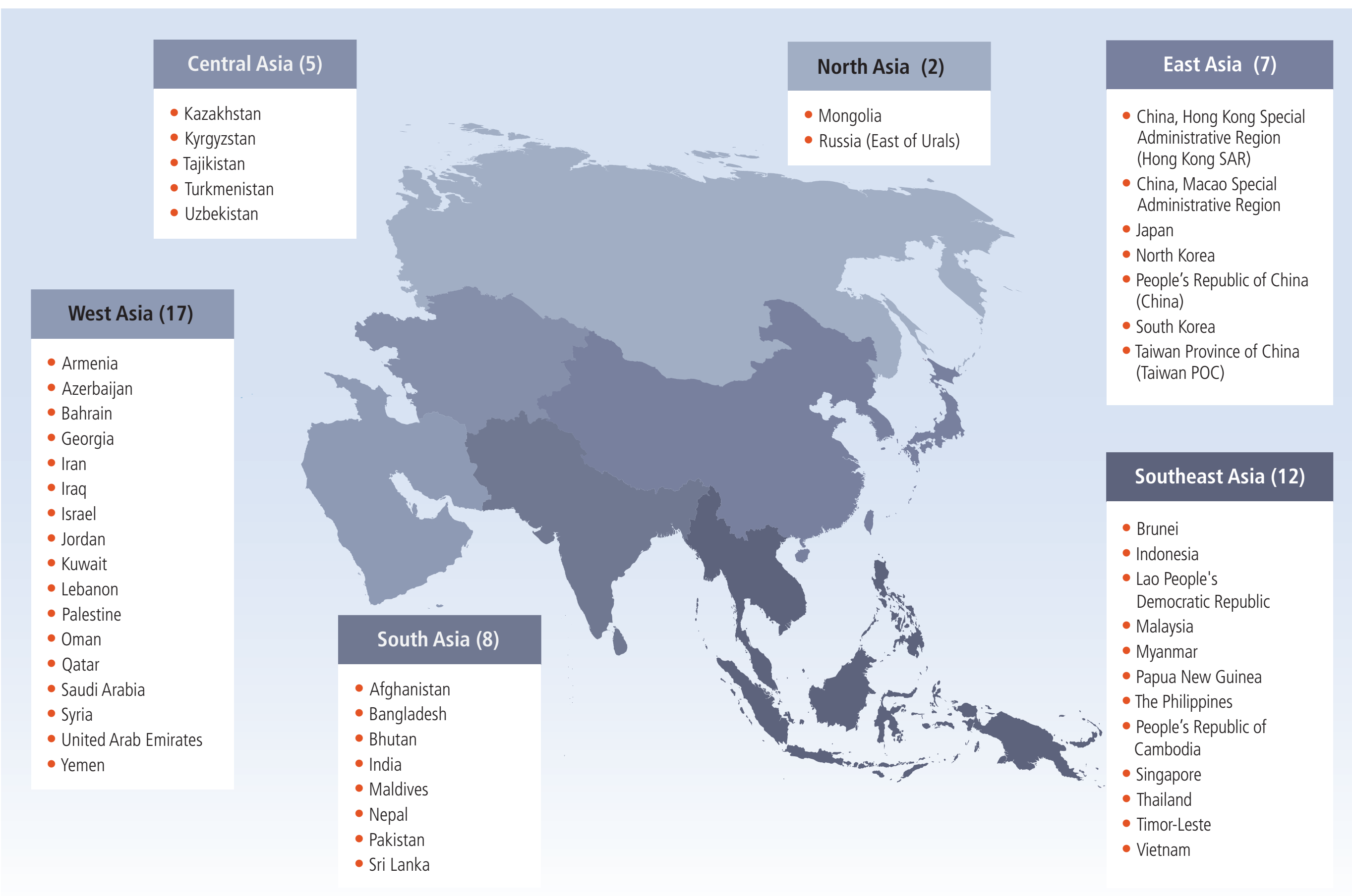


Figure 24-1 | The land and territories of 51 countries/regions in Asia. Maps contained in this report are only for the purpose of geographic information reference.

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

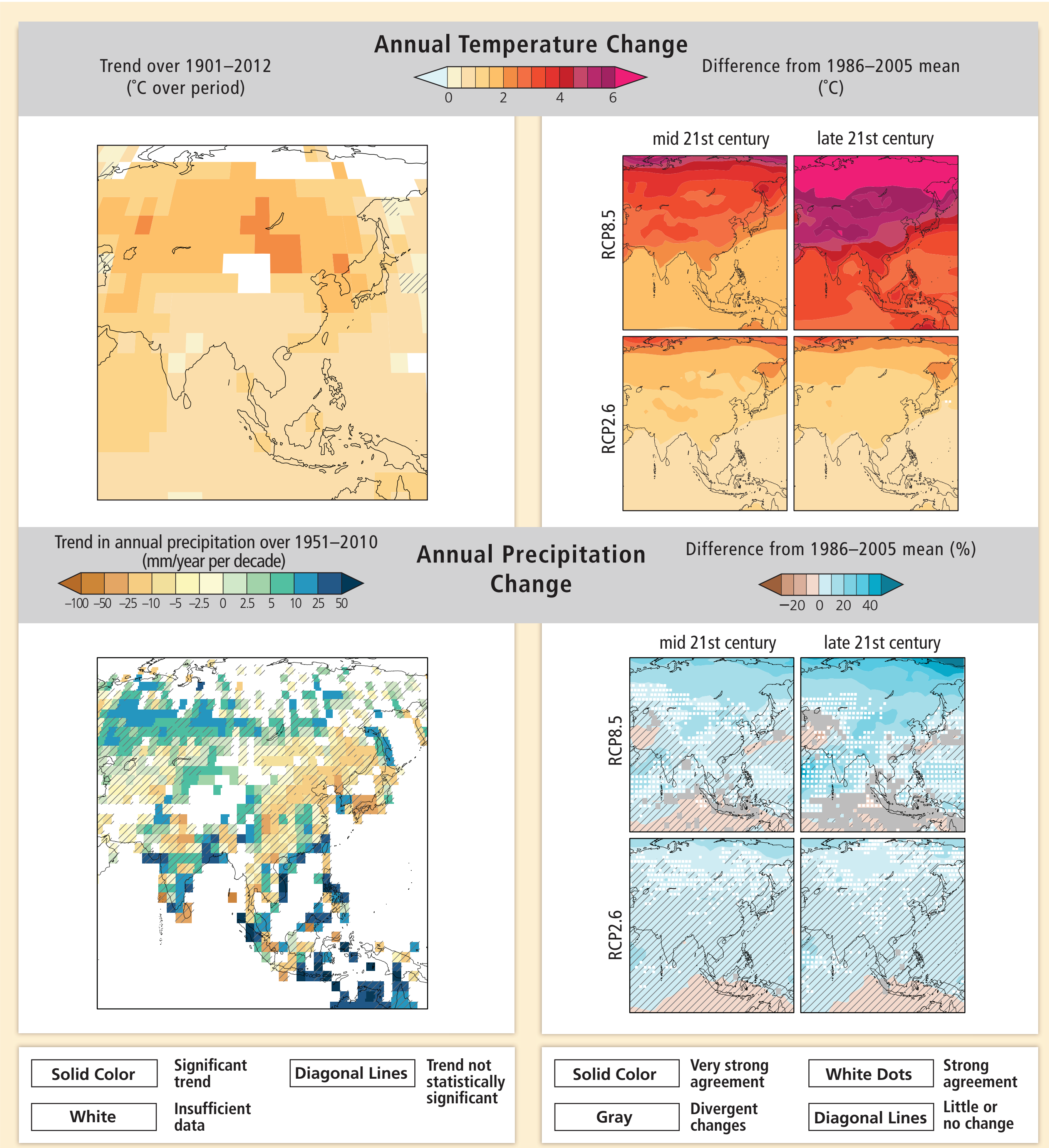
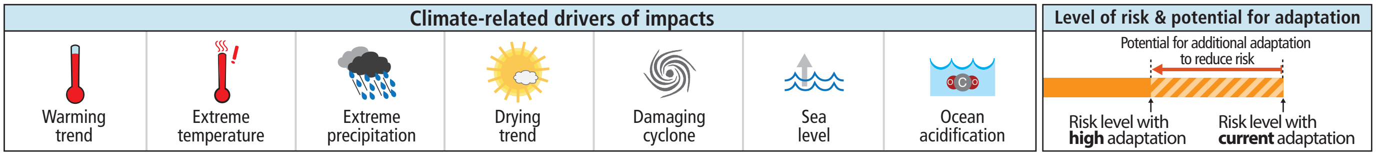


Figure 24-2 | Observed and projected changes in annual average temperature and precipitation in Asia. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation 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]

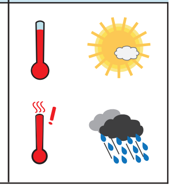
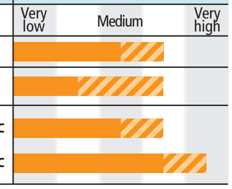
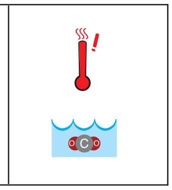
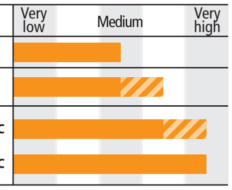
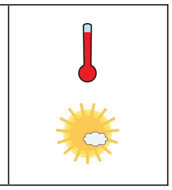
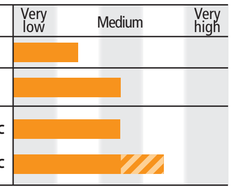
Table 24-1 | Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Asia. Key risks are identified based on assessment of the literature and expert judgments, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each 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.



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 2°C / 4°C (2080–2100)	Very low / Medium / Very high
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 2°C / 4°C (2080–2100)	Very low / Medium / Very high
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 2°C / 4°C (2080–2100)	Very low / Medium / Very high
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 2°C / 4°C (2080–2100)	Very low / Medium / Very high
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 2°C / 4°C (2080–2100)	Very low / Medium / Very high
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 2°C / 4°C (2080–2100)	Very low / Medium / Very high
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 2°C / 4°C (2080–2100)	Very low / Medium / Very high

Continued next page →

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).

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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).

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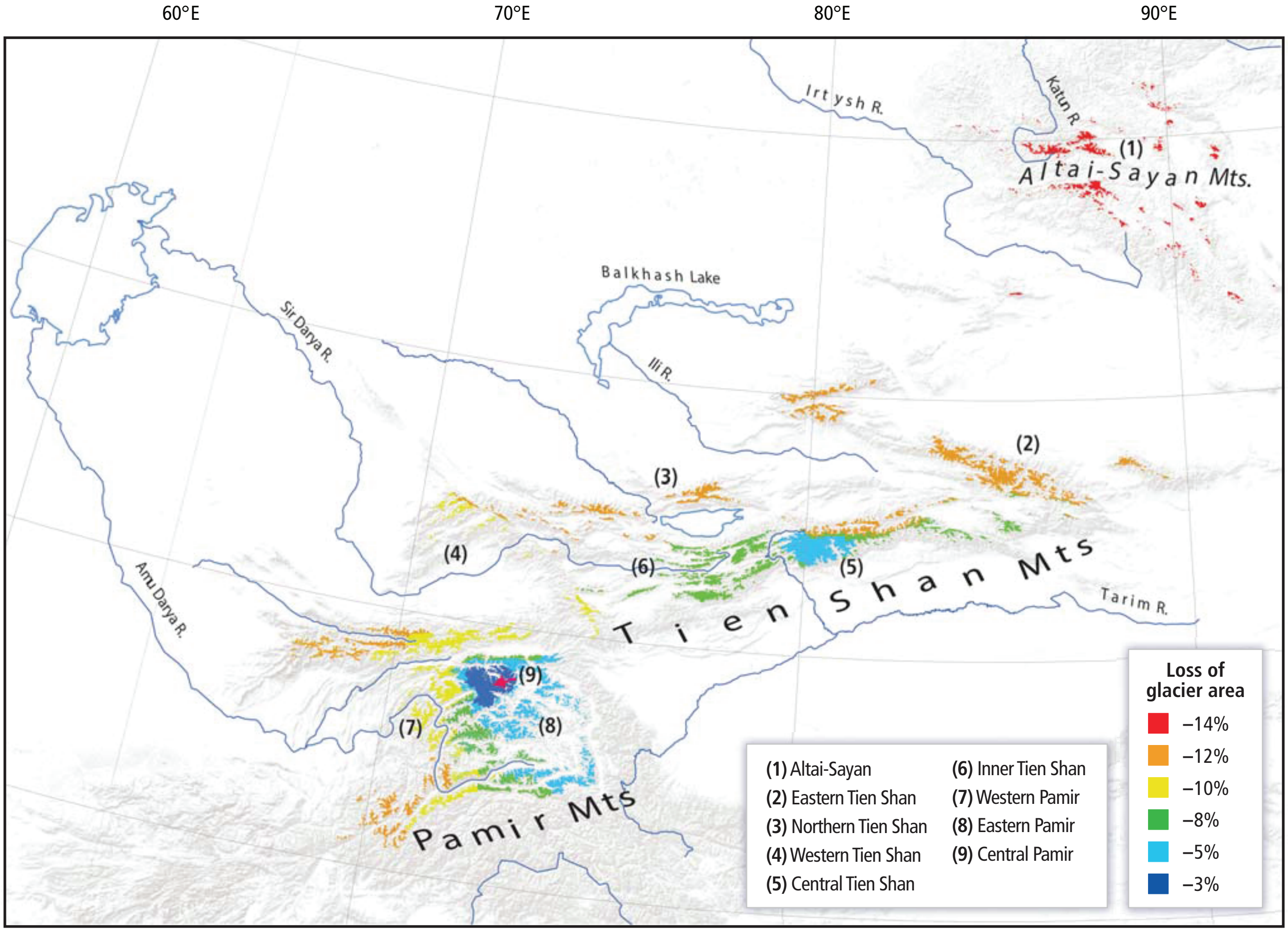

Figure 24-3 | Losses of glacier area in the Altai-Sayan, Pamir, and Tien Shan. Remote-sensing data analysis from 1960s (Corona) through 2008 (Landsat, ASTER, and Alos Prism).

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25 Australasia

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Frequently Asked Questions

25

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 +/–

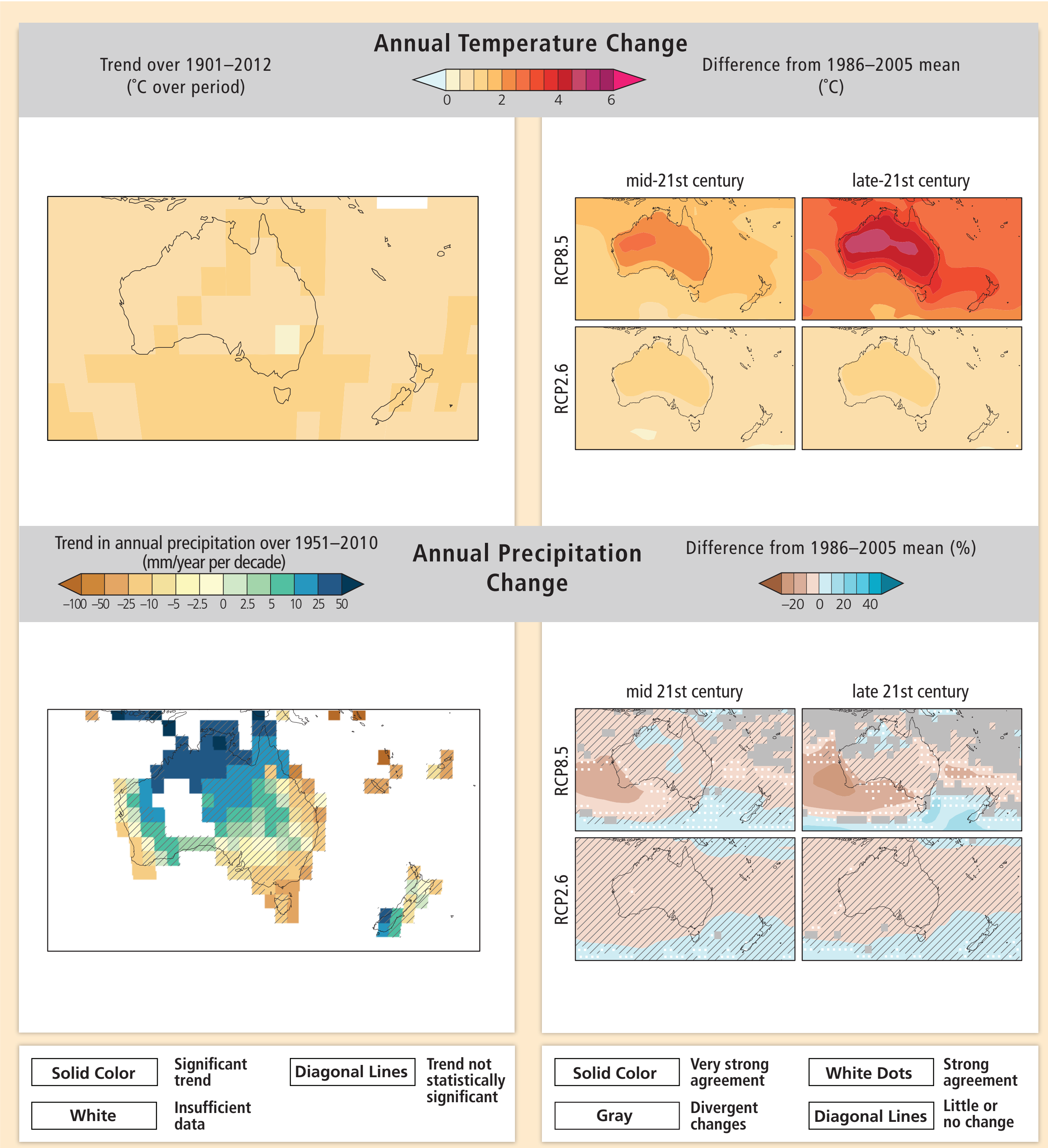

Figure 25-1 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change 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).

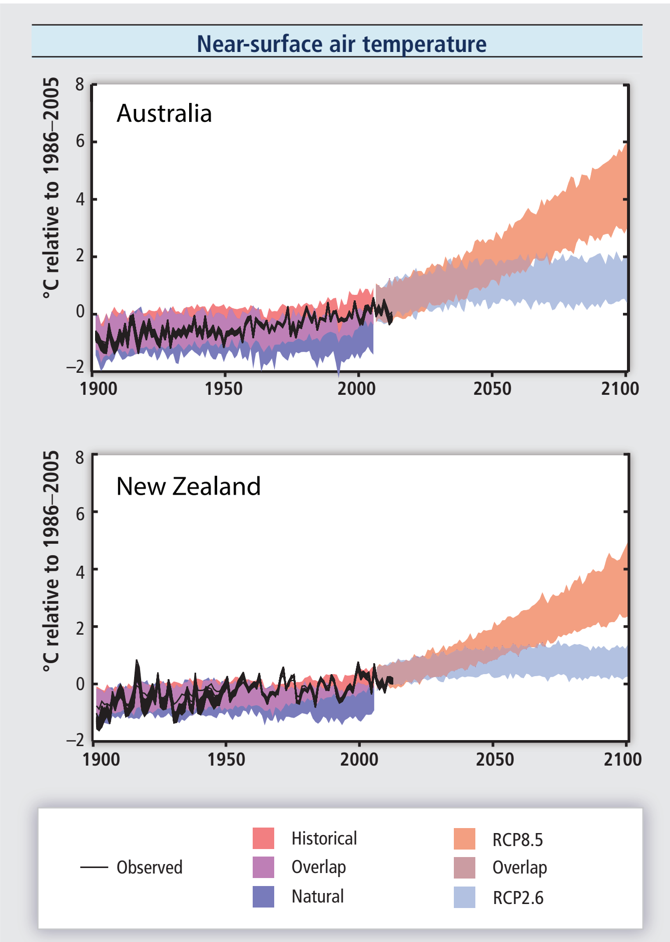

Figure 25-2 | Observed and simulated variations in past and projected future annual average near-surface air temperature over land areas of Australia (top) and New Zealand (bottom). Black lines show various estimates from observational measurements. Shading denotes the 5th to 95th percentile range of 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.

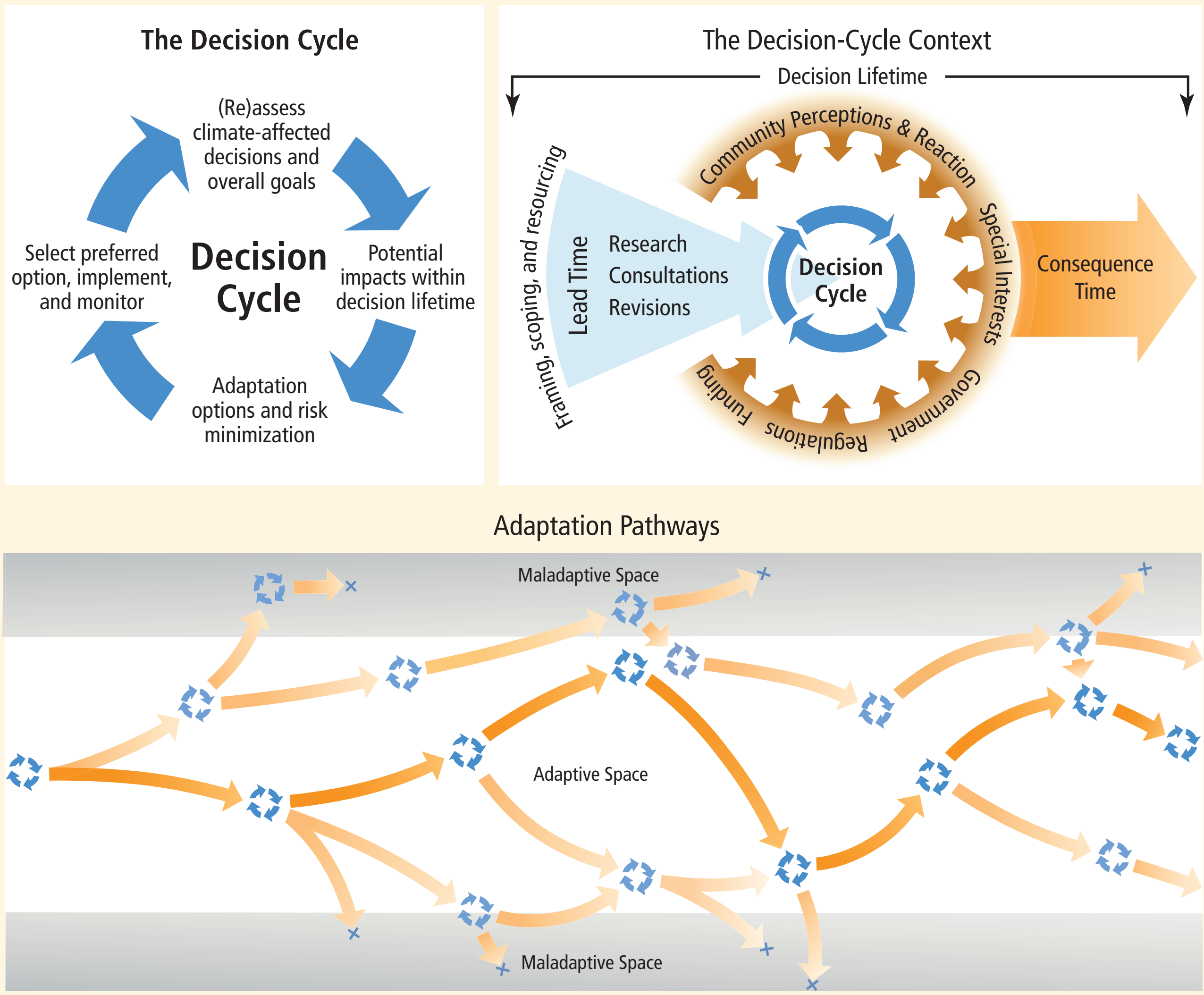

Figure 25-3 | Adaptation as an iterative risk management process. Individual adaptation decisions comprise well known aspects of risk assessment and management (top left panel). Each decision occurs within and exerts its own sphere of influence, determined by the lead and consequence time of the decision, 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.

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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,

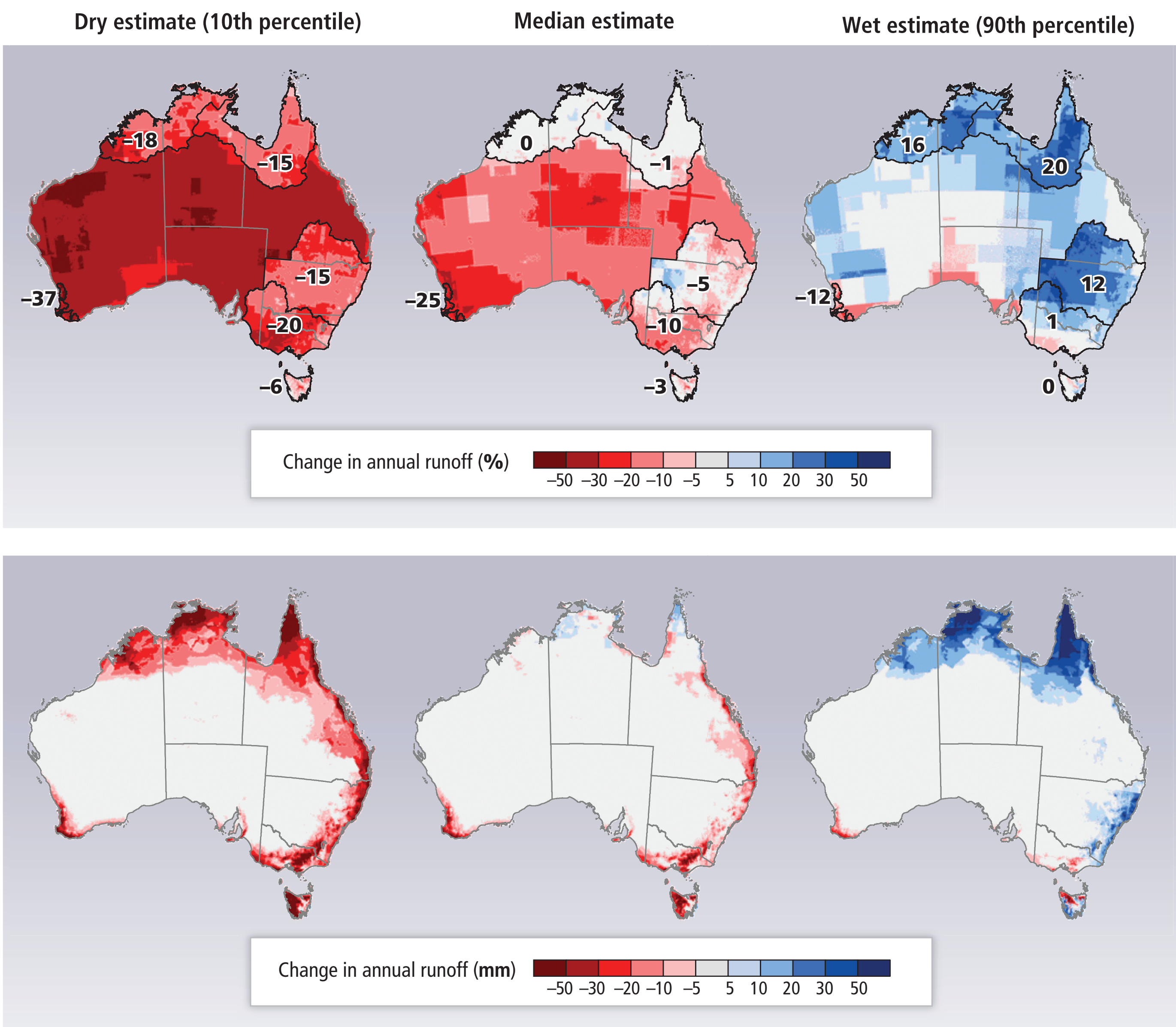

Figure 25-4 | Estimated changes in mean annual runoff for 1°C global average warming above current levels. Maps show changes in annual runoff (percentage change; top row) and runoff depth (millimeters; bottom row), for dry, median, and wet (10th to 90th percentile) range of estimates, based on hydrological 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).

Continued next page →

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).

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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;

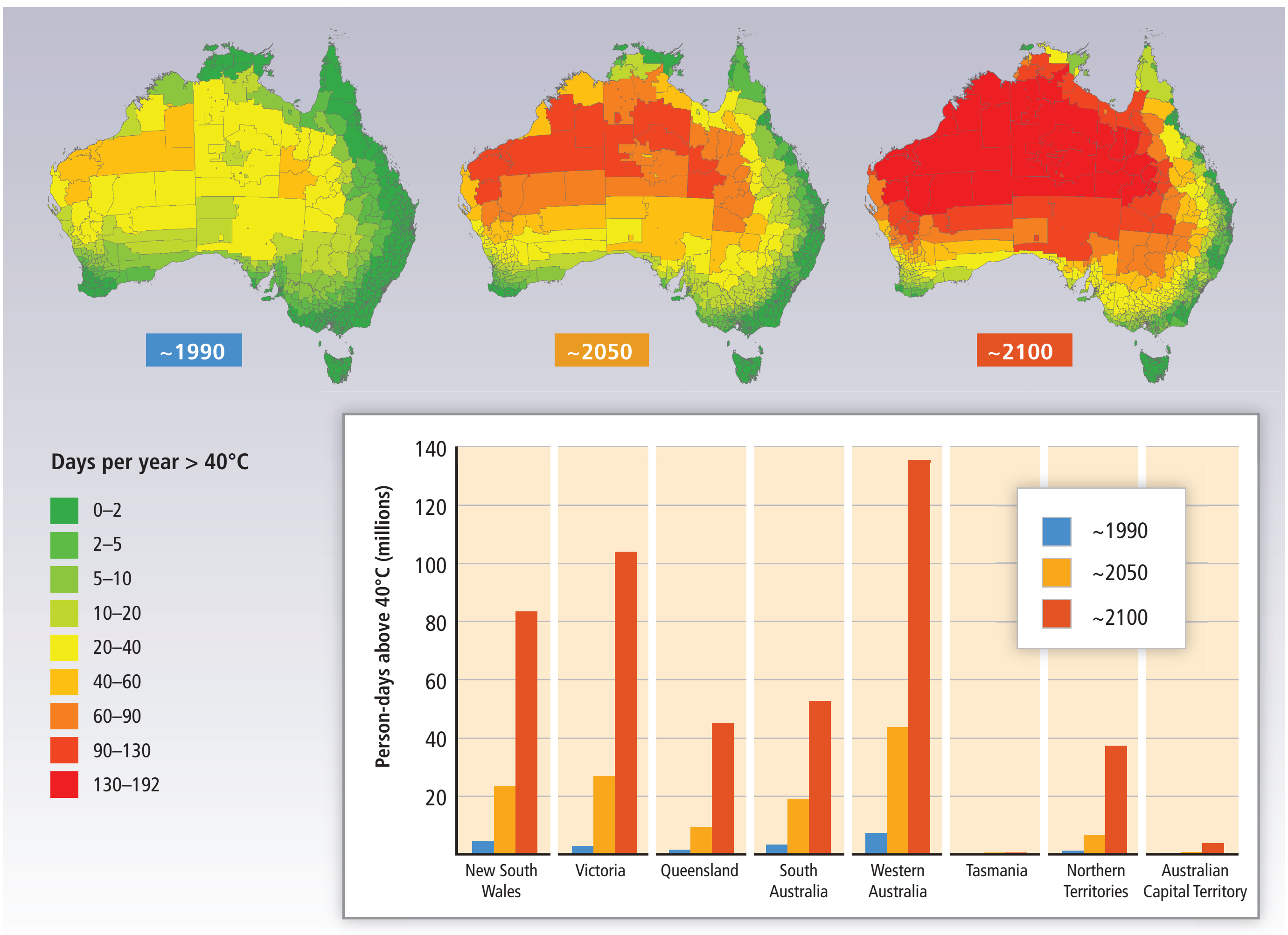

Figure 25-5 | Projected changes in exposure to heat under a high emissions scenario (A1FI). Maps show the average number of days with peak temperatures >40°C, for approximately 1990 (based on available meteorological station data for the period 1975–2004), approximately 2050, and approximately 2100. 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).

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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

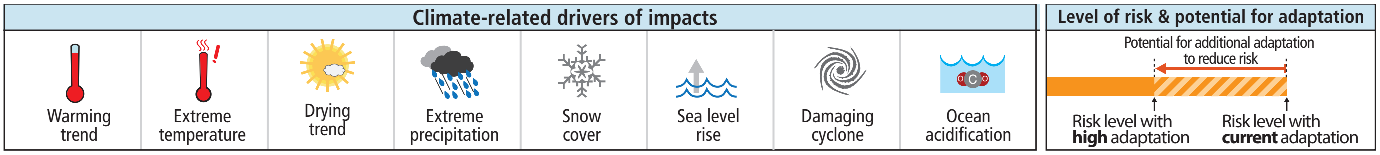
Globally effective mitigation could reduce or delay some of the risks associated with climate change and make adaptation more feasible beyond about 2050, when projected climates begin to diverge substantially between mitigation and non-mitigation scenarios (see also Section 19.7). Literature quantifying 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.

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.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	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				
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.	Warming trend, Damaging cyclone, Ocean acidification	Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
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.	Warming trend, Snow cover, Drying trend	Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Impacts have the potential to be severe but can be reduced substantially by globally effective mitigation combined with 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.	Extreme precipitation	Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
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.	Warming trend, Drying trend	Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
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.	Extreme temperature	Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
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).	Warming trend, Extreme temperature, Drying trend	Present Near term (2030–2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high
Impacts whose severity depends on changes in climate variables that span a particularly large range; the most severe end would present major challenges				
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.	Sea level rise, Damaging cyclone	Moderate sea level rise / High end sea level rise (AR5 WGI 13.5; Box 25-2) Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
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.	Drying trend, Warming trend, Extreme temperature	Wet end of scenario / Dry end of scenario (25.2, 25.5.2, Figure 25-4) Present Near-term (2030-2040) 1.5°C Long term (2080–2100) 2°C 4°C	Very low – Medium – Very high

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).

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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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