26 North America

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Frequently Asked Questions

Executive Summary

Overview

North America's climate has changed and some societally relevant changes have been attributed to anthropogenic causes (*very high confidence*). {Figure 26-1} Recent climate changes and individual extreme events demonstrate both impacts of climate-related stresses and vulnerabilities of exposed systems (*very high confidence*). {Figure 26-2} Observed climate trends in North America include an increased occurrence of severe hot weather events over much of the USA, decreases in frost days, and increases in heavy precipitation over much of North America (*high confidence*). {26.2.2.1} The attribution of observed changes to anthropogenic causes has been established for some climate and physical systems (e.g., earlier peak flow of snowmelt runoff and declines in the amount of water stored in spring snowpack in snow-dominated streams and areas of western USA and Canada (*very high confidence*). {Figure 26-1} Evidence of anthropogenic climatic influence on ecosystems, agriculture, water resources, infrastructure, and urban and rural settlements is less clearly established, though, in many areas, these sectors exhibit substantial sensitivity to climate variability (*high confidence*). {26.3.1-2, 26.4.2.1-2, 26.4.3.1, 26.5.1, 26.7.1.1, 26.7.2, 26.8.1; Figure 26-2; Box 26-3}

Many climate stresses that carry risk—particularly related to severe heat, heavy precipitation, and declining snowpack—will increase in frequency and/or severity in North America in the next decades (*very high confidence*). Global warming of approximately 2°C (above the preindustrial baseline) is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low-snow years, and shifts toward earlier snowmelt runoff over much of the western USA and Canada. {26.2.2.2} Together with climate hazards such as higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability, these changes are projected to lead to increased stresses to water, agriculture, economic activities, and urban and rural settlements (*high confidence*). {26.3.2, 26.5.2, 26.7.1.2, 26.8.3} Global warming of approximately 4°C is *very likely* to cause larger changes in extreme heat events, daily-scale precipitation extremes and snow accumulation and runoff, as well as emergence of a locally novel temperature regime throughout North America. {26.2.2.2} This higher level of global temperature change is *likely* to cause decreases in annual precipitation over much of the southern half of the continent and increases in annual precipitation over much of the northern half of the continent. {26.2.2.2} The higher level of warming would present additional and substantial risks and adaptation challenges across a range of sectors (*high confidence*). {26.3.3, 26.5.2, 26.6.2, 26.7.2.2, 26.8.3}

We highlight below key findings on impacts, vulnerabilities, projections, and adaptation responses relevant to specific North American sectors: ecosystems, water, agriculture, human health, urban and rural settlements, infrastructure, and the economy. We then highlight challenges and opportunities for adaptation, and future risks and adaptive capacity for three key climate-related risks.

Sector-Specific Climate Risks and Adaptation Opportunities

North American ecosystems are under increasing stress from rising temperatures, carbon dioxide (CO_2) concentrations, and sea levels, and are particularly vulnerable to climate extremes (*very high confidence*). Climate stresses occur alongside other anthropogenic influences on ecosystems, including land use changes, non-native species, and pollution, and in many cases will exacerbate these pressures (*very high confidence*). {26.4.1, 26.4.3}. Evidence since the Fourth Assessment Report (AR4) highlights increased ecosystem vulnerability to multiple and interacting climate stresses in forest ecosystems, through wildfire activity, regional drought, high temperatures, and infestations (*medium confidence*); {26.4.2.1; Box 26-2} and in coastal zones due to increasing temperatures, ocean acidification, coral reef bleaching, increased sediment load in runoff, sea level rise (SLR), storms, and storm surges (*high confidence*). {26.4.3.1} In the near term, conservation and adaptation practices can buffer against climate stresses to some degree in these ecosystems, both through increasing system resilience, such as forest management to reduce vulnerability to infestation, and in reducing co-occurring non-climate stresses, such as careful oversight of fishing pressure (*medium confidence*). {26.4.4}

Water resources are already stressed in many parts of North America due to non-climate change anthropogenic forces, and are expected to become further stressed due to climate change (*high confidence*). {26.3} Decreases in snowpacks are already influencing seasonal streamflows (*high confidence*). {26.3.1} Though indicative of future conditions, recent floods, droughts, and changes in mean flow conditions cannot yet be attributed to climate change (*medium* to *high confidence*). {26.3.1-2} The 21st century is projected to witness decreases in water quality and increases in urban drainage flooding throughout most of North America under climate change as well as a decrease in instream uses such as hydropower in some regions (*high confidence*). {26.3.2.2-4} In addition, there will be decreases in water supplies for urban areas and irrigation in North America except in general for southern tropical Mexico, northwest coastal USA, and west coastal Canada (*high* to *medium confidence*). {26.3.2.1} Many adaptation options currently available can address water supply deficits; adaptation responses to flooding and water quality concerns are more limited (*medium confidence*). {26.3.3}

Effects of temperature and climate variability on yields of major crops have been observed (*high confidence*). {25.5.1} Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st century without adaptation, although the rate of decline varies by model and scenario, and some regions, particularly in the north, may benefit (*very high confidence*). {26.5.2} Given that North America is a significant source of global food supplies, projected productivity declines here may affect global food security (*medium confidence*). At 2°C, adaptation has high potential to offset projected declines in yields for many crops, and many strategies offer mitigation co-benefits; but effectiveness of adaptation would be reduced at 4°C (*high confidence*). {26.5.3} Adaptation capacity varies widely among producers, and institutional support—currently lacking in some regions—greatly enhances adaptive potential (*medium confidence*). {26.5.4}

Human health impacts from extreme climate events have been observed, although climate change-related trends and attribution have not been confirmed to date. Extreme heat events currently result in increases in mortality and morbidity in North America (*very high confidence*), with impacts that vary by age, location, and socioeconomic factors (*high confidence*). {26.6.1.2} Extreme coastal storm events can cause excess mortality and morbidity, particularly along the East Coast of the USA, and the Gulf Coast of both Mexico and the USA (*high confidence*). {26.6.1.1} A range of water-, food-, and vector-borne infectious diseases, air pollutants, and airborne pollens are influenced by climate variability and change (*medium confidence*). {26.6.1.3-6} Further climate warming in North America will impose stresses on the health sector through more severe extreme events such as heat waves and coastal storms, as well as more gradual changes in climate and CO_2 levels. {26.6.2} Human health impacts in North America from future climate extremes can be reduced by adaptation measures such as targeted and sustainable air conditioning, more effective warning and response systems, enhanced pollution controls, urban planning strategies, and resilient health infrastructure (*high confidence*). {26.6.3}

Observed impacts on livelihoods, economic activities, infrastructure, and access to services in North American urban and rural settlements have been attributed to SLR, changes in temperature and precipitation, and occurrences of such extreme events as heat waves, droughts, and storms (*high confidence*). {26.8.2.1} Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific social and environmental factors and processes that contribute to risk, vulnerability, and adaptive capacity such as hazard magnitude, populations access to assets, built environment features, and governance (*high confidence*). {26.8.2.1-2}. Some of these processes (e.g., the legacy of previous and current stresses) are common to urban and rural settlements, while others are more pertinent to some types of settlements than others. For example, human and capital risks are highly concentrated in some highly exposed urban locations, while in rural areas, geographic isolation and institutional deficits are key sources of vulnerability. Among the most vulnerable are indigenous peoples due to their complex relationship with their ancestral lands and higher reliance on subsistence economies, and those urban centers where high concentrations of populations and economic activities in risk-prone areas combine with several socioeconomic and environmental sources of vulnerability (*high confidence*). {26.8.2.1-2} Although larger urban centers would have higher adaptation capacities, future climate risks from heat waves, droughts, storms, and SLR in cities would be enhanced by high population density, inadequate infrastructures, lack of institutional capacity, and degraded natural environments (*medium evidence*, *high agreement*). {26.8.3}

Much of North American infrastructure is currently vulnerable to extreme weather events and, unless investments are made to strengthen them, would be more vulnerable to climate change (*medium confidence*). Water resources and transportation infrastructure are in many cases deteriorating, thus more vulnerable to extremes than strengthened ones (*high confidence*). Extreme events have caused significant damage to infrastructure in many parts of North America; risks to infrastructure are particularly acute in Mexico but are a big concern in all three countries (*high confidence*). {26.7}

Most sectors of the North American economy have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). {Figure 26-2} Despite a growing experience with reactive adaptation, there are few examples of proactive adaptation anticipating future climate change impacts, and these are largely found in sectors with longer term decision making, including energy and public infrastructure. Knowledge about lessons learned and best adaptive practices by industry sector are not well documented in the published literature. {26.7} There is an emerging concern that dislocation in one sector of the economy may have an adverse impact on other sectors as a result of supply chain interdependency (*medium confidence*). {26.7} Slow-onset perils—such as SLR, drought, and permafrost thaw—are an emerging concern for some sectors, with large regional variation in awareness and adaptive capacity (*medium confidence*).

Adaptation Responses

Adaptation—including through technological innovation, institutional strengthening, economic diversification, and infrastructure design—can help to reduce risks in the current climate, and to manage future risks in the face of climate change (*medium confidence*). {26.8.4, 26.9.2} There is increasing attention to adaptation among planners at all levels of government but particularly at the municipal level, with many jurisdictions engaging in assessment and planning processes. These efforts have revealed the significant challenges and sources of resistance facing planners at both the planning and implementation stages, particularly the adequacy of informational, institutional, financial, and human resources, and lack of political will (*medium confidence*). {26.8.4.2, 26.9.3} Specific strategies introduced into policy to date tend to be incremental rather than transformational. Fiscal constraints are higher for Mexican jurisdictions and sectors than for Canada or the USA. The literature on sectoral-level adaptation is stronger in the areas of technological and engineering adaptation strategies than in social, behavioral, and institutional strategies. Adaptation actions have the potential to result in synergies or trade-offs with mitigation and other development actions and goals (*high confidence*). {26.8.4.2, 26.9.3}

26.1. Introduction

This chapter assesses literature on observed and projected impacts, vulnerabilities, and risks as well as on adaptation practices and options in three North American countries: Canada, Mexico, and the USA. The North American Arctic region is assessed in Chapter 28: Polar Regions. North America ranges from the tropics to frozen tundra, and contains a diversity of topography, ecosystems, economies, governance structures, and cultures. As a result, risk and vulnerability to climate variability and change differ considerably across the continent depending on geography, scale, hazard, socio-ecological systems, ecosystems, demographic sectors, cultural values, and institutional settings. This chapter seeks to take account of this diversity and complexity as it affects and is projected to affect vulnerabilities, impacts, risks, and adaptation across North America.

No single chapter would be adequate to cover the range and scope of the literature about climate change vulnerabilities, impacts, and adaptations in the three focus countries of this assessment. (Interested readers are encouraged to review these reports: Lemmen et al., 2008; INECC and SEMARNAT, 2012a; NCADAC, 2013.) We therefore attempt to take a more integrative and innovative approach. In addition to describing current and future climatic and socioeconomic trends of relevance to understanding risk and vulnerability in North America (Section 26.2), we contrast climate impacts, vulnerabilities, and adaptations across and within the three countries in the following key sectors: water resources and management (Section 26.3); ecosystems and biodiversity (Section 26.4); agriculture and food security (Section 26.5); human health (Section 26.6); and key economic sectors and services (Section 26.7). We use a comparative and place-based approach to explore the factors and processes associated with differences and commonalities in vulnerability, risk, and adaptation between urban and rural settlements (Section 26.8); and to illustrate and contrast the nuanced challenges and opportunities adaption entails at the city, subnational, and national levels (Sections 26.8.4, 26.9; Box 26-3). We highlight two case studies that cut across sectors, systems, or national boundaries. The first, on wildfires (Box 26-2), explores some of the connections between climatic and physical and socioeconomic process (e.g., decadal climatic oscillation, droughts, wildfires land use, and forest management) and across systems and sectors (e.g., fires direct and indirect impacts on local economies, livelihoods, built environments, and human health). The second takes a look at one of the world's longest borders between a high-income (USA) and middle-income country (Mexico) and briefly reflects on the challenges and opportunities of responding to climate change in a transboundary context (Box 26-1). We close with a section (26.10) summarizing key multi-sectoral risks and uncertainties and discussing some of the knowledge gaps that will need to be filled by future research.

Findings from the Fourth Assessment Report

This section summarizes key findings on North America, as identified in Chapter 13 of the Fourth Assessment Report (AR4) focused on Mexico (Magrin et al., 2007) and Chapter 14 on Canada and the USA (Field et al., 2007). It focuses on observed and projected impacts, vulnerabilities, and risks, as well as on adaptation practices and options, and highlights areas of agreement and difference between the AR4's two chapters and our consolidated North American chapter.

Observed Impacts and Processes Associated with Vulnerability

Both WGII AR4 Section 14.2 and our chapter (Figure 26-2) find that, over the past decades, economic damage from severe weather has increased dramatically. Our chapter confirms that although Canada and the USA have considerably more adaptive capacity than Mexico, their vulnerability depends on the effectiveness and timing of adaptation and the distribution of capacity, which vary geographically and between sectors (WGII AR4 Sections 14.2.6, 14.4-5; Sections 26.2.2, 26.8.2).

WGII AR4 Chapters 13 and 14 did not assess impacts, vulnerabilities, and risks in urban and rural settlements, but rather assessed literature on future risks in the following sectors:

- *Ecosystems*: Both AR4 and our chapter find that ecosystems are under increased stress from increased temperatures, climate variability, and other climate stresses (e.g., sea level rise (SLR) and storm-surge flooding), and that these stresses interact with developmental and environmental stresses (e.g., as salt intrusion, pollution, population growth, and the rising value of infrastructure in coastal areas) (WGII AR4 Sections 13.4.4, 14.2.3, 14.4.3). Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections would alter ecosystem structure, function, and services in terrestrial ecosystems (WGII AR4 Sections 14.2, 14.4). Both reports show that dry soils and warm temperatures are associated with increased wildfire activity and insect outbreaks in Canada and the USA (WGII AR4 Sections 14.2, 14.4; Section 26.4.2.1).
- *Water resources*: AR4 projects millions in Mexico to be at risk from the lack of adequate water supplies due to climate change (WGII AR4 Section 13.4.3); our chapter, however, finds that water resources are already stressed by non-climatic factors, such as population pressure that will be compounded by climate change (Section 26.3.1). Both reports find that in the USA and Canada rising temperatures would diminish snowpack and increase evaporation (Section 26.2.2.1), thus affecting seasonal availability of water (WGII AR4 Section 14.2.1; Section 26.3.1). The reports also agree that these effects will be amplified by water demand from economic development, agriculture, and population growth, thus imposing further constraints to over-allocated water resources and increasing competition among agricultural, municipal, industrial, and ecological uses (WGII AR4 Sections 14.4.1, 14.4.6; Section 26.3.3). Both agree water quality will be further stressed (WGII AR4 Sections 13.4.3, 14.4.1; Section 26.3.2.2). There is more information available now on water adaptation than in AR4 (WGII AR4 Sections 13.5.1.3, 14.5.1; Section 26.3.3), and it is possible to attribute changes in extreme precipitation, snowmelt, and snowpack to climate change (WGII AR4 Sections 13.2.4, 14.2.1; Section 26.3.1).
- *Agriculture*: The AR4 noted that while increases in grain yields in the USA and Canada are projected by most scenarios (WGII AR4 Section 14.4.4), in Mexico the picture is mixed for wheat and maize, with different projected impacts depending on scenario used (WGII AR4 Section 13.4.2). Research since the AR4 has offered more cautious projections of yield change in North America due to shifts in temperature and precipitation, particularly by 2100; and significant harvest losses due to recent extreme weather events have been observed (Section 26.5.1). Furthermore, our chapter reports on recent research that underscores the context-specific nature of adaptation

capacity and of institutional support and shows that these factors, which greatly enhance adaptive potential, are currently lacking in some regions (Section 26.5.3).

- *Health*: AR4 focused primarily on a set of future health risks. These include changes in the geographical distribution and transmission of diseases such as dengue (WGII AR4 Section 13.4.5) and increases in respiratory illness, including exposure to pollen and ozone (WGII AR4 Section 14.4) and in mortality from hot temperatures and extreme weather in Canada and the USA. AR4 also projects that climate change impacts on infrastructure and human health in cities of Canada and the USA would be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth, and an aging population (WGII AR4 Sections 14.4-5). Without increased investments in measures such

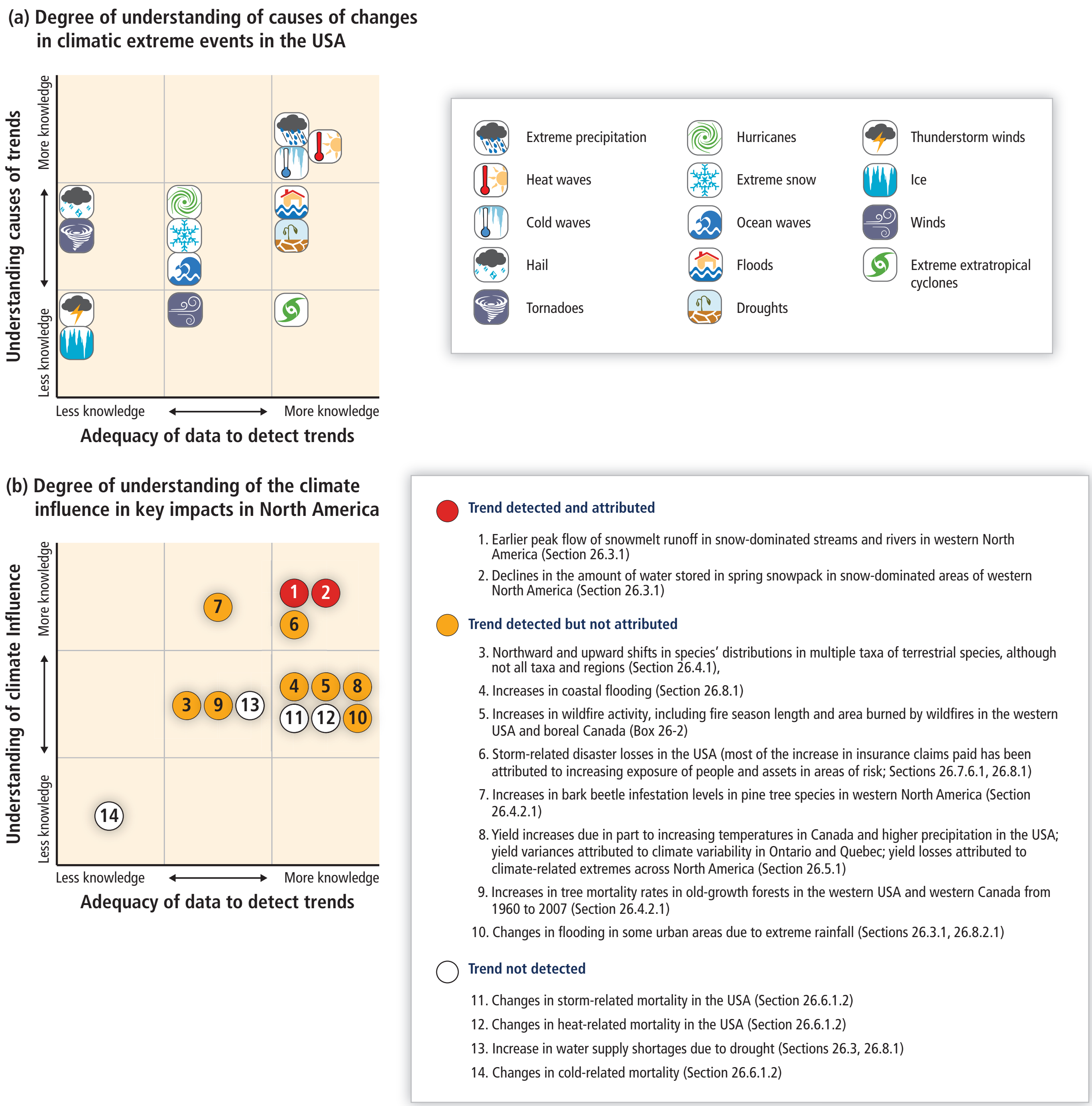

Figure 26-1 | (a) Detection and attribution of climate change impacts. Comparisons of the adequacy of currently available data to detect trends and the degree of understanding of causes of those changes in climatic extreme events in the USA (Peterson et al., 2013), and (b) degree of understanding of the climate influence in key impacts in North America. Note that "climate influence" means that the impact has been documented to be sensitive to climate, not that it has been attributed to climate change. Red circles indicate that formal detection and attribution to climate change has been performed for the given impact; yellow circles indicate that a trend has been detected from background variability in the given impact, but formal attribution to climate change has not occurred and the trend could be due to other drivers; and white circles indicate that a trend has not currently been detected.

as early warning and surveillance systems, air conditioning, and access to health care, hot temperatures and extreme weather in Canada and the USA are predicted to result in increased adverse health impacts (WGII AR4 Sections 14.4-5). Our chapter provides a more detailed assessment of these future risks (Section 26.6), besides assessing a richer literature on observed health impacts (Section 26.6.1).

- *Adaptation*: AR4 found that Mexico has early warning and risk management systems, yet it faces planning and management barriers. In Canada and the USA, a decentralized response framework has resulted in adaptation that tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems (WGII AR4 Section 14.5). Both chapters see "mainstreaming" climate issues into decision making as key to successful adaptation (WGII AR4 Sections 13.5, 14.5). The current chapter provides a summary of the growing empirical literature on emerging opportunities and constraints associated with recent institutional adaptation planning activities since the AR4 (Sections 26.3.3, 26.4.4, 26.5.4, 26.6.3, 26.8.4, 26.9).

In summary, scholarship on climate change impacts, adaptation, and vulnerability has grown considerably since the AR4 in North America, particularly in Canada and the USA. It is possible now not only to detect and attribute to anthropogenic climate change some impacts such as changes in extreme precipitation, snowmelt, and snowpack, but also to examine trends showing increased insect outbreaks, wildfire events, and coastal flooding. These latter trends have been shown to be sensitive to climate, but, like the local climate patterns that cause them, have not yet been positively attributed to anthropogenic climate change (see Figure 26-1).

26.2. Key Trends Influencing Risk, Vulnerability, and Capacities for Adaptation

26.2.1. Demographic and Socioeconomic Trends

26.2.1.1. Current Trends

Canada, Mexico, and USA share commonalities but also differ in key dimensions shaping risk, vulnerability, and adaptation such as population dynamics, economic development, and institutional capacity. During the last years, the three countries, particularly the USA, have suffered economic losses from extreme weather events (Figure 26-2). Hurricanes, droughts, floods, and other climate-related hazards produce risk as they interact with increases in exposed populations, infrastructure, and other assets and with the dynamics of such factors shaping vulnerability as wealth, population size and structure, and poverty (Figures 26-2 and SPM.1). Population growth has been slower in Canada and USA than in Mexico (UN DESA Population Division, 2011). Yet population growth in Mexico also decreased from 3.4% between 1970 and 1980 to 1.5% yearly during 2000–2010. Populations in the three countries are aging at different

Box 26-1 | Adapting in a Transboundary Context: The Mexico-USA Border Region

Extending over 3111 km (1933 miles; U.S. Census Bureau, 2011), the border between the USA and Mexico, which can be defined in different ways (Varady and Ward, 2009), illustrates the challenges and opportunities of responding to climate change in a transboundary context. Changing regional climate conditions and socioeconomic processes combined shape differentiated vulnerabilities of exposed populations, infrastructure, and economic activities.

Since at least 1999, the region has experienced high temperatures and aridity anomalies leading to drought conditions (Woodhouse et al., 2010; Wilder et al., 2013) affecting large areas on both sides of the border, and considered the most extreme in over a century of recorded precipitation patterns for the area (Cayan et al., 2010; Seager and Vecchi, 2010; Nielsen-Gammon, 2011). Streamflow in already oversubscribed rivers such as the Colorado and Rio Grande (Nakaegawa et al., 2013) has decreased. Climatological conditions for the area have been unprecedented, with sustained high temperatures that may have exceeded any experienced for 1200 years. Although these changes cannot conclusively be attributed to anthropogenic climate change, they are consistent with climate change projections (Woodhouse et al., 2010).

The population of the Mexico-USA border is rapidly growing and urbanizing, doubling from just under 7 million in 1983 to more than 15 million in 2012 (Peach and Williams, 2000). Since 1994, rapid growth in the area has been fueled by rapid economic development subsequent to passage of the North American Free Trade Agreement (NAFTA). Between 1990 and 2001 the number of assembly factories or maquiladoras in Mexico grew from 1700 to nearly 3800, with 2700 in the border area. By 2004, it was estimated that more than 1 million Mexicans were employed in more than 3000 maquiladoras located along the border (Border Indicators Task Force, 2011; EPA and SEMARNAT, 2012).

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Box 26-1 (continued)

Notwithstanding this growth, challenges to adaptive capacity include high rates of poverty in a landscape of uneven economic development (Wilder et al., 2013). Large sections of the urban population, particularly in Mexico, live in informal housing lacking the health and safety standards needed to respond to hazards, and with no insurance (Collins et al., 2011). Any effort to increase regional capacity to respond to climate needs to take existing gaps into account. In addition, there is a prevalence of incipient or actual conflict (Mumme, 1999), given by currently or historically contested allocation of land and water resources (e.g., an over-allocated Colorado River ending in Mexico above the Sea de Cortes (Getches, 2003)). Climate change, therefore, would bring additional significant consequences for the region's water resources, ecosystems, and rural and urban settlements.

The impacts of regional climatic and non-climatic stresses compound existing urban vulnerabilities that are different across countries. For instance, besides degrading highly diverse ecosystems (Wilder et al., 2013), residential growth in flood-prone areas in Ciudad Juárez has not been complemented with the provision of determinants of adaptive capacity to residents, such as housing, health care, and drainage infrastructure. As a result, although differences in mean hazard scores are not significant between Ciudad Juárez (Mexico) and El Paso (USA), social vulnerability and average risk are three times and two times higher in Ciudad Juárez than in El Paso respectively (Collins, 2008).

Projected warming and drying would impose additional burdens on already stressed water resources and ecosystems and compound existing vulnerabilities for populations, infrastructure, and economic activities (Wilder et al., 2013). The recent drought in the region illustrated the multiple dimensions of climate-related events, including notable negative impacts on the agricultural sector, water supplies, food security, and risk of wildfire (discussed in Box 26-2) (Wehner et al., 2011; Hoerling et al., 2012; Schwalm et al., 2012).

Adaptation opportunities and *constraints* are shared across international borders, creating the need for cooperation among local, national, and international actors. Although there are examples of efforts to manage transborder environmental issues, such as the USA-Mexico International Boundary and Water Commission agreement (United States and Mexico International Boundary and Water Commission, 2012), constraints to effective cooperation and collaboration include different governance structures (centralized in Mexico, decentralized in the USA), institutional fragmentation, asymmetries in the use and dissemination of information, and language (Wilder et al., 2010, 2013; Megdal and Scott, 2011).

rates (Figure 26-2). In 2010, 14.1% of the population in Canada was 60 years and older, compared to 12.7% in the USA and 6.1% in Mexico (UN DESA Population Division, 2011). Urban populations have grown faster than rural populations, resulting in a North America that is highly urbanized (Canada 84.8%, Mexico 82.8%, and USA 85.8%). Urban populations are also expanding into peri-urban spaces, producing rapid changes in population and land use dynamics that can exacerbate risks from such hazards as floods and wildfires (Eakin et al., 2010; Romero-Lankao et al., 2012a). Mexico has a markedly higher poverty rate (34.8%) than Canada (9.1%) and the USA (12.5%) (Figure 26-2), with weather events and climate affecting poor people's livelihood assets, including crop yields, homes, food security, and sense of place (Chapter 13; Section 26.8.2). Between 1970 and 2012, a 10% increase in single-person households—who can be vulnerable because of isolation and low income and housing quality (Roorda et al., 2010)—has been detected in the USA (Vespa et al., 2013).

While concentrations of growing populations, water, sanitation, transportation and energy infrastructure, and industrial and service sectors in urban areas can be a source of risk, geographic isolation and high dispersion of rural populations also introduce risk because of long distances to essential services (Section 26.8.2). Rural populations are more vulnerable to climate events due to smaller labor markets, lower income levels, and reduced access to public services. Rural poverty could also be aggravated by changes in agricultural productivity, particularly in Mexico, where 65% of the rural population is poor, agricultural income is seasonal, and most households lack insurance (Scott, 2007). Food price increases, which may also result from climate events, would contribute to food insecurity (Lobell et al., 2011; World Bank, 2011).

Migration is a key trend affecting North America, recently with movements between urban centers and from rural Mexico into Mexico's cities, and in the USA. Rates of migration from rural Mexico are positively associated with natural disaster occurrence and increased poverty trends (Saldaña-Zorilla and Sandberg, 2009), and with decreasing precipitation (Nawrotski et al., 2013). Studies of migration induced by past climate variability and change indicate a preference for short-range domestic movement, a complex relationship to assets with indications that the poorest are less able to migrate, and the role of preexisting immigrant networks in facilitating international migration (Oppenheimer, 2013).

North America has become more economically integrated following the 1994 North American Free Trade Agreement. Prior to a 2007–2008 reduction in trade, the three countries registered dynamic growth in industry, employment, and global trade of agricultural and manufactured goods (Robertson et al., 2009). Notwithstanding North America's economic dynamism, increased socioeconomic disparities (Autor et al., 2008) have affected such determinants of vulnerability as differentiated human development and institutional capacity within and across countries.

26.2.1.2. Future Trends

The North American population is projected to continue growing, reaching between 531.8 (SRES B2) and 660.1 (A2) million by 2050 (IIASA, 2007).

(a) Significant weather events taking place during 1993–2012

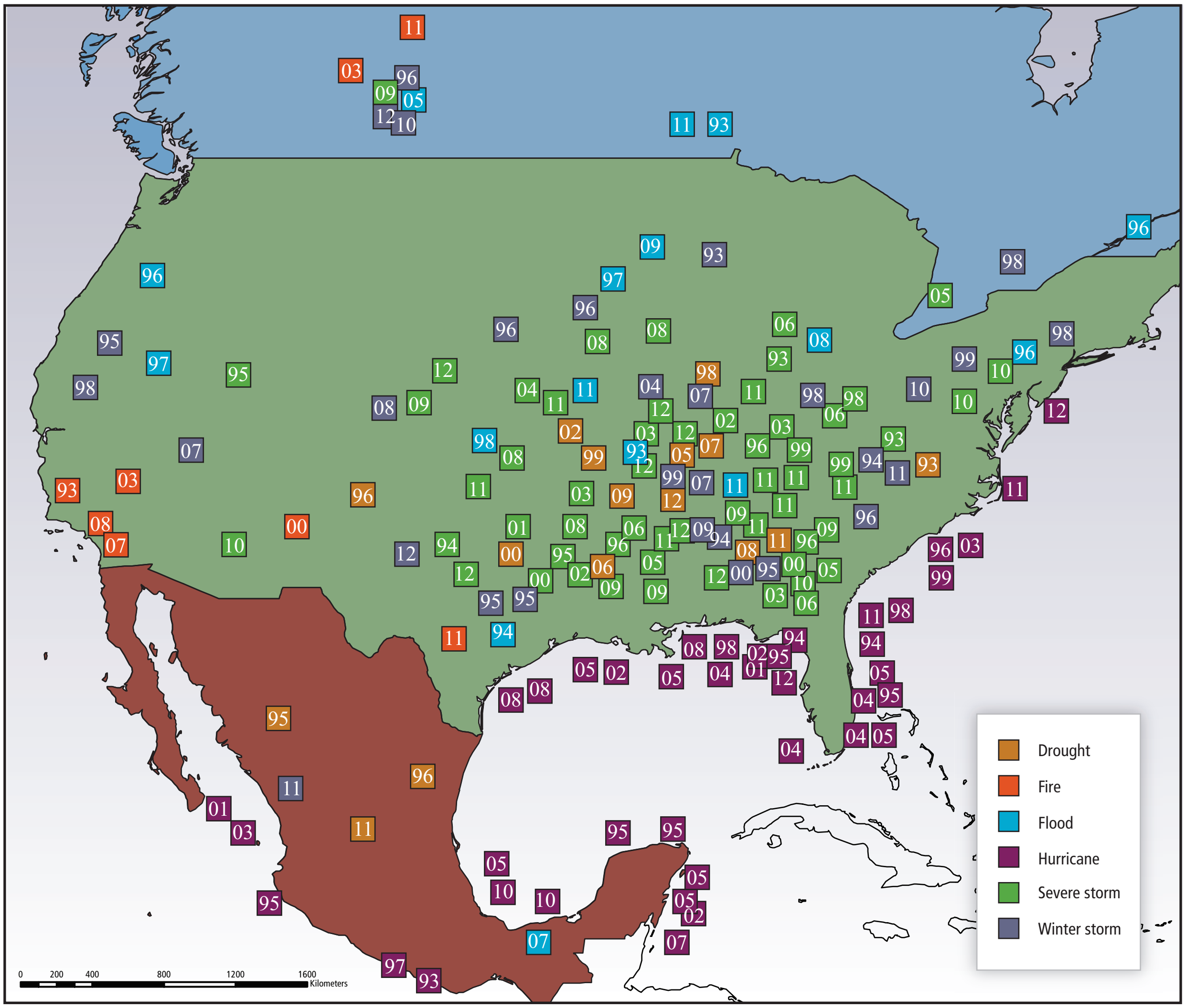

Figure 26-2 | Extreme events illustrating vulnerabilities for Mexico, the USA, and Canada. This figure offers a graphic illustration of location of extreme events and relevant vulnerability trends. The observed extreme events have not been attributed to anthropogenic climate change, yet they are climate-sensitive sources of impact illustrating vulnerability of exposed systems, particularly if projected future increases in the frequency and/or intensity of such events should materialize. The figure contains three elements. (a) A map with significant weather and climate events taking place during 1993–2012 (data derived from NatCatSERVICE, 2013). The categories "Severe storm" and "Winter storm" are aggregations of multiple types of storms; e.g., hailstorms are shown as Winter storms and tornadoes as Severe storms. Boxed numbers refer to the years in which the extreme events occurred. Hurricanes are placed offshore of the point of initial landfall, and placement of all other boxes (which may span multiple subnational jurisdictions) is weighted towards areas with the highest expected impacts (defined by estimated affected populations when finer subnational detail was not available). The map includes only events with overall losses ≥ US$1 billion in the USA, or ≥US$500 million in Mexico and Canada, adjusted to 2012 values; hence, it does not include events of small and medium impact. Additionally, losses do not capture the impacts of disasters on populations' livelihoods and well-being. (b) A map (facing page) with population density per ~0.0083° gridbox at 1-km resolution highlighting exposure and represented using 2011 Landsat data (Bright et al., 2012). Note that a ~0.0083° grid box is approximately1 km^2, but this approximation varies by latitude. (c) Four panels (facing page) with trends in socio-demographic indicators used in the literature to measure vulnerability to hazards (Romero-Lankao et al., 2012b): poverty rates, percentage of elderly, GDP per capita and total population (U.S. Census Bureau, 2011; Statistics Canada, 2012, CEPAL, 2013).

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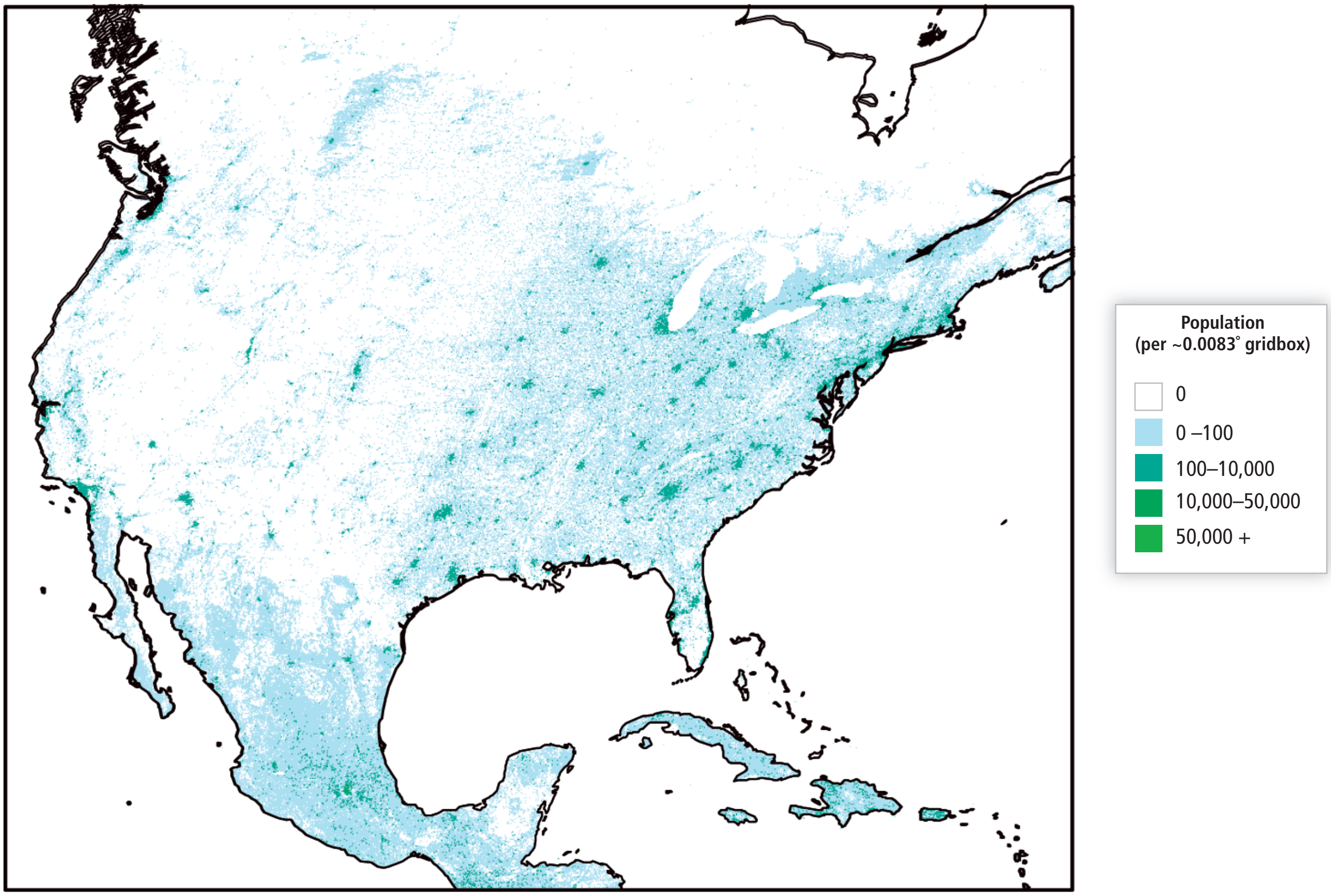
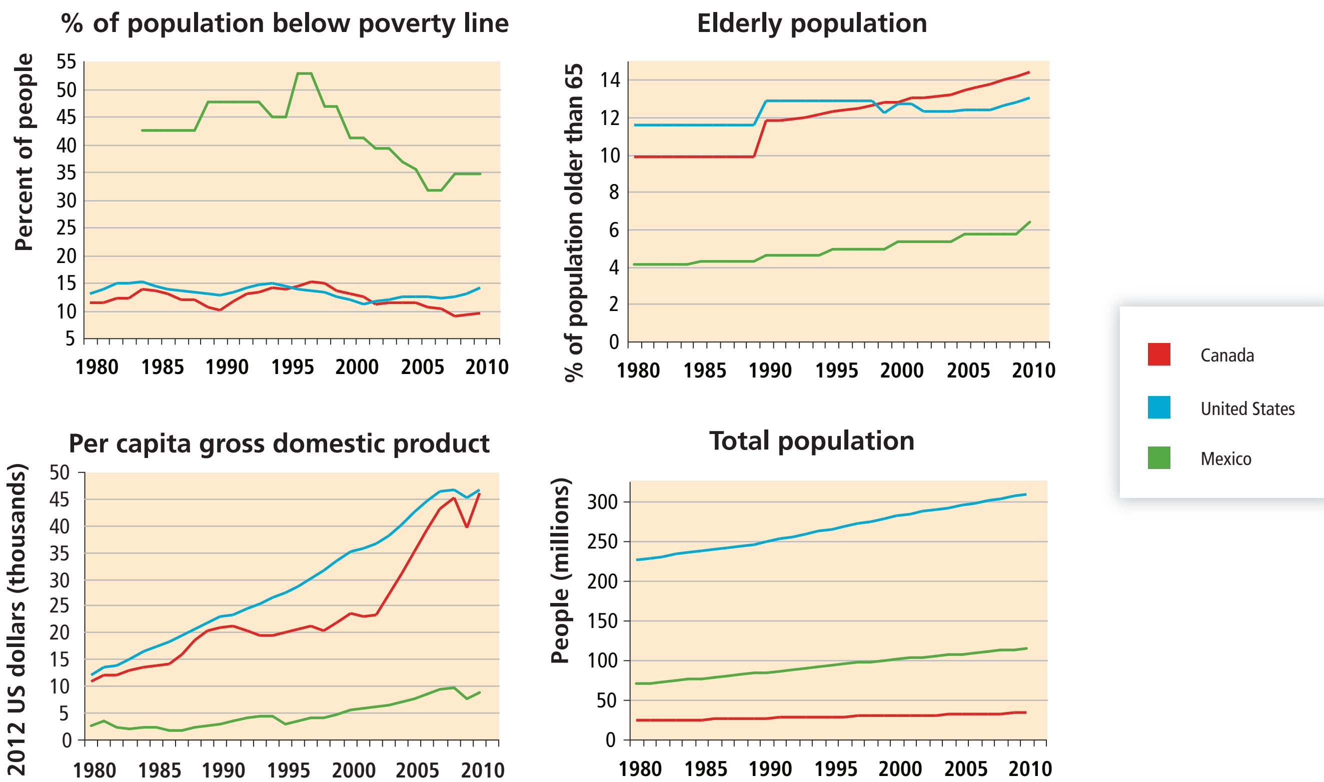
Figure 26-2 (continued)

(b) Population density at 1 km resolution



(c) Trends in socioeconomic indicators



The percentage of elderly people (older than 64 years) is also projected to continue to increase, by 23.4 to 26.9% in Canada, 12.4 to 18.4% in Mexico, and 17.3 to 20.9% in the USA by 2050 (B2 and A2, respectively) (IIASA, 2007). The elderly are highly vulnerable to extreme weather events (heat waves in particular, Figure 26-2) (Martiello and Giacchi, 2010; Diffenbaugh and Scherer, 2011; Romero-Lankao, 2012; White-Newsome et al., 2012). Numbers of single-person households and female-headed households—both of which are vulnerable because of low income and housing quality—are anticipated to increase (Roorda et al., 2010). Institutional capacity to address the demands posed by increasing numbers of vulnerable populations may also be limited, with resulting stress on health and the economy.

Three other shifts are projected to influence impacts, vulnerabilities, and adaptation to climate change in North America: urbanization, migration, and socioeconomic disparity. With small differences between countries, both the concentration of growing populations in some urban areas and the dispersion of rural populations are projected to continue to define North America by 2050. Assuming no change in climate, between 2005 and 2030 the population of Mexico City Metro Area will increase by 17.5%, while between 2007 and 2030 available water will diminish by 11.2% (Romero-Lankao, 2010). Conversely, education, a key determinant of adaptive capacity (Chapter 13), is expected to expand to low-income households, minorities, and women, which could increase the coping capacity of households and have a positive impact on economic growth (Goujon et al., 2004). However, the continuation of current patterns of economic disparity and poverty would hinder future adaptive capacity. Inequality in Mexico is larger (Figure 26-2), having a Gini coefficient (according to which the higher the number the higher economic disparity) of 0.56, in contrast to 0.317 for Canada and 0.389 for the USA (OECD, 2010). Mexico is one of five countries in the world that is projected to experience the highest increases in poverty due to climate-induced extreme events (52% increase in rural households, 95.4% in urban wage-labor households; Coupled Model Intercomparison Project Phase 3 (CMIP3), A2) (Ahmed et al., 2009).

Some studies project increased North American migration in response to climate change. Feng, Krueger, and Oppenheimer (2010) estimated the emigration of an additional 1.4 to 6.7 million Mexicans by 2080 based on projected maize yield declines, range depending on model (B1, United Kingdom Meteorological Office (UKMO), and Geophysical Fluid Dynamics Laboratory (GFDL)). Oppenheimer speculates that the indirect impacts of migration "could be as substantial as the direct effects of climate change in the receiving area," because the arrival migrants can increase pressure on climate sensitive urban regions (Oppenheimer, 2013, p. 442).

26.2.2. Physical Climate Trends

Some processes important for climate change in North America are assessed eslewhere in the Fifth Assessment Report, including WGI AR5 Chapter 2 (Observations: Atmosphere and Surface), WGI AR5 Chapter 4 (Observations: Cryosphere), WGI AR5 Chapter 12 (Long-term Climate Change: Projections, Commitments, and Irreversibility), WGI AR5 Chapter 14 (Climate Phenomena and Their Relevance for Future Regional Climate Change), WGI AR5 Annex I (Atlas of Global and Regional Climate Projections), and Chapter 21 of this volume (Regional Context). In addition, comparisons of emissions, concentrations, and radiative forcing in the Representative Concentration Pathways (RCPs) and *Special Report on Emission Scenarios* (SRES) scenarios can be found in WGI AR5 Annex II (Climate System Scenario Tables).

26.2.2.1. Current Trends

It is *very likely* that mean annual temperature has increased over the past century over most of North America (WGI AR5 Figure SPM.1b; Figure 26-3). Observations also show increases in the occurrence of severe hot events over the USA over the late 20th century (Kunkel et al., 2008), a result in agreement with observed late-20th-century increases in extremely hot seasons over a region encompassing northern Mexico, the USA, and parts of eastern Canada (Diffenbaugh and Scherer, 2011). These increases in hot extremes have been accompanied by observed decreases in frost days over much of North America (Alexander et al., 2006; Brown et al., 2010; see also WGI AR5 Section 2.6.1), decreases in cold spells over the USA (Kunkel et al., 2008; see also WGI AR5 Section 2.6.1), and increasing ratio of record high to low daily temperatures over the USA (Meehl et al., 2009). However, warming has been less pronounced and less robust over areas of the central and southeastern USA (e.g., Alexander et al., 2006; Peterson et al., 2008; see also WGI AR5 Section 2.6.1; WGI AR5 Figure SPM.1b; Figure 26-3). It is possible that this pattern of muted temperature change has been influenced by changes in the hydrologic cycle (e.g., Pan et al., 2004; Portmann et al., 2009), as well as by decadal-scale variability in the ocean (e.g., Meehl et al., 2012; Kumar et al., 2013b).

It is *very likely* that annual precipitation has increased over the past century over areas of the eastern USA and Pacific Northwest (WGI AR5 Figure 2.29; Figure 26-3). Observations also show increases in heavy precipitation over Mexico, the USA, and Canada between the mid-20th and the early 21st century (DeGaetano, 2009; Peterson and Baringer, 2009; Pryor et al., 2009; see also WGI AR5 Section 2.6.2). Observational analyses of changes in drought are more equivocal over North America, with mixed sign of trend in dryness over Mexico, the USA, and Canada (Dai, 2011; Sheffield et al., 2012; see also WGI AR5 Section 2.6.2; WGI AR5 Figure 2.42). There is also evidence for earlier occurrence of peak flow in snow-dominated rivers globally (Rosenzweig, 2007; WGI AR5 Section 2.6.2). Observed snowpack and snow-dominated runoff have been extensively studied in the western USA and western Canada, with observations showing primarily decreasing trends in the amount of water stored in spring snowpack from 1960 to 2002 (with the most prominent exception being the central and southern Sierra Nevada; Mote, 2006) and primarily earlier trends in the timing of peak runoff over the 1948–2000 period (Stewart et al., 2006; WGI AR5 Section 4.5; WGI AR5 Figure 4.21). Observations also show decreasing mass and length of glaciers in North America (WGI AR5 Section 4.3; WGI AR5 Figures 4.9, 4.10, 4.11). Further, in assessing changes in the hydrology of the western USA, it has been concluded that "up to 60% of the climate-related trends of river flow, winter air temperature, and snowpack between 1950 and 1999 are human-induced" (Barnett et al., 2008, p. 1080).

Observational limitations prohibit conclusions about trends in severe thunderstorms (WGI AR5 Section 2.6.2) and tropical cyclones (WGI AR5

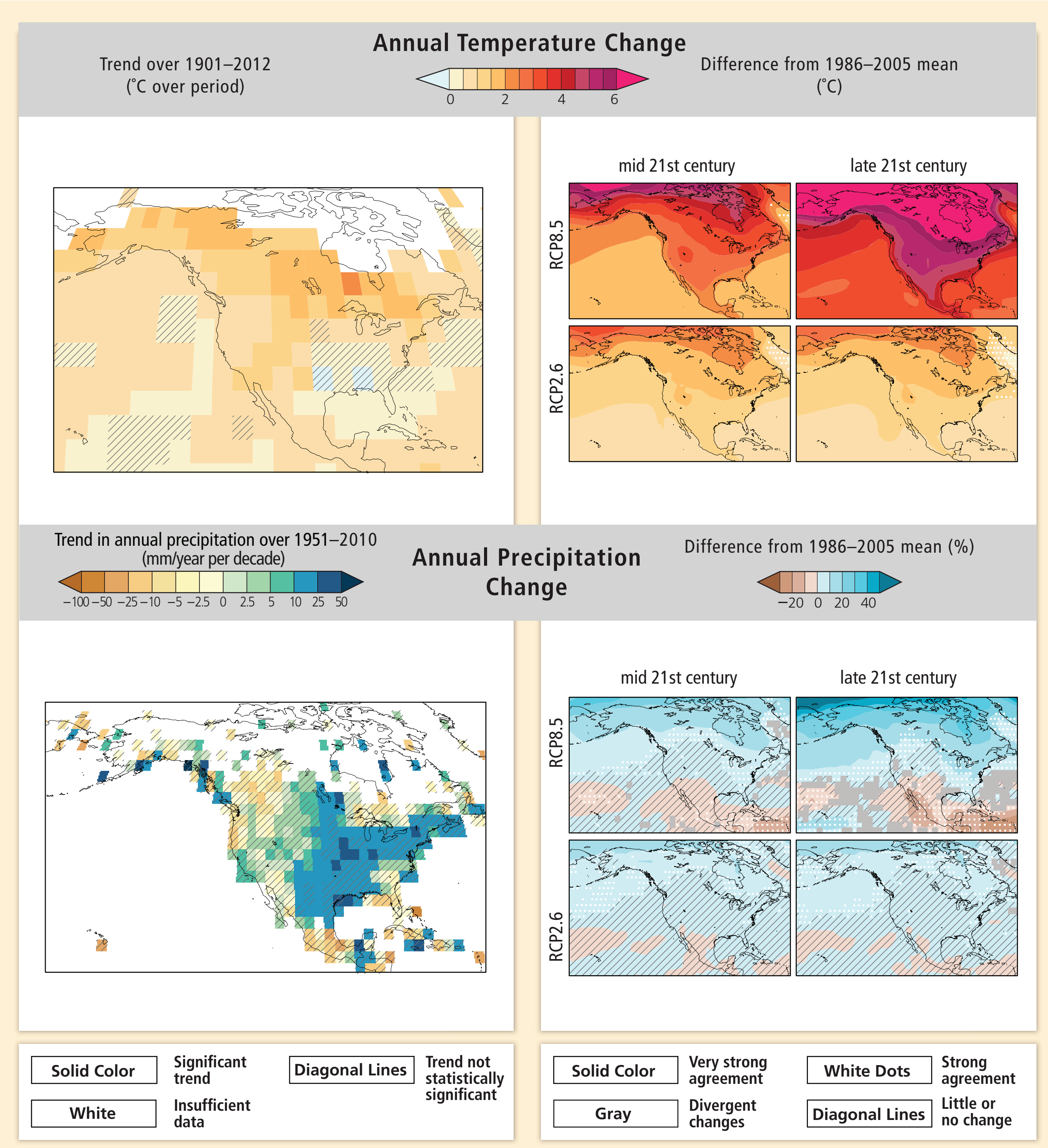


Figure 26-3 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change from 1951–2010, derived from a linear trend. [WGI AR5 Figures SPM.2 and 2.29] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where trends are significant at the 10% level. Diagonal lines indicate areas where trends are not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent changes in annual mean precipitation for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

Section 2.6.3) over North America. The most robust trends in extratropical cyclones over North America are determined to be toward more frequent and intense storms over the northern Canadian Arctic and toward less frequent and weaker storms over the southeastern and southwestern coasts of Canada over the 1953–2002 period (Wang et al., 2006; see also WGI AR5 Section 2.7.4).

WGI concludes that "Global mean sea level (GMSL) has risen by 0.19 (0.17 to 0.21) m over the period 1901–2010" and that "it is *very likely* that the mean rate was 1.7 (1.5 to 1.9) mm yr^{-1} between 1901 and 2010 and increased to 3.2 (2.8 to 3.6) mm yr^{-1} between 1993 and 2010" (WGI AR5 Chapter 3 ES). In addition, observed changes in extreme sea level have been caused primarily by increases in mean sea level (WGI AR5 Section 3.7.5). Regional variations in the observed rate of SLR can result from processes related to atmosphere and ocean variability (such as lower rates along the west coast of the USA) or vertical land motion (such as high rates along the US Gulf Coast), but the persistence of the observed regional patterns is unknown (WGI AR5 Section 3.7.3).

26.2.2.2. Climate Change Projections

WGI AR5 Chapters 11 and 12 assess near- and long-term future climate change, respectively. WGI AR5 Chapter 14 assesses processes that are important for regional climate change, with WGI AR5 Section 14.8.3 focused on North America. Many of the WGI AR5 conclusions are drawn from Annex I of the WGI contribution to the AR5.

The CMIP5 ensemble projects *very likely* increases in mean annual temperature over North America, with *very likely* increases in temperature over all land areas in the mid- and late-21st-century periods in RCP2.6 and RCP8.5 (Figure 26-3). Ensemble-mean changes in mean annual temperature exceed 2°C over most land areas of all three countries in the mid-21st-century period in RCP8.5 and the late-21st-century period in RCP8.5, and exceed 4°C over most land areas of all three countries in the late-21st-century period in RCP8.5. However, ensemble-mean changes in mean annual temperature remain within 2°C above the late-20th-century baseline over most North American land areas in both the mid- and late-21st-century periods in RCP2.6. The largest changes in mean annual temperature occur over the high latitudes of the USA and Canada, as well as much of eastern Canada, including greater than 6°C in the late-21st-century period in RCP8.5. The smallest changes in mean annual temperature occur over areas of southern Mexico, the Pacific Coast of the USA, and the southeastern USA.

The CMIP5 ensemble projects warming in all seasons over North America beginning as early as the 2016–2035 period in RCP2.6, with the greatest warming occurring in winter over the high latitudes (WGI AR5 Annex I; Figure 26-3) (Diffenbaugh and Giorgi, 2012). The CMIP5 and CMIP3 ensembles suggest that the response of warm-season temperatures to elevated radiative forcing is larger as a fraction of the baseline variability than the response of cold-season temperatures (Diffenbaugh and Scherer, 2011; Kumar et al., 2013b), and the CMIP3 ensemble suggests that the response of temperature in low-latitude areas of North America is larger as a fraction of the baseline variability than the response of temperature in high-latitude areas (Diffenbaugh and Scherer, 2011). In addition, CMIP3 and a high-resolution climate model ensemble suggest that the signal-to-noise ratio of 21st century warming is far greater over the western USA, northern Mexico, and the northeastern USA than over the central and southeastern USA (Diffenbaugh et al., 2011), a result that is similar to the observed pattern of temperature trend significance in the USA (Figure 26-3).

Most land areas north of 45°N exhibit *likely* or *very likely* increases in mean annual precipitation in the late-21st-century period in RCP8.5 (Figure 26-3). The high-latitude areas of North America exhibit *very likely* changes in mean annual precipitation throughout the illustrative RCP periods, with *very likely* increases occurring in the mid-21st-century period in RCP2.6 and becoming generally more widespread at higher levels of forcing. In contrast, much of Mexico exhibits *likely* decreases in mean annual precipitation beginning in the mid-21st-century period in RCP8.5, with the area of *likely* decreases expanding to cover most of Mexico and parts of the south-central and southwestern USA in the late-21st-century period in RCP8.5. *Likely* changes in mean annual precipitation are much less common at lower levels of forcing. For example, *likely* changes in mean annual precipitation in the mid- and late-21st-century periods in RCP2.6 are primarily confined to increases over areas of Canada and Alaska, with no areas of Mexico and very few areas of the contiguous USA exhibiting differences that exceed the baseline variability in more than 66% of the models.

CMIP5 projects increases in winter precipitation over Canada and Alaska, consistent with projections of a poleward shift in the dominant cold-season storm tracks (Yin, 2005; see also WGI AR5 Section 14.8.3), extratropical cyclones (Trapp et al., 2009), and areas of moisture convergence (WGI AR5 Section 14.8.3), as well as with projections of a shift toward positive North Atlantic Oscillation (NAO) trends (Hori et al., 2007; see also WGI AR5 Section 14.8.3). CMIP5 also projects decreases in winter precipitation over the southwestern USA and much of Mexico associated with the poleward shift in the dominant stormtracks and the expansion of subtropical arid regions (Seager and Vecchi, 2010; see WGI AR5 Section 14.8.3). However, there are uncertainties in hydroclimatic change in western North America associated with the response of the tropical Pacific sea surface temperatures (SSTs) to elevated radiative forcing (particularly given the influence of tropical SSTs on the Pacific North American (PNA) pattern and north Pacific storm tracks; Cayan et al., 1999; Findell and Delworth, 2010; Seager and Vecchi, 2010; see also WGI AR5 Section 14.8.3), and not all CMIP5 models simulate the observed recent hydrologic trends in the region (Kumar et al., 2013a).

For seasonal-scale extremes, CMIP5 projects substantial increases in the occurrence of extremely hot seasons over North America in early, middle, and late-21st-century periods in RCP8.5 (Diffenbaugh and Giorgi, 2012; Figure 26-4). For example, during the 2046–2065 period in RCP8.5, more than 50% of summers exceed the respective late-20th-century maximum seasonal temperature value over most of the continent. CMIP3 projects similar increases in extremely hot seasons, including greater than 50% of summers exceeding a mid-20th-century baseline throughout much of North America by the mid-21st-century in the A2 scenario (Duffy and Tebaldi, 2012), and greater than 70% of summers exceeding the highest summer temperature observed on record over much of the western USA, southeastern USA, and southern Mexico by the mid-21st-century in the A2 scenario (Battisti and Naylor, 2009). CMIP5 also projects substantial decreases in snow accumulation over

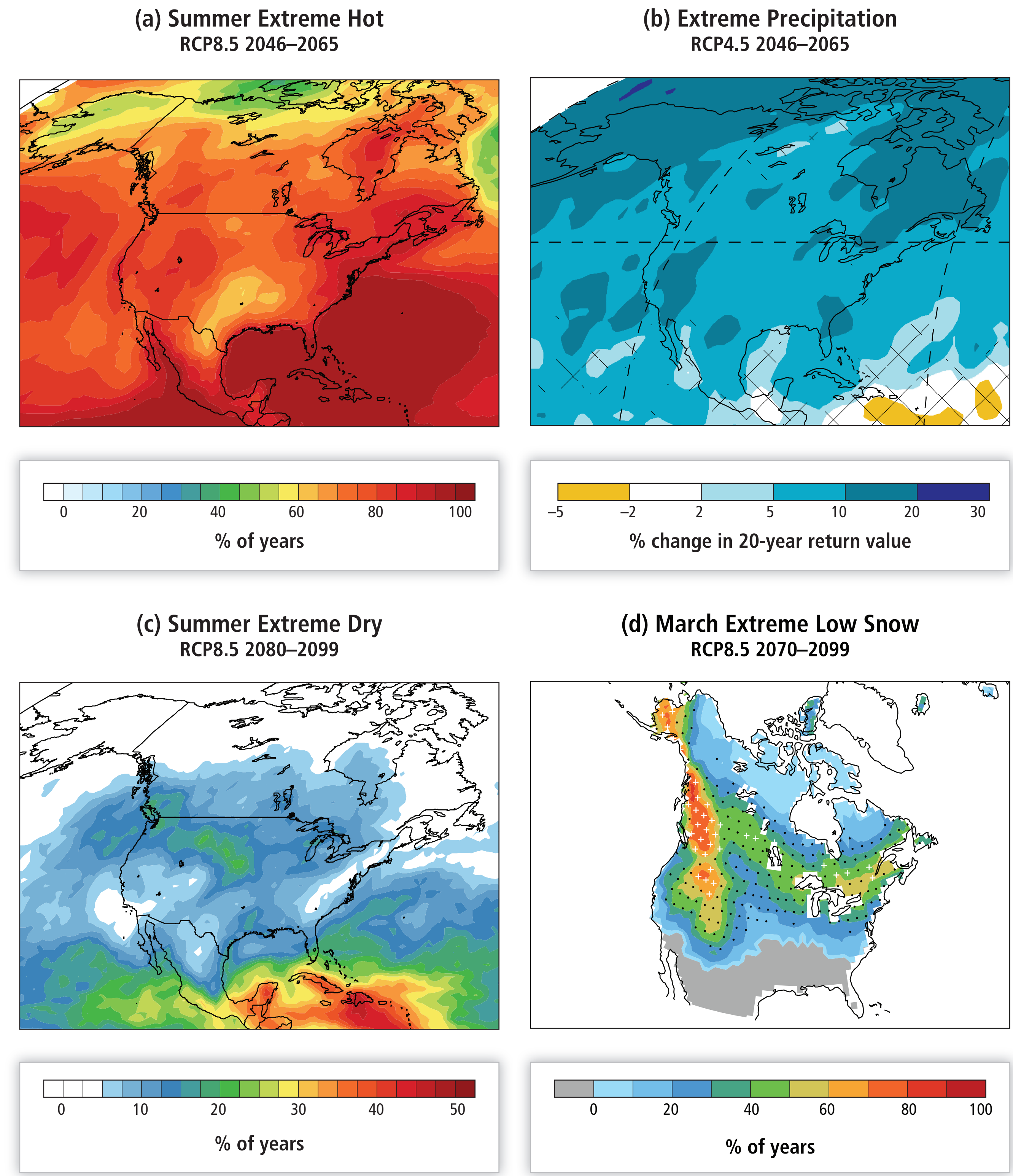


Figure 26-4 | Projected changes in extremes in North America. (a) The percentage of years in the 2046–2065 period of Representative Concentration Pathway 8.5 in which the summer temperature is greater than the respective maximum summer temperature of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 2012). (b) The percentage difference in the 20-year return value of annual precipitation extremes between the 2046–2065 period of RCP4.5 and the 1986–2005 baseline period (Kharin et al., 2013). The hatching indicates areas where the differences are not significant at the 5% level. (c) The percentage of years in the 2080–2099 period of RCP8.5 in which the summer precipitation is less than the respective minimum summer precipitation of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 2012). (d) The percentage of years in the 2070–2099 period of RCP8.5 in which the March snow water equivalent is less than the respective minimum March snow water equivalent of the 1976–2005 period (Diffenbaugh et al., 2012). The black (white) stippling indicates areas where the multi-model mean exceeds 1.0 (2.0) standard deviations of the multi-model spread. (a-d) The RCPs and time periods are those used in the peer-reviewed studies in which the panels appear. The 2046–2065 period of RCP8.5 and the 2046–2065 period of RCP4.5 exhibit global warming in the range of 2°C to 3°C above the preindustrial baseline (WGI AR5 Figure 12.40). The 2080–2099 and 2070–2099 periods of RCP8.5 exhibit global warming in the range of 4°C to 5°C above the preindustrial baseline (WGI AR5 Figure 12.40).

the USA and Canada (Diffenbaugh et al., 2012; Figure 26-4), suggesting that the increases in cold-season precipitation over these regions reflect a shift towards increasing fraction of precipitation falling as rain rather than snow (Diffenbaugh et al., 2012). Over much of the western USA and western Canada, greater than 80% of years exhibit March snow amount that is less than the late-20th-century median value beginning in the mid-21st-century period in RCP8.5, with the ensemble-mean change exceeding 2 standard deviations of the ensemble spread. Likewise, greater than 60% of years exhibit March snow amount that is less than the late-20th-century minimum value in the late-21st-century period in RCP8.5, with the ensemble-mean change exceeding 2 standard deviations of the ensemble spread (Diffenbaugh and Giorgi, 2012; Figure 26-4). CMIP5 also projects increases in the occurrence of extremely dry summer seasons over much of Mexico, the USA, and southern Canada (Figure 26-4). The largest increases occur over southern Mexico, where greater than 30% of summers in the late-21st-century period in RCP8.5 exhibit seasonal precipitation that is less than the late-20th-century minimum summer precipitation.

For daily-scale extremes, almost all areas of North America exhibit *very likely* increases of at least 5°C in the warmest daily maximum temperature by the late-21st-century period in RCP8.5. Likewise, most areas of Canada exhibit *very likely* increases of at least 10°C in the coldest daily minimum temperature by the late-21st-century period in RCP8.5, while most areas of the USA exhibit *very likely* increases of at least 5°C and most areas of Mexico exhibit *very likely* increases of at least 3°C (Sillmann et al., 2013; see also WGI AR5 Figure 12.13). In addition, almost all areas of North America exhibit *very likely* increases of 5 to 20% in the 20-year return value of extreme precipitation by the mid-21st-century period in RCP4.5 (Figure 26-4), while most areas of the USA and Canada exhibit *very likely* increases of at least 5% in the maximum 5-day precipitation by the late-21st-century period in RCP8.5 (Sillmann et al., 2013; see also WGI AR5 Figure 12.13). Further, almost all areas of Mexico exhibit *very likely* increases in the annual maximum number of consecutive dry days by the late-21st-century period in RCP8.5 (Sillmann et al., 2013; see also WGI AR5 Figure 12.13).

26.3. Water Resources and Management

Water withdrawals are exceeding stressful levels in many regions of North America such as the southwestern USA, northern and central Mexico (particularly Mexico City), southern Ontario, and the southern Canadian Prairies (CONAGUA, 2010; Romero-Lankao, 2010; Sosa-Rodriguez, 2010; Averyt et al., 2011; Environment Canada, 2013a). Water quality is also a concern with 10 to 30% of the surface monitoring sites in Mexico having polluted water (CONAGUA, 2010), and about 44% of assessed stream miles and 64% of assessed lake areas in the USA not clean enough to support their uses (EPA, 2004). Stations in Canada's 16 most populated drainage basins reported at least fair quality, with many reporting good or excellent quality (Environment Canada, 2013b). In basins outside of the populated areas there are some cases of declining water quality where impacts are related to resource extraction, agriculture, and forestry (Hebben, 2009).

Water management infrastructure in most areas of North America is in need of repair, replacement, or expansion (Section 26.7). Climate change, land use changes and population growth, and demand increases will add to these stresses (Karl et al., 2009).

26.3.1. Observed Impacts of Climate Change on Water Resources

26.3.1.1. Droughts and Floods

As reported in WGI AR5 Chapter 10 and in Section 26.2.2.1, it is not possible to attribute changes in drought frequency in North America to anthropogenic climate change (Prieto-González et al., 2011; Axelson et al., 2012; Orlowsky and Senevirantne, 2013; Figure 26-1). Few discernible trends in flooding have been observed in the USA (Chapter 3). Changes in the magnitude or frequency of flood events have not been attributed to climate change. Floods are generated by multiple mechanisms (e.g., land use, seasonal changes, and urbanization); trend detection is confounded by flow regulation, teleconnections, and long-term persistence (Section 26.2.2.1; Collins, 2009; Kumar et al., 2009; Smith et al., 2010; Villarini and Smith, 2010; Villarini et al., 2011; Hirsch and Ryberg, 2012; INECC and SEMARNAT, 2012a; Prokoph et al., 2012; Peterson et al., 2013).

26.3.1.2. Mean Annual Streamflow

Whereas annual precipitation and runoff increases have been found in the midwestern and northwestern USA, decreases have been observed in southern states (Georgakakos et al., 2013). Chapter 3 notes the correlation between changes in streamflow and observed regional changes in temperature and precipitation. Kumar et al. (2009) suggest that human activities have influenced observed trends in streamflow, making attribution of changes to climate difficult in many watersheds. Nonetheless, earlier peak flow of snowmelt runoff in snow-dominated streams and rivers in western North America has been formally detected and attributed to anthropogenic climate change (Barnett et al., 2008; Das et al., 2011; Figure 26-1).

26.3.1.3. Snowmelt

Warm winters produced earlier runoff and discharge but less snow water equivalent and shortened snowmelt seasons in many snow-dominated areas of North America (Barnett et al., 2005; Rood et al., 2008; Reba et al., 2011; see also Section 26.2.2; Chapter 3).

26.3.2. Projected Climate Change Impacts and Risks

26.3.2.1. Water Supply

Most of this assessment focuses on surface water as there are few groundwater studies (Tremblay et al., 2011; Georgakakos et al., 2013). Impacts and risks vary by region and model used.

In arid and semiarid western USA and Canada and in most of Mexico, except the southern tropical area, water supplies are projected to be further stressed by climate change, resulting in less water availability and increased drought conditions (Seager et al., 2007; Cayan et al., 2010; MacDonald, 2010; Martínez Austria and Patiño Gómez, 2010; Montero Martínez et al., 2010; CONAGUA, 2011; Prieto-González et al., 2011; Bonsal et al., 2012; Diffenbaugh and Field, 2013; Orlowsky and Seneviratne, 2013; Sosa-Rodriguez, 2013). Compounding factors include saltwater intrusion, and increased groundwater and surface water pollution (Leal Asencio et al., 2008).

In the southwest and southeast USA, ecosystems and irrigation are projected to be particularly stressed by decreases in water availability due to the combination of climate change, growing water demand, and water transfers to urban and industrial users (Seager et al., 2009; Georgakakos et al., 2013). In the Colorado River basin, crop irrigation requirements for pasture grass are projected to increase by 20% by 2040 and by 31% by 2070 (Dwyer et al., 2012). In the Rio Grande basin, New Mexico, runoff is projected to decrease by 8 to 30% by 2080 due to climate change. Water transfers may entail significant transaction costs associated with adjudication and potential litigation, and might have economic, environmental, social, and cultural impacts that vary by water user (Hurd and Coonrod, 2012). In Mexico, water shortages combined with increased water demands are projected to increase surface and groundwater over-exploitation (CONAGUA, 2011).

Other parts of North American are projected to have different climate risks. The vulnerability of water resources over the tropical southern region of Mexico is projected to be low for 2050: precipitation decreases from 10 to 5% in the summer and no precipitation changes in the winter. After 2050, greater winter precipitation is projected, increasing the possibility of damaging hydropower and water storage dams by floods, while precipitation is projected to decrease by 40 to 35% in the summer (Martínez Austria and Patiño Gómez, 2010).

Throughout the 21st century, cities in northwest Washington are projected to have drawdown of average seasonal reservoir storage in the absence of demand reduction because of less snowpack even though annual streamflows increase. Without accounting for demand increases, projected reliability of all systems remains above 98% through mid- and late-21st century (Vano et al., 2010a; CONAGUA, 2011). Throughout the eastern USA, water supply systems will be negatively impacted by lost snowpack storage, rising sea levels contributing to increased storm intensities and saltwater intrusion, possibly lower streamflows, land use and population changes, and other stresses (Sun et al., 2008; Obeysekera et al., 2011).

In Canada's Pacific Northwest region, cool season flows are expected to increase, while warm seasons flows would decrease (Hamlet, 2011). Southern Alberta, where approximately two-thirds of Canadian irrigated land is located, is projected to experience declines in mean annual streamflow, especially during the summer (Shepherd et al., 2010; Poirier and de Loë, 2012; Tanzeeba and Gan, 2012). In the Athabasca River basin in northern Alberta, modeling results consistently indicate large projected declines in mean annual flows (Kerkhoven and Gan, 2011). In contrast, modeling results for basins in Manitoba indicate an increase in mean annual runoff (Choi et al., 2009). Some model results for the Fraser River basin in British Columbia indicate increases in mean annual runoff by the end of the 21st century, while others indicate decreases (Kerkhoven and Gan, 2011). In central Quebec, J. Chen et al. (2011) project a general increase in discharge during November to April, and a general decrease in summer discharge under most climate change conditions.

26.3.2.2. Water Quality

Many recent studies project water quality declines due to the combined impacts of climate change and development (Daley et al., 2009; Tu, 2009; Praskievicz and Chang, 2011; Wilson and Weng, 2011; Tong et al., 2012). Increased wildfires linked to a warming climate are expected to affect water quality downstream of forested headwater regions (Emelko et al., 2011).

Model simulation of lakes under a range of plausible higher air temperatures (Tahoe, Great Lakes, Lake Onondaga, and shallow polymictic lakes), depending on the system, predict a range of impacts such as increased phytoplankton, fish,and cyanobacteria biomass; lengthened stratification periods with risks of significant hypolimnetic oxygen deficits in late summer with solubilization of accumulated phosphorus and heavy metals with accelerated reaction rates; and decreased lake clarity (Dupuis and Hann, 2009; Trumpickas et al., 2009; Sahoo et al., 2011; Taner et al., 2011). Model simulations have found seasonal climate change impacts on nonpoint source pollution loads, while others have found no impact (Marshall and Randhir, 2008; Tu, 2009; Taner et al., 2011; Praskievicz and Chang, 2011).

Changes in physical-chemical-biological parameters and micropollutants are predicted to negatively affect drinking water treatment and distribution systems (Delpla et al., 2009; Carriere et al., 2010; Emelko et al., 2011). Wastewater treatment plants would be more vulnerable as increases in rainfall and wet weather lead to higher rates of inflow and infiltration (King County Department of Natural Resources and Parks, 2008; New York City Department of Environmental Protection, 2008; Flood and Cahoon, 2011). They would also face reduced hydraulic capacities due to higher sea levels and increased river and coastal flooding (Flood and Cahoon, 2011), with higher sea levels also threatening sewage collection systems (Rosenzweig et al., 2007; King County Department of Natural Resources and Parks, 2008).

26.3.2.3. Flooding

Projected increases in flooding (Georgakakos et al., 2013) may affect sectors ranging from agriculture and livestock in southern tropical Mexico (CONAGUA, 2010) to urban and water infrastructure in areas such as Dayton (Ohio), metro Boston, and the Californian Bay-Delta region (NRC, 1995; Kirshen et al., 2006; DWR, 2009; Wu, 2010). Floods could begin earlier, and have earlier peaks and longer durations (e.g., southern Quebec basin). Urbanization can compound the impacts of increased flooding due to climate change, particularly in the absence of flood management infrastructure that takes climate change into account (Hejazi and Markus, 2009; Mailhot and Duchesne, 2010; Sosa-Rodriguez, 2010). Ntelekos et al. (2010) estimate that annual riverine flood losses in the USA could increase from approximately US$2 billion now to US$7 to US$19 billion annually by 2100 depending on emission scenario and economic growth rate.

26.3.2.4 Instream Uses

Projections of climate impacts on instream uses vary by region and time frame. Hydropower generation, affected by reduced lake levels, is projected to decrease in arid and semiarid areas of Mexico (CICC, 2009; Sosa-Rodriguez, 2013) and in the Great Lakes (Buttle et al., 2004; Mortsch et al., 2006; Georgakakos et al., 2013). In the US Pacific Northwest under several emissions scenarios, it is projected to increase in 2040 by approximately 5% in the winter and decrease by approximately 13% in the summer, with annual reductions of approximately 2.5%. Larger increases and decreases are projected by 2080 (Hamlet et al., 2010). On the Peribonka River system in Quebec, annual mean hydropower production will similarly decrease in the short term and increase by as much as 18% in the late-21st century (Minville et al., 2009). Navigation on the Great Lakes, Mississippi River, and other inland waterways may benefit from less ice cover but will be hindered by increased floods and low river levels during droughts (Georgakakos et al., 2013).

26.3.3. Adaptation

A range of structural and non-structural adaptation measures are being implemented, many of which are no-regret policies. For instance, in preparation for more intense storms, New York City is using green infrastructure to capture rainwater before it can flood the combined sewer system and is elevating boilers and other equipment above ground (Bloomberg, 2012). The Mexican cities of Monterrey, Guadalajara, Mexico City, and Tlaxcala are reducing leaks from water systems (CICC, 2009; CONAGUA, 2010; Romero-Lankao, 2010; Sosa-Rodriguez, 2010). Regina, Saskatchewan, has increased urban water conservation efforts (Lemmen et al., 2008).

The 540-foot high, 1300-foot long concrete Ross Dam in the state of Washington, USA, was built on a special foundation so it could later be raised in height (Simmons, 1974). Dock owners in the Trent-Severn Waterway in the Great Lakes have moved their docks into deeper water to better manage impacts on shorelines (Coleman, 2005). The South Florida Water Management District is assessing the vulnerability to sea level rise of its aging coastal flood control system and exploring adaptation strategies, including a strategy known as forward pumping (Obeysekera et al., 2011). In Cambridge, Ontario, extra-capacity culverts are being installed in anticipation of larger runoff (Scheckenberger et al., 2009).

Water meters have been installed to reduce consumption by different users such as Mexican and Canadian farmers and in households of several Canadian cities (INE and SEMARNAT, 2006; Lemmen et al., 2008). Agreements and regulations are underway such as the 2009 SECURE Water Act, which establishes a federal climate change adaptation program with required studies to assess future water supply risks in the western USA (42 USC § 10363). One such large, multi-year study was recently completed in the USA for the Colorado River (Bureau of Reclamation, 2013), and others are planned. Agreements and regulations are underway, such as the 2007 Shortage Sharing Agreement for the management of the Colorado River, driven by concerns about water conservation, planning, better reservoir coordination, and preserving flexibility to respond to climate change (Bureau of Reclamation, 2007). Quebec Province is requiring dam safety inspections every 10 years to account for new knowledge on climate change impacts (Centre d'Expertise Hydrique du Québec, 2003). Expanded beyond flood and hydropower management to now include climate change, the Columbia River Treaty is a good example of an international treaty to manage a range of water resources challenges (U.S. Army Corps of Engineers and Bonneville Power Administration, 2013).

26.4. Ecosystems and Biodiversity

26.4.1. Overview

Recent research has documented gradual changes in physiology, phenology, and distributions in North American ecosystems consistent with warming trends (Dumais and Prévost, 2007). Changes in phenology and species' distributions, particularly in the USA and Canada, have been attributed to rising temperatures, which have in turn been attributed to anthropogenic climate change via joint attribution (Root et al., 2005; Vose et al., 2012). Concomitant with 20th-century temperature increases, northward and upward shifts in plant, mammal, bird, lizard, and insect species' distributions have been documented extensively in the western USA and eastern Mexico (Parmesan, 2006; Kelly and Goulden, 2008; Moritz et al., 2009; Tingley et al., 2009; Sinervo et al., 2010). These distribution shifts consistent with climate change interact with other environmental changes such as land use change, hindering the ability of species to respond (Ponce-Reyes et al., 2013).

A range of techniques have been applied to assess the vulnerability of North American ecosystems and species to changes in climate (Anderson et al., 2009; Loarie et al., 2009; Glick and Stein, 2011). A global risk analysis based on dynamic global vegetation models identified boreal forest in Canada as notably vulnerable to ecosystem shift (Scholze et al., 2006). Since the AR4, the role of extreme events, including droughts, flood, hurricanes, storm surges, and heat waves, is a more prominent theme in studies of climate change impacts on North American ecosystems (Chambers et al., 2007; IPCC, 2012).

A number of ecosystems in North America are vulnerable to climate change. For example, species in alpine ecosystems are at high risk due to limited geographic space into which to expand (Villers Ruiz and Castañeda-Aguado, 2013). Many forest ecosystems are susceptible to wildfire and large-scale mortality and infestation events (Section 26.4.1). Across the continent, potentially rapid rates of climate change may require location shifts at velocities well outside the range in historical reconstructions (Sandel et al., 2011; Schloss et al., 2012). Changes in temperature, precipitation amount, and CO_2 concentrations can have different effects across species and ecological communities (Parmesan, 2006; Matthews et al., 2011), leading to ecosystem disruption and reorganization (Dukes et al., 2011; Smith et al., 2011), as well as movement or loss.

The following subsections focus in more depth on climate vulnerabilities in forests and coastal ecosystems. These ecosystems, spanning all three North American countries, are illustrative cases of where understanding opportunities for conservation and adaptation practices is important, and recent research advances on and new evidence of increased vulnerabilities since AR4 motivate further exploration. Further treatment of grasslands and shrublands can be found in Section 4.3.3.2.2; wetlands and peatlands in Section 4.3.3.3; and tundra, alpine, and permafrost systems in Section 4.3.3.4. Additional synthesis of climate change impacts on terrestrial, coastal, and ocean ecosystems can be found in Chapter 8 of the U.S. National Climate Assessment (Groffman et al., 2013).

26.4.2. Tree Mortality and Forest Infestation

26.4.2.1. Observed Impacts

Droughts of unusual severity, extent, and duration have affected large parts of western and southwestern North America and resulted in regional-scale forest dieback in Canada, the USA, and Mexico. Extensive tree mortality has been related to drought exacerbated by high summertime temperatures in trembling aspen (*Populus tremuloides*), pinyon pine (*Pinus edulis*), and lodgepole pine (*Pinus contorta*) since the early 2000s (Breshears et al., 2005; Hogg et al., 2008; Raffa et al., 2008; Michaelian et al., 2011; Anderegg et al., 2012). In 2011 and 2012, forest dieback in northern and central Mexico was associated with extreme temperatures and severe droughts (Comisión Nacional Forestal, 2012a). Widespread forest-mortality events triggered by extreme climate events can alter ecosystem structure and function (Phillips et al., 2009; Allen et al., 2010; Anderegg et al., 2013). Similarly, multi-decadal changes in demographic rates, particularly mortality, indicate climate-mediated changes in forest communities over longer periods (Hogg and Bernier, 2005; Williamson et al., 2009). Average annual mortality rates increased from less than 0.5% of trees per year in the 1960s in forests of western Canada and the USA to, respectively, 1.5 to 2.5% (Peng et al., 2011), and 1.0 to 1.5% in the 2000s in the USA (van Mantgem et al., 2009).

The influences of climate change on ecosystem disturbance, such as insect outbreaks, have become increasingly salient and suggest that these disturbances could have a major influence on North American ecosystems and economy in a changing climate. In terms of carbon stores these outbreaks have the potential to turn forests into carbon sources (Kurz et al., 2008a,b; Hicke et al., 2012). Warm winters in western Canada and USA have increased winter survival of the larvae of bark beetles, helping drive large-scale forest infestations and forest die-off in western North America since the early 2000s (Bentz et al., 2010). Beginning in 1994, mountain pine beetle outbreaks have severely affected more than 18 million hectares of pine forests in British Columbia, and outbreaks are expanding northwards (Energy, Mines and Resources, 2012).

26.4.2.2. Projected Impacts and Risks

Projected increases in drought severity in southwestern forests and woodlands in USA and in northwestern Mexico suggest that these ecosystems may be increasingly vulnerable, with impacts including vegetation mortality (Overpeck and Udall, 2010; Seager and Vecchi, 2010; Williams et al., 2010) and an increase of biological agents such as beetles, borers, pathogenic fungi, budworms, and other pests (Drake et al., 2005). An index of forest drought stress calibrated from tree rings indicates that projected drought stress by the 2050s in the SRES A2 scenario from the CMIP3 model ensemble, due primarily to warming-induced rises in vapor pressure deficit, exceeds the most severe droughts of the past 1000 years (Williams et al., 2013).

Under a scenario with large changes in global temperature (SRES A2) increases in growing-season temperature in forest soils in southern Quebec are as high as 5.0°C toward the end of the century and decreases of soil water content reach 20 to 40% due to elevated evapotranspiration rates (Houle et al., 2012). More frequent droughts in tropical forests may change forest structure and regional distribution, favoring a higher prevalence of deciduous species in the forests of Mexico (Drake et al., 2005; Trejo et al., 2011).

Shifts in climate are expected to lead to changes in forest infestation, including shifts of insect and pathogen distributions into higher latitudes and elevations (Bentz et al., 2010). Predicted climate warming is expected to have effects on bark beetle population dynamics in the western USA, western Canada, and northern Mexico that may include increases in developmental rates, generations per year, and changes in habitat suitability (Waring et al., 2009). As a result, the impacts of bark beetles on forest resources are expected to increase (Waring et al., 2009).

Wildfire, a potentially powerful influence on North American forests in the 21st century, is discussed in Box 26-2.

26.4.3. Coastal Ecosystems

Highly productive estuaries, coastal marshes, and mangrove ecosystems are present along the Gulf Coast and the East and West Coasts of North America. These ecosystems are subject to a wide range of non-climate stressors, including urban and tourist developments and the indirect effects of overfishing (Bhatti et al., 2006; Mortsch et al., 2006; CONABIO et al., 2007; Lund et al., 2007). Climate change adds risks from SLR, warming, ocean acidification, extratropical cyclones, altered upwelling, and hurricanes and other storms.

26.4.3.1. Observed Climate Impacts and Vulnerabilities

SLR, which has not been uniform across the coasts of North America (Crawford et al., 2007; Kemp et al., 2008; Leonard et al., 2009; Zavala-Hidalgo et al., 2010; Sallenger, Jr. et al., 2012), is directly related to flooding and loss of coastal dunes and wetlands, oyster beds, seagrass, and mangroves (Feagin et al., 2005; Cooper et al., 2008; Najjar et al., 2010; Ruggiero et al., 2010; Martinez Arroyo et al., 2011; McKee, 2011).

Increases in sea surface temperature in estuaries alter metabolism, threatening species, especially coldwater fish (Crawford et al., 2007). Historical warm periods have coincided with low salmon abundance and restriction of fisheries in Alaska (Crozier et al., 2008; Karl et al., 2009). North Atlantic cetaceans and tropical coral reefs in the Gulf of California and the Caribbean have been affected by increases in the incidence of diseases associated with warm waters and low water quality (ICES, 2011; Mumby et al., 2011).

Increased concentrations of CO_2 in the atmosphere due to human emissions are causing ocean acidification (Chapters 5 ES, 6 ES; FAQ 5.1). Along the temperate coasts of North America acidification directly affects calcareous organisms, including colonial mussel beds, with indirect influences on food webs of benthic species (Wootton et al., 2008). Increased acidity in conjunction with high temperatures has been identified as a serious threat to coral reefs and other marine ecosystems in the Bahamas and the Gulf of California (Doney et al., 2009; Hernández et al., 2010; Mumby et al., 2011).

Tropical storms and hurricanes can have a wide range of effects on coastal ecosystems, potentially altering hydrology, geomorphology (erosion), biotic structure in reefs, and nutrient cycling. Hurricane impacts on the coastline change dramatically the marine habitat of sea turtles, reducing feeding habitats, such as coral reefs and areas of seaweed, and nesting places (Liceaga-Correa et al., 2010; Montero Martínez et al., 2010).

26.4.3.2. Projected Impacts and Risks

Projected increases in sea levels, particularly along the coastlines of Florida, Louisiana, North Carolina, and Texas (Kemp et al., 2008; Leonard et al., 2009; Weiss et al., 2011), will threaten many plants in coastal ecosystems through increased inundation, erosion, and salinity levels. In settings where landward shifts are not possible, a 1 m rise in sea level will result in loss of wetlands and mangroves along the Gulf of Mexico of 20% in Tamaulipas to 94% in Veracruz (Flores Verdugo et al., 2010).

Projected impacts of increased water temperatures include contraction of coldwater fish habitat and expansion of warmwater fish habitat (Mantua et al., 2010), which can increase the presence of invasive species that threaten resident populations (Janetos et al., 2008). Depending on scenario, Chinook salmon in the Pacific Northwest may decline by 20 to 50% by 2040–2050 (Battin et al., 2007; Crozier et al., 2008), integrating across restrictions in productivity and abundance at the southern end of their range and expansions at the northern end (Azumaya et al., 2007), although habitat restoration and protection particularly at lower elevations may help mitigate declines in abundance.

Continuing ocean acidification will decrease coral growth and interactions with temperature increases will lead to increased risk of coral bleaching, leading to declines in coral ecosystem biodiversity (Veron et al., 2009; see also Section 5.4.2.4; Box CC-OA). Oyster larvae in the Chesapeake Bay grew more slowly when reared with CO_2 levels between 560 and 480 ppm compared to current environmental conditions (Gazeau et al., 2007; Miller et al., 2009; Najjar et al., 2010).

Although future trends in thunderstorms and tropical cyclones are uncertain (Section 26.2.2), any changes, particularly an increase in the frequency of category 4 and 5 storms (Bender et al., 2010; Knutson et al., 2010), could have profound impacts on mangrove ecosystems, which require 25 years for recovery from storm damage (Kovacs et al., 2004; Flores Verdugo et al., 2010).

26.4.4. Ecosystems Adaptation, and Mitigation

In North America, a number of adaptation strategies are being applied in novel and flexible ways to address the impacts of climate change (Mawdsley et al., 2009; NOAA, 2010; Gleeson et al., 2011; Poiani et al., 2011). The best of these are based on detailed knowledge of the vulnerabilities and sensitivities of species and ecosystems, and with a focus on opportunities for building resilience through effective ecosystem management. Government agencies and nonprofit organizations have established initiatives that emphasize the value of collaborative dialog between scientists and practitioners, indigenous communities, and grass-roots organizations to develop no-regrets and co-benefits adaptation strategies (Ogden and Innes, 2009; Gleeson et al., 2011; Halofsky et al., 2011; Cross et al., 2012, 2013; INECC and SEMARNAT, 2012b).

Examples of adaptation measures implemented to respond to climate change impacts on ecosystems are diverse. They include programs to reduce the incidence of Canadian forest pest infestations (Johnston et al., 2010); breeding programs for resistance to diseases and insect pests (Yanchuk and Allard, 2009); use of forest programs to reduce the incidence of forest fires and encourage agroforestry in areas of Mexico (Sosa-Rodriguez, 2013); and selection by forest or fisheries managers of activities that are more adapted to new climatic conditions (Vasseur

Box 26-2 | Wildfires

Wildfire is a natural process, critical to nutrient cycling, controlling populations of pests and pathogens, biodiversity, and fire-adapted species (Bond and Van Wilgen, 1996). However, since the mid-1980s large wildfire activity in North America has been marked by increased frequency and duration, and longer wildfire seasons (Westerling et al., 2006; Williamson et al., 2009). Recent wildfires in western Canada, the USA, and Mexico relate to long and warm spring and summer droughts, particularly when they are accompanied by winds (Holden et al., 2007; Comisión Nacional Forestal, 2012b). Interacting processes such as land use changes associated with the expansion of settlements and activities in peri-urban areas or forested areas, combined with the legacies of historic forest management that prescribed fire suppression, also substantially increase wildfire risk (Radeloff et al., 2005; Peter et al., 2006; Fischlin et al., 2007; Theobald and Romme, 2007; Gude et al., 2008; Collins and Bolin, 2009; Hammer et al., 2009; Brenkert-Smith, 2010).

Continued next page →

Box 26-2 (continued)

Drought conditions are strongly associated with wildfire occurrence, as dead fuels such as needles and dried stems promote the incidence of firebrands and spot fires (Keeley and Zedler, 2009; Liu et al., 2012). Drought trends vary across regions (Groisman et al., 2007; Girardin et al., 2012): The western USA has experienced drier conditions since the 1970s (Peterson et al., 2013); drought periods in Alberta and Idaho have coincided with large burned areas (Pierce and Meyer, 2008; Kulshreshtha, 2011); and heterogeneous patterns of drought severity and a reduction of wildfire risk have been detected for the circumboreal region (Girardin et al., 2009). Decadal climatic oscillations also contribute to differences in drought, and thus in wildfire occurrences. The areas burned in the continent boreal forest and in northwest and central Mexico correlate with the dynamics of seasonal land/ocean temperature variability (Macias Fauria and Johnson, 2006; Skinner et al., 2006; Villers Ruíz and Hernández-Lozano, 2007; Girardin and Sauchyn, 2008; Macias Fauria and Johnson, 2008), which is shifting toward hotter temperatures and longer droughts. Such human practices as slash-and-burn agriculture can have negative impacts on Mexican forests (Bond and Keeley, 2005; CONANP and The Nature Conservancy, 2009).

Drought index projections and climate change regional models show increases in wildfire risk during the summer and fall on the southeast Pacific Coast, Northern Plains, and the Rocky Mountains (Liu et al., 2012). In places like Sierra Nevada, mixed conifer forests, which have a natural cycle of small, non-crown fires, are projected to have massive crown fires (Bond and Keeley, 2005; see also Table 26-1).

While healthy forests (Davis, 2004) and many fire-maintained systems that burn at lower intensities can provide carbon sequestration and thus mitigation co-benefits (e.g., longleaf pine savanna, Sierra mixed-conifer; Fried et al., 2008; North et al., 2012), forests affected by pests and fires are less effective carbon sinks, and wildfires themselves are a source of emissions.

Wildfires pose a direct threat to human lives, property, and health. Over the last 30 years, 155 people were killed in wildfires across North America, including 103 in the USA, 50 in Mexico, and 2 in Canada (Centre for Research on the Epidemiology of Disasters, 2012). Direct effects include injury and respiratory effects from smoke inhalation, with firefighters at increased risk (Naeher et al., 2007; Reisen and Brown, 2009; Reisen et al., 2011). Wildfire activity causes impacts on human health (Section 26.6).

Minimizing adverse effects of wildfires involves short- and long-term strategies such as planned manipulation of vegetation composition and stand structure (Girardin et al., 2012; Terrier et al., 2013), suppression of fires where required, fuel treatments, use of fire-safe materials in construction, community planning, and reduction of arson. Not all negative consequences of fire can be avoided, though a mixture of techniques can be used to minimize adverse effects (Girardin et al., 2012). Prescribed fire may be an important tool for managing fire risk in Canada and the USA (Hurteau and North, 2010; Wiedinmyer and Hurteau, 2010; Hurteau et al., 2011). Managers in the USA have encouraged reduction of flammable vegetation around structures with different levels of success (Stewart et al., 2006). However, such efforts depend largely on land use planning; the socioeconomic capacity of communities at risk; the extent of resource dependence; community composition; and the risk perceptions, attitudes, and beliefs of decision makers, private property owners, and affected populations (McFarlane, 2006; Repetto, 2008; Collins and Bolin, 2009; Martin et al., 2009; Trainor et al., 2009; Brenkert-Smith, 2010). Indigenous peoples are at higher risk from wildfire and may have unique requirements for adaptation strategies (Carroll et al., 2010; Christianson et al., 2012a,b).

Effective forest management requires stakeholder involvement and investment. The provision of adequate information on smoke, prescribed fire, pest management, and forest thinning is crucial, as is building trust between stakeholders and land managers (Dombeck et al., 2004; Flint et al., 2008; Chang et al., 2009). Institutional shifts from reliance on historical records toward incorporation of climate forecasting in forest management is also crucial to effective adaptation (McKenzie et al., 2004; Millar et al., 2007; Kolden and Brown, 2010).

and Catto, 2008). Example programs have addressed commercial fishing, mass tourism (Pratchett et al., 2008), and enforcement mechanisms for using water regulation technologies to maintain quantity and quality in wetlands around the Great Lakes and San Francisco, California (Mortsch et al., 2006; Okey et al., 2012). Assisted migration is increasingly discussed as a potential management option to maintain health and productivity of forests; yet the technique has logistical and feasibility challenges (Keel, 2007; Hoegh-Guldberg et al., 2008; Winder et al., 2011).

Several lines of evidence indicate that effective adaptation requires changes in approach and becomes much more difficult if warming exceeds 2°C above preindustrial levels (CONABIO et al., 2007; Mansourian et al., 2009; U.S. Forest Service, 2010; Glick and Stein, 2011; March et al., 2011; INECC and SEMARNAT, 2012b). Even though options for effective adaptation are increasingly constrained at warming over 2°C, some opportunities will remain. In particular, efforts to maintain or increase forest carbon stocks can lead to numerous benefits, including not only benefits for atmospheric CO_2 (Anderson and Bell, 2009; Anderson et al., 2011). Even where there are opportunities, managers face challenges in designing management practices that favor carbon stocks, while at the same time maintaining biodiversity, recognizing the rights of indigenous people, and contributing to local economic development (FAO, 2012).

26.5. Agriculture and Food Security

Projected declines in global agricultural productivity (Chapter 7) have implications for food security among North Americans. Because North America is a major exporter (FAO, 2009; Schlenker and Roberts, 2009), shifts in agricultural productivity here may have implications for global food security. Canada and the USA are relatively food secure, although households living in poverty are vulnerable. 17.6% of Mexicans are food insecure (Monterroso et al., 2012). Indigenous peoples are highly vulnerable due to high reliance on subsistence (Chapter 12). While this section focuses on agricultural production, food security is related to multiple factors (see Chapter 7).

26.5.1. Observed Climate Change Impacts

Historic yield increases are attributed in part to increasing temperatures in Canada and higher precipitation in the USA (*medium evidence*, *high agreement*; Pearson et al., 2008; Nadler and Bullock, 2011; Sakurai et al., 2011), although multiple non-climatic factors affect historic production rates. In many North American regions optimum temperatures have been reached for dominant crops; thus continued regional warming would diminish rather than enhance yields (*high confidence*; Jones et al., 2005). Regional yield variances over time have been attributed to climate variability, for example Ontario (Cabas et al., 2010) and Quebec (Almaraz et al., 2008). Since 1999 a marked increase in crop losses attributed to climate-related events such as drought, extreme heat, and storms has been observed across North America (Hatfield et al., 2013), with significant negative economic effects (*high confidence*; Swanson et al., 2007; Chen and McCarl, 2009; Costello et al., 2009). In Mexico, agriculture accounted for 80% of weather-related financial losses since 1990 (Saldaña-Zorrilla, 2008; Figure 26-2).

26.5.2. Projected Climate Change Risks

Studies project productivity gains in northern regions and where water is not projected to be a limiting factor, across models, time frames, and scenarios (*high confidence*; Hatfield et al., 2008; Pearson et al., 2008; Stöckle et al., 2010; Wheaton et al., 2010). Overall yields of major crops in North America are projected to decline modestly by mid-century and more steeply by 2100 among studies that do not consider adaptation (*very high confidence*). Certain regions and crops may experience gains in the absence of extreme events, and projected yields vary by climate model (Paudel and Hatch, 2012; Liu et al., 2013).

Among studies projecting yield declines, two factors stand out: exceedance of temperature thresholds and water availability. Yields of several important North American agriculture sectors—including grains, forage, livestock, and dairy—decline significantly above temperature thresholds (Wolfe et al., 2008; Schlenker and Roberts, 2009; Craine et al., 2010). Temperature increases affect product quality as well, for example, coffee (Lin, 2007), wine grapes (Hayhoe et al., 2004; Jones et al., 2005), wheat (Porter and Semenov, 2005), fruits and nuts (Lobell et al., 2006), and cattle forage (Craine et al., 2010). Projected temperature increases would reduce corn, soy, and cotton yields by 2020, with declines ranging from 30 to 82% by 2099 depending on crop and scenario (steepest decline for corn, A1; Schlenker and Roberts, 2009). Studies also project increasing interannual yield variability over time (Sakurai et al., 2011; Urban et al., 2012). Several studies focus on California, one of North America's most productive agricultural regions. Modest and variable yield changes among several California crops are projected to 2026, with yield declines from 9 to 29% by 2097 (A2, DAYCENT model). Lee et al. (2011) and Lobell and Field (2011) found little negative effect for California perennials by 2050 due to projected climate change, assuming irrigation access (General Circulation Model (GCM) ensemble, A2 and B1). Hannah et al. (2013), however, project large declines in land suitability for California viticulture by 2050 (with increases further north) with RCP4.5 and RCP8.5 (GCM ensemble); declines are greater under RCP8.5. Heat-induced livestock stress, combined with reduced forage quality, would reduce milk production and weight gain in cattle (Wolfe et al., 2008; Hernández et al., 2011).

Precipitation increases offset but do not entirely compensate for temperature-related declines in productivity (Kucharik and Serbin, 2008). In regions projected to experience increasing temperatures combined with declining precipitation, declines in yield and quality are more acute (Craine et al., 2010; Monterroso Rivas et al., 2011).

Projected change in climate will reduce soil moisture and water availability in the US West/Southwest, the Western Prairies in Canada, and central and northern Mexico (*very high confidence*; Pearson et al., 2008; Cai et al., 2009; Karl et al., 2009; Sanchez-Torres Esqueda, 2010; Vano et al., 2010b; Kulshreshtha, 2011). CMIP5 models indicate soil moisture decreases across the continent in spring and summer under RCP8.5, with *high agreement* (Dirmeyer et al., 2013). Based on a combined exposure/consumptive water use model, the US Great Plains is identified as one of four global future vulnerability hotspots for water availability from the 2030s and beyond, where anticipated water withdrawals would exceed 40% of freshwater resources (Liu et al., 2013). In western USA and Canada, projected earlier spring snowmelt and reduced snowpack would affect productivity negatively regardless of precipitation, as water availability in summer and fall are reduced (Schlenker et al., 2007; Forbes et al., 2011; Kienzle et al., 2012).

Projected increases in extreme heat, drought, and storms affect productivity negatively (Chen and McCarl, 2009; Kulshreshtha, 2011). The northeastern and southeastern USA have been identified as "vulnerability hotspots" for corn and wheat production respectively by 2045 with vulnerability worsening thereafter, using a combined drought exposure and adaptive capacity assessment, with only slight differences between A1B and B2 scenarios (Fraser et al., 2013). Central North America is identified as among the globe's regions of highest risk of heat stress by 2070 (National Institute for Environmental Studies (NIES) GCM, A1B; Teixeira et al., 2013).

26.5.3. A Closer Look at Mexico

Much of Mexico's land base is already marginal for two of the country's major crops: corn and beef (Buechler, 2009). Severe desertification in Mexico due to non-climate drivers further compromises productivity (Huber-Sannwald et al., 2006). Land classified suitable for rain-fed corn is projected to decrease from 6.2% currently to between 3 and 4.3% by 2050 (UKHadley B2, European Centre for Medium Range Weather Forecasts and Hamburg 5 (ECHAM5)/Max Planck Institute (MPI) A2; Monterroso Rivas et al., 2011). The distribution of most races of corn is expected to be reduced and some eliminated by 2030 (A2, three climate models; Ureta et al., 2012). Precipitation declines of 0 to 30% are projected over Mexico by 2040, with the most acute declines in northwestern Mexico, the primary region of irrigated grain farming (declines steeper in A2 than A1B, 18-model ensemble).

Although projected increases in precipitation may contribute to increase in rangeland productivity in some regions (Monterroso Rivas et al., 2011), a study in Veracruz indicates that the effects of projected maximum summer temperatures on livestock heat stress are expected to reach the "danger level" (at which losses can occur) by 2020 and continue to rise (A2, B2, three GCMs; Hernández et al., 2011). Coffee, an economically important crop supporting 500,000 primarily indigenous households (González Martínez, 2006), is projected to decline 34% by 2020 in Veracruz if historic temperature and precipitation trends continue (Gay et al., 2006); see also Schroth et al. (2009), on declines in Chiapas.

Many of Mexico's agricultural communities are also considered highly vulnerable, due to high sensitivity and/or low adaptive capacity (Monterroso et al., 2012). The agriculture sector here consists primarily of small farmers (Claridades Agropecuarias, 2006), who face high livelihood risks due to limited access to credit and insurance (Eakin and Tucker, 2006; Wehbe et al., 2008; Saldaña-Zorilla and Sandberg, 2009; Walthall et al., 2012).

26.5.4. Adaptation

The North American agricultural industry has the adaptive capacity to offset projected yield declines and capitalize on opportunities under 2°C warming. Butler and Huybers (2012) project a reduction in US corn yield loss from 14 to 6% with 2°C warming, with spatial shifts in varietal selection (not accounting for variability in temperature and precipitation). Incremental strategies, such as planting varieties better suited to future climate conditions and changing planting dates, have been observed across the continent (Bootsma et al., 2005; Conde et al., 2006; Eakin and Appendini, 2008; Coles and Scott, 2009; Nadler and Bullock, 2011; Paudel and Hatch, 2012; Campos et al., 2013). In some sectors we are seeing multi-organizational investments in adaptation. International coffee retailers and non-governmental organizations, for example, are engaged in enhancing coffee farmers' adaptive capacity (Schroth et al., 2009; Soto-Pinto and Anzueto, 2010). Other strategies specifically recommended for Mexico include soil remediation, improved use of climate information, rainwater capture, and drip irrigation (Sosa-Rodriguez, 2013). New crop varieties better suited to future climates, including genetically modified organisms (GMOs), are under development in the USA (e.g., Chen et al., 2012), although potential risks have been noted (Quist and Chapela, 2001). Current trends in agricultural practices in commercial regions such as the midwestern USA, however, amplify productivity risks posed by climate change (Hatfield et al., 2013). Incremental strategies will have reduced effectiveness under a 2099/4°C warming scenario, which would require more systemic adaptation, including production and livelihood diversification (Howden et al., 2007; Asseng et al., 2013; Mehta et al., 2013; Smith and Gregory, 2013).

Some adaptive strategies impose financial costs and risks onto producers (Wolfe et al., 2008; Craine et al., 2010), which may be beyond the means of smallholders (Mercer et al., 2012) or economically precluded for low-value crops. Technological improvements improve yields under normal conditions but do not protect harvests from extremes (Karl et al., 2009; Wittrock et al., 2011). Others may have maladaptive effects (e.g., increased groundwater and energy consumption). Crop-specific weather index insurance, for example (widely implemented in Mexico to support small farmers), may impose disincentives to invest in diversification and irrigation (Fuchs and Wolff, 2010).

Many strategies have co-benefits, however. In fact, investments in agricultural adaptation represent a cost-effective mitigation strategy (Lobell et al., 2013). Low- and no-till practices reduce soil erosion and runoff, protect crops from extreme precipitation (Zhang and Nearing, 2005), retain soil moisture, reduce biogenic and geogenic greenhouse gas emissions (Nelson et al., 2009; Suddick et al., 2010), and build soil organic carbon (Aguilera et al., 2013). Planting legumes and weed management on pastures enhance both forage productivity and soil carbon sequestration (Follett and Reed, 2010). Shade perennials increase soil moisture retention (Lin, 2010) and contribute to local cooling (Georgescu et al., 2011). Crop diversification mediates the impacts of climate and market shocks (Eakin and Appendini, 2008) and enhances management flexibility (Chhetri et al., 2010).

Barriers and Enablers

Market forces and technical feasibility alone are insufficient to foster sectoral-level adaptation (Kulshreshtha, 2011). Institutional support is key, but found to be inadequate in many contexts (*high confidence*; Bryant et al., 2008; Klerkx and Leeuwis, 2009; Jacques et al., 2010; Tarnoczi and Berkes, 2010; Brooks and Loevinsohn, 2011; Alam et al., 2012; Anderson and McLachlan, 2012). Many suggested adaptation strategies with anticipated economic benefits are often not adopted by farmers, suggesting the need for more attention to culture and behavior (Moran et al., 2013). Attitudinal studies among US farmers indicate limited acknowledgment of anthropogenic climate change, associated with lower levels of support for adaptation (*medium evidence*, *high agreement*; Arbuckle, Jr. et al., 2013; Gramig et al., 2013).

Other key enablers are access to and quality of information (Tarnoczi and Berkes, 2010; Tarnoczi, 2011; Baumgart-Getz et al., 2012; Tambo and Abdoulaye, 2012), particularly regarding optimum crop management, production inputs, and optimum crop-specific geographic information. Social networks are important for information dissemination and farmer support (Chiffoleau, 2009; Wittrock et al., 2011; Baumgart-Getz et al., 2012). Networks among producers may be especially important to the level of awareness and concern farmers hold about climate change (Frank et al., 2010; Sánchez-Cortés and Chavero, 2011), while also enabling extensive farmer-to-farmer exchange of adaptation strategies (Eakin et al., 2009).

26.6. Human Health

Large national assessments of climate and health have been carried out in the USA and Canada (Bélanger et al., 2008; see references in Section 26.1). These have highlighted the potential for changes in impacts of extreme storm and heat events, air pollution, pollen, and infectious diseases, drawing from a growing North American research base analyzing observed and projected relationships among weather, vulnerability, and health. The causal pathways leading from climate to health are complex, and can be modified by factors including economic status, preexisting illness, age, other health risk factors, access to health care, built and natural environments, adaptation actions, and others. Human health is an important dimension of adaptation planning at the local level, much of which has so far focused on warning and response systems to extreme heat events (New York State Climate Action Council, 2012).

26.6.1. Observed Impacts, Vulnerabilities, and Trends

26.6.1.1. Storm-Related Impacts

The magnitude of health impacts of extreme storms depends on interactions between exposure and characteristics of the affected communities (Keim, 2008). Coastal and low-lying infrastructure and populations can be vulnerable owing to flood-related interruptions in communications, health care access, and mobility. Health impacts can arise through direct pathways of traumatic death and injury (e.g., drowning, impacts of blowing and falling objects, contact with power wires) as well as more indirect, longer term pathways related to damage to health and transportation infrastructure, contamination of water and soil, vector-borne diseases, respiratory diseases, and mental health (CCSP, 2008a). Infectious disease impacts from flooding include creation of breeding sites for vectors (Ivers and Ryan, 2006) and bacterial transmission through contaminated water and food sources causing gastrointestinal disease. Chemical toxins can be mobilized from industrial or contaminated sites (Euripidou and Murray, 2004). Elevated indoor mold levels associated with flooding of buildings and standing water are identified as risk factors for cough, wheeze, and childhood asthma (Bornehag et al., 2001; Jaakkola et al., 2005). Mental health impacts can arise as a result of the stress of evacuation, property damage, economic loss, and household disruption (Weisler et al., 2006; CCSP, 2008a; Berry et al., 2010, 2011). Since 1970, there has been no clear trend in US hurricane deaths, once the singular Katrina event is set aside (Blake et al., 2007).

26.6.1.2. Temperature Extremes

Studies throughout North America have shown that high temperatures can increase mortality and/or morbidity (e.g., Medina-Ramon and Schwartz, 2007; Kovats and Hajat, 2008; Anderson and Bell, 2009; Deschênes et al., 2009; Knowlton et al., 2009; O'Neill and Ebi, 2009; Hajat and Kosatsky, 2010; Kenny et al., 2010; Cueva-Luna et al., 2011; Hurtado-Díaz et al., 2011; Romero-Lankao et al., 2012b). Extremely cold temperatures have also been associated with increased mortality (Medina-Ramon and Schwartz, 2007), an effect separate from the seasonal phenomenon of excess winter mortality, which does not appear to be directly related to cold temperatures (Kinney, 2012). To date, trends over time in cold-related deaths have not been investigated.

Most available North American evidence derives from the USA and Canada, though one study reported significant heat- and cold-related mortality impacts in Mexico City (McMichael et al., 2008). US EPA has tracked the death rate in the USA from 1979 to 2009 for which death certificates list the underlying cause of death as heat related (EPA, 2012). No clear trend upwards or downwards is yet apparent in this indicator. Note that this case definition is thought to significantly underestimate the total impacts of heat on mortality.

26.6.1.3. Air Quality

Ozone and particulate matter (e.g., particulate matter with aerodynamic diameter <2.5 μm ($PM_{2.5}$) and PM_{10}) have been associated with adverse health effects in many locations in North America (Romero-Lankao et al., 2013b). Emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorological variables such as temperature, humidity, wind speed and direction, and mixing height (Kinney, 2008). Although air pollution emission trends will play a dominant role in future pollution levels, climate change may make it harder to achieve some air quality goals (Jacob and Winner, 2009). Forest fire is a source of particle emissions in North America, and can lead to increased cardiac and respiratory disease incidence, as well as direct mortality (Rittmaster et al., 2006; Ebi et al., 2008). The indoor environment also can affect health in many ways, for example, via penetration of outdoor pollution, emissions or pollutants indoors, moisture-related problems, and transmission of respiratory infections. Indoor moisture leads to mold growth, a problem that is exacerbated in colder regions such as northern North America in the winter (Potera, 2011). Climate variability and change will affect indoor air quality, but with direction and magnitude that remains largely unknown (Institute of Medicine, 2011).

26.6.1.4. Pollen

Exposure to pollen has been associated with a range of allergic outcomes, including exacerbations of allergic rhinitis (Cakmak et al., 2002; Villeneuve et al., 2006) and asthma (Delfino, 2002). Temperature and precipitation in the months prior to the pollen season affect production of many types of tree and grass pollen (Reiss and Kostic, 1976; Minero et al., 1998; Lo and Levetin, 2007; EPA, 2008). Ragweed pollen production is responsive to temperatures and to CO_2 concentrations (Ziska and Caulfield, 2000; Wayne et al., 2002; Ziska et al., 2003; Singer et al., 2005). Because pollen production and release can be affected by temperature, precipitation, and CO_2 concentrations, pollen exposure and allergic disease morbidity could change in response to climate change. However, to date, the timing of the pollen season is the only evidence for observed climate-related impacts. Many studies have indicated that pollen seasons are beginning earlier (Emberlin et al., 2002; Rasmussen, 2002; Clot, 2003; Teranishi et al., 2006; Frei and Gassner, 2008; Levetin and de Water, 2008; Ariano et al., 2010). Ragweed season length has increased at some monitoring stations in the USA (Ziska et al., 2011). Research on trends in North America has been hampered by the lack of long-term, consistently collected pollen records (EPA, 2008).

26.6.1.5. Water-borne Diseases

Water-borne infections are an important source of morbidity and mortality in North America. Commonly reported infectious agents in US and Canadian outbreaks include *Legionella* bacterium, the cryptosporidium parasite *Campylobacter*, and *Giardia* (Bélanger et al., 2008; Centers for Disease Control and Prevention, 2011). Cholera remains an important agent in Mexico (Greer et al., 2008). Risk of water-borne illness is greater among the poor, infants, elderly, pregnant women, and immune-compromised individuals (Rose et al., 2001; CCSP, 2008a). In Mexico City, declining water quality has led to ineffective disinfection of drinking water supplies (Mazari-Hiriart et al., 2005; Sosa-Rodriguez, 2010).

Changes in temperature and hydrological cycles can influence the risk of water-borne diseases (Curriero et al., 2001; Greer et al., 2008; Harper et al., 2011). Severe storms have been shown to play a role in water-borne disease risks in Canada (Thomas et al., 2006). Floods enhance the potential for runoff to carry sediment and pollutants to water supplies (CCSP, 2008b). Disparities in access to treated water were identified as a key determinant of under age-5 morbidity due to water-borne illnesses in the central State of Mexico (Jiménez-Moleón and Gómez-Albores, 2011).

26.6.1.6. Vector-borne Diseases

The extent to which climate change has altered, and will alter, the geographic distribution of vectors of infectious disease remains uncertain because of the inherent complexity of the ecological system. Spatial and temporal distribution of disease vectors depend not only on climate factors, but also on land use/change, socioeconomic and sociocultural factors, prioritization of vector control, access to health care, and human behavioral responses to perception of disease risk, among other factors (Lafferty, 2009; Wilson, 2009). Although temperature drives important biological processes in these organisms, climate variability on a daily, seasonal, or interannual scale may result in organism adaptation and shifts, though not necessarily expansion, in geographic range (Lafferty, 2009; Tabachnick, 2010; McGregor, 2011). Range shifts may alter the incidence of disease depending on host receptiveness and immunity, as well as the ability of the pathogen to evolve so that strains are more effectively and efficiently acquired (Reiter, 2008; Beebe et al., 2009; Rosenthal, 2009; Russell, 2009; Epstein, 2010).

North Americans are currently at risk from a number of vector-borne diseases, including Lyme disease (Ogden et al., 2008; Diuk-Wasser et al., 2010), dengue fever (Jury, 2008; Ramos et al., 2008; Johansson et al., 2009; Degallier et al., 2010; Kolivras, 2010; Lambrechts et al., 2011; Riojas-Rodriguez et al., 2011; Lozano-Fuentes et al., 2012), West Nile virus (Gong et al., 2011; Morin and Comrie, 2010), and Rocky Mountain spotted fever, to name a few. Risk is increasing from invasive vector-borne pathogens, such as chikungunya (Ruiz-Moreno et al., 2012) and Rift Valley fever viruses (Greer et al., 2008). Mexico is listed as high risk for dengue fever by the World Health Organization (WHO). There has been an increasing number of cases of Lyme disease in Canada, and Lyme disease vectors are spreading along climate-determined trajectories (Koffi et al., 2012; Leighton et al., 2012).

26.6.2. Projected Climate Change Impacts

Projecting future consequences of climate warming for heat-related mortality and morbidity is challenging, due in large part to uncertainties in the nature and pace of adaptations that populations and societal infrastructure will undergo in response to long-term climate change (Kinney et al., 2008). Additional uncertainties arise from changes over time in population demographics, economic well-being, and underlying disease risk, as well as in the model-based predictions of future climate and our understanding of the exposure-response relationship for heat-related mortality. However, climate warming will lead to continuing health stresses related to extreme high temperatures, particularly for the northern parts of North America. The health implications of warming winters remain uncertain (Kinney, 2012).

Several recent studies have projected future health impacts due to air pollution in a changing climate (Knowlton et al., 2004; Bell et al., 2007; Tagaris et al., 2009, 2010; Chang et al., 2010). There is a large literature examining future climate influences on outdoor air quality in North America, particularly for ozone (Murazaki and Hess, 2006; Steiner et al., 2006; Kunkel et al., 2007;Tao et al., 2007; Holloway et al., 2008; Lin et al., 2008, 2010; Nolte et al., 2008; Wu et al., 2008; Avise et al., 2009; Chen et al., 2009; Liao et al., 2009; Racherla and Adams, 2009; Tai et al., 2010). This work suggests with *medium confidence* that ozone concentrations could increase under future climate change scenarios if emissions of precursors were held constant (Jacob and Winner, 2009). However, analyses show that future increases can be offset through measures taken to limit emission of pollutants (Kelly et al., 2012). The literature for $PM_{2.5}$ is more limited than that for ozone, and shows a more complex pattern of climate sensitivities, with no clear net influence of warming temperatures (Liao et al., 2007; Tagaris et al., 2008; Avise et al., 2009; Pye et al., 2009; Mahmud et al., 2010). On the other hand, $PM_{2.5}$ plays a crucial role in potential health co-benefits of some climate mitigation measures. Regarding outdoor pollen, warming will lead to further changes in the seasonal timing of pollen release (*high confidence*). Another driver of future pollen could be changing spatial patterns of vegetation as a result of climate change. Regarding clean water supplies, extreme precipitation can overwhelm combined sewer systems and lead to overflow events that threaten human health (Patz et al., 2008). Conditional on a future increase in such events, we can anticipate increasing risks related to water-borne diseases.

Whether future warmer winters in the USA and Canada will promote transmission of diseases like dengue and malaria is uncertain, in part because of access to amenities such as screening and air-conditioning that provide barriers to human-vector contact. Socioeconomic factors also play important roles in determining risks. Better longitudinal data sets and empirical models are needed to address research gaps on climate-sensitive infectious diseases, as well as to provide a better mechanism for weighting the roles of external drivers such as climate change on a macro/micro scale, human-environmental changes on a regional to local scale, and extrinsic factors in the transmission of vector-borne infectious diseases (Wilson, 2009; McGregor, 2011).

26.6.3. Adaptation Responses

Early warning and response systems can be developed to build resilience to events like heat waves, storms, and floods (Ebi, 2011) and protect susceptible populations, which include infants, children, the elderly, individuals with pre-existing diseases, and those living in socially and/or economically disadvantaged conditions (Pinkerton et al., 2012). Adaptation planning at all scales to build resilience for health systems in the face of a changing climate is a growing priority (Kinney et al., 2011). Adaptation to heat events can occur via physiologic mechanisms, indoor climate control, urban-scale cooling initiatives, and with implementation of warning and response systems (Romero-Lankao et al., 2012b). Additional research is needed on the extent to which warning systems prevent deaths (Harlan and Ruddell, 2011). Efforts to reduce GHG emissions could provide health co-benefits, including reductions in heat-related and respiratory illnesses (Luber et al., 2014).

26.7. Key Economic Sectors and Services

There is mounting evidence that many economic sectors across North America have experienced climate impacts and are adapting to the risk of loss and damage from weather perils. This section covers the literature for the energy, transportation, mining, manufacturing, construction and housing, and insurance sectors in North America. Recent studies find a range of adaptive practices and adaptation responses to experience with extreme events, and only an emerging consideration of proactive adaptation in anticipation of future global warming.

26.7.1. Energy

26.7.1.1. Observed Impacts

Energy demand for cooling has increased as building stock and air conditioning penetration have increased (Wilbanks et al., 2012). Extreme weather currently poses risk to the energy system (Wilbanks et al., 2012). For example, Hurricane Sandy resulted in a loss of power to 8.5 million customers in the northeastern USA (NOAA, 2013). Energy consumption is a major user of water resources in North America, with 49% of the water withdrawals in the USA for thermoelectric power (Kenny et al., 2009).

26.7.1.2. Projected Impacts

Demand for summer cooling is projected to increase and demand for winter heating is projected to decrease. Total energy demand in North America is projected to increase in coming decades because of non-climate factors (Galindo, 2009; National Energy Board, 2011; EIA, 2013). Climate change is projected to have varying geographic impacts. In Canada, a net decrease in residential annual energy demand is projected by 2050 and by 2100 (Isaac and Van Vuuren, 2009; Schaeffer et al., 2012). It is difficult to project changes in net energy demand in the USA because of uncertainties in such factors as climate change, and change in technology, population, and energy prices. Peak demand for electricity is projected to increase more than the average demand for electricity, with capacity expansion needed in many areas (Wilbanks et al., 2012). Given the projected increases in energy demand in the southern USA from climate change (Auffhammer and Aroonruengsawat, 2011, 2012), it is reasonable to conclude that Mexico will have a net increase in demand.

Major water resource-related concerns include effects of increased cooling and other demands for water and water scarcity in the west; effects of extreme weather events, SLR, hurricanes, and seasonal droughts in the southeast; and effects of increased cooling demands in the northern regions (CCSP, 2007; MacDonald et al., 2012; Wilbanks et al., 2012; DOE-PI, 2013).

The magnitude of projected impacts on hydropower potential will vary significantly between regions and within drainage basins (Desrochers et al., 2009; Kienzle et al., 2012; Shrestha et al., 2012). Annual mean hydropower production in the Peribonka River in Quebec is estimated to increase by approximately 10% by mid-century and 20% late in the century under the A2 scenario (Minville et al., 2009).

Higher temperatures and increased climate variability can have adverse impacts on renewable energy production such as wind and solar (DOE-PI, 2013). Changing cloud cover affects solar energy resources, changes in winds affect wind power potentials, and temperature change and water availability can affect biomass production (CCSP, 2007; DOE-PI, 2013).

26.7.1.3. Adaptation

Many adaptations are underway to reduce vulnerability of the energy sector to extreme climate events such as heat, drought, and flooding (DOE-PI, 2013). Adaptation includes many approaches such as increased supply and demand efficiency (e.g., through more use of insulation), more use of urban vegetation and reflective surfaces, improved electric grid, reduced reliance on above-ground distribution systems, and distributed power (Wilbanks et al., 2012). Important barriers to adaptation include uncertainty about future climate change, inadequate information on costs of adaptation, lack of climate resilient energy technologies, and limited price signals (DOE-PI, 2013). Strategies resulting in energy demand reduction would reduce GHG emissions and reduce the vulnerability of the sector to climate change.

26.7.2. Transportation

26.7.2.1. Observed Impacts

Much of the transportation infrastructure across North America is aging, or inadequate (Mexico), which may make it more vulnerable to damage from extreme events and climate change. Approximately 11% of all US bridges are structurally deficient, 20% of airport runways are in fair or poor condition, and more than half of all locks are more than 50 years old (U.S. Department of Transportation, 2013). More than US$2 trillion is needed to bring infrastructure in the USA up to "good condition" (ASCE, 2009, p. 6). Canadian infrastructure had an investment deficit of CA$125 billion in the 1980s and 1990s (Mirza and Haider, 2003).

Some transportation systems have been harmed (Figure 26-2). For example, in 2008, Hurricane Ike caused US$2.4 billion in damages to ports and waterways in Texas (MacDonald et al., 2012). The "superflood" in Tennessee and Kentucky in 2010 caused US$2.3 billion in damage (NOAA, 2013).

Hurricane Sandy flooded portions of New York City's subway system, overtopped runways at La Guardia airport, and caused US$400 million in damage to the New Jersey transit system (NOAA, 2013).

26.7.2.2. Projected Impacts

Scholarship on projected climate impacts on transportation infrastructure focuses mostly on USA and Canada. Increases in high temperatures, intense precipitation, drought, sea level, and storm surge could affect transportation across the USA. The greatest risks would be to coastal transportation infrastructure, but there could be benefits to marine and lake transportation in high latitudes from less ice cover (TRB, 2008). A 1-m SLR combined with a 7-m storm surge could inundate over half of the highways, arterials, and rail lines in the US Gulf Coast (CCSP, 2008c). Declining water levels in the Great Lakes would increase shipping costs by restricting vessel drafts and reducing vessel cargo volume (Millerd, 2011). In southern Canada by the 2050s, cracking of roads from freeze and thaw would decrease under the B2 and A2 scenarios, structures would freeze later and thaw earlier, while higher extreme temperatures could increase rutting (Mills et al., 2009) and related maintenance and rehabilitation costs (Canadian Council of Professional Engineers, 2008).

A 1°C to 1.5°C increase in global mean temperature would increase the costs of keeping paved and unpaved roads in the USA in service by, respectively, US$2 to US$3 billion per year by 2050 (Chinowsky et al., 2013). Tens of thousands to more than 100,000 bridges in the USA could be vulnerable to increasing peak river flows in the mid- and late-21st century under the A1B and A2 scenarios. Strengthening vulnerable bridges to be less vulnerable to climate change is estimated to cost approximately US$100 to US$250 billion (Wright et al., 2012).

26.7.2.3. Adaptation

Adaptation steps are being taken in North America, particularly to protect transportation infrastructure from SLR and storm surge in coastal regions. Almost all of the major river and bay bridges destroyed by Hurricane Katrina surge waters were rebuilt at higher elevations, and the design of the connections between the bridge decks and piers were strengthened (Grenzeback and Luckmann, 2006).

Adaptation actions include protecting coastal transportation from SLR and more intense coastal storms or possibly relocating infrastructure. Many midwestern states are examining channel protection and drainage designs, while transportation agencies in Canada and the USA have been preparing to manage the aftermath of extreme weather events (Meyer et al., 2013). In addition, new materials may be needed so pavement and rail lines can better withstand more extreme temperatures.

26.7.3. Mining

26.7.3.1. Observed Impacts

Climatic sensitivities of mining activities, including exploration, extraction, processing, operations, transportation, and site remediation, have been noted in the limited literature (Chiotti and Lavender, 2008; Furgal and Prowse, 2008; Meza-Figueroa et al., 2009; Ford et al., 2010a; Gómez-Álvarez et al., 2011; Kirchner et al., 2011; Locke et al., 2011; Pearce et al., 2011; Stratos Inc. and Brodie Consulting Ltd., 2011). Drought-like conditions have affected the mining sector by limiting water supply for operations (Pearce et al., 2011), enhancing dust emissions from quarries (Pearce et al., 2011), and increasing concentrations of heavy metals in sediments (Gómez-Álvarez et al., 2011). Heavy precipitation events have caused untreated mining wastewater to be flushed into river systems (Pearce et al., 2011). High loads of contamination (from metals, sulfate, and acid) at three mine sites in the USA were measured during rainstorm events following dry periods (Nordstrom, 2009).

26.7.3.2. Projected Impacts

Climate change is perceived by Canadian mine practitioners as an emerging risk and, in some cases, a potential opportunity (Ford et al., 2010a, 2011; Pearce et al., 2011; NRTEE, 2012), with potential impacts on transportation (Ford et al., 2011) and limited water availability (Acclimatise, 2009) from projected drier conditions (Sun et al., 2008; Seager and Vecchi, 2010) being identified as key issues.

An increase in heavy precipitation events projected for much of North America (Warren and Egginton, 2008; Nordstrom, 2009) would adversely affect the mining sector. A study on acid rock damage drainage in Canada concluded that an increase in heavy precipitation events presented a risk of both environmental impacts and economic costs

(Stratos Inc. and Brodie Consulting Ltd., 2011) Damage to mining infrastructure from extreme events, for active and post-operation mines, is also a concern (Pearce et al., 2011). Climate change impacts that affect the bottom-line of mining companies (through direct impacts or associated costs of adaptation), would have consequences for employment, for both the mining sectors and local support industries (Backus et al., 2013).

26.7.3.3. Adaptation

Despite increasing awareness, there are presently few documented examples of proactive adaptation planning within the mining sector (Acclimatise, 2009; Ford et al., 2010a, 2011). However, adjustments to management practices to deal with short-term water shortages, including reducing water intake, increasing recycling, and establishing infrastructure to move water from tailing ponds, pits, and quarries, have worked successfully in the past (Chiotti and Lavender, 2008). Integrating climate change considerations at the mine planning and design phase increases the opportunity for effective and cost-efficient adaptation (Stratos Inc. and Brodie Consulting Ltd., 2011).

26.7.4. Manufacturing

26.7.4.1. Observed Impacts

There is little literature focused on climate change and manufacturing, although one study suggested that manufacturing is among the most sensitive sectors to weather in the USA (Lazo et al., 2011). Weather affects the supply of raw material, production process, transportation of goods, and demand for certain products. In 2011, automobile manufacturers in North America experienced production losses associated with shortages of components due to flooding in Thailand (Kim, 2011). In 2013, reduced cattle supply and higher feed prices associated with drought in Texas led to a decision to close a beef processing plant (Beef Today Editors, 2013). Drought also caused delays for barge shipping on the Mississippi River in 2012 (Polansek, 2012). Major storms, like Hurricanes Sandy, Katrina, and Andrew, significantly disrupted manufacturing activities, including plant shutdowns due to direct damages and/or loss of electricity and supply disruptions due to unavailability of parts, and difficulties delivering products due to compromised transportation networks (Baade et al., 2007; Dolfman et al., 2007).

26.7.4.2. Projected Impacts

The drier conditions (Sun et al., 2008; Seager and Vecchi, 2010; Wehner et al., 2011) would present challenges, especially for manufacturers located in regions already experiencing water stress. This could lead to increased conflicts over water between sectors and regions, and affect the ability of regions to attract new facilities or retain existing operations. A study of the effect of changes in precipitation (A1B scenario) on 70 industries in the USA between 2010 and 2050 found potentially significant losses in production and employment due to declines in water availability and the interconnectedness of different industries (Backus et al., 2013).

Another potential concern for manufacturing relates to impacts of heat on worker safety and productivity. Several studies suggest that higher temperatures and humidity would lead to decreased productivity and increased occupational health risks (e.g., Kjellstrom et al., 2009; Hanna et al., 2011; Kjellstrom and Crowe, 2011).

26.7.4.3. Adaptation

Some companies are beginning to recognize the risks climate change presents to their manufacturing operations, and consider strategies to build resilience (NRTEE, 2012). Coca Cola has a water stewardship strategy focusing on improving water use efficiency at its manufacturing plants, while Rio Tinto Alcan is assessing climate change risks for their operations and infrastructure, which include vulnerability of transport systems, increased maintenance costs, and disruptions due to extreme events (NRTEE, 2012). Air conditioning is a viable and effective adaptation option to address some of the impacts of warming, though it does incur greater demands for electricity and additional costs (Scott et al., 2008a). Sourcing raw materials from different regions and relocating manufacturing plants are other adaptation strategies that can be used to increase resiliency and reduce vulnerability.

26.7.5. Construction and Housing

26.7.5.1. Observed Impacts

The risk of damage from climate change is important for construction industries, though little research has systematically explored the topic (Morton et al., 2011). Private data from insurance companies report a significant increase in severe weather damage to buildings and other insured infrastructure over several decades (Munich Re, 2012).

26.7.5.2. Projected Impacts

Most studies project a significant further increase in damage to homes, buildings, and infrastructure (Bjarndadottir et al., 2011; IPCC, 2012). Affordable adaptation in design and construction practices could reduce much of the risk of climate damage for new buildings and infrastructure, involving reform in building codes and other standards (Kelly et al., 2012). However, adaptation best practices in design and construction are often prohibitively expensive to apply to existing buildings and infrastructure, so much of the projected increase in climate damage risk involves existing buildings and infrastructure.

26.7.5.3. Adaptation

Engineering and construction knowledge exists to design and construct new buildings to accommodate the risk of damage from historic extremes and anticipated changes in severe weather (IBHS, 2008; Kelly, 2010; Ministry of Municipal Affairs and Housing, 2011). Older buildings may be retrofit to increase resilience, but these changes are often more expensive to introduce into an existing structure than if they were included during initial construction.

The housing and construction industries have made advances toward climate change mitigation by incorporating energy efficiency in building design (Heap, 2007). Less progress has been made in addressing the risk of damage from extreme weather events (Kenter, 2010). In some markets, such as the Gulf Coast of the USA, change is underway in the design and construction of new homes in reaction to recent hurricanes (Levina et al., 2007; Kunreuther and Michel-Kerjan, 2009; IBHS, 2011), but in most markets across North America there has been little change in building practices. The cost of adaptation measures combined with limited long-term liability for future buildings has influenced some builders to take a wait-and-see attitude (Morton et al., 2011). Exploratory work is underway to consider implementation of building codes that would focus on historic weather experience and also introduce expected future weather risks (Auld et al., 2010; Ontario Ministry of Environment, 2011).

26.7.6. Insurance

26.7.6.1. Observed Impacts

Property insurance and reinsurance companies across North America experienced a significant increase in severe weather damage claims paid over the past 3 or 4 decades(Cutter and Emrich, 2005; Bresch and Spiegel, 2011; Munich Re, 2011). Most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk (Pielke, Jr. et al., 2008; Barthel and Neumayer, 2012). A role for climate change has not been excluded, but the increase to date in damage claims is largely due to growth in wealth and population (IPCC, 2012).

Severe weather and climate risks have emerged over the past decade as the leading cost for property insurers across North America, resulting in significant change in industry practices. The price of insurance increased in regions where the risk of loss and damage has increased. Discounts have been introduced where investments in adaptation have reduced the risk of future weather losses (Mills, 2012). Further detailed discussion on the insurance sector and climate change can be found in Section 10.7.

26.7.6.2. Projected Impacts

Without adaptation, there is an expectation that severe weather insurance damage claims would increase significantly over the next several decades across North America (World Bank, 2010). The risk of damage is expected to rise due to continuing growth in wealth, the population living at risk, and climate change. There is also an expectation that some weather perils in North America will increase in severity, including Atlantic hurricanes and the area burned by wildfire (Karl et al., 2008; Balshi et al., 2009), and other perils in frequency, including intense rainfall events (IPCC, 2012).

26.7.6.3. Adaptation

The insurance industry is one of the most studied sectors in North America in terms of climate impacts and adaptation. Most adaptation in the insurance industry has been in response to an increase in severe weather damage, with little evidence of proactive adaptation in anticipation of future climate change (Mills and Lecomte, 2006; Mills, 2007, 2009; Kunreuther and Michel-Kerjan, 2009; AMF, 2011; Leurig, 2011; Gallagher, 2012). In addition to pricing decisions based on an actuarial analysis of historic loss experience, many insurance companies in the USA and Canada now use climate model information to help determine the prices they charge and discounts they offer. Most insurance companies have established specialized claims handling procedures for responding to catastrophic events (Kovacs, 2005; Mills, 2009).

A recent study of more than 2000 major catastrophes since 1960 found that insurance is a critical adaptive tool available to help society minimize the adverse economic consequences of natural disasters (von Peter et al., 2012). Government insurance programs for coverage of flood in the USA have been affected by recent hurricanes and previously subsidized premiums have been changed to more accurately reflect risk (FEMA, 2013). In the USA and Canada, homeowners make extensive use of insurance to manage a broad range of risks, and those with insurance recover quickly following most extreme weather events. However, the majority of public infrastructure is not insured and it frequently takes more than a decade before government services fully recover. In contrast, Mexico has a well-developed program for financing the rebuilding of public infrastructure following a disaster (Fondo de Desastres Naturales (FONDEN)) but insurance markets are only beginning to emerge for homeowners and businesses. In 2012, per capita spending on property and casualty insurance was US$2239.20 in the USA, US$2040.40 in Canada, and US$113.00 in Mexico (Swiss Re, 2013).

Insurance companies are also working to influence the behavior of their policyholders to reduce the risk of damage from climate extremes (Kovacs, 2005; Anderson et al., 2006; Mills, 2009). For example, the industry supports the work of the Insurance Institute for Business and Home Safety in the USA, and the Institute for Catastrophic Loss Reduction in Canada, in working to champion change in the building code and communicate to property owners, governments, and other stakeholders best practices for reducing the risk of damage from hurricanes, tornadoes, winter storms, wildfire, flood, and other extremes.

26.8. Urban and Rural Settlements

Recently a growing body of literature and national assessments have focused on climate-related impacts, vulnerabilities, and risks in North American settlements (e.g., US-NCA Chapters 11, 14; Chapters 8, 9).

26.8.1. Observed Weather and Climate Impacts

Observed impacts on lives, livelihoods, economic activities, infrastructure, and access to services in North American human settlements have been attributed to SLR (Section 26.2.2.1), changes in temperature and precipitation, and occurrences of extreme events such as heat waves, droughts, and storms (Figure 26-2).

Only a handful of these impacts have been attributed to anthropogenic climate change, such as shifts in Pacific Northwest marine ecosystems, which have restricted fisheries and thus affected fishing communities (Karl et al., 2009). As well, MacKendrick and Parkins (2005), Parkins and MacKendrick (2007), Parkins (2008), and Holmes (2010) identified 30 communities and 25,000 families in British Columbia negatively affected by the mountain pine beetle outbreak (see Section 26.4.1.1).

While *droughts* are among the more notable extreme events affecting North American urban and rural settlements recently, with severe occurrences in the Canadian Prairies causing economic and employment losses (2001–2002; Wheaton et al., 2007), changes in drought frequency in North America have not been attributed to anthropogenic climate change (Figure 26-1). The 2010–2012 drought across much of the USA and northern Mexico was considered the most severe in a century (MacDonald, 2010). It affected 80% of agricultural land in the USA, with 2000 counties designated disaster zones by September (USDA ERS, 2012). Impacts include the loss of 3.2 million tons of maize in Mexico, placing 2.5 million at risk of food insecurity (DGCS, 2012). Among the most severely affected were indigenous peoples, such as the Rarámuri of Chihuahua (DGCS, 2012). Closely associated with droughts, the impacts of recent wildfires have been significant (see Box 26-2), and have intensified inequalities in vulnerability between amenity migrants and low-income residents in peri-urban areas of California and Colorado (Collins and Bolin, 2009).

Other extreme events include heat waves, resulting in excess urban mortality (O'Neill and Ebi, 2009; Romero-Lankao et al., 2012b) and affecting infrastructure and built environments. For example, road pavement in Chicago buckled under temperatures higher than 100°F (CBS Chicago, 2012); in Colorado two wildfires burned more than 600 homes (NOAA NCDC, 2013).

Extreme storms and extreme precipitation have also impacted several North American regions (Figures 26-1, 26-2). Flood frequency has increased in some cities, a trend sometimes associated with more intense precipitation (e.g., Mexico City and Charlotte, North Carolina, USA; Villarini et al., 2009; Magana, 2010), while in others this trend is associated with a transition from flood events dominated by snowmelt to those caused by warm-season thunderstorms (e.g., Québec, Canada, and Milwaukee, Wisconsin, USA; Ouellet et al., 2012; Yang et al., 2013). As illustrated by Hurricane Sandy (Neria and Shultz, 2012; Powell et al., 2012), storms impact human health and health care access (Section 26.6.1.1), and impacts on infrastructure and the built environment have been costly. Heavy precipitation, storm surges, flash floods, and wind—including flooding on the US East Coast and Midwest (2011), hurricanes and floods in the city of Villa Hermosa (Galindo et al., 2009) and other urban areas in southern Mexico (2004–2005)—have compromised homes and businesses (Comfort, 2006; Kirshen et al., 2008; Jonkman et al., 2009; Romero-Lankao, 2010). Hurricane Wilma alone caused US$1.8 billion in damage, among the biggest insurance losses in Latin American history (Galindo et al., 2009).

The impacts of interacting hazards compound vulnerabilities (Section 26.8.2). Coastal settlements are at risk from the combined occurrence of coastal erosion, health effects, infrastructure, and economic damage from storm surges. Earlier thaw (Friesinger and Bernatchez, 2010), SLR, and coastal flooding have been detected along the Mid-Atlantic, Gulf of Mexico, and St. Lawrence (Kirshen et al., 2008; Friesinger and Bernatchez, 2010; Zavala-Hidalgo et al., 2010; Rosenzweig et al., 2011; Tebaldi et al., 2012).

Climate impacts on the ecosystem function and services (e.g., water supplies, biodiversity, or flood protection) provided to human settlements are another concern. While acknowledged in some places (e.g., Mexico City Climate Action Plan), they have received relatively less scholarship attention (Hunt and Watkiss, 2011).

26.8.2. Observed Factors and Processes Associated with Vulnerability

Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific vulnerability factors and processes (Table 26-1; Cutter et al., 2013), some of which are common to many settlements, while others are more pertinent to some types of settlements than others. Human settlements simultaneously face a multi-level array of non-climate-related hazards (e.g., economic, industrial, technological) that contribute to climate change vulnerability (McGranahan et al., 2007; Satterthwaite et al., 2007; Romero-Lankao and Dodman, 2011). In the following subsections we highlight key sources of vulnerability for urban and rural systems.

26.8.2.1. Urban Settlements

Hazard risks in urban settlements are enhanced by the *concentration* of populations, economic activities, cultural amenities, and built environments particularly when they are in highly exposed locations such as coastal and arid areas. Cities of concern include those in the Canadian prairies and USA-Mexico border region; and major urban areas including Boston, New York, Chicago, Washington DC, Los Angeles, Villa Hermosa, Mexico City, and Hermosillo (Bin et al., 2007; Collins, 2008; Kirshen et al., 2008; Collins and Bolin, 2009; Galindo et al., 2009; Gallivan et al., 2009; Hayhoe et al., 2010; Romero-Lankao, 2010; Rosenzweig et al., 2010; Wittrock et al., 2011).

Risks may also be heightened by *multiple interacting hazards*. Slow-onset events such as urban heat islands, for instance, interact with poor air quality in large North American cities to exacerbate climate impacts on human health (Romero-Lankao et al., 2013a). As illustrated by recent weather events (Figure 26-2), however, hazard interactions can also follow individual, high-magnitude extreme events of short duration, with cascading effects across interconnected energy, transportation, water, and health infrastructures and services to contribute to and compound urban vulnerability (Gasper et al., 2011). Wildfire vulnerability in the southwest has been compounded by peri-urban growth (Collins and Bolin, 2009; Brenkert-Smith, 2010). Under current financial constraints in many cities, climate-related economic losses can reduce resources available to address social issues, thus threatening institutional capacity and urban livelihoods (Kundzewicz et al., 2008).

The *urbanization process* and *urban built-environments* of North America can amplify climate impacts as they change land use and land surface physical characteristics (e.g., surface albedo; Chen, F. et al., 2011). A 34% increase in US urban land development (Alig et al., 2004) between

1982 and 1997 had implications for water supplies and extreme event impacts. Effects on water are of special concern (Section 26.3), as urbanization can enhance or reduce precipitation, depending on climate regime; geographical location; and regional patterns of land, energy, and water use (Cuo et al., 2009). Urbanization also has significant impacts on flood climatology through atmospheric processes tied to the urban heat island (UHI), the urban canopy layer (UCL), and the aerosol composition of airsheds (Ntelekos et al., 2010). The UHI can also increase health risks differentially, due to socio-spatial inequalities across and within North American cities (Harlan et al., 2008; Miao et al., 2011).

Urbanization imposes path dependencies that can amplify or attenuate vulnerability (Romero-Lankao and Qin, 2011). The overexploitation of Mexico City's aquifer by 19.1 to 22.2 $m^3 s^{-1}$, for example, has reduced groundwater levels and caused subsidence, undermining building foundations and infrastructure and increasing residents' vulnerability to earthquakes and heavy rains (Romero-Lankao, 2010).

Elements of the *built-environment* such as housing stock, urban form, the condition of water and power infrastructures, and changes in urban and ecological services also affect vulnerability. Large, impermeable surfaces and buildings disrupt drainage channels and accelerate runoff (Walsh et al., 2005). Damage from floods can be much more catastrophic if drainage or waste collection systems are inadequate to accommodate peak flows (Richardson, 2010; Sosa-Rodriguez, 2010). While many Canadian and US cities are in need of infrastructure adaptation upgrades (Doyle et al., 2008; Conrad, 2010), Mexican cites are faced with existing infrastructure deficits (Niven et al., 2010; Hardoy and Romero-Lankao, 2011), and high levels of socio-spatial segregation (Smolka and Larangeira, 2008; see also Section 26.7).

Recent weather hazards (Figure 26-2) illustrate that economic activities and highly valued physical capital of cities (real estate, interconnected infrastructure systems) are very sensitive to climate-related disruptions that can result in high impacts; activities in some urban areas are particularly exposed to key resource constraints (e.g., water in the USA-Mexico border; oil industry in Canada, USA, and Mexico; Conrad, 2010; Levy et al., 2010); others are dependent upon climate-sensitive sectors (e.g., tourism; Lal et al., 2011). Disruptions to production, services, and livelihoods, and changes in the costs of raw materials, also impact the economic performance of cities (Hunt and Watkiss, 2011).

Cities are relatively better endowed than rural populations with individual and neighborhood assets such as income, education, quality of housing, and access to infrastructure and services that offer protection from climate hazards. However, intra-urban socio-spatial differences in access to these assets shape response capacities (Harlan and Ruddell, 2011; Romero-Lankao et al., 2013a). All this means that class and socio-spatial segregation are key determinants not only of vulnerability but also of inequalities in risk generation and distribution within cities. Economic elites are better positioned to access the best land and enjoy the rewards of environmental amenities such as clean air, safe drinking water, open space, and tree shade (Morello-Frosch et al., 2002; Harlan et al., 2006, 2008; Ruddell et al., 2011). Although wealthy sectors are moving into risk prone coastal and forested areas (Collins, 2008), and certain hazards (air pollution) affect both rich and poor alike (Romero-Lankao et al., 2013a), climate risks tend to be disproportionally borne by the poor or otherwise marginalized populations (Cutter et al., 2008; Collins and Bolin, 2009; Romero-Lankao, 2010; Wittrock et al., 2011). In some cities, marginalized populations are moving to peri-urban areas with inadequate services, a portfolio of precarious livelihood mechanisms, and inappropriate risk-management institutions (Collins and Bolin, 2009; Eakin et al., 2010; Monkkonen, 2011; Romero-Lankao et al., 2012a).

Although cities have comparatively higher access than rural municipalities to determinants of institutional capacity such as human resources and revenue pools, their governance arrangements are often hampered by jurisdictional conflicts, asymmetries in information and communication access, fiscal constraints on public services including emergency personnel, and top-down decision making. These governance issues exacerbate urban vulnerabilities and constrain urban adaptation planning (Carmin et al., 2012; Romero-Lankao et al., 2013a).

26.8.2.2. Rural Settlements

The legacy of previous and current stressors in North American rural communities, including rapid population growth or loss, reduced employment, and degradation of local knowledge systems, can increase vulnerability (Brklacich et al., 2008; Coles and Scott, 2009; McLeman, 2010). North American rural communities have a higher proportion of lower income and unemployed populations and higher poverty than cities (Whitener and Parker, 2007; Lal et al., 2011; Skoufias et al., 2011). 55% of Mexico's rural residents live in poverty, and the livelihood of 72% of these is in farming (Saldaña-Zorrilla, 2008). US and Canadian rural communities have older populations (McLeman, 2010) and lower education levels (Lal et al., 2011). Indigenous communities have lower education levels and high levels of poverty, but are younger than average populations (Downing and Cuerrier, 2011). The legacy of their colonial history, furthermore, has stripped Indigenous communities of land and many sources of social and human capital (Brklacich et al., 2008; Hardess et al., 2011). Conversely, rural and Indigenous community members possess valuable local and experiential knowledge regarding regional ecosystem services (Galloway McLean et al., 2011).

Rural economies have limited economic diversity and relatively high dependence on climate-sensitive sectors (Johnston et al., 2008; Lemmen et al., 2008; Molnar, 2010); they are sensitive to climate-induced reductions in resource supply and productivity, in addition to direct exposure to climate hazards (Daw et al., 2009). Single-sector economic dependence contributes significantly to vulnerability (Cutter et al., 2003). Engagement in export markets presents opportunity but also exposure to economic volatility (Eakin, 2006; Saldaña-Zorilla and Sandberg, 2009), and economic downturns take attention away from climate change adaptation. Farming and fishing provide both economic and food security, the impacts of climate thus posing a double threat to livelihood (Badjek et al., 2010), particularly among women (Bee et al., 2013). Inter-related factors affecting vulnerability in forestry and fishing communities include over-harvesting and the cumulative environmental effects of multiple land use activities (Brklacich et al., 2008).

Many tourism-based communities are dominated by seasonal economies and low-wage, service-based employment (Tufts, 2010), and small businesses that lack resources for emergency planning (Hystad and

Keller, 2006, 2008). Non-renewable resource industries are sensitive to power, water, and transportation disruptions associated with hazards.

Geographic isolation can be a key source of vulnerability for rural communities in North America, imposing long commutes to essential services like hospitals and non-redundant transportation corridors that can be compromised during extreme events (Chouinard et al., 2008). Many Indigenous communities are isolated, raising the costs and limiting the diversity of imported food, fuel, and other supplies, rendering the ability to engage in subsistence harvesting especially critical for both cultural and livelihood well-being (Andrachuk and Pearce, 2010; Hardess et al., 2011). Many Indigenous peoples also maintain strong cultural attachment to ancestral lands, and thus are especially sensitive to declines in the ability of that land to sustain their livelihoods and cultural well-being (Downing and Cuerrier, 2011).

Rural physical infrastructure is often inadequate to meet service needs or is in poor condition (McLeman and Gilbert, 2008; Krishnamurthy et al., 2011), especially for Indigenous communities (Brklacich et al., 2008; Hardess et al., 2011; Lal et al., 2011; see also Section 26.9). A lack of redundant power and communication services can compromise hazard response capacity.

26.8.3. Projected Climate Risks on Urban and Rural Settlements

Urbanization, migration, economic disparity, and institutional capacity will influence future impacts and adaptation to climate change in North American human settlements (Section 26.2.1). Water-related concerns are assessed in Sections 26.3.2.1, 26.3.2.3). We describe below a variety of future climate risks identified in the literature, many of which focus on cities (Chapters 8, 9) and, with the exception of larger centers such as New York and Boston, are qualitative in nature (Hunt and Watkiss, 2011). This is due in part to the difficulty in downscaling the shifts in key trends in climate parameters to an appropriate scale.

Model-based SLR projections of future risks to cities are characterized by large uncertainties due to global factors (e.g., the dynamics of polar ice sheets) and regional factors (e.g., regional shifts in ocean circulation, high of the adjacent ocean and local land elevation; Blake et al., 2011; see WGI AR5 Chapter 3). The latter will determine differential SLR impacts on regional land development of coastal settlements (GAO, 2007; Yin et al., 2009; Conrad, 2010; Millerd, 2011; Biasutti et al., 2012), making some areas particularly vulnerable to inundation (Cooper and Sehlke, 2012). SLR can also exacerbate vulnerability to extreme events such as hurricanes (Frazier et al., 2010).

Temperature increases would lead to additional health hazards. Baseline warmer temperatures in cities are expected to be further elevated by extreme heat events whose intensity and frequency is projected to increase during the 21st century (Section 26.2.2), particularly in northern mid-latitude cities (Jacob and Winner, 2009).

Participation in some outdoor activities would increase as a result of projected increases in warm days (Scott and McBoyle, 2007). Projected snowfall declines in Canada and the northeastern USA would reduce length of winter sport seasons and thus affect the economic well-being of some communities (McBoyle et al., 2007; Scott et al., 2008b).

Any increase in frequency of extreme events, such as intense precipitation, flooding, and prolonged dry periods, would affect particularly the populations, economic activities, infrastructures, and services on coasts, flood-prone deltas, and arid regions (Kirshen et al., 2008; Nicholls et al., 2008; Richardson, 2010; Weiss et al., 2011). For example, by the end of this century, New York City is projected to experience nearly twice as many extreme precipitation days compared to today (A2, mean ensemble of 17 models). Ntelekos et al. (2010) and Cayan et al. (2010) project an increase in the number and duration of droughts in the southwestern USA, with most droughts expected to last more than 5 years by 2050 (GDFL CM2.1 and National Centre for Meteorological Research (CNRM) CM3, A2 and B1). Assuming no adaptation, total losses from river flooding in metropolitan Boston are estimated to exceed US$57 billion by 2100, of which US$26 billion is attributed to climate change (Kirshen et al., 2008; Nicholls et al., 2008; Richardson, 2010; Weiss et al., 2011).

Future climate risks on lives and livelihoods have been relatively less studied. A handful of studies focused on forestry are notable, indicating potentially substantial shifts in livelihood options without adaptation. Sohngen and Sedjo (2005) estimate losses from climate change in the Canadian/US timber sector of US$1.4 to US$2.1 billion per year over the next century. Anticipated future supply reductions in British Columbia as a consequence of the pine beetle outbreak vary from 10 to 62% (Patriquin et al., 2007). Substantial declines in suitable habitat for valued tree species in Mexico have been projected (Gómez-Mendoza and Arriaga, 2007; Gómez Diaz et al., 2011).

Scholars are starting to project future risks from interacting hazards. For instance, by 2070 with a 0.5 m rise in sea level and under scenarios of socioeconomic growth, storm surges, and subsidence, populations at risk in New York, Miami, and New Orleans might increase three-fold, while asset exposure will increase more than 10-fold (Hanson et al., 2011).

Essential *infrastructure and services* are key concerns (Sections 26.3, 26.7). Increased occurrence of drought affecting water availability is projected for southwestern USA/northern Mexico, the southern Canadian Prairies and central Mexico, combined with projected increases in water demand due to rapid population growth and agriculture (Schindler and Donahue, 2006; MacDonald, 2010; Lal et al., 2011). Using A1B and A2 scenarios, Escolero-Fuentes et al. (2009) projected that, by 2050, Mexico City and its watersheds will experience a more intense hydrological cycle and a reduction of between 10 to 17% in per capita available water. SLR is predicted to threaten water and electricity infrastructure with inundation and increasing salinity (Sharp, 2010).

26.8.4. Adaptation

26.8.4.1. Evidence of Adaptation

26.8.4.1.1. What are populations doing? Autonomous adaptation

As illustrated by recent extreme events (Figure 26-2), individuals and households in North America not only have been affected by extremes, but have also been responding to climate impacts mostly through incremental actions, for example, by purchasing additional insurance or reinforcing homes to withstand extreme weather (Simmons and Sutter, 2007; Romero-Lankao et al., 2012a). Some individuals respond by diversifying livelihoods (Newland et al., 2008; Rose and Shaw, 2008) or migrating (see Section 26.1.1; Black et al., 2011).

The propensity to respond to climate and weather hazards is strongly influenced not only by access to household assets, but also by community and governmental support. The emergency response to Hurricane Sandy illustrates this. Although New York and New Jersey witnessed vivid scenes of "medical humanitarianism," because of inadequate communication and coordination among agencies, public health support did not always reach those most in need (Abramson and Redlener, 2013).

The perceived risks of climate change among individuals are equally important. Strong attachment to place and occupation may motivate willingness to support incremental adaptation, enhance coping capacity, and foster adaptive learning (Collins and Bolin, 2009; Romero-Lankao, 2010; Aguilar and Santos, 2011; Wittrock et al., 2011). They have also been found to serve as barriers to transformational adaptation (Marshall et al., 2012). Residents of the USA stand out in international research as holding lower levels of perceived risk of climate change (AXA Group and Ipsos Research, 2012), which may limit involvement in household-level adaptation or support for public investments in adaptation.

26.8.4.1.2. What are governments doing? Planned adaptation

Leadership in adaptation is far more evident locally than at other tiers of government in North America (Richardson, 2010; Vasseur, 2011; Vrolijks et al., 2011; Carmin et al., 2012; Henstra, 2012). Few municipalities have moved into the implementation stage, however; most programs are in the process of problem diagnosis and planning (Perkins et al., 2007; Moser and Satterthwaite, 2008; Romero-Lankao and Dodman, 2011). Systematic assessments of vulnerability are rare, particularly in relation to population groups (Vrolijks et al., 2011). Surveys of municipal leaders showed adaptation is rarely incorporated into planning, due to lack of resources, information, and expertise (Horton and Richardson, 2011), and the prevalence of other issues considered higher priority, suggesting the need for subnational and federal-level facilitation in the form of resources and enabling regulations.

Climate change policies have been motivated by concerns for local economic or energy security and the desire to play leadership roles (Rosenzweig et al., 2010; Anguelovski and Carmin, 2011; Romero-Lankao et al., 2013a). Some policies constitute "integrated" strategies (New York; Perkins et al., 2007; Rosenzweig et al., 2010), and coordinated participation of multiple municipalities (Vancouver; Richardson, 2010). Sector-specific climate risk management plans have also emerged (e.g., water conservation in Phoenix, USA and Regina, Canada; wildfire protection in Kamloops, Canada and Boulder, USA). Municipalities affected by the mountain pine beetle have taken many steps toward adaptation (Parkins, 2008), and coastal communities in eastern Canada are investing in saltwater marsh restoration to adapt to rising sea levels (Marlin et al., 2007). Green roofs, forest thinning, and urban agriculture have all been expanding (Chicago, New York, Kamloops, Mexico City), as have flood protection (New Orleans, Chicago), private and governmental insurance policies (Browne and Hoyt, 2000; Ntelekos et al., 2010; see also Section 26.10), saving schemes (common in Mexico), air pollution controls (Mexico City), and hazard warning systems (Collins and Bolin, 2009; Coffee et al., 2010; Romero-Lankao, 2010; Aguilar and Santos, 2011).

26.8.4.2. Opportunities and Constraints

Adaptation in human settlements is influenced by local access to resources, political will, and the capacity for institutional-level attention and multi-level/sectoral coordination (Burch, 2010; Romero-Lankao et al., 2013a).

26.8.4.2.1. Adaptation is path-dependent

Adaptation options are constrained by past settlement patterns and decisions. The evolution of cities as economic hubs, for example, affects vulnerability and resilience (Leichenko, 2011). Urban expansion into mountain, agricultural, protected, and otherwise risk-prone areas (Boruff et al., 2005; McGranahan et al., 2007; Collins and Bolin, 2009; Conrad, 2010) invariably alters regional environments. Development histories foreclose some resilience pathways. Previous water development, for example, can result in irreversible over-exploitation and degradation of water resources.

26.8.4.2.2. Institutional capacity

At all levels of governance, adaptation in North America is affected by numerous determinants of institutional capacity. Three have emerged in the literature as particularly significant challenges for urban and rural settlements:

- *Economic resources*: Rural communities face limited revenues combined with higher costs of supplying services (Williamson et al., 2008; Posey, 2009). Small municipal revenue pools translate into fiscal constraints necessary to support public services, including emergency personnel and health care (Lal et al., 2011). Although large cities tend to have greater fiscal capacity, most do not receive financial support for adaptation (Carmin et al., 2012), yet face the risk of higher economic losses.
- *Information and social capital*: Differences in access and use of information, and capacity for learning and innovation, affect adaptive capacity (Romero-Lankao et al., 2013a). Levels of knowledge and prioritization can be low among municipal planners. Information access can be limited, even among environmental planners (Picketts et al., 2012). The relationship between trust and participation in support networks (social capital) and adaptive capacity is generally positive; however, strong social bonds may support narratives that underestimate climate risk (Wolf et al., 2010; Romero-Lankao et al., 2012b).
- *Participation*: Considering the overlap among impacts and sources of vulnerability in North American human settlements, long-term effectiveness of local adaptation hinges on inclusion of all stakeholders. Stakeholder involvement lengthens planning time frames, may elicit conflicts, and power relationships can constrain

Box 26-3 | Climate Responses in Three North American Cities

With populations of 20.5, 14, and 2.3 million people, respectively, the metropolitan areas of Mexico City, New York, and Vancouver are facing multiple risks that climate change is projected to aggravate. These risks range from sea level rise, coastal flooding, and storm surges in New York and Vancouver to heat waves, heavy rains and associated flooding, air pollution, and heat island effects in all three cities (Leon and Neri, 2010; Rosenzweig and Solecki, 2010; City of Vancouver, 2012). Many of these risks result not only from long-term global and regional processes of environmental change, but also from local changes in land and water uses and in atmospheric emissions induced by urbanization (Leon and Neri, 2010; Romero-Lankao, 2010; Kinney et al., 2011; Solecki, 2012).

The three cities have been frontrunners in the climate arena. In Mexico City, the Program of Climate Action 2008–2012 (PAC) and the 2011 Law for Mitigation and Adaptation to Climate Change are parts of a larger 15-year "Green Agenda," with most of designated funds committed to reducing 7 million tonnes of CO_2-equivalent by 2012 (Romero-Lankao et al., 2013). New York City and Vancouver's plans are similarly mitigation centered. As of 2007 New York's long-term sustainability plan included adaptation (Solecki, 2012; Ray et al., 2013), while Vancouver launched its municipal adaptation plan in July 2012. The shifts in focus from mitigation to adaptation have followed as it has become increasingly clear that even if mitigation efforts are wholly successful, some adverse impacts due to climate change are unavoidable.

Urban leaders in all three cities have emerged as global leaders in sustainability. Mayor Bloomberg of New York, Mayor Ebrard of Mexico City, and David Cadman of Vancouver have, respectively, led the C40, World Mayors Council on Climate Change, and International Council for Local Environmental Initiatives (ICLEI). Scientists, private sector actors, and non-governmental organizations have been of no lesser importance. To take advantage of a broad-based interaction between various climate change actors, Mexico City has set up a Virtual Climate Change Center to serve as a repository of knowledge, models, and data on climate change impacts, vulnerability, and risks (Romero-Lankao et al., 2013a). Information sharing by climate change actors has also taken place in New York, where scientists and insurance and risk management experts have served on the Panel on Climate Change to advise the city on the science of climate change impacts and "protection levels specific to the city's critical infrastructure" (Solecki, 2012, p. 564).

The climate plans of the three cities are far reaching, including mitigation and adaptation strategies related to their sustainability goals. The three cities emphasize different priorities in their climate action plans. Mexico City seeks to reduce water consumption and transportation emissions through such actions as improvements in infrastructure and changes in the share of public transport. Vancouver has prioritized the separation of sanitary and storm water systems, yet this adaptation is not expected to be complete until 2050 (City of Vancouver, 2012). It will also take New York much time, money, and energy to expand adaptation strategies beyond the protection of water systems to include all essential city infrastructure (Ray et al., 2013). Overall, few proposed actions will result in immediate effects, and instead call for additional planning, highlighting the significant effort necessary for comprehensive responses. Overall, adaptation planning in the three cities faces many challenges. In all three regions, multi-jurisdictional governance structures with differing approaches to climate change challenge the ability for coordinated responses (Solecki, 2012; Romero-Lankao et al., 2013a). Conflicts in priorities and objectives between various actors and sectors are also prevalent (Burch, 2010). For instance, authorities in Mexico City concerned with avoiding growth into risk-prone and conservation areas (Aguilar and Santos, 2011) compete for regulatory space within a policy agenda that is already coping with a wide range of economic and developmental imperatives (Romero-Lankao et al., 2013a).

Climate responses require new types of localized scientific information, such as vulnerability analyses and flood risk assessments, which are not always available (Romero-Lankao et al., 2012a; Ray et al., 2013). Little is known, for instance, about how to predict and respond to common and differential levels of risk experienced by different human settlements. Comprehensive planning is still limited as well. For example, although scholarship exists on disparities in household- and population-level vulnerability and adaptive capacity (Cutter et al., 2003; Villeneuve and Burnett, 2003; Douglas et al., 2012; Romero-Lankao et al., 2013b), equity concerns have received relatively less attention by the three cities. Even when local needs are identified, such as the need to protect higher risk homeless and low-income populations (Vancouver), they are often not addressed in action plans.

access (Few et al., 2007; Colten et al., 2008). However, effective stakeholder engagement has tremendously enhanced adaptation planning, eliciting key sources of information regarding social values, securing legitimacy (Aguilar and Santos, 2011), and fostering adaptive capacity of involved stakeholders.

26.9. Federal and Subnational Level Adaptation

Along with many local governments (Section 26.8.4), federal, and subnational tiers of government across North America are developing climate change adaptation plans. These initiatives, which began at the subnational levels (e.g., Nunavut Department of Sustainable Development, 2003), appear to be preliminary and relatively little has been done to implement specific measures.

26.9.1. Federal Level Adaptation

All three national governments are addressing adaptation to some extent, with a national strategy and a policy framework (Mexico), a federal policy framework (Canada), and the USA having delegated all federal agencies to develop adaptation plans.

In 2005, the Mexican government created the Inter-Secretarial Commission to Climate Change (Comisión Inter-Secretarial de Cambio Climático (CICC)) to coordinate national public policy on climate change (CICC, 2005; Sosa-Rodriguez, 2013). The government's initiatives are being delivered through the *National Strategy for Climate Change 2007–2012* (Intersecretarial Commission on Climate Change, 2007) and, the *Special Programme on Climate Change 2009–2012*, which identify priorities in research, cross-sectoral action such as developing early warning systems, and capacity development to support mitigation and adaptation actions (CICC, 2009). The *Policy Framework for Medium Term Adaptation* (CICC, 2010) aims at framing a single national public policy approach on adaptation with a time horizon up to 2030. The General Law of Climate Change requires state governments to implement mitigation and adaptation actions (Diario Oficial de la Federación, 2012).

Canada is creating a Federal Adaptation Policy Framework intended to mainstream climate risks and impacts into programs and activities to help frame government priorities (Government of Canada, 2011). In 2007, the federal Government made a 4-year adaptation commitment to develop six Regional Adaptation Collaboratives (RAC) in provinces across Canada, ranging in size and scope, from flood protection and drought planning, to extreme weather risk management; and assessing the vulnerability of Nunavut's mining sector to climate change (Natural Resources Canada, 2011). In 2011, the federal government renewed financial support for several adaptation programs and provided new funding to create a Climate Adaptation and Resilience Program for Aboriginals and Northerners, and Enhancing Competitiveness in a Changing Climate program (Environment Canada, 2011). Canada recently launched an Adaptation Platform to advance adaptation priorities across the country (Natural Resources Canada, 2013).

The US government embarked in 2009 on a government-wide effort to have all federal agencies address adaptation; to apply understanding of climate change to agency missions and operations; to develop, prioritize, and implement actions; and to evaluate adaptations and learn from experience (The White House, 2009; Bierbaum et al., 2012). A 2013 plan issued by the president enhanced the US government effort supporting adaptation (Executive Office of the President, 2013). The US government provides technical and information support for adaptation by non-federal actors, but does not provide direct financial support for adaptation (Parris et al., 2010).

Some federal agencies took steps to address climate change adaptation prior to this broader interagency effort. In 2010, the US Department of Interior created Climate Science Centers to integrate climate change information and management strategies in eight regions and 21 Landscape Conservation Cooperatives (Secretary of the Interior, 2010), while the US Environmental Protection Agency's Office of Water developed a climate change strategy (EPA, 2011).

26.9.2. Subnational Level Adaptation

A number of states and provinces in all three countries have developed adaptation plans. For example, in Canada, Quebec's 2013–2020 adaptation strategy outlines 17 objections covering a number of managed sectors and ecosystems (Government of Quebec, 2012). British Columbia is modernizing its Water Act to alter water allocation during drought to reduce agricultural crop and livestock loss and community conflict, while protecting aquatic ecosystems (BC Ministry of the Environment, 2010).

In the USA, California was the first state to publish an adaptation plan calling for a 20% reduction in per capita water use by 2020 (California Natural Resources Agency, 2009). Maryland first developed a plan on coastal resources and then broadened it to cover human health, agriculture, ecosystems, water resources, and infrastructure (Maryland Commission on Climate Change, 2008, 2010). The State of Washington is addressing environment, infrastructure, and communities; human health and security; ecosystems, species, and habitat; and natural resources (Built Environment: Infrastructure & Communities Topic Advisory Group, 2011; Human Health and Security Topic Advisory Group, 2011; Natural Resources Working Lands and Waters Topic Advisory Group, 2011; Species, Habitats and Ecosystems Topic Advisory Group, 2011).

Of the three national governments, only Mexico requires that states develop adaptation plans. In Mexico, seven of 31 states—Veracruz, Mexico City, Nuevo León, Guanajuato, Puebla, Tabasco, and Chiapas—have developed their *State Programmes for Climate Change Action* (Programas Estatales de Acción ante el Cambio Climático (PEACC)), while Baja California Sur, Hidalgo, and Campeche are in the final stage and 17 states are still in the planning and development stage (Instituto de Ecología del Estado de Guanajuato, 2011). The proposed adaptation actions focus mainly on: (1) reducing physical and social vulnerability of key sectors and populations; (2) conservation and sustainable management of ecosystems, biodiversity, and ecosystem services; (3) developing risk management strategies; (4) strengthening water management; (5) protecting human health; and (6) improving current urban development strategies, focusing on settlements and services, transport, and land use planning.

26.9.3. Barriers to Adaptation

Chapter 16 provides a more in-depth discussion on adaptation barriers and limits. Adaptation plans tend to exist as distinct documents and are often not integrated into other planning activities (Preston et al., 2011). Most adaptation activities have only involved planning for climate change rather than specific actions, and few measures have been implemented (Preston et al., 2011; Bierbaum et al., 2012).

Even though Canada and the USA are relatively well endowed in their capacity to adapt, there are significant constraints on adaptation, with financing being a significant constraint in all three countries (Carmin et al., 2012). Barriers include legal constraints (e.g., Jantarasami et al., 2010), lack of coordination across different jurisdictions (Smith et al., 2009; NRC, 2010; INECC and SEMARNAT, 2012b), leadership (Smith et al., 2009; Moser and Ekstrom, 2010), and divergent perceptions about climate change (Bierbaum et al., 2012; Moser, 2013). Although obtaining accurate scientific data was ranked less important by municipalities (Carmin et al., 2012), an important constraint is lack of access to scientific information and capacity to manage and use it (Moser and Ekstrom, 2010; INECC and SEMARNAT, 2012b). Adaptation activities in developed countries such as the USA tend to address hazards and propose adaptations that tend to protect current activities rather than facilitate long-term change. In addition, the adaptation plans generally do not attempt to increase adaptive capacity (Eakin and Patt, 2011). However, making changes to institutions needed to enable or promote adaptations can be costly (Marshall, 2013).

Although multi-level and multi-sectoral coordination is a key component of effective adaptation, it is constrained by factors such as mismatch between climate and development goals, political rivalry, and lack of national support to regional and local efforts (Brklacich et al., 2008; Brown, 2009; Sander-Regier et al., 2009; Sydneysmith et al., 2010; Craft and Howlett, 2013; Romero-Lankao et al., 2013a). Traditionally, environmental or engineering agencies are responsible for climate issues (e.g., Mexico City, Edmonton and London, Canada), but have neither the decision-making power nor the resources to address all dimensions involved. Adaptation planning requires long-term investments by government, business, grassroots organizations, and individuals (e.g., Romero-Lankao, 2007; Burch, 2010; Croci et al., 2010; Richardson, 2010).

26.9.4. Maladaptation, Trade-Offs, and Co-Benefits

Adaptation strategies may introduce trade-offs or maladaptive effects for policy goals in mitigation, industrial development, energy security, and health (Hamin and Gurran, 2009; Laukkonen et al., 2009). Snow-making equipment, for example, mediates snowpack reductions, but has high water and energy requirements (Scott et al., 2007). Irrigation and air conditioning have immediate adaptive benefits for North American settlements, but are energy-consumptive. Sea walls protect coastal properties, yet negatively affect coastal processes and ecosystems (Richardson, 2010).

Conventional sectoral approaches to risk management and adaptation planning undertaken at different temporal and spatial scales have exacerbated vulnerability in some cases, for example, peri-urban areas in Mexico (Eakin et al., 2010; Romero-Lankao, 2012). Approaches that delegate response planning to residents in the absence of effective knowledge exchange have resulted in maladaptive effects (Friesinger and Bernatchez, 2010).

Other strategies offer synergies and co-benefits. Policies addressing air pollution (Harlan and Ruddell, 2011) or housing for the poor, particularly in Mexico (Colten et al., 2008), can often be adapted at low or no cost to fulfill adaptation and sustainability goals (Badjek et al., 2010). Efforts to temper declines in production or competitiveness in rural communities could involve mitigation innovations, including carbon sequestration forest plantations (Holmes, 2010). Painting roofs white reduces the effects of heat and lowers energy demand for cooling (Akbari et al., 2009).

Adaptation planning can be greatly enhanced by incorporating regionally or locally specific vulnerability information (Clark et al., 1998; Barsugli et al., 2012; Romsdahl et al., 2013). Methods for mapping vulnerability have been improved and effectively utilized (Romero-Lankao et al., 2013b). Similarly, strategies supporting cultural preservation and subsistence livelihood needs among Indigenous peoples would enhance adaptation (Ford et al., 2010b), as would integrating traditional culture with other forms of knowledge, technologies, education, and economic development (Hardess et al., 2011).

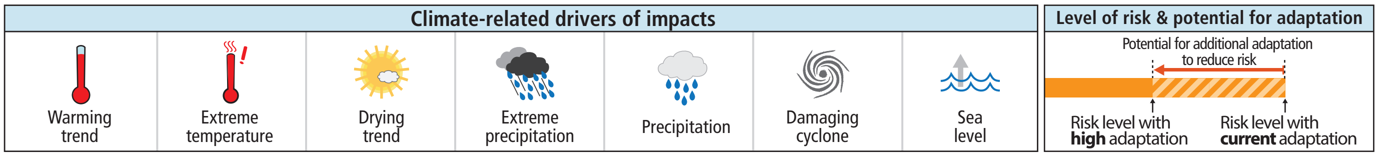
26.10. Key Risks, Uncertainties, Knowledge Gaps, and Research Needs

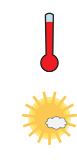
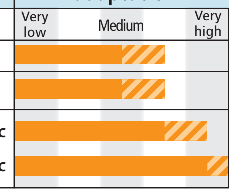
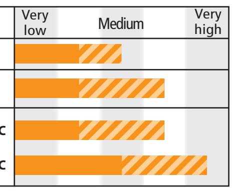
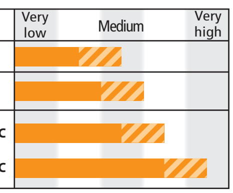
26.10.1. Key Multi-sectoral Risks

We close this chapter with our assessment of key current and future regional risks from climate change with an evaluation of the potential for risk reduction through adaptation (Table 26-1). Two of the three examples, wildfires and urban floods, illustrate that multiple climate drivers can result in multiple impacts (e.g., loss of ecosystems integrity, property damage, and health impacts due to wildfires and urban floods). The three risks evaluated in Table 26-1 also show that relative risks depend on the context-specific articulation and dynamics of such factors as the following:

- The magnitude and rate of change of relevant climatic and non-climatic drivers and hazards. For instance, the risk of urban floods depends not only on global climatic conditions (current vs. future global mean temperatures of 2°C and 4°C), but also on urbanization, a regional source of hazard risk that can enhance or reduce precipitation, as it affects the hydrologic cycle and, hence, has impacts on flood climatology (Section 26.8.2.1).
- The internal properties and dynamics of the system being stressed. For example, some ecosystems are more fire adapted than others. Some populations are more vulnerable to heat stress because of age, preexisting medical conditions, working conditions and lifestyles (e.g., outdoor workers, athletes).
- Adaptation potentials and limits. For example, while residential air conditioning can effectively reduce health risk, availability and usage is often limited among the most vulnerable individuals. Furthermore, air conditioning is sensitive to power failures and its use has mitigation implications.

Table 26-1 | Key risks from climate change and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of this chapter, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Wildfire-induced loss of ecosystem integrity, property loss, human morbidity, and mortality as a result of increased drying trend and temperature trend (*high confidence*) [26.4, 26.8, Box 26-2]	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity. • Agroforestry can be an effective strategy for reduction of slash and burn practices in Mexico.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Heat-related human mortality (*high confidence*) [26.6, 26.8]	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is highly variable and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, early heat warning systems, cooling centers, greening, and high-albedo surfaces.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	
Urban floods in riverine and coastal areas, inducing property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment, due to sea level rise, extreme precipitation, and cyclones (*high confidence*) [26.2-4, 26.8]	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions. • Conservation of wetlands, including mangroves, and land-use planning strategies can reduce the intensity of flood events.		Present Near term (2030–2040) Long term (2080–2100) 2°C 4°C	

The judgments about risk conveyed by the Table 26-1 are based on assessment of the literature and expert judgment by chapter authors living under current socioeconomic conditions. Therefore, risk levels are estimated for each time frame, assuming a continuation of current adaptation potentials and constraints. Yet over the course of the 21st century, socioeconomic and physical conditions can change considerably for many sectors, systems, and places. The dynamics of wealth generation and distribution, technological innovations, institutions, and even culture can substantially affect North American levels of risk tolerance within the social and ecological systems considered (see also Box TS.8).

26.10.2. Uncertainties, Knowledge Gaps, and Research Needs

The literature on climate impacts, adaptation, and vulnerability in North America has grown considerably, as has the diversity of sectors and topics covered (e.g., urban and rural settlements; food security; and adaptation at local, state, and national levels). However, limitations in the topical and geographical scope of this literature are still a challenge (e.g., more studies have focused on insurance than on economic sectors such as industries, construction, and transportation). It is also challenging to summarize results across many studies and identify trends in the literature when there are differences in methodology, theoretical frameworks, and causation narratives (e.g., between outcome and contextual approaches), making it hard to compare "apples to oranges" (Romero-Lankao et al., 2012b). While the USA and Canada have produced large volumes of literature, Mexico lags well behind. It was, therefore, difficult to devote equal space to observed and projected impacts, vulnerabilities, and adaptations in Mexico in comparison with its northern neighbors. With its large land area, population, and important, albeit under-studied, climate change risks and vulnerabilities, more climate change research focusing on Mexico is direly needed.

The literature on North America tends to be dominated by sector level analyses. Yet, climate change interacts with other physical and social processes to create differential risks and impact levels. These differences are mediated by context-specific physical and social factors shaping the vulnerability of exposed systems and sectors. Furthermore, while studies often focus on isolated sectoral effects, impacts happen in communities, socio-ecologic systems, and regions, and shocks and dislocations in one sector or region often affect other sectors and regions as a result of social and physical interdependencies. This point is illustrated by Boxes 26-1 and 26-2 and the human settlements section, which discuss place-based impacts, vulnerabilities, and adaptations. Unfortunately, literature using placed-based or integrated approaches to these complexities is limited. Indeed, although in early drafts the authors of this chapter attempted to put more emphasis on place-based analysis and comparisons, the literature was inadequate to support such an effort. The IPCC includes chapters on continents and large regions to make it possible to assess

Frequently Asked Questions
FAQ 26.1 | What impact are climate stressors having on North America?

Recent climate changes and extreme events such as floods and droughts depicted in Figure 26-2 demonstrate clear impacts of climate-related stresses in North America (*high confidence*). There has been increased occurrence of severe hot weather events over much of the USA and increases in heavy precipitation over much of North America (*high confidence*). Such events as droughts in northern Mexico and south-central USA, floods in Canada, and hurricanes such as Sandy demonstrate exposure and vulnerability to extreme climate (*high confidence*). Many urban and rural settlements, agricultural production, water supplies, and human health have been observed to be vulnerable to these and other extreme weather events (Figure 26-2). Forest ecosystems have been stressed through wildfire activity, regional drought, high temperatures, and infestations, while aquatic ecosystems are being affected by higher temperatures and sea level rise.

Many decision makers, particularly in the USA and Canada, have the financial, human, and institutional capacity to invest in resilience, yet a trend of rising losses from extremes has been evident across the continent (Figure 26-2), largely due to socioeconomic factors, including a growing population, equity issues, and increased property value in areas of high exposure. In addition, climate change is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low snow years, and shifts toward earlier snowmelt runoff over much of the western USA and Canada (*high confidence*). These changes combined with higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability are projected to lead to increased stresses to water, agriculture, economic activities, and urban and rural settlements (*high confidence*).

Frequently Asked Questions
FAQ 26.2 | Can adaptation reduce the adverse impacts of climate stressors in North America?

Adaptation—including land use planning, investments in infrastructure, emergency management, health programs, and water conservation—has significant capacity to reduce risks from current climate and climate change (Figure 26-3). There is increasing attention to adaptation among planners at all levels of government but particularly at the municipal level, with many jurisdictions engaging in assessment and planning processes. Yet, there are few documented examples of implementation of proactive adaptation and these are largely found in sectors with longer term decision making, including energy and public infrastructure (*high confidence*). Adaptation efforts have revealed the significant challenges and sources of resistance facing planners at both the planning and implementation stages, particularly the adequacy of informational, institutional, financial, and human resources, and lack of political will (*medium confidence*). While there is high capacity to adapt to climate change across much of North America, there are regional and sectoral disparities in economic resources, governance capacity, and access to and ability to utilize information on climate change, which limit adaptive capacity in many regions and among many populations such as the poor and Indigenous communities. For example, there is limited capacity for many species to adapt to climate change, even with human intervention. At lower levels of temperature rise, adaptation has high potential to offset projected declines in yields for many crops, but this effectiveness is expected to be much lower at higher temperatures. The risk that climate stresses will cause profound impacts on ecosystems and society—including the possibility of species extinction or severe adverse socioeconomic shocks—highlights limits to adaptation.

how multiple climate change impacts can affect these large areas. However, this macro view gives insufficient detail on context-specific local impacts and risks, missing the on-the-ground reality that the effects of climate change are and will be experienced at much smaller scales, and those smaller scales are often where meaningful mitigation and adaptation actions can be generated. To give local actors relevant information on which to base these local actions, more research is needed to understand better the local and regional effects of climate change across sectors.

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Central and South America

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Frequently Asked Questions

Executive Summary

Significant trends in precipitation and temperature have been observed in Central America (CA) and South America (SA) (*high confidence*). In addition, changes in climate variability and in extreme events have severely affected the region (*medium confidence*). Increasing trends in annual rainfall in southeastern South America (SESA; 0.6 mm day^{-1} 50 yr^{-1} during 1950–2008) contrast with decreasing trends in CA and central-southern Chile (–1 mm day^{-1} 50 yr^{-1} during 1950–2008). Warming has been detected throughout CA and SA (near 0.7°C to 1°C 40 yr^{-1} since the mid-1970s), except for a cooling off the Chilean coast of about –1 °C 40 yr^{-1}. Increases in temperature extremes have been identified in CA and most of tropical and subtropical SA (*medium confidence*), while more frequent extreme rainfall in SESA has favored the occurrence of landslides and flash floods (*medium confidence*). {27.2.1.1; Table 27-1; Box 27-1}

Climate projections suggest increases in temperature, and increases or decreases in precipitation for CA and SA by 2100 (*medium confidence*). In post-Fourth Assessment Report (AR4) climate projections, derived from dynamic downscaling forced by Coupled Model Intercomparison Project Phase 3 (CMIP3) models for various Special Report on Emission Scenarios (SRES) scenarios, and from different global climate models from the CMIP5 for various Representative Concentration Pathways (RCPs) (4.5 and 8.5), warming varies from +1.6°C to +4.0°C in CA, and +1.7°C to +6.7°C in SA (*medium confidence*). Rainfall changes for CA range between –22 and +7% by 2100, while in SA rainfall varies geographically, most notably showing a reduction of –22% in northeast Brazil, and an increase of +25% in SESA (*low confidence*). By 2100 projections show an increase in dry spells in tropical SA east of the Andes, and in warm days and nights in most of SA (*medium confidence*). {27.2.1.2; Table 27-2}

Changes in streamflow and water availability have been observed and projected to continue in the future in CA and SA, affecting already vulnerable regions (*high confidence*). The Andean cryosphere is retreating, affecting the seasonal distribution of streamflows (*high confidence*). {Table 27-3} Increasing runoffs in the La Plata River basin and decreasing ones in the Central Andes (Chile, Argentina) and in CA in the second half of the 20th century were associated with changes in precipitation (*high confidence*). Risk of water supply shortages will increase owing to precipitation reductions and evapotranspiration increases in semi-arid regions (*high confidence*) {Table 27-4}, thus affecting water supply for cities (*high confidence*) {27.3.1.1, 27.3.5}, hydropower generation (*high confidence*) {27.3.6, 27.6.1}, and agriculture. {27.3.1.1} Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability (*medium confidence*). Ongoing constitutional and legal reforms toward more efficient and effective water resources management and coordination constitute another adaptation strategy (*medium confidence*). {27.3.1.2}

Land use change contributes significantly to environmental degradation, exacerbating the negative impacts of climate change (*high confidence*). Deforestation and land degradation are attributed mainly to increased extensive and intensive agriculture. The agricultural expansion, in some regions associated with increases in precipitation, has affected fragile ecosystems, such as the edges of the Amazon forest and the tropical Andes. Even though deforestation rates in the Amazon have decreased substantially since 2004 to a value of 4,656 km^2 yr^{-1} in 2012, other regions such as the Cerrado still present high levels of deforestation, with average rates as high as 14,179 km^2 yr^{-1} for the period 2002–2008. {27.2.2.1}

Conversion of natural ecosystems is the main cause of biodiversity and ecosystem loss in the region, and is a driver of anthropogenic climate change (*high confidence*). Climate change is expected to increase the rates of species extinction (*medium confidence*). For instance, vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains. In Brazil, distribution of some groups of birds and plants will be dislocated southward, where there are fewer natural habitats remaining. However, CA and SA have still large extensions of natural vegetation cover for which the Amazon is the main example. {27.3.2.1} Ecosystem-based adaptation practices are increasingly common across the region, such as the effective management and establishment of protected areas, conservation agreements, and community management of natural areas. {27.3.2.2}

Socioeconomic conditions have improved since AR4; however, there is still a high and persistent level of poverty in most countries, resulting in high vulnerability and increasing risk to climate variability and change (*high confidence*). Poverty levels in most countries remain high (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade. The Human Development Index varies greatly between countries, from Chile and Argentina with the highest values to Guatemala and Nicaragua with the

lowest values in 2007. The economic inequality translates into inequality in access to water, sanitation, and adequate housing, particularly for the most vulnerable groups, translating into low adaptive capacities to climate change. {27.2.2.2}

Sea level rise (SLR) and human activities on coastal and marine ecosystems pose threats to fish stocks, corals, mangroves, recreation and tourism, and control of diseases (*high confidence*). SLR varied from 2 to 7 mm yr^{-1} between 1950 and 2008. Frequent coral bleaching events associated with ocean warming and acidification occur in the Mesoamerican Coral Reef. In CA and SA, the main drivers of mangrove loss are deforestation and land conversion to agriculture and shrimp ponds. {27.3.3.1} Brazilian fisheries' co-management (a participatory multi-stakeholder process) is an example of adaptation as it favors a balance between conservation of marine biodiversity, the improvement of livelihoods, and the cultural survival of traditional populations. {27.3.3.2}

Changes in agricultural productivity with consequences for food security associated with climate change are expected to exhibit large spatial variability (*medium confidence*). In SESA, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (*medium confidence*; SRES: A2, B2). {Table 27-5} In CA, northeast of Brazil, and parts of the Andean region, increases in temperature and decreases in rainfall could decrease the productivity in the short term (by 2030), threatening the food security of the poorest population (*medium confidence*). {Table 27-5} Considering that SA will be a key food-producing region in the future, one of the challenges will be to increase the food and bioenergy quality and production while maintaining environmental sustainability under climate change. {27.3.4.1} Some adaptation measures include crop, risk, and water use management along with genetic improvement (*high confidence*). {27.3.4.2}

Renewable energy based on biomass has a potential impact on land use change and deforestation and could be affected by climate change (*medium confidence*). Sugarcane and soy are likely to respond positively to CO_2 and temperature changes, even with a decrease in water availability, with an increase in productivity and production (*high confidence*). The expansion of sugarcane, soy, and oil palm may have some effect on land use, leading to deforestation in parts of the Amazon and CA, among other regions, and loss of employment in some countries (*medium confidence*). {27.3.6.1} Advances in second-generation bioethanol from sugarcane and other feedstocks will be important as a measure of mitigation. {27.3.6.2}

Changes in weather and climatic patterns are negatively affecting human health in CA and SA, by increasing morbidity, mortality, and disabilities (*high confidence*), and through the emergence of diseases in previously non-endemic areas (*high confidence*). With *very high confidence,* climate-related drivers are associated with respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), hantaviruses and rotaviruses, chronic kidney diseases, and psychological trauma. Air pollution is associated with pregnancy-related outcomes and diabetes, among others. {27.3.7.1} Vulnerabilities vary with geography, age, gender, race, ethnicity, and socioeconomic status, and are rising in large cities (*very high confidence*). {27.3.7.2} Climate change will exacerbate current and future risks to health, given the region's population growth rates and vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, pollution, and food production in poor regions (*medium confidence*).

In many CA and SA countries, a first step toward adaptation to future climate changes is to reduce the vulnerability to present climate. Long-term planning and the related human and financial resource needs may be seen as conflicting with the present social deficit in the welfare of the CA and SA population. Various examples demonstrate possible synergies between development, adaptation, and mitigation planning, which can help local communities and governments to allocate efficiently available resources in the design of strategies to reduce vulnerability. However, the generalization of such actions at a continental scale requires that both the CA and SA citizens and governments address the challenge of building a new governance model, where imperative development needs, vulnerability reduction, and adaptation strategies to climate stresses will be truly intertwined. {27.3.4, 27.4-5}

27.1. Introduction

27.1.1. The Central and South America Region

The Central America (CA) and South America (SA) region harbors unique ecosystems and has the highest biodiversity on the planet and a variety of eco-climatic gradients. Unfortunately, this natural wealth is threatened by advancing agricultural frontiers resulting from a rapidly growing agricultural and cattle production (Grau and Aide, 2008). The region experienced a steady economic growth, accelerated urbanization, and important demographic changes in the last decade; poverty and inequality are decreasing continuously, but at a low pace (ECLAC, 2011c). Adaptive capacity is improving in part thanks to poverty alleviation and development initiatives (McGray et al., 2007).

The region has multiple stressors on natural and human systems derived in part from significant land use changes and exacerbated by climate variability/climate change. Climate variability at various time scales has been affecting social and natural systems, and extremes in particular have affected large regions. In Central and South America, 613 climatological and hydro-meteorological extreme events occurred in the period 2000–2013, resulting in 13,883 fatalities, 53.8 million people affected, and economic losses of US$52.3 billion (www.emdat.be). Land is facing increasing pressure from competing uses such as cattle ranching, food production, and bioenergy.

The region is regarded as playing a key role in the future world economy because countries such as Brazil, Chile, Colombia, and Panama, among others, are rapidly developing and becoming economically important in the world scenario. The region is bound to be exposed to the pressure related to increasing land use and industrialization. Therefore, it is expected to have to deal with increasing emission potentials. Thus, science-based decision making is thought to be an important tool to control innovation and development of the countries in the region.

Two other important contrasting features characterize the region: having the biggest tropical forest of the planet on the one side, and possessing the largest potential for agricultural expansion and development during the next decades on the other. This is the case because the large countries of SA, especially, would have a major role in food and bioenergy production in the future, as long as policies toward adaptation to global climate change will be strategically designed. The region is already one of the top producers and user of bioenergy and this experience will serve as an example to other developing regions as well as developed regions.

27.1.2. Summary of the Fourth Assessment Report and IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation Findings

27.1.2.1. Fourth Assessment Report Findings

According to the Working Group II contribution to the Fourth Assessment Report (WGII AR4), Chapter 13 (Latin America), during the last decades of the 20th century, unusual extreme weather events have been severely affecting the Latin America (LA) region, contributing greatly to the strengthening of the vulnerability of human systems to natural disasters. In addition, increases in precipitation were observed in southeastern South America (SESA), northwest Peru, and Ecuador; while decreases were registered in southern Chile, southwest Argentina, southern Peru, and western CA since 1960. Mean warming was near 0.1°C per decade. The rate of sea level rise (SLR) has accelerated over the last 20 years, reaching 2 to 3 mm yr^{-1}. The glacier-retreat trend has intensified, reaching critical conditions in the Andean countries. Rates of deforestation have been continuously increasing, mainly due to agricultural expansion, and land degradation has been intensified for the entire region.

Mean warming for LA at the end of 21st century could reach 1°C to 4°C (SRES B2) or 2°C to 6°C (SRES A2) (*medium confidence*; WGII AR4 Chapter 13, p. 583). Rainfall anomalies (positive or negative) will be larger for the tropical part of LA. The frequency and intensity of weather and climate extremes is *likely* to increase (*medium confidence*).

Future impacts include: "significant species extinctions, mainly in tropical LA" (*high confidence*); "replacement of tropical forest by savannas, and semi-arid vegetation by arid vegetation" (*medium confidence*); "increases in the number of people experiencing water stress" (*medium confidence*); "probable reductions in rice yields and possible increases of soy yield in SESA" (WGII AR4 Chapter 13, p. 583); and "increases in crop pests and diseases" (*medium confidence*; WGII AR4 Chapter 13, p. 607)—with "some coastal areas affected by sea level rise, weather and climatic variability and extremes" (*high confidence*; WGII AR4 Chapter 13, p. 584).

Some countries have made efforts to adapt to climate change and variability, for example, through the conservation of key ecosystems (e.g., biological corridors in Mesoamerica, Amazonia, and Atlantic forest; compensation for ecosystem services in Costa Rica), the use of early warning systems and climate forecast (e.g., fisheries in eastern Pacific, subsistence agriculture in northeast Brazil), and the implementation of disease surveillance systems (e.g., Colombia) (WGII AR4 Chapter 13, p. 591). However, several constraints such as the lack of basic information, observation, and monitoring systems; the lack of capacity-building and appropriate political, institutional, and technological frameworks; low income; and settlements in vulnerable areas outweigh the effectiveness of these efforts.

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

As reported in Section 3.4 of the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; IPCC, 2012b), a changing climate leads to changes in the frequency, intensity, spatial extent, or duration of weather and climate extremes, and can result in unprecedented extremes. Levels of confidence in historical changes depend on the availability of high-quality and homogeneous data and relevant model projections. This has been a major problem in CA and SA, where a lack of long-term homogeneous and continuous climate and hydrological records and of complete studies on trends has not allowed for an identification of trends in extremes, particularly in CA.

Recent observational studies and projections from global and regional models suggest changes in extremes. With *medium confidence*, increases in warm days and decreases in cold days, as well as increases on warm nights and decreases in cold nights, have been identified in CA, northern SA, northeast Brazil (NEB), SESA, and the west coast of SA. In CA, there is *low confidence* that any observed long-term increase in tropical cyclone activity is robust, after accounting for past changes in observing capabilities. In other regions, such as Amazonia (insufficient evidence), inconsistencies among studies and detected trends result in *low confidence* of observed rainfall trends. Although it is *likely* that there has been an anthropogenic influence on extreme temperature in the region, there is *low confidence* in attribution of changes in tropical cyclone activity to anthropogenic influences.

Projections for the end of the 21st century for differing emissions scenarios (SRES A2 and A1B) show that for all CA and SA, models project substantial warming in temperature extremes. It is *likely* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century on the global scale. With *medium confidence*, it is *very likely* that the length, frequency, and/or intensity of heat waves will experience a large increase over most of SA, with a weaker tendency toward increasing in SESA. With *low confidence*, the models also project an increase of the proportion of total rainfall from heavy falls for SESA and the west coast of SA, while for Amazonia and the rest of SA and CA there are not consistent signals of change. In some regions, there is *low confidence* in projections of changes in fluvial floods. Confidence is low owing to limited evidence and because the causes of regional changes are complex. There is *medium confidence* that droughts will intensify along the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration in Amazonia and NEB.

The character and severity of the impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. These are influenced by a wide range of factors, including anthropogenic climate change, climate variability, and socioeconomic development.

Table 27-1 | Regional observed changes in temperature, precipitation, and climate extremes in various sectors of Central America (CA) and South America (SA). Additional information on changes in observed extremes can be found in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; Seneviratne et al., 2012) and the IPCC WGI AR5, Sections 2.4–2.6. (CDDs = consecutive dry days; NAMS = North American Monsoon System; PDSI = Palmer Drought Severity Index; SAMS = South American Monsoon System; SD = standard deviation.)

Region	Variable	Reference	Period	Observed changes
Central America and northern South America	Precipitation in NAMS	Englehart and Douglas (2006)	1943–2002	+0.94 mm day^{-1} over 58 years
	Rainfall onset in NAMS	Grantz et al. (2007)	1948–2004	–10 to –20 days over 57 years
	Summertime precipitation in NAMS	Anderson et al. (2010)	1931–2000	+17.6 mm per century
	Rainfall extremes (P95) in NAMS	Cavazos et al. (2008)	1961–1998	+1.3% per decade
	Cold days and nights in CA and northern SA	Donat et al. (2013)	1951–2010	Cold days: –1 day per decade. Cold nights: –2 days per decade
	Warm days and nights in northern SA	Donat et al. (2013)	1951–2010	Warm days: +2 to +4 days per decade. Warm nights: +1 to +3 days per decade
	Heavy precipitation (R10) in northern SA	Donat et al. (2013)	1951–2010	+1 to +2 days per decade
	CDDs in northern SA	Donat et al. (2013)	1951–2010	–2 days per decade
West coast of South America	Sea surface temperature and air temperatures off coast of Peru and Chile (15°S–35°S)	Falvey and Garreaud (2009); Gutiérrez et al. (2011a,b); Kosaka and Xie (2013)	1960–2010	–0.25°C per decade, –0.7°C over 11 years for 2002–2012
	Temperature, precipitation, cloud cover, and number of rainy days since the mid-1970s off the coast of Chile (18°S–30°S)	Schulz et al. (2012)	1920–2009	–1°C over 40 years, –1.6 mm over 40 years, –2 oktas over 40 years, and –0.3 day over 40 years
	Wet days until 1970, increase after that, reduction in the precipitation rate in southern Chile (37°S–43°S)	Quintana and Aceituno (2012)	1900–2007	–0.34% until 1970 and +0.37% after that, –0.12%
	Cold days and nights on all SA coast	Donat et al. (2013)	1951–2010	Cold days: –1 day per decade. Cold nights: –2 days per decade
	Warm nights on all SA coast, warm days in the northern coast of SA, warm days off the coast of Chile	Donat et al. (2013)	1951–2010	Warm nights: –1 day per decade. Warm days: +3 days per decade. Warm days: –1 day per decade
	Warm nights on the coast of Chile	Dufek et al. (2008)	1961–1990	+5% to +9% over 31 years
	Dryness as estimated by the PDSI for most of the west coast of SA (Chile, Ecuador, northern Chile)	Dai (2011)	1950–2008	–2 to –4 over 50 years
	Heavy precipitation (R95) in northern and central Chile	Dufek et al. (2008)	1961–1990	–45 to –105 mm over 31 years
	Temperature and extreme precipitation in southern Chile	Vicuña et al. (2013)	1976–2008	Increase in annual maximum temperature from +0.5°C to +1.1°C per decade; change in number of days with intense rainfall events from –2.7 to +4.2 days per decade.

Continued next page →

Table 27-1 (continued)

Region	Variable	Reference	Period	Observed changes
Southeastern South America	Mean annual air temperature in southern Brazil	Sansigolo and Kayano (2010)	1913–2006	+0.5°C to +0.6°C per decade
	Frequency of cold days and nights, warm days in Argentina and Uruguay	Rusticucci and Renom (2008)	1935–2002	–1.2% per decade, –1% per decade, +0.2% per decade
	Highest annual maximum temperature, lowest annual minimum air temperature in Argentina and Uruguay	Rusticucci and Tencer (2008)	1956–2003	+0.8°C over 47 years, +0.6°C over 47 years
	Warm nights in Argentina and Uruguay and southern Brazil	Rusticucci (2012)	1960–2009	+10–20% over 41 years
	Warm nights in most of the region	Dufek et al. (2008)	1961–1990	+7% to +9% over 31 years
	Cold nights in most of the region	Dufek et al. (2008)	1961–1990	–5% to –9% over 31 years
	Warm days and nights in most of the region	Donat et al. (2013)	1951–2010	Warm nights: +3 days per decade. Warm days: +4 days per decade
	Cold days and nights in most of the region	Donat et al. (2013)	1951–2010	Cold nights: –3 days per decade. Cold days: –3 days per decade
	CDDs in the La Plata Basin countries (Argentina, Bolivia, and Paraguay) and decrease of CDDs in SA south of 30°S	Dufek et al. (2008)	1961–1990	+15 to +21 days over 31 years, –21 to –27 days over 31 years
	Number of dry months during the warm season (October–March) in the Pampas region between 25°S and 40°S	Barrucand et al. (2007)	1904–2000	From 2–3 months in 1904–1920 to 1–2 months in 1980–2000
	Moister conditions as estimated by the PDSI in most of southeastern SA	Dai (2011)	1950–2008	0–4 PDSI over 50 years
	Rainfall trends in the Paraná River Basin	Dai et al. (2009)	1948–2008	+1.5 mm day^{-1} over 50 years
	Number of days with precipitation above 10 mm (R10) in most of the region	Donat et al. (2013)	1951–2010	+2 days per decade
	Heavy precipitation (R95) in most of the region	Donat et al. (2013)	1951–1910	+1% per decade and –4 days per decade
	Heavy precipitation (R95) in most of the region	Dufek et al. (2008)	1961–1990	+45 to +135 mm over 31 years
	Heavy precipitation (R95) in the state of São Paulo	Dufek and Ambrizzi (2008)	1950–1999	+50 to +75 mm over 40 years
	CDDs in the state of São Paulo	Dufek and Ambrizzi (2008)	1950–1990	–25 to –50 days over 40 years
	Lightning activity varies significantly with change in temperature in the state of São Paulo	Pinto and Pinto (2008); Pinto et al. (2013)	1951–2006	+40% per 1°C for daily and monthly time scales and approximately +30% per 1°C for decadal time scale
	Number of days with rainfall above 20 mm in the city of São Paulo	Silva Dias et al. (2012); Marengo et al. (2013)	2005–2011	+5 to +8 days over 11 years
	Excess rainfall events duration after 1950	Krepper and Zucarelli (2010)	1901–2003	+21 months over 53 years
	Dry events and events of extreme dryness from 1972 to 1996	Vargas et al. (2011)	1972–1996	–29 days over 24 years
	Number of dry days in Argentina	Rivera et al. (2013)	1960–2005	–2 to –4 days per decade
	Extreme daily rainfall in La Plata Basin	Penalba and Robledo (2010)	1950–2000	+33% to +60% increase in spring, summer, and autumn, –10% to –25% decrease in winter
	Frequency of heavy rainfall in Argentina, southern Brazil, and Uruguay	Re and Barros (2009)	1959–2002	+50 to +150 mm over 43 years
	Annual precipitation in the La Plata Basin	Doyle and Barros (2011); Doyle et al. (2012)	1960–2005	+5 mm $year^{-1}$

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27.2. Major Recent Changes and Projections in the Region

27.2.1. Climatic Stressors

27.2.1.1. Climate Trends, Long-Term Changes in Variability, and Extremes

In CA and SA, decadal variability and changes in extremes have been affecting large sectors of the population, especially those more vulnerable and exposed to climate hazards. Observed changes in some regions have been attributed to natural climate variability, while in others they have been attributed to land use change (e.g., increased urbanization), meaning that land use change is a result of anthropogenic drivers. Table 27-1 summarizes the observed trends in the region's climate.

Since around 1950, in CA and the North American Monsoon System (NAMS), rainfall has been starting increasingly later and has become more irregular in space and time, while rainfall has been increasing and the intensity of rainfall has been increasing during the onset season (see references in Table 27-1). Arias et al. (2012) relate those changes to decadal rainfall variations in NAMS.

The west coast of SA experienced a prominent but localized coastal cooling of about 1°C during the past 30 to 50 years extending from central Peru down to central Chile. This occurs in connection with an increased upwelling of coastal waters favored by the more intense trade winds (Falvey and Garreaud, 2009; Narayan et al., 2010; Gutiérrez et al., 2011a,b; Schulz et al., 2012; Kosaka and Xie, 2013). In the extremely arid northern coast of Chile, rainfall, temperature, and cloudiness show strong interannual and decadal variability, and since the mid-1970s,

Table 27-1 (continued)

Region	Variable	Reference	Period	Observed changes
Andes	Mean maximum temperature along the Andes, and increase in the number of frost days	Marengo et al. (2011b)	1921–2010	+0.10°C to +0.12°C per decade in 1921–2010, and +0.23–0.24°C per decade during 1976–2010; +8 days per decade during 1996–2002
	Air temperature and changes in precipitation in northern Andes (Colombia, Ecuador)	Villacís (2008)	1961–1990	+0.1°C to +0.22°C per decade, –4% to +4% per decade
	Temperature and precipitation in northern and central Andes of Peru	SENAMHI (2005, 2007, 2009a,c,d)	1963–2006	+0.2°C to +0.45°C per decade, –20% to –30% over 40 years
	Temperature and precipitation in the southern Andes of Peru	SENAMHI (2007, 2009a,b,c,d); Marengo et al. (2011b)	1964–2006	+0.2°C to +0.6°C per decade, –11 to +2 mm per decade
	Air temperature and rainfall over Argentinean and Chilean Andes and Patagonia	Masiokas et al. (2008); Falvey and Garreaud (2009)	1950–1990	+0.2°C to +0.45°C per decade, –10% to –12% per decade
	Number of days with rainfall above 10 mm (R10)	Donat et al. (2013)	1950–2010	–3 days per decade
	Dryness in the Andes between 35.65°S and 39.9°S using the PDSI	Christie et al. (2011)	1950–2003	–7 PDSI over 53 years
	Rainfall decrease in the Mantaro Valley, central Andes of Peru	SENAMHI (2009c)	1970–2005	–44 mm per decade
	Air temperature in Colombian Andes	Poveda and Pineda (2009)	1959–2007	+1°C over 20 years
Amazon region	Decadal variability of rainfall in northern and southern Amazonia	Marengo et al. (2009b); Satyamurty et al. (2010)	1920–2008	–3 SDs over 30 years in northern Amazonia and +4 SDs over 30 years in southern Amazonia since the mid-1970s
	Rainfall in all the region	Espinoza et al. (2009a,b)	1975–2003	–0.32% over 28 years
	Onset of the rainy season in southern Amazonia	Butt et al. (2011); Marengo et al. (2011b)	1950–2010	–1 month since 1976–2010
	Precipitation in the SAMS core region	Wang et al. (2012)	1979–2008	+2 mm day^{-1} per decade
	Onset becomes steadily earlier from 1948 to early 1970s, demise dates have remained later, and SAMS duration was longer after 1972	Carvalho et al. (2011)	1948–2008	SAMS from 170 days (1948–1972) to 195 days (1972–1982)
	Spatially varying trends of heavy precipitation (R95), increase in many areas and insufficient evidence in others	Marengo et al. (2009b)	1961–1990	+100 mm over 31 years in western and extreme eastern Amazonia
	Spatially varying trends in dry spells (CDDs), increase in many areas and decrease in others	Marengo et al. (2009b, 2010)	1961–1990	+15 mm over 31 years in western Amazonia, –20 mm in southern Amazonia
	Rainfall in most of Amazonia and in western Amazonia	Dai et al. (2009); Dai (2011)	1948–2008	+1 mm day^{-1} over 50 years, –1.5 mm day^{-1} over 50 years
	Dryness as estimated by the PDSI in southern Amazonia and moister conditions in western Amazonia	Dai (2011)	1950–2008	–2 to –4 over 50 years, +2 to +4 over 50 years
	Seasonal mean convection and cloudiness	Arias et al. (2011)	1984–2007	+30 W m^{-2} over 23 years, –8% over 23 years
	Onset of rainy season in southern Amazonia due to land use change	Butt et al. (2011)	1970–2010	–0.6 days over 30 years
	Precipitation in the region	Gloor et al. (2013)	1990–2010	–20 mm over 21 years
Northeastern Brazil	Rainfall trends in interior northeastern Brazil and in northern northeastern Brazil	Dai et al. (2009); Dai (2011)	1948–2008	–0.3 mm day^{-1} over 50 years, +1.5 mm day^{-1} over 50 years
	Heavy precipitation (R95) in some areas, and in southern northeastern Brazil	Silva and Azevedo (2008)	1970–2006	–2 mm over 24 years to +6 mm over 24 years
	CDDs in most of southern northeastern Brazil	Silva and Azevedo (2008)	1970–2006	–0.99 day over 24 years
	Total annual precipitation in northern northeastern Brazil	Santos and Brito (2007)	1970–2006	+1 to +4 mm $year^{-1}$ over 24 years
	Spatially varying trends in heavy precipitation (R95) in northern northeastern Brazil	Santos and Brito (2007)	1970–2006	–0.1 to +5 mm $year^{-1}$ over 24 years
	Spatially varying trends in heavy precipitation (R95) and CDDs in northern northeastern Brazil	Santos et al. (2009)	1935–2006	–0.4 to +2.5 mm $year^{-1}$ over 69 years, –1.5 to +1.5 days $year^{-1}$ over 69 years
	Dryness in southern northeastern Brazil as estimated by the PDSI, and northern northeastern Brazil	Dai (2011)	1950–2008	–2 to –4 over 50 years, 0 to +1 over 50 years

the minimum daily temperature, cloudiness, and precipitation have decreased. In central Chile, a negative precipitation trend was observed over the period 1935–1976, and an increase after 1976, while further south, the negative trend in rainfall that prevailed since the 1950s has intensified by the end of the 20th century (Quintana and Aceituno, 2012). To the east of the Andes, NEB exhibits large interannual rainfall variability, with a slight decrease since the 1970s (Marengo et al. 2013a). Droughts in this region (e.g., 1983, 1987, 1998) have been associated with El Niño and/or a warmer Tropical North Atlantic Ocean. However, not all El Niño years result in drought in NEB, as the 2012–2013 drought occurred during La Niña (Marengo et al., 2013a).

In the La Plata Basin in SESA, various studies have documented interannual and decadal scale circulation changes that have led to decreases in the

Box 27-1 | Extreme Events, Climate Change Perceptions, and Adaptive Capacity in Central America

Central America (CA) has traditionally been characterized as a region with high exposure to geo-climatic hazards derived from its location and topography and with high vulnerability of its human settlements (ECLAC, 2010c). It has also been identified as the most responsive tropical region to climate change (Giorgi, 2006). Evidence for this has been accumulating particularly in the last 30 years, with a steady increase in extreme events including storms, floods, and droughts. In the period 2000–2009, 39 hurricanes occurred in the Caribbean basin compared to 15 and 9 in the 1980s and 1990s, respectively (UNEP and ECLAC, 2010). The impacts of these events on the population and the economy of the region have been tremendous: the economic loss derived from 11 recent hydrometereological events evaluated amounted to US$13.64 billion and the number of people impacted peaked with Hurricane Mitch in 1998, with more than 600,000 persons affected (ECLAC, 2010c). A high percentage of the population in CA live on or near highly unstable steep terrain with sandy, volcanic soils prone to mudslides, which are the main cause of casualties and destruction (Restrepo and Alvarez, 2006).

The increased climatic variability in the past decade certainly changed the perception of people in the region with respect to climate change. In a survey to small farmers in 2003, Tucker et al. (2010) found that only 25% of respondents included climate events as a major concern. A subsequent survey in 2007 (Eakin et al., 2013) found that more than 50% of respondents cited drought conditions and torrential rains as their greatest concern. Interestingly, there was no consensus on the direction in climate change pattern: The majority of households in Honduras reported an increase in the frequency of droughts but in Costa Rica and Guatemala a decrease or no trend at all was reported. A similar discrepancy in answers was reported with the issue of increased rainfall. But there was general agreement in all countries that rainfall patterns were more variable, resulting in higher difficulty in recognizing the start of the rainy season.

The high levels of risk to disasters in CA are the result of high exposure to hazards and the high vulnerability of the population and its livelihoods derived from elevated levels of poverty and social exclusion (Programa Estado de la Nación-Región, 2011). Disaster management in the region has focused on improving early warning systems and emergency response for specific extreme events (Saldaña-Zorrilla, 2008) but little attention has been paid to strengthening existing social capital in the form of local organizations and cooperatives. These associations can be central in increasing adaptive capacity through increased access to financial instruments and strategic information on global markets and climate (Eakin et al., 2011). There is a need to increase the communication of the knowledge from local communities involved in processes of autonomous adaptation to policymakers responsible for strengthening the adaptive capacities in CA (Castellanos et al., 2013).

frequency of cold nights in austral summer, as well as to increases in warm nights and minimum temperatures during the last 40 years. Simultaneously, a reduction in the number of dry months in the warm season is found since the mid-1970s, while heavy rain frequency is increasing in SESA (references in Table 27-1). In SESA, increases in precipitation are responsible for changes in soil moisture (Collini et al., 2008; Saulo et al., 2010), and although feedback mechanisms are present at all scales, the effect on atmospheric circulation is detected at large scales. Moreover, land use change studies in the Brazilian southern Amazonia for the last decades showed that the impact on the hydrological response is time lagged at larger scales (Rodriguez, D.A. et al., 2010).

In the central Andes, in the Mantaro Valley (Peru), precipitation shows a strong negative trend, while warming is also detected (SENAMHI, 2007). In the southern Andes of Peru air temperatures have increased during 1964–2006, but no clear signal on precipitation changes has been detected (Marengo et al., 2009a). In the northern Andes (Colombia, Ecuador), changes in temperature and rainfall in 1961–1990 have been identified by Villacís (2008). In the Patagonia region, Masiokas et al. (2008) have identified an increase of temperature together with precipitation reductions during 1912–2002. Vuille et al. (2008a) found that climate in the tropical Andes has changed significantly over the past 50 to 60 years. Temperature in the Andes has increased by approximately 0.1°C per decade, with only 2 of the last 20 years being below the 1961–1990 average. Precipitation has slightly increased in the second half of the 20th century in the inner tropics and decreased in the outer tropics. The general pattern of moistening in the inner tropics and drying in the subtropical Andes is dynamically consistent with observed changes in the large-scale circulation, suggesting a strengthening of the tropical atmospheric circulation. Moreover, a positive significant trend in mean temperature of 0.09°C per decade during 1965–2007 has been detected over the Peruvian Andes by Lavado et al. (2012).

For the Amazon basin, Marengo (2004) and Satyamurty et al. (2010) concluded that no systematic unidirectional long-term trends toward drier or wetter conditions in both the northern and southern Amazon have been identified since the 1920s. Rainfall fluctuations are more characterized by interannual scales linked to El Niño-Southern Oscillation (ENSO) or decadal variability. Analyzing a narrower time period, Espinoza et al. (2009a,b) found that mean rainfall in the Amazon basin for 1964–2003 has decreased, with stronger amplitude after 1982, especially in the Peruvian western Amazonia (Lavado et al., 2012), consistent with reductions in convection and cloudiness in the same region (Arias et al., 2011). Recent studies by Donat et al. (2013) suggest that heavy rains are increasing in frequency in Amazonia. Regarding seasonal extremes in the Amazon region, two major droughts and three floods have affected the region from 2005 to 2012, although these events have been related to natural climate variability rather than to deforestation (Marengo et al., 2008, 2012, 2013a; Espinoza et al., 2011, 2012, 2013; Lewis et al., 2011; Satyamurty et al., 2013).

On the impacts of land use changes on changes in the climate and hydrology of Amazonia, Zhang et al. (2009) suggest that biomass-burning aerosols can work against the seasonal monsoon circulation transition, and thus reinforce the dry season rainfall pattern for southern Amazonia,

Table 27-2 | Regional projected changes in temperature, precipitation, and climate extremes in different sectors of Central America (CA) and South America (SA). Various studies used A2 and B2 scenarios from Coupled Model Intercomparison Project Phase 3 (CMIP3) and various Representative Concentration Pathway (RCP) scenarios for CMIP5, and different time slices from 2010 to 2100. To make results comparable, the CMIP3 and CMIP5 at the time slice ending in 2100 are included. Additional information on changes in projected extremes can be found in the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX; see IPCC, 2012), and in IPCC WGI AR5 Sections 9.5, 9.6, 14.2, and 14.7. (CDDs = consecutive dry days.)

Region	Variable	Reference	Models and scenarios	Projected changes
Central America and northern South America	Leaf Area Index, evapotranspiration by 2070–2099 in CA	Imbach et al. (2012)	23 CMIP3 models, A2	Evapotranspiration: +20%; Leaf Area Index: –20% + 0.94 mm/day/58 years
	Air temperature by 2075 and 2100 in CA	Aguilar et al. (2009)	9 CMIP3 models, A2	+2.2°C by 2075; +3.3°C by 2100
	Rainfall in CA and Venezuela, air temperature in the region	Kitoh et al. (2011); Hall et al. (2013)	20 km MRI-AGCM3.1S model, A1B	Rainfall decrease/increase of about –10%/+10% by 2079. Temperature increases of about +2.5°C to +3.5°C by 2079
	Precipitation and evaporation in most of the region. Soil moisture in most land areas in all seasons	Nakaegawa et al. (2013b)	20 km MRI-AGCM3.1S model, A1B	Precipitation decrease of about –5 mm day^{-1}, evaporation increase of about +3 to +5 mm day^{-1}; soil moisture to decrease by –5 mm day^{-1}
	Rainfall in Nicaragua, Honduras, northern Colombia, and northern Venezuela; rainfall in Costa Rica and Panama. Temperature in all regions by 2071–2100	Campbell et al. (2011)	PRECIS forced with HadAM3, A2	Rainfall: –25% to –50%, and +25% to +50%; temperature: +3°C to +6°C
	Precipitation and temperature in northern SA, decrease in interior Venezuela, temperature increases by 2071–2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Increases by +30% to +50%; reductions by –10% to –20%; temperature: +4°C to +5°C
	Precipitation and temperature by 2100 in CA	Karmalkar et al. (2011)	PRECIS forced with HadAM3, A2	Precipitation: –24% to –48%; temperature: +4°C to +5°C
	Warm nights, CDDs, and heavy precipitation in Venezuela by 2100	Marengo et al. (2009a, 2010)	PRECIS forced with HadAM3, A2	Increase of +12% to +18%, +15 to +25 days, and reduction of 75 to 105 days
	Air temperature and precipitation in CA by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +3°C to +5°C; reduction of –10% to –30%
	CDDs and heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Increase of +5 days, increase of +2% to +8%
	Rainfall over Panama by 2099	Fábrega et al. (2013)	20 km MRI-AGCM3.1S model, A1B	Increase of +5%
West coast of South America	Precipitation, runoff, and temperature at the Limari river basin in semi-arid Chile by 2100	Vicuña et al. (2011)	PRECIS forced with HadAM3, A2	Precipitation: –15% to –25%; runoff: –6% to –27%; temperature: +3°C to +4°C
	Air temperature and surface winds in west coast of SA (Chile) by 2100	Garreaud and Falvey (2009)	15 CMIP3 models, PRECIS forced with HadAM3, A2	Temperature: +1°C; coastal winds: +1.5 m s^{-1}
	Precipitation in the bands 5°N–10°S, 25°S–30°S, 10°S–25°S, and 30°S–50°S; temperature increase by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Increases of 30–40%; increases of 3°C to 5°C
	Warm nights, CDDs, and heavy precipitation in 5°N–5°S by 2100	Marengo et al. (2009a, 2010)	PRECIS forced with HadAM3, A2	Increase of +3% to +18%, reduction of –5 to –8 days, increase of +75 to +105 days
	Air temperature, increase in precipitation between 0° and 10°S, and between 20°S and 40°S by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +2°C to +3°C; increase of 10%, reduction of –10% to –30%
	CDDs between 5°N and 10°S and south of 30°S; heavy precipitation between 5°S and 20°S and south of 20°S by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Increase of 10 days and between +2% and +10%
	Precipitation between 15°S and 35°S and south of 40°S; temperature by 2100	Nuñez et al. (2009)	MM5 forced with HadAM3, A2	Precipitation: –2 mm day^{-1}; +2 mm day^{-1}; temperature: +2.5°C
	Precipitation in Panama and Venezuela by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5–MPI OM model, A1B	Precipitation: –1 to –3 mm day^{-1}

Continued next page →

Table 27-2 (continued)

Region	Variable	Reference	Models and scenarios	Projected changes
Southeastern South America	Precipitation and runoff, and air temperature by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Precipitation: +20% to +30%; runoff: +10% to +20%; air temperature: +2.5°C to +3.5°C
	Precipitation and temperature in the La Plata basin by 2050	Cabré et al. (2010)	MM5 forced with HadAM3, A2	Precipitation: +0.5 to 1.5 mm day^{-1}; temperature: +1.5°C to 2.5°C
	Warm nights, CDDs, and heavy precipitation by 2100	Menendez and Carril (2010)	7 CMIP3 models, A1B	Warm nights: +10% to +30%; CDDs: +1 to +5 days; heavy precipitation: +3% to +9%
	Precipitation during summer and spring, and in fall and winter by 2100	Seth et al. (2010)	9 CMIP3 models, A2	Precipitation: +0.4 to +0.6 mm day^{-1}, –0.02 to –0.04 mm day^{-1}
	Warm nights, CDDs, and heavy precipitation by 2100	Marengo et al. (2009a, 2010)	PRECIS forced with HadAM3, A2	Increase of +6% to +12%, +5 to +20 days, +75 to +105 days
	Air temperature and rainfall by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +2°C to +4°C, increase of +20% to +30%
	CDDs and heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Increase of +5% to +10% and of +2% to +8%
	Precipitation in north central Argentina, decrease in southern Brazil, increase of air temperature by 2100	Nuñez et al. (2009)	MM5 forced with HadAM3, A2	Increase of +0.5 to +1 mm day^{-1}, reduction of –0.5 mm day^{-1}, increase of +3°C to +4.5°C
	Drought frequency, intensity, and duration in SA south of 20°S for 2011–2040 relative to 1979–2008	Penalba and Rivera (2013)	15 CMIP5 models, RCP4.5 and 8.5	Frequency increase of 10–20%, increase in severity of 5–15%, and reduction in duration of 10–30%
	Precipitation, heavy precipitation, reduction of CDDs in the eastern part of the region, increase in the western part of the region by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increase of +2 mm day^{-1}, of +5 to +15 mm, reduction of –10 days and increase of +5 days
	Precipitation in southeastern SA by 2100	Sörensson et al. (2010)	9 CMIP3 models, A1B	Increase of +0.3 to +0.5 mm day^{-1}
Andes	Precipitation and temperature, increase by 2100 in the Altiplano	Minvielle and Garreaud (2011)	11 CMP3 models, A2	Precipitation: –10% to –30%; temperature: >3°C
	Precipitation at 5°N–5°S and 30°S–45°S, at 5°S–25°S; temperature by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Increase of +10% to +30%, decrease of –20% to –30%, increase of +3.5°C to +4.5°C
	Warm nights, heavy precipitation, and CDDs south of 15°S by 2100	Marengo et al. (2009a)	PRECIS forced with HadAM3, A2	Increase of +3% to +18%, reduction of –10 to –20 days, and reduction of –75 to –105 days
	Air temperature, rainfall between 0° and 10°S, and reduction between 10°S and 40°S	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +3°C to +4°C, increase of 10%, and reduction of –10%
	CDDs and increase of heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of –5 days, increase of +2 to +4% south of 20°S
	Precipitation, heavy precipitation, and CDDs by 2070–2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increases of +1 to +3 mm day^{-1}, +5 mm and of +5 to +10 days
	Summer precipitation and surface air temperature in the Altiplano region by 2099	Minvielle and Garreaud (2011)	9 CMIP3 models, A2	Reduction in precipitation between –10% and –30%, and temperature increase of +3°C
	Temperature and rainfall in lowland Bolivia in 2070–2099	Seiler et al. (2013)	5 CMIP3 models (A1B) and 5 CMIP5 models (RCP4.5, 8.5)	Increase of 2.5°C to 5°C, reduction of 9% annual precipitation
	Precipitation in the dry season, temperature, and evapotranspiration 2079–2098	Guimberteau et al. (2013)	CMIP3 models, A1B	–1.1 mm; +2°C; +7%

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while Wang et al. (2011) suggests the importance of deforestation and vegetation dynamics on decadal variability of rainfall in the region. Costa and Pires (2010) have suggested a possible decrease in precipitation due to soybean expansion in Amazonia, mainly as a consequence of its very high albedo. In the South American Monsoon System (SAMS) region, positive trends in rainfall extremes have been identified in the last 30 years, with a pattern of increasing frequency and intensity of heavy rainfall events, and earlier onsets and late demise of the rainy season (see Table 27-1).

27.2.1.2. Climate Projections

Since the AR4, substantial additional regional analysis has been carried out using the Coupled Model Intercomparison Project Phase 3 (CMIP3) model ensemble. In addition, projections from CMIP5 models and new experiences using regional models (downscaling) have allowed for a better description of future changes in climate and extremes in CA and SA. Using CMIP3 and CMIP5 models, Giorgi (2006), Diffenbaugh et al. (2008), Xu et al. (2009), Diffenbaugh and Giorgi (2012), and Jones and Carvalho (2013) have identified areas of CA/western North America and the Amazon as persistent regional climate change hotspots throughout the 21st century of the Representative Concentration Pathway (RCP)8.5 and RCP4.5. Table 27-2 summarizes projected climatic changes derived from global and regional models for the region, indicating the projected change, models, emission scenarios, time spans, and references.

In CA and Northern Venezuela, projections from CMIP3 models and from downscaling experiments suggest precipitation reductions and warming together with an increase in evaporation, and reductions in

Table 27-2 (continued)

Region	Variable	Reference	Models and scenarios	Projected changes
Amazon region	Rainfall in central and eastern Amazonia and in western Amazonia; air temperature in all regions by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Precipitation: –20% to –30%, +20% to +30%; temperature: +5°C to +7°C
	Intensity of the South Atlantic Convergence Zone and in rainfall in the South American monsoon region, 2081–2100	Bombardi and Carvalho (2009)	10 CMIP3 models, A1B	Precipitation: –100 to –200 mm over 20 years
	Precipitation in western Amazonia during summer and in winter in Amazonia by 2100	Mendes and Marengo (2010)	5 CMIP3 models, A2 and ANN	+1.6% in summer and –1.5% in winter
	Number of South American Low Level Jet (SALLJ) events east of the Andes, and the moisture transport from Amazonia to the La Plata basin by 2090	Soares and Marengo (2009)	PRECIS forced with HadAM3, A2	+50% SALLJ events during summer, increase in moisture transport by 50%
	Precipitation in the South American monsoon during summer and spring, and during fall and winter by 2100	Seth et al. (2010)	9 CMIP3 models, A2	Increase of +0.15 to +0.4 mm/day, reductions of –0.10 to –0.26 mm/day
	Warm nights, CDDs in eastern Amazonia; heavy precipitation in western Amazonia and in eastern Amazonia by 2100	Marengo et al. (2009a)	PRECIS forced with HadAM3, A2	Increase of +12% to +15%, of 25–30 days in eastern Amazonia, increase in western Amazonia of 75–105 days, and reduction of –15 to –75 days in eastern Amazonia
	Increase in air temperature; rainfall increase in western Amazonia and decrease in eastern Amazonia by 2100	Giorgi and Diffenbaugh (2008)	CMIP3 models, A1B	Increase of +4°C to +6°C, increase of +10%, and decrease between –10% and –30%
	Reduction of CDDs and increase in heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of –5 to –10 days, increase of +2% to +8%
	Onset and late demise of the rainy season in South American Monsoon System (SAMS) by 2040–2050 relative to 1951–1980	Jones and Carvalho (2013)	10 CMIP5 models, RCP8.5	Onset 14 days earlier than present, demise 17 days later than present
	Precipitation in SAMS during the monsoon wet season in 2071–2100 relative to 1951–1980	Jones and Carvalho (2013)	10 CMIP5 models, RCP8.5	Increase of 300 mm during the wet season
	Precipitation in western Amazonia, heavy precipitation in northern Amazonia and in southern Amazonia, CDDs in western Amazonia and increase by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increase of +1 to +3 mm day^{-1}, reduction of –1 to –3 mm, increase of +5 to +10 mm, decrease of –5 to –10 days, increase of +20 to +30 days
Northeastern Brazil	Rainfall and temperature in the entire region by 2100	Marengo et al. (2011a)	Eta forced with HadCM3, A1B	Precipitation: –20% to +20%; temperature: +3°C to +4°C
	Warm nights, CDDs, heavy precipitation by 2100	Marengo et al. (2009a)	PRECIS forced with HadAM3, A2	Increase of +18% to +24%, of +25 to +30 days, and –15 to –75 days
	Air temperature and precipitation by 2100	Giorgi and Diffenbaugh (2008)	23 CMIP3 models, A1B	Increase of +2°C to +4°C, reduction of –10% to –30%
	CDDs and heavy precipitation by 2099	Kamiguchi et al. (2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of –5% to –10%, increase of +2% to +6%
	Precipitation, heavy precipitation, and CDDs by 2099	Sörensson et al. (2010)	RCA forced with ECHAM5, A1B	Increase of +1 to +2 mm day^{-1}, increase of +5 to +10 mm, and increase of +10 to +30 days

soil moisture for most of the land during all seasons by the end of the 21st century (see references in Table 27-2). However, the spread of projections is high for future precipitation.

Analyses from global and regional models in tropical and subtropical SA show common patterns of projected climate in some sectors of the continent. Projections from CMIP3 regional and high-resolution global models show by the end of the 21st century, for the A2 emission scenario, a consistent pattern of increase of precipitation in SESA, northwest of Peru and Ecuador, and western Amazonia, while decreases are projected for northern SA, eastern Amazonia, central eastern Brazil, NEB, the Altiplano, and southern Chile (Table 27-2). For some regions, projections show mixed results in rainfall projections for Amazonia and the SAMS region, suggesting high uncertainties on the projections (Table 27-2).

As for extremes, CMIP3 models and downscaling experiments show increases in dry spells are projected for eastern Amazonia and NEB, while rainfall extremes are projected to increase in SESA, in western Amazonia, northwest Peru, and Ecuador, while over southern Amazonia, NEB, and eastern Amazonia, the maximum number of consecutive dry days tends to augment, suggesting a longer dry season. Increases in warm nights throughout SA are also projected by the end of the 21st century (see references in Table 27-2). Shiogama et al. (2011) suggest that, although the CMIP3 ensemble mean assessment suggested wetting across most of SA, the observational constraints indicate a higher probability of drying in the eastern Amazon basin.

The CMIP5 models project an even larger expansion of the monsoon regions in NAMS in future scenarios (Jones and Carvalho, 2013; Kitoh et al., 2013). A comparison from eight models from CMIP3 and CMIP5 identifies some improvements in the new generation models. For example, CMIP5 inter-model variability of temperature in summer was lower over northeastern Argentina, Paraguay, and northern Brazil, in the last decades of the 21st century, as compared to CMIP3. Although

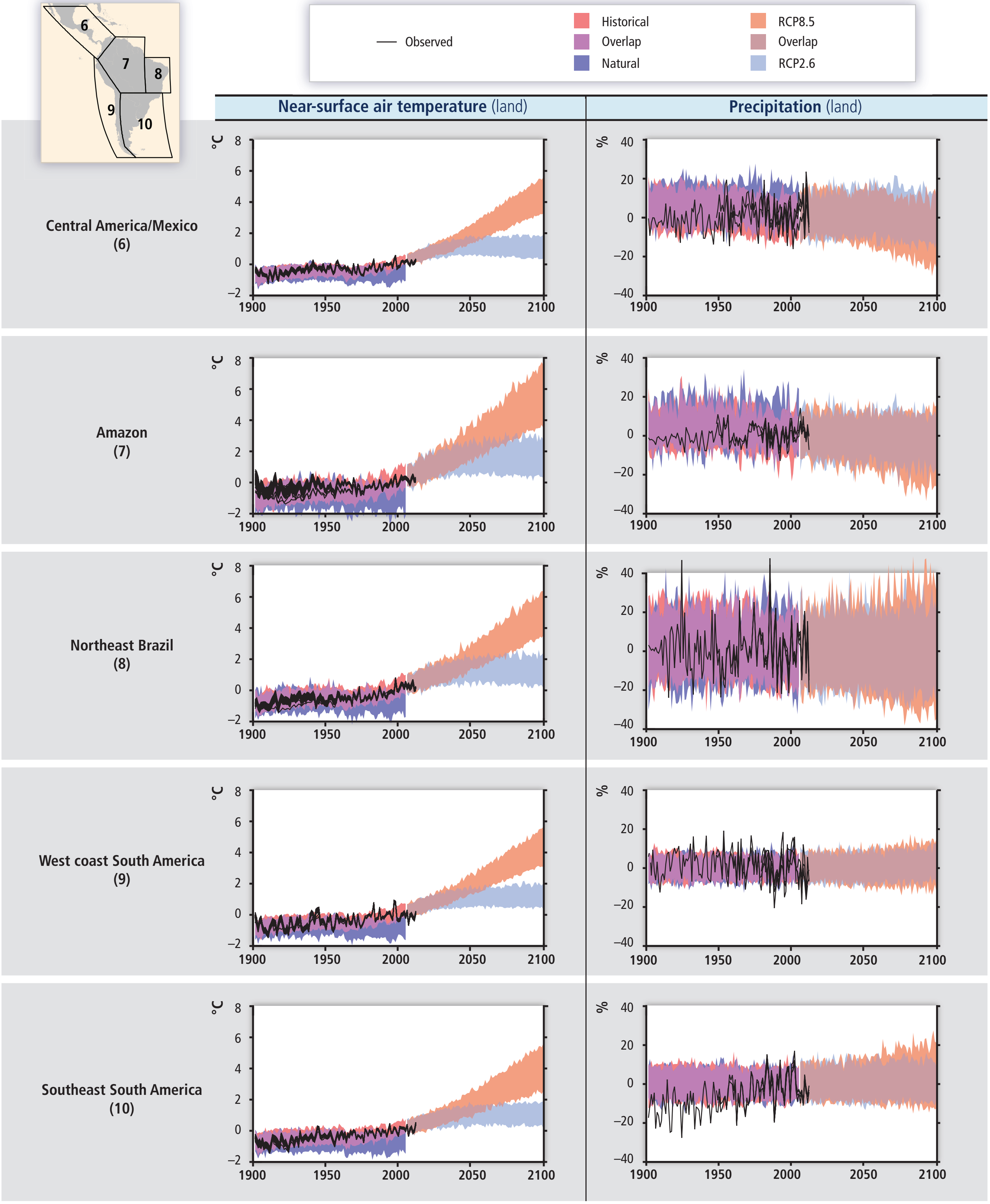

Figure 27-1 | Observed and simulated variations in past and projected future annual average temperature over the Central and South American regions defined in IPCC (2012a). Black lines show various estimates from observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the Representative Concentration Pathway (RCP)2.6 emissions scenario (63), and RCP8.5 (63). Data are anomalies from the 1986–2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Table SM21-5.

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no major differences were observed in both precipitation data sets, CMIP5 inter-model variability was lower over northern and eastern Brazil in the summer by 2100 (Blázquez and Nuñez, 2013; Jones and Carvalho, 2013).

The projections from the CMIP5 models at regional level for CA and SA (using the same regions from SREX) are shown in Figure 27-1, and update some of these previous projections based on SRES A2 and B2 emission scenarios from CMIP3. Figure 27-1 shows that in relation to the baseline period 1986–2005, for CA and northern SA–Amazonia, temperatures are projected to increase by approximately 0.6°C and 2°C for the RCP2.6 scenario, and by 3.6°C and 5.2°C for the RCP8.5 scenario. For the rest of SA, increases by about 0.6°C to 2°C are projected for the RCP4.5 and by about 2.2°C to 7°C for the RCP8.5 scenario. The observed records show increases of temperature from 1900 to 1986 by about 1°C. For precipitation, while for CA and northern SA–Amazonia precipitation is projected to vary between +10 and –25% (with a large spread among models). For NEB, there is a spread among models between +30 and –30%, making it hard to identify any projected rainfall change. This spread is much lower in the western coast of SA and SESA, where the spread is between +20 and –10% (Chapter 21; Box 21-3).

CMIP5-derived RCP8.5 projections for the late 21st century, as depicted in Figure 27-2, follow: CA – mean annual warming of 2.5°C and rainfall reduction of 10%, and reduction in summertime precipitation; SA – mean warming of 4°C, with rainfall reduction up to 15% in tropical SA east of the Andes, and an increase of about 15 to 20% in SESA and in other regions of the continent. Changes shown for the mid-21st century are small. Both Figures 27-1 and 27-2 illustrate that there is some degree of uncertainty on climate change projections for regions, particularly for rainfall in CA and tropical SA.

27.2.2. Non-Climatic Stressors

27.2.2.1. Trends and Projections in Land Use and Land Use Change

Land use change is a key driver of environmental degradation for the region that exacerbates the negative impacts from climate change (Sampaio et al., 2007; Lopez-Rodriguez and Blanco-Libreros, 2008). The high levels of deforestation observed in most of the countries in the region have been widely discussed in the literature as a deliberate development strategy based on the expansion of agriculture to satisfy the growing world demand for food, energy, and minerals (Benhin, 2006; Grau and Aide, 2008; Müller et al., 2008). Land is facing increasing pressure from competing uses, among them cattle ranching, food, and bioenergy production. The enhanced competition for land increases the

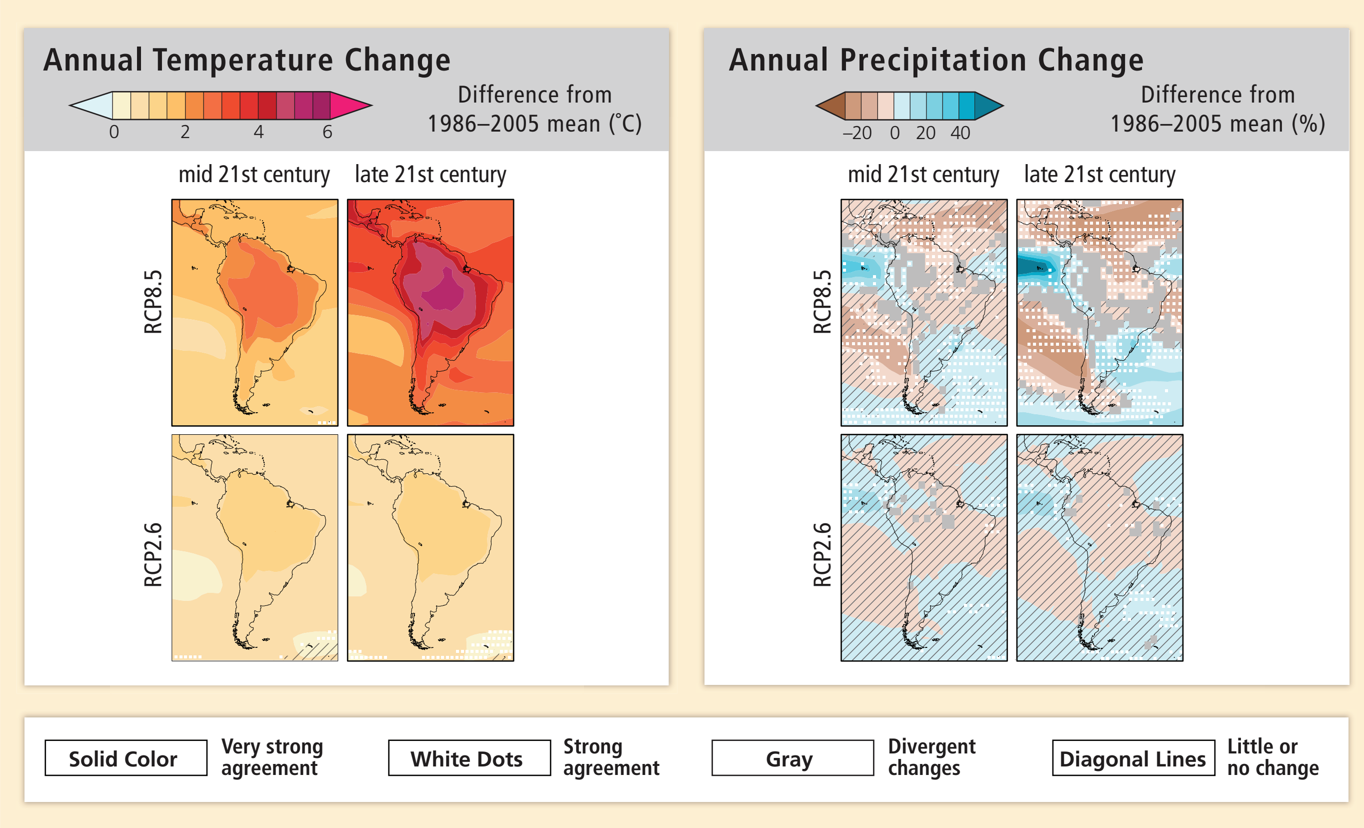

Figure 27-2 | Projected changes in annual average temperature and precipitation. CMIP5 multi-model mean projections of annual average temperature changes (left panel) and average percent changes in annual mean precipitation (right panel) for 2046–2065 and 2081–2100 under RCP2.6 and 8.5, relative to 1986–2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability (natural internal variability in 20-yr means) and ≥90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where ≥66% of models show change greater than the baseline variability and ≥66% of models agree on sign of change. Gray indicates areas with divergent changes, where ≥66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where <66% of models show change greater than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC] risk of land use changes, which may lead to negative environmental and socioeconomic impacts. Agricultural expansion has relied in many cases on government subsidies, which have often resulted in lower land productivity and more land speculation (Bulte et al., 2007; Roebeling and Hendrix, 2010). Some of the most affected areas due to the expansion of the agricultural frontier are fragile ecosystems such as the edges of the Amazon forest in Brazil, Colombia, Ecuador, and Peru, and tropical Andes including the Paramo, where activities such as deforestation, agriculture, cattle ranching, and gold mining are causing severe environmental degradation (ECLAC, 2010d), and the reduction of environmental services provided by these ecosystems.

Deforestation rates for the region remain high in spite of a reducing trend in the last decade (Ramankutty et al., 2007; Fearnside, 2008). Brazil is by far the country with the highest area of forest loss in the world according to the latest Food and Agriculture Organization (FAO) statistics (2010): 21,940 $km^2 yr^{-1}$, equivalent to 39% of world deforestation for the period 2005–2010. Bolivia, Venezuela, and Argentina follow in deforested area (Figure 27-3), with 5.5, 5.2, and 4.3% of the total world deforestation, respectively. The countries of CA and SA lost a total of 38,300 km^2 of forest per year in that period (69% of the total world deforestation; FAO, 2010). These numbers are limited by the fact that many countries do not have comparable information through time, particularly for recent years. Aide et al. (2013) completed a wall-to-wall analysis for the region for the period 2001–2010, analyzing not only deforestation but also reforestation, and reported very different results than FAO (2010) for some countries where reforestation seems to be higher than deforestation, particularly in Honduras, El Salvador, Panama, Colombia, and Venezuela. For Colombia and Venezuela, these results are contradictory with country analyses that align better with the FAO data (Rodríguez, J.P. et al., 2010; Armenteras et al., 2013).

Deforestation in the Amazon forest has received much international attention in the last decades, both because of its high rates and its rich biodiversity. Brazilian Legal Amazon is now one of the best-monitored ecosystems in terms of deforestation since 1988 (INPE, 2011). Deforestation for this region peaked in 2004 and has steadily declined since then to a lowest value of 4656 $km^2 yr^{-1}$ for the year 2012 (see Figure 27-4). Such reduction results from a series of integrated policies to control illegal deforestation, particularly enforcing protected areas, which now shelter 54% of the remaining forests of the Brazilian Amazon (Soares-Filho et al., 2010). Deforestation in Brazil is now highest in the Cerrado (drier ecosystem south of Amazon), with an average value of 14,179 $km^2 yr^{-1}$ for the period 2002–2008 (FAO, 2009).

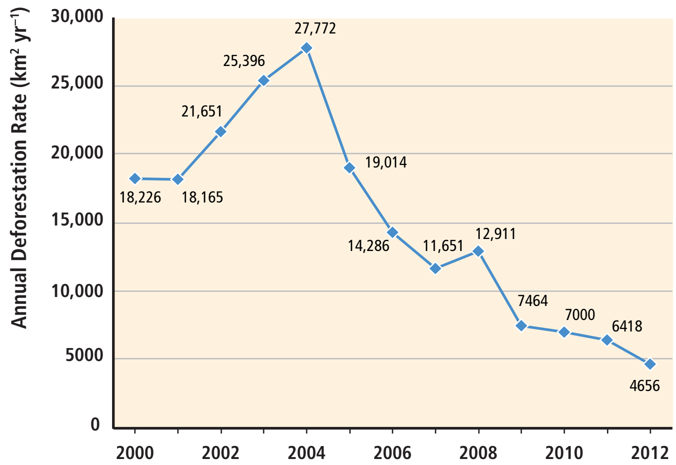

Figure 27-4 | Deforestation rates in Brazilian Amazonia ($km^2 yr^{-1}$) based on measurements by the PRODES project (INPE, 2011).

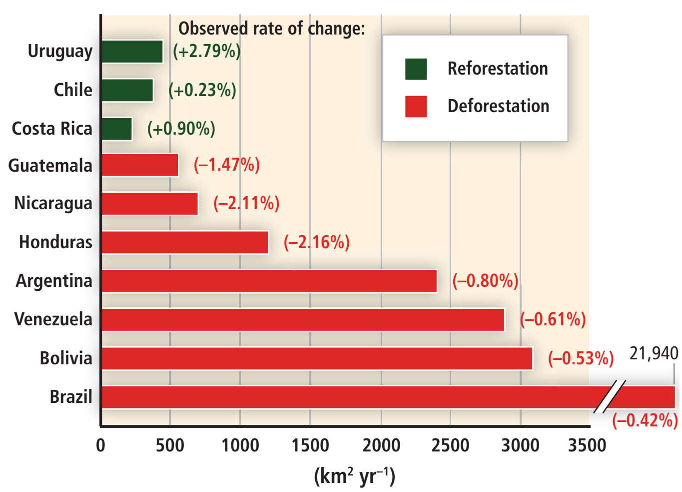

Figure 27-3 | Forest cover change per year for selected countries in Central and South America (2005–2010). Notice three countries listed with a positive change in forest cover (based on data from FAO, 2010).

The area of forest loss in CA is considerably less than in SA, owing to smaller country sizes (Carr et al., 2009), but when relative deforestation rates are considered, Honduras and Nicaragua show the highest values for CA and SA (FAO, 2010). At the same time, CA includes some countries where forest cover shows a small recovery trend in the last years: Costa Rica, El Salvador, Panama, and possibly Honduras, where data are conflicting in the literature (FAO, 2010; Aide et al., 2013). This forest transition is the result of (1) economies less dependent on agriculture, and more on industry and services (Wright and Samaniego, 2008); (2) processes of international migration with the associated remittances (Hecht and Saatchi, 2007); and (3) a stronger emphasis on the recognition of environmental services of forest ecosystems (Kaimowitz, 2008). The same positive trend is observed in some SA countries (Figure 27-3). However, a substantial amount of forest is gained through (single-crop) plantations, most noticeably in Chile (Aguayo et al., 2009), which has a much lower ecological value than the depleted natural forests (Echeverría et al., 2006; Izquierdo et al., 2008).

Land degradation is also an important process compromising extensive areas of CA and SA very rapidly. According to data from the Global Land Degradation Assessment and Improvement (GLADA) project of the Global Environmental Facility (GEF), additional degraded areas reached 16.4% of the entire territory of Paraguay, 15.3% of Peru, and 14.2% of Ecuador for the period 1982–2002. In CA, Guatemala shows the highest proportion of degraded land, currently at 58.9% of the country's territory, followed by Honduras (38.4%) and Costa Rica (29.5%); only El Salvador shows a reversal of the land degradation process, probably due to eased land exploitation following intensive international migratory processes (ECLAC, 2010d).

Deforestation and land degradation are attributed mainly to increased extensive and intensive agriculture. Two activities have traditionally dominated the agricultural expansion: soy production (only in SA) and beef. But, more recently, biomass for biofuel production has become as important (Nepstad and Stickler, 2008) with some regions also affected by oil and mining extractions. Deforestation by small farmers, coming mainly from families who migrate in search for land, is relatively low: extensive cattle production is the predominant land use in deforested areas of tropical and subtropical Latin America (Wassenaar et al., 2007). Cattle is the only land use variable correlated with deforestation in Colombia (Armenteras et al., 2013), and in the Brazilian Amazon the peak of deforestation in 2004 (Figure 27-4) was primarily the result of increased cattle ranching (Nepstad et al., 2006). Mechanized farming, agro-industrial production, and cattle ranching are the major land use change drivers in eastern Bolivia but subsistence agriculture by indigenous colonists is also important (Killeen et al., 2008).

In recent years, soybean croplands have expanded continuously in SA, becoming increasingly more important in the agricultural production of the region. Soybean-planted area in Amazonian states (mainly Mato Grosso) in Brazil expanded 12.1% per year during the 1990s, and 16.8% per year from 2000 to 2005 (Costa et al., 2007). This landscape-scale conversion from forest to soy and other large-scale agriculture can alter substantially the water balance for large areas of the region, resulting in important feedbacks to the local climate (Hayhoe et al., 2011; Loarie et al., 2011; see Section 27.3.4.1).

Soybean and beef production have also impacted other ecosystems next to the Amazon, such as the Cerrado (Brazil) and the Chaco dry forests (Bolivia, Paraguay, Argentina, and Brazil). Gasparri et al. (2008) estimated carbon emissions from deforestation in northern Argentina, and concluded that deforestation in the Chaco forest has accelerated in the past decade from agricultural expansion and is now the most important source of carbon emissions for that region. In northwest Argentina (Tucumán and Salta provinces), 14,000 km^2 of dry forest were cleared from 1972 to 2007 as a result of technological improvements and increasing rainfall (Gasparri and Grau, 2009). Deforestation continued during the 1980s and 1990s, resulting in cropland area covering up to 63% of the region by 2005 (Viglizzo et al., 2011). In central Argentina (northern Córdoba province), cultivated lands have increased from 3 to 30% (between 1969 and 1999); and the forest cover has decreased from 52.5 to 8.2%. This change has also been attributed to the synergistic effect of climatic, socioeconomic, and technological factors (Zak et al., 2008). Losses in the Atlantic forest are estimated in 29% of the original area in 1960, and in 28% of the Yunga forest area, mainly due to cattle ranching migration from the Pampas and Espinal (Viglizzo et al., 2011).

Palm oil is a significant biofuel crop also linked to recent deforestation in tropical CA and SA. Its magnitude is still small compared with deforestation related to soybean and cattle ranching, but is considerable for specific countries and expected to increase due to increasing demands for biofuels (Fitzherbert et al., 2008). The main producers of palm oil in the region are Colombia and Ecuador, followed by Costa Rica, Honduras, Guatemala, and Brazil; Brazil has the largest potential for expansion, as nearly half of the Amazonia is suitable for oil palm cultivation (Butler and Laurance, 2009). Palm oil production is also growing in the Amazonian region of Peru, where 72% of new plantations have expanded into forested areas, representing 1.3% of the total deforestation for that country for the years 2000–2010 (Gutiérrez-Vélez et al., 2011).

However, forests are not the only important ecosystems threatened in the region. An assessment of threatened ecosystems in SA by Jarvis et al. (2010) concluded that grasslands, savannahs, and shrublands are more threatened than forests, mainly from excessively frequent fires (>1 yr^{-1}) and grazing pressure. An estimation of burned land in LA by Chuvieco et al. (2008) also concluded that herbaceous areas presented the highest occurrence of fires. In the Río de la Plata region (central-east Argentina, southern Brazil, and Uruguay), grasslands decreased from 67.4 to 61.4% between 1985 and 2004. This reduction was associated with an increase in annual crops, mainly soybean, sunflower, wheat, and maize (Baldi and Paruelo, 2008).

Even with technological changes that might result in agricultural intensification, the expansion of pastures and croplands is expected to continue in the coming years (Wassenaar et al., 2007; Kaimowitz and Angelsen, 2008), particularly from an increasing global demand for food and biofuels (Gregg and Smith, 2010) with the consequent increase in commodity prices. This agricultural expansion will be mainly in LA and sub-Saharan Africa as these regions hold two-thirds of the global land with potential to expand cultivation (Nepstad and Stickler, 2008). It is important to consider the policy and legal needs to keep this process of large-scale change under control as much as possible; Takasaki (2007) showed that policies to eliminate land price distortions and promote technological transfers to poor colonists could reduce deforestation. It is also important to consider the role of indigenous groups; there is a growing acknowledgment that recognizing the land ownership and authority of indigenous groups can help central governments to better manage many of the natural areas remaining in the region (Oltremari and Jackson, 2006; Larson, 2010). The impact of indigenous groups on land use change can vary: de Oliveira et al. (2007) found that only 9% of the deforestation in the Peruvian Amazon between 1999 and 2005 happened in indigenous territories, but Killeen et al. (2008) found that Andean indigenous colonists in Bolivia were responsible for the largest land cover changes in the period 2001–2004. Indigenous groups are important stakeholders in many territories in the region and their well-being should be considered when designing responses to pressures on the land by a globalized economy (Gray et al., 2008; Killeen et al., 2008).

27.2.2.2. Trends and Projections in Socioeconomic Conditions

Development in the region has traditionally displayed four characteristics: low growth rates, high volatility, structural heterogeneity, and very unequal income distribution (ECLAC, 2008; Bárcena, 2010). This combination of factors has generated high and persistent poverty levels (45% for CA and 30% for SA for year 2010), with the rate of poverty being generally higher in rural than urban areas (ECLAC, 2009b). SA has based its economic growth in natural resource exploitation (mining, energy, agricultural), which involves direct and intensive use of land and water, and in energy-intensive and, in many cases, highly polluting natural resource-based manufactures. In turn, CA has exploited its proximity to the North American market and its relatively low labor costs (ECLAC, 2010e). The region shows a marked structural heterogeneity, where modern production structures coexist with large segments of the population with low productivity and income levels (ECLAC, 2010g). The gross domestic product (GDP) per capita in SA is twice that of CA; in addition, in the latter, poverty is 50% higher (see Figure 27-5).

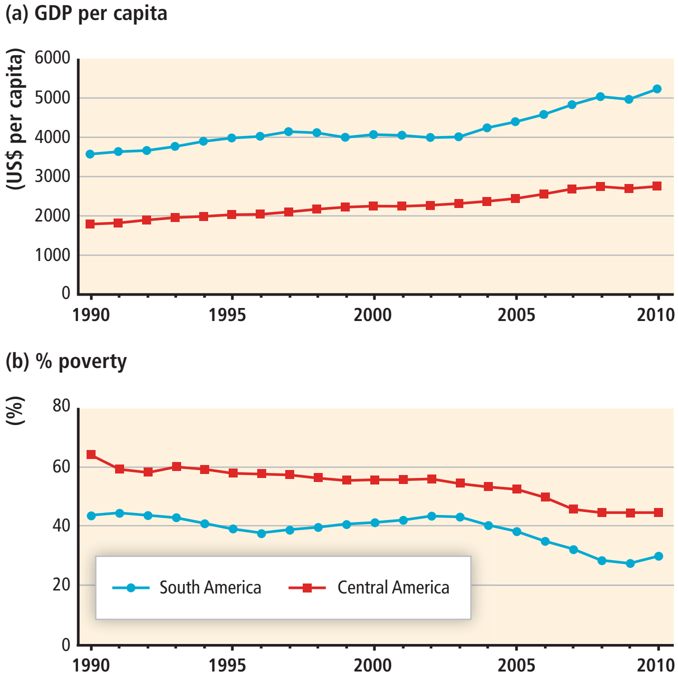

Figure 27-5 | Evolution of GDP per capita and poverty (income below US$2 per day) from 1990–2010: Central and South America (US$ per inhabitant at 2005 prices and percentages) (ECLAC, 2011c; 2012a).

The 2008 financial crisis reached CA and SA through exports and credits, remittances, and worsening expectations by consumers and producers (Bárcena, 2010; Kacef and López-Monti, 2010). This resulted in the sudden stop of six consecutive years of robust growth and improving social indicators (ECLAC, 2010e), which contributed to higher poverty in 2009 after 6 years where poverty had declined by 11%. Poverty rates fell from 44 to 33% of the total population from 2003 to 2008 (Figure 27-5), leaving 150 million people in this situation while extreme poverty diminished from 19.4 to 12.9% (which represents slightly more than 70 million people) (ECLAC, 2009b).

In the second half of 2009, industrial production and exports began to recover and yielded a stronger economic performance (GDP growth of 6.4% in SA and 3.9% in CA in 2010; ECLAC, 2012b). SA benefited the most because of the larger size of their domestic markets and the greater diversification of export markets. Conversely, slower growth was observed in CA, with more open economies and a less diversified portfolio of trading partners and a greater emphasis on manufacturing trade (ECLAC, 2010g).

The region is expected to continue to grow in the short term, albeit at a pace that is closer to potential GDP growth, helped by internal demand as the middle class becomes stronger and as credit becomes more available. In SA, this could be boosted by external demand from the Asian economies as they continue to grow at a rapid pace. The macroeconomic challenge is to act counter cyclically, creating conditions for productive development that is not based solely on commodity exports (ECLAC, 2010f).

In spite of its economic growth, CA and SA still display high and persistent inequality: most countries have Gini coefficients between 0.5 and 0.6, whereas the equivalent figures in a group of 24 developed countries vary between under 0.25 and around 0.4. The average per capita income of the richest 10% of households is approximately 17 times that of the poorest 40% of households (ECLAC, 2010g). Nevertheless, during the first decade of the century, prior to the financial crisis, the region has shown a slight but clear trend toward a more equitable distribution of income and a stronger middle class population, resulting in a higher demand for goods (ECLAC, 2010g,h, 2011b). Latin American countries also reported gains in terms of human development, although these gains have slowed down slightly over recent years. In comparative terms, as measured by the Human Development Index (HDI), the performance of countries varied greatly in 2007 (from Chile with 0.878 and Argentina with 0.866 to Guatemala with 0.704 and Nicaragua with 0.699), although those with lower levels of HDI showed notably higher improvements than countries with the highest HDI (UNDP, 2010).

Associated with inequality are disparities in access to water, sanitation, and adequate housing for the most vulnerable groups—for example, indigenous peoples, Afro-descendants, children, and women living in poverty—and in their exposure to the effects of climate change. The strong heterogeneity of subnational territorial entities in the region takes the form of high spatial concentration and persistent disparities in the territorial distribution of wealth (ECLAC, 2010g,h, 2011b).

The region faces significant challenges in terms of environmental sustainability and adaptability to a changing climate (ECLAC, 2010h), resulting from the specific characteristics of its population and economy already discussed and aggravated with a significant deficit in infrastructure development. CA and SA countries have made progress in incorporating environmental protection into decision-making processes, particularly in terms of environmental institutions and legislation, but there are still difficulties to effectively incorporate environmental issues into relevant public policies (ECLAC, 2010h). Although climate change imposes new challenges, it also provides an opportunity to shift development and economic growth patterns toward a more environmentally friendly course.

27.3. Impacts, Vulnerabilities, and Adaptation Practices

27.3.1. Freshwater Resources

CA and SA are regions with high average but unevenly distributed water resources availability (Magrin et al., 2007a). The main user of water is agriculture, followed by the region's 580 million inhabitants (including the Caribbean), of which 86% had access to water supply by 2006 (ECLAC, 2010b). According to the International Energy Agency (IEA), the region meets 60% of its electricity demand through hydropower generation, which contrasts with the 20% average contribution of other regions (see Table 27-6 and case study in Section 27.6.1).

27.3.1.1. Observed and Projected Impacts and Vulnerabilities

In CA and SA there is much evidence of changing hydrologic related conditions. The most robust trend for major rivers is found in the sub-basins of the La Plata River basin (*high confidence,* based on *robust* *evidence*, *high agreement*). This basin, second only to the Amazon in size, shows a positive trend in streamflow in the second half of the 20th century at different sites (Pasquini and Depetris, 2007; Krepper et al., 2008; Saurral et al., 2008; Amsler and Drago, 2009; Conway and Mahé, 2009; Dai et al., 2009; Krepper and Zucarelli, 2010; Dai, 2011; Doyle and Barros, 2011). An increase in precipitation and a reduction in evapotranspiration from land use changes have been associated with the trend in streamflows (Saurral et al., 2008; Doyle and Barros, 2011), with the former being more important in the southern sub-basins and the latter in the northern ones (Doyle and Barros, 2011; see Section 27.2.1). Increasing trends in streamflows have also been found in the Patos Lagoon in southern Brazil (Marques, 2012) and Laguna Mar Chiquita (a closed lake), and in the Santa Fe Province, both in Argentina, with ecological and erosive consequences (Pasquini et al., 2006; Rodrigues Capítulo et al., 2010; Troin et al., 2010; Venencio and García, 2011; Bucher and Curto, 2012).

Table 27-3 | Observed trends related to Andean cryosphere. (LIA = Little Ice Age; w.e. = water equivalent.)

(a) Andean tropical glacier trends.

Country	Documented massifs	Latitude	Significant changes recorded		References
			Variable code number[a]	Description of trend [period of observed trend]	
Venezuela	Cordillera de Mérida	10°N	1	+300 to +500 m [between LIA maximum and today]	Morris et al. (2006); Polissar et al. (2006)
			5	Accelerated melting [since 1972]. Risk of disappearing completely, as equilibrium line altitude is close to the highest peak (Pico Bolívar, 4979 m)	
Colombia	Parque Los Nevados	4°50′N	3	LIA maximum between 1600 and 1850	Ceballos et al. (2006); Ruiz et al. (2008); Poveda and Pineda (2009); IDEAM (2012); Rabatel et al. (2013)
	Sierra Nevada del Cocuy	6°30′N	3	Many small/low elevation glaciers (<5000 meters above sea level) have disappeared.	
	Sierra Nevada de Santa Marta	10°40′N	3	–60 to –84% [1850–2000]; –50% [last 50 years]; –10 to –50% [past 15 years]; retreat 3.0 km² year⁻¹ [since 2000]	
Ecuador	Antisana	0°28′S	1	+300 m [between the middle of the 18th century (LIA maximum) and the last decades of the 20th century]; about +200 m [20th century]	Francou et al. (2007); Vuille et al. (2008); Jomelli et al. (2009); Cáceres (2010); Rabatel et al. (2013)
	Chimborazo and Carihuayrazo	1°S	3	About –45% [1976–2006]. Glaciers below 5300 m in process of extinction	
Peru	Cordillera Blanca	9°S	1	About +100 m [between LIA maximum and beginning of the 20th century]; +150 m [20th century]	Raup et al. (2007); Jomelli et al. (2009); Mark et al. (2010); UGHR (2010); Bury et al. (2011); Baraer et al. (2012); Rabatel et al. (2013)
			3	–12 to –17% [18th century]; –17 to –20% [19th century]; –20 to –35% [1960s–2000s]	
			4	-8 m decade^{-1} [since 1970] (Yanamarey glacier)	
			8	+1.6% (±1.1) (watersheds with >20% glacier area)	
			8	Seven out of nine watersheds decreasing dry-season discharge	
	Coropuna volcano	15°33′S	3	–26% [1962–2000]	Racoviteanu et al. (2007)
	Cordillera Vilcanota	13°55′S	3	10 times faster [in 1991–2005 compared to 1963–2005]	Thompson et al. (2006, 2011)
			3, 5	About –30% area and about –45% volume [since 1985]	Salzmann et al. (2013)
Bolivia	Cordillera Real and Cordillera Quimsa Cruz	16°S	1	+300 m [between LIA maximum and late 20th century]; +180 to +200 m [20th century]	Rabatel et al. (2006, 2008); Francou et al. (2007); Vuille et al. (2008); Soruco et al. (2009); Gilbert et al. (2010); Jomelli et al. (2011); Rabatel et al. (2013)
			3	–48% [1976–2006] in the Cordillera Real; Chacaltaya vanished [in 2010].	
			5	Zongo glacier has lost a mean of 0.4 m (w.e.) year^{-1} [in the 1991–2011 period]; glaciers in the Cordillera Real lost 43% of their volume [1963–2006; maximum rate of loss in 1976–2006].	
			2	+1.1°C ± 0.2°C [over the 20th century] at about 6340 meters above sea level	
	Caquella rock glacier (South Bolivian Altiplano)	21°30′S	7	Evidence of recent degradation	Francou et al. (1999)

(b) Extratropical Andean cryosphere (glaciers, snowpack, runoff effects) trends.

Region	Documented massifs/sites	Latitude	Significant changes recorded		References
			Variable code number[a]	Value of trend [period of observed trend]	
Chile, Argentina, Bolivia, and Argentinean Patagonia		South of 15°S	6	No significant trend	Foster et al. (2009)
Desert Andes (17°S–31°S)	Huasco basin glaciers	29°S	5	-0.84 m (w.e.) year^{-1} [2003/2004–2007/2008]	Nicholson et al. (2009); Gascoin et al. (2011); Rabatel et al. (2011)

Continued next page →

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Table 27-3(b) (continued)

Region	Documented massifs/sites	Latitude	Significant changes recorded: Variable code number[a]	Significant changes recorded: Value of trend [period of observed trend]	References
Central Andes (31°S–36°S)	Piloto/Las Cuevas	32°S	5	–10.50 m (w.e.) [last 24 years]	Leiva et al. (2007)
	Aconcagua basin glaciers	33°S	3	–20% [last 48 years]	Pellicciotti et al. (2007); Bown et al. (2008)
			3	–14% [1955–2006]	
			8	Significant decrease in Aconcagua basin streamflow	
	Central Andes glaciers	33°S–36°S	3	–3% [since 1955]	Le Quesne et al. (2009)
			4	–50 to –9 m $year^{-1}$ [during 20th century]	
			5	–0.76 to –0.56 m (w.e.) $year^{-1}$ [during 20th century]	
	Central Andes		1	+122 ± 8 m (winter) and +200 ± 6 m (summer) [1975–2001]	Carrasco et al. (2005)
	Snowpack	30°S–37°S	6	Positive, though nonsignificant, linear trend [1951–2005]	Masiokas et al. (2006); Vich et al. (2007); Vicuña et al. (2013)
			8	Mendoza River streamflow: possible link to rising temperatures and snowpack/glacier effects. Not conclusive; increase in high and low flows possibly associated with increase in temperature and effects on snowpack	
	Morenas Coloradas rock glacier	32°S–33°S	7	Significant change in active layer possibly associated with warming processes	Trombotto and Borzotta (2009)
	Cryosphere in the Andes of Santiago	33.5°S	5	Expansion of thermokarst depressions	Bodin et al. (2010)
	Basins	28°S–47°S	8	Non-significant increase in February runoff; possible increase of glacier melt [1950–2007]	Casassa et al. (2009)
		30°S–40°S	8	Significant negative timing trend (centroid timing date shifting toward earlier in the year) for 23 out of the 40 analyzed series	Cortés et al. (2011)
Patagonian Andes (36°S–55°S)	Basins	28°S–47°S	8	Not significant increase in February runoff trends that might suggest an increase of glacier melt in the Andes [1950–2007]	Casassa et al. (2009)
	Northwest Patagonia	38°S–45°S	4	Recession of six glaciers based on aerial photograph analysis	Masiokas et al. (2008)
	Proglacial lakes	40°S–50°S	8	Summertime negative trend on lakes indicating that melt water is decreasing	Pasquini et al. (2008)
	Casa Pangue glacier	41°S	5	–2.3 ± 0.6 m (w.e.) $year^{-1}$ [1961–1998]	Bown and Rivera (2007)
			4	–3.6 ± 0.6 m $year^{-1}$ [1981–1998]	
	Manso Glacier	41°S	8	Reduction in discharge associated with reduction in melt and precipitation	Pasquini et al. (2013)
	Patagonian Ice Field	47°S–51°S	5	–1.6 m (w.e.) $year^{-1}$ or –27.9 ± 11 km^3 (w.e.) $year^{-1}$ [2002–2006]	Chen et al. (2007)
	Northern Patagonian Ice Field	47°S	8	Glacial lake outburst flood possible response to retreat of Calafate glacier [20th century]	Harrison et al. (2006)
	Southern Patagonian Ice Field	48°S–51°S	4	Larger retreating rates observed on the west side coinciding with lower elevations of equilibrium line altitudes	Barcaza et al. (2009)
	Northern Patagonian, Southern Patagonian, and Cordillera Darwin ice fields	47°S–51°S, 54°S	4	5.7 to 12.2 km [1945–2005]	Lopez et al. (2010)
	Gran Campo Nevado	53°S	4	–2.8% of glacier length per decade [1942–2002]	Schneider et al. (2007)
			3	–2.4% per decade [1942–2002]	
	Cordón Martial glaciers	54°S	5	Slow retreat from late LIA. Acceleration started 60 years ago.	Sterlin and Iturraspe (2007)

[a]Variable coding: (1) Increase in equilibrium line altitude; (2) atmospheric warming revealed by englacial temperature measured at high elevation; (3) area reduction; (4) frontal retreat; (5) volume reduction; (6) snow cover; (7) rock glaciers; (8) runoff change.

There is no clear long-term trend for the Amazon River. Espinoza et al. (2009a, 2011) showed that the 1974–2004 apparent stability in mean discharge at the main stem of the Amazon in Obidos is explained by opposing regional features of Andean rivers (e.g., increasing trends during the high-water period in Peruvian and Colombian Amazons and decreasing trend during the low-water period in Peruvian and Bolivian Amazons (Lavado et al., 2012). In recent years extremely low levels were experienced during the droughts of 2005 and 2010, while record high levels were detected during the 2009 and 2012 floods (Section 27.2.1). Major Colombian rivers draining to the Caribbean Sea (Magdalena and Cauca) exhibit decreasing trends along their main channels (Carmona and Poveda, 2011), while significant trends are absent for all other major large rivers in NEB and northern SA (Dai et al., 2009). Dai (2011) showed a drying trend in CA rivers.

A rapid retreat and melting of the tropical Andes glaciers of Venezuela, Colombia, Ecuador, Peru, and Bolivia has been further reported following the IPCC AR4, through use of diverse techniques (*high confidence*, based

Table 27-4 | Synthesis of projected climate change impacts on hydrological variables in Central American and South American basins and major glaciers.

Region	Basins studied	Variable code number[a]	Projected change	Period	General circulation model (greenhouse gas scenario)	References
Río de La Plata Basin and Southeastern South America	Paraná River	1	+4.9% (not robust)	2081–2100	CMIP3 models (A1B)	Nohara et al. (2006)
			+10 to +20%	2100	Eta-HadCM3 (A1B)	Marengo et al. (2011a)
			+18.4% (significant)	2075–2100	CMIP3 models (A1B)	Nakaegawa et al. (2013a)
	Rio Grande	1	+20 to –20%	Different periods	7 CMIP3 models	Gosling et al. (2011); Nóbrega et al. (2011); Todd et al. (2011)
	Itaipu Power Plant (on the Paraná River)	1	Left bank: –5 to –15%; right bank: +30%	2010–2040	CCCMA–CGCM2 (A2)	Rivarola et al. (2011)
			0 to –30%	2070–2100		
	Concórdia River	1	–40%	2070–2100	HadRM3P (A2, B2)	Perazzoli et al. (2013)
	Carcarañá River	2	Increase	2010–2030	HadCM3 (A2)	Venencio and García (2011)
		3	Slight reduction			
Amazon Basin	Peruvian Amazon basins	1	Increase in some basins; reduction in others	Three time slices	BCM2, CSMK3 and MIHR (A1B, B1)	Lavado et al. (2011)
	Basins in region of Alto Beni, Bolivia	1	Increase and reduction	2070–2100	CMIP3 models (A1B)	Fry et al. (2012)
		3	Always reduction			
		5	Increase in water stress			
	Paute and Tomebamba Rivers	1	Increase in some scenarios; reduction in others	2070–2100	CMIP3 models (A1B)	Buytaert et al. (2011)
	Amazon River	1	+5.4% (not robust)	2081–2100	CMIP3 models (A1B)	Nohara et al. (2006)
			+6%	2000–2100	ECBilt–CLIO–VECODE (A2)	Aerts et al. (2006)
			+3.7% (significant)	2075–2100	CMIP3 models (A1B)	Nakaegawa et al. (2013a)
			At Óbidos Station: no change in high flow; reduction in low flow	2046–2065/ 2079–2098	8 AR4 GCMs (B1, A1B, and A2)	Guimberteau et al. (2013)
	Amazon and Orinoco Rivers	1	–20%	2050s	HadCM3 (A2)	Palmer et al.(2008)
	Basins in Brazil	1	Consistent decrease	2050s	HadCM3 and CMIP3 models (A1B)	Arnell and Gosling (2013)
Tropical Andes	Colombian glaciers	4	Disappearance by 2020s	Linear extrapolation		Poveda and Pineda (2009)
	Cordillera Blanca glacierized basins	1	Increase for next 20–50 years, reduction afterwards	2005–2020	Temperature output only (B2)	Chevallier et al. (2011)
		4	Area –38 to –60%. Increased seasonality	2050	Not specified (A1, A2, B1, B2)	Juen et al. (2007)
			Area –49 to –75%. Increased seasonality	2080		
			Increased seasonality	2030	16 CMIP3 models (A1B, B1)	Condom et al. (2012)
	Basins providing water to cities of Bogotá, Quito, Lima, and La Paz	5	Inner tropics: only small change; increase in precipitation and increase in evapotranspiration	2010–2039 and 2040–2069	19 CMIP3 models (A1B, A2)	Buytaert and De Bièvre (2012)
			Outer tropics: severe reductions; decrease in precipitation and increase in evapotranspiration			
Central Andes	Limarí River	1	–20 to –40%	2070–2100	HadCM3 (A2, B2)	Vicuña et al. (2011)
			–20%	2010–2040	15 CMIP3 models (A1B, B2, B1)	Vicuña et al. (2012)
			–30 to –40%; change in seasonality	2070–2100		
	Maipo River	1	–30%	Three 30-year periods	HadCM3 (A2, B2)	ECLAC (2009a); Melo et al. (2010); Meza et al. (2012)
		5	Unmet demand up to 50%	2070–2090		
	Mataquito River	1	Reduction in average and low flows Increase in high flows	Three 30-year periods	CMIP3 (A2, B1) and CMIP5 (RCP4.5 and 8.5) models	Demaria et al. (2013)
	Maule and Laja Rivers	1	–30%	Three 30-year periods	HadCM3 (A2, B2)	ECLAC (2009a); McPhee et al. (2010)
	Bío Bío River	1	–81 to +7%	2070–2100	8 GCMs (6 SRES)	Stehr et al. (2010)
	Limay River	1	–10 to –20%	2080s	HadCM2 (NS)	Seoane and López (2007)

Continued next page →

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Table 27-4 (continued)

Region	Basins studied	Variable code number[a]	Projected change	Period	General circulation model (greenhouse gas scenario)	References
Northeastern Brazil	Basins in the Brazilian states of Ceará and Piauí	1	No significant change up to 2025. After 2025: strong reduction with ECHAM4; slight increase with HadCM2.	2000–2100	HadCM2, ECHAM4 (NS)	Krol et al. (2006); Krol and Bronstert (2007)
	Paracatu River	1	+31 to +131%	2000–2100	HadCM3 (A2)	De Mello et al. (2008)
			No significant change	2000–2100	HadCM3 (B2)	
	Jaguaribe River	2	Demand: +33 to +44%	2040	HadCM3 (A2, B2)	Gondim et al. (2008, 2012)
			Irrigation water needs: +8 to +9%	2025–2055	HadCM3 (B2)	
	Parnaíba River	1	–80%	2050s	HadCM3 (A2)	Palmer et al. (2008)
	Mimoso River	1	Dry scenario: –25 to –75%	2010–2039, 2040–2069, and 2070–2099	CSMK3 and HadCM3 (A2, B1)	Montenegro and Ragab (2010)
			Wet scenario: +40 to +140%			
		3	No change			
	Tapacurá River	1	B1: –4.89%, –14.28%, –20.58%	Three 30-year periods	CSMK3 and MPEH5 (A2, B1)	Montenegro and Ragab (2012)
			A2: +25.25%, +39.48%, +21.95%			
	Benguê Catchment	1	–15% reservoir yield	Sensitivity scenario in 2100 selected from Third and Fourth Assessment Report general circulation models with good skill. +15% potential evapostranspiration, –10% precipitation		Krol et al. (2011)
	Aquifers in northeastern Brazil	3	Reduction	2040–2070	HadCM3, ECHAM4 (A2,B2)	Hirata and Conicelli (2012)
Northern South America	Essequibo River	1	–50%	2050s	HadCM3 (A2)	Palmer et al. (2008)
	Magdalena River	1	Non-significant changes in near future. End of 21st century changes in seasonality.	2015–2035 and 2075–2099	CMIP3 multi-model ensemble (A1B)	Nakaegawa and Vergara (2010)
	Sinú River	1	–2 to –35%	2010–2039	CCSRNIES, CSIROMK2B, CGCM2, HadCM3 (A2)	Ospina-Noreña et al. (2009a,b)
Central America	Lempa River	1	–13%	2070–2100	CMIP3 models (B1)	Maurer et al. (2009)
			–24%	2070–2100	CMIP3 models (A2)	
	Río Grande de Matagalpa	1	–70%	2050s	HadCM3 (A2)	Palmer et al. (2008)
	Basins in Mesoamerica	1	Decrease across the region	2070–2100	CMIP3 (A2, A1B, B1)	Imbach et al. (2012)
			Consistent decrease	2050s	HadCM3 and CMIP3 models (A1B)	Arnell and Gosling (2013)
			Consistent reduction in northern CA	2050–2099	30 GCMs (A1B)	Hidalgo et al. (2013)
	Basins in Panama	1	Basins discharging into the Pacific: +35 to +40%	2075–2099	MRI-AGCM3.1 (A1B)	Fábrega et al. (2013)
			Basins in the Bocas del Toro region: –50%			

[a]Variable coding: (1) Runoff/discharge; (2) demand; (3) recharge; (4) glacier change; (5) unmet demand/water availability.

on *robust evidence*, *high agreement*). Rabatel et al. (2013) provides a synthesis of these studies (specific papers are presented in Table 27-3a). Tropical glaciers' retreat has accelerated in the second half of the 20th century (area loss between 20 and 50%), especially since the late 1970s in association with increasing temperature in the same period (Bradley et al., 2009). In early stages of glacier retreat, associated streamflow tends to increase due to an acceleration of glacier melt, but after a peak in streamflow as the glacierized water reservoir gradually empties, runoff tends to decrease, as evidenced in the Cordillera Blanca of Peru (Chevallier et al., 2011; Baraer et al., 2012), where seven out of nine river basins have probably crossed a critical threshold, exhibiting a decreasing dry-season discharge (Baraer et al., 2012). Likewise, glaciers and ice fields in the extratropical Andes located in central-south Chile and Argentina face significant reductions (see review in Masiokas et al. (2009) and details in Table 27-3b), with their effect being compounded by changes in snowpack extent, thus magnifying changes in hydrograph seasonality by reducing flows in dry seasons and increasing them in wet seasons (Pizarro et al., 2013; Vicuña et al., 2013). Central-south Chile and Argentina also face significant reductions in precipitation as shown in Section 27.2.1, contributing to runoff reductions in the last decades of the 20th century (Seoane and López, 2007; Rubio-Álvarez and McPhee, 2010; Urrutia et al., 2011; Vicuña et al., 2013), corroborated with long-term trends found through dendrochronology (Lara et al., 2007; Urrutia et al., 2011). Trends in precipitation and runoff are less evident in the central-north region in Chile (Fiebig-Wittmaack et al., 2012; Souvignet et al., 2012).

As presented in Table 27-4, the assessment of future climate scenarios implications in hydrologic related conditions shows a large range of uncertainty across the spectrum of climate models (mostly using CMIP3 simulations with the exception of Demaria et al. (2013)) and scenarios considered. Nohara et al. (2006) studied climate change impacts on 24 of the main rivers in the world considering a large number of General Circulation Models (GCMs), and found no robust change for the Paraná

(La Plata Basin) and Amazon Rivers. Nevertheless, in both cases the average change showed a positive value consistent, at least with observations for the La Plata Basin. In a more recent work Nakaegawa et al. (2013a) showed a statistically significant increase for both basins in a study that replicated that of Nohara et al. (2006) but with a different hydrologic model. Focusing in extreme flows Guimberteau et al. (2013) show that by the middle of the century no change is found in high flow on the main stem of the Amazon River but there is a systematic reduction in low-flow streamflow. In contrast, the northwestern part of the Amazon River shows a consistent increase in high flow and inundated area (Guimberteau et al., 2013; Langerwisch et al., 2013). On top of such climatic uncertainty, future streamflows and water availability projections are confounded by the potential effects of land use changes (Moore et al., 2007; Coe et al., 2009; Georgescu et al., 2013).

The CA region shows a consistent future runoff reduction. Maurer et al. (2009) studied climate change projections for the Lempa River basin, one of the largest basins in CA, covering portions of Guatemala, Honduras, and El Salvador. They showed that future climate projections (increase in evaporation and reduction in precipitation) imply a reduction of 20% in inflows to major reservoirs in this system (see Table 27-4). Imbach et al. (2012) found similar results using a modeling approach that also considered potential changes in vegetation. These effects could have large hydropower generation implications as discussed in the case study in Section 27.6.1.

The evolution of tropical Andes glaciers associated future climate scenarios has been studied using trend (e.g., Poveda and Pineda, 2009), regression (e.g., Juen et al., 2007; Chevallier et al., 2011), and explicit modeling (e.g., Condom et al., 2012) analysis. These studies indicate that glaciers will continue their retreat (Vuille et al., 2008a) and even disappear as glacier equilibrium line altitude rises, with larger hydrological effects during the dry season (Kaser et al., 2010; Gascoin et al., 2011). This is expected to happen during the next 20 to 50 years (Juen et al., 2007; Chevallier et al., 2011; see Table 27-4). After that period water availability during the dry months is expected to diminish. A projection by Baraer et al. (2012) for the Santa River in the Peruvian Andes finds that once the glaciers are completely melt, annual discharge would decrease by 2 to 30%, depending on the watershed. Glacier retreat can exacerbate current water resources-related vulnerability (Bradley et al., 2006; Casassa et al., 2007; Vuille et al., 2008b; Mulligan et al., 2010), diminishing the mountains' water regulation capacity, making the supply of water for diverse purposes, as well as for ecosystems integrity, more expensive and less reliable (Buytaert et al., 2011). Impacts on economic activities associated with conceptual scenarios of glacier melt reduction have been monetized (Vergara et al., 2007), representing about US$100 million in the case of water supply for Quito, and between US$212 million and US$1.5 billion in the case of the Peruvian electricity sector due to losses of hydropower generation (see the case study in Section 27.6.1). Andean communities will face an important increase in their vulnerability, as documented by Mark et al. (2010), Pérez et al. (2010), and Buytaert and De Bièvre (2012).

In central Chile, Vicuña et al. (2011) project changes in the seasonality of streamflows of the upper snowmelt-driven watersheds of the Limarí River, associated with temperature increases and reductions in water availability owing to a reduction (increase) in precipitation (evapotranspiration). Similar conclusions are derived across the Andes on the Limay River in Argentina by Seoane and López (2007). Under these conditions, semi-arid highly populated basins (e.g., Santiago, Chile) and with extensive agriculture irrigation and hydropower demands are expected to increase their current vulnerability (*high confidence*; ECLAC, 2009a; Souvignet et al., 2010; Fiebig-Wittmaack et al., 2012; Vicuña et al., 2012; see Table 27-4). Projected changes in the cryosphere conditions of the Andes could affect the occurrence of extreme events, such as extreme low and high flows (Demaria et al., 2013), Glacial Lake Outburst Floods (GLOF) occurring in the ice fields of Patagonia (Dussaillant et al., 2010; Marín et al., 2013), volcanic collapse and debris flow associated with accelerated glacial melting in the tropical Andes (Carey, 2005; Carey et al., 2012b; Fraser, 2012), and with volcanoes in southern Chile and Argentina (Tormey, 2010), as well as scenarios of water quality pollution by exposure to contaminants as a result of glaciers' retreat (Fortner et al., 2011).

Another semi-arid region that has been studied thoroughly is northeast Brazil (Hastenrath, 2012). de Mello et al. (2008), Gondim et al. (2008), Souza et al. (2010), and Montenegro and Ragab (2010) have shown that future climate change scenarios would decrease water availability for agriculture irrigation owing to reductions in precipitation and increases in evapotranspiration (*medium confidence*). Krol and Bronstert (2007) and Krol et al. (2006) presented an integrated modeling study that linked projected impacts on water availability for agriculture with economic impacts that could potentially drive full-scale migrations in the NEB region.

27.3.1.2. Adaptation Practices

At an institutional level, a series of policies have been developed to reduce vulnerability to climate variability as faced today in different regions and settings. In 1997, Brazil instituted the National Water Resources Policy and created the National Water Resources Management System under the shared responsibility between the states and the federal government. Key to this new regulation has been the promotion of decentralization and social participation through the creation of National Council of Water Resources and their counterparts in the states, the States Water Resources Councils. The challenges and opportunities dealing with water resources management in Brazil in the face of climate variability and climate change have been well studied (Abers, 2007; Kumler and Lemos, 2008; Medema et al., 2008; Engle et al., 2011; Lorz et al., 2012). Other countries in the region are following similar approaches. In the last years, there have been constitutional and legal reforms toward more efficient and effective water resources management and coordination among relevant actors in Honduras, Nicaragua, Ecuador, Peru, Uruguay, Bolivia, and Mexico; although in many cases, these innovations have not been completely implemented (Hantke-Domas, 2011). Institutional and governance improvements are required to ensure an effective implementation of these adaptation measures (e.g., Halsnæs and Verhagen, 2007; Engle and Lemos, 2010; Lemos et al., 2010; Zagonari, 2010; Pittock, 2011; Kirchhoff et al. 2013).

With regard to region-specific freshwater resources issues it is important to consider adaptation to reduce vulnerabilities in the communities along the tropical Andes and the semi-arid basins in Chile-Argentina, NEB, and the northern CA basins. Different issues have been addressed in

Frequently Asked Questions

FAQ 27.1 | What is the impact of glacier retreat on natural and human systems in the tropical Andes?

The retreat of glaciers in the tropical Andes mountains, with some fluctuations, started after the Little Ice Age (16th to 19th centuries), but the rate of retreat (area reduction between 20 and 50%) has accelerated since the late 1970s. The changes in runoff from glacial retreat into the basins fed by such runoff vary depending on the size and phase of glacier retreat. In an early phase, runoff tends to increase as a result of accelerated melting, but after a peak, as the glacierized water reservoir gradually empties, runoff tends to decrease. This reduction in runoff is more evident during dry months, when glacier melt is the major contribution to runoff (*high confidence*).

A reduction in runoff could endanger high Andean wetlands (bofedales) and intensify conflicts between different water users among the highly vulnerable populations in high-elevation Andean tropical basins. Glacier retreat has also been associated with disasters such as glacial lake outburst floods that are a continuous threat in the region. Glacier retreat could also impact activities in high mountainous ecosystems such as alpine tourism, mountaineering, and adventure tourism (*high confidence*).

assessment of adaptation strategies for tropical Andean communities such as the role of governance and institutions (Young and Lipton, 2006; Lynch, 2012), technology (Carey et al., 2012a), and the dynamics of multiple stressors (McDowell and Hess, 2012; Bury et al., 2013). Semi-arid regions are characterized by pronounced climatic variability and often by water scarcity and related social stress (Krol and Bronstert, 2007; Scott et al., 2012, 2013). Adaptation tools to face the threats of climate change for the most vulnerable communities in the Chilean semi-arid region are discussed by Young et al. (2010) and Debels et al. (2009). In CA, Benegas et al. (2009), Manuel-Navarrete et al. (2007), and Aguilar et al. (2009) provide different frameworks to understand vulnerability and adaptation strategies to climate change and variability in urban and rural contexts, although no specific adaptation strategies are suggested. The particular experience in NEB provides other examples of adaptation strategies to manage actual climate variability. Broad et al. (2007) and Sankarasubramanian et al. (2009) studied the potential benefits of streamflow forecast as a way to reduce the impacts of climate change and climate variability on water distribution under stress conditions. An historical review and analysis of drought management in this region are provided by Campos and Carvalho (2008). de Souza Filho and Brown (2009) studied different water distribution policy scenarios, finding that the best option depended on the degree of water scarcity. The study by Nelson and Finan (2009) provides a critical perspective of drought-related policies, arguing that they constitute an example of maladaptation as they do not try to solve the causes of vulnerability and instead undermine resilience. Tompkins et al. (2008) are also critical of risk reduction practices in this region because they have fallen short of addressing the fundamental causes of vulnerability needed for efficient longer term drought management. Other types of adaptation options that stem from studies on arid and semi-arid regions are related to (1) increase in water supply from groundwater pumping (Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010; Burte et al., 2011; Nadal et al., 2013), fog interception practices (Holder, 2006; Klemm et al., 2012), and reservoirs and irrigation infrastructure (Fry et al., 2010; Vicuña et al., 2010, 2012); and (2) improvements in water demand management associated with increased irrigation efficiency and practices (Geerts et al., 2010; Montenegro and Ragab, 2010; van Oel et al., 2010; Bell et al., 2011; Jara-Rojas et al., 2012) and changes toward less water-intensive crops (Montenegro and Ragab, 2010).

Finally, flood management practices also provide a suite of options to deal with actual and future vulnerabilities related to hydrologic extremes, such as the management of ENSO-related events in Peru via participatory (Warner and Oré, 2006) or risk reduction approaches (Khalil et al., 2007), the role of land use management (Bathurst et al., 2010, 2011; Coe et al., 2011), and flood hazard assessment (Mosquera-Machado and Ahmad, 2006) (*medium confidence*).

27.3.2. Terrestrial and Inland Water Systems

27.3.2.1. Observed and Projected Impacts and Vulnerabilities

CA and SA house the largest biological diversity and several of the world's megadiverse countries (Mittermeier et al., 1997; Guevara and Laborde, 2008). However, land use change has led to the existence of six biodiversity hotspots, that is, places with a great species diversity that show high habitat loss and also high levels of species endemism: Mesoamerica, Chocó-Darien-Western Ecuador, Tropical Andes, Central Chile, Brazilian Atlantic forest, and Brazilian Cerrado (Mittermeier et al., 2005). Thus, conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss in the region (Ayoo, 2008). Tropical deforestation is the second largest driver of anthropogenic climate change on the planet, adding up to 17 to 20% of total greenhouse gas (GHG) emissions during the 1990s (Gullison et al., 2007; Strassburg et al., 2010). In parallel, the region still has large extensions of wilderness areas for which the Amazon is the most outstanding example. Nevertheless, some of these areas are precisely the new frontier of economic expansion. For instance, between 1996 and 2005, Brazil deforested about 19,500 $km^2\ yr^{-1}$, which represented 2 to 5% of global annual carbon dioxide (CO_2) emissions (Nepstad et al., 2009). Between 2005 and 2009, deforestation in the Brazilian Amazon dropped by 36%, which is partly related to the network of protected areas that now covers around 45.6% of the biome in Brazil (Soares-Filho et al., 2010). Using the LandSHIFT modeling framework for land use change and the IMPACT projections of crop/livestock production, Lapola et al. (2011) projected that zero deforestation in the Brazilian Amazon forest by 2020 (and of the Cerrado by 2025) would require either a reduction of 26 to 40% in livestock production until 2050 or a doubling of average livestock density from 0.74 to 1.46 head per hectare. Thus, climate change may imply reduction of yields and entail further deforestation.

Local deforestation rates or rising GHGs globally drive changes in the regional SA that during this century might lead the Amazon rainforest into crossing a critical threshold at which a relatively small perturbation can qualitatively alter the state or development of a system (Cox et al., 2000; Salazar et al., 2007; Sampaio et al., 2007; Lenton et al., 2008; Nobre and Borma, 2009). Various models are projecting a risk of reduced rainfall and higher temperatures and water stress, which may lead to an abrupt and irreversible replacement of Amazon forests by savanna-like vegetation, under a high emission scenario (A2), from 2050–2060 to 2100 (Betts et al., 2004, 2008; Cox et al., 2004; Salazar et al., 2007; Sampaio et al., 2007; Malhi et al., 2008, 2009; Sitch et al., 2008; Nobre and Borma, 2009; Marengo et al., 2011c). The possible "savannization" or "die-back" of the Amazon region would potentially have large-scale impacts on climate, biodiversity, and people in the region. The possibility of this die-back scenario occurring, however, is still an open issue and the uncertainties are still very high (Rammig et al., 2010; Shiogama et al., 2011).

Plant species are rapidly declining in CA, SA, Central and West Africa, and Southeast Asia (Bradshaw et al., 2009). Risk estimates of plant species extinction in the Amazon, which do not take into account possible climate change impacts, range from 5 to 9% by 2050 with a habitat reduction of 12 to 24% (Feeley and Silman, 2009) to 33% by 2030 (Hubbell et al., 2008). The highest percentage of rapidly declining amphibian species occurs in CA and SA. Brazil is among the countries with most threatened bird and mammal species (Bradshaw et al., 2009).

A similar scenario is found in inland water systems. Among components of aquatic biodiversity, fish are the best-known organisms (Abell et al., 2008), with Brazil accounting for the richest icthyofauna of the planet (Nogueira et al., 2010). For instance, the 540 Brazilian small microbasins host 819 fish species with restrict distribution. However, 29% of these microbasins have historically lost more than 70% of their natural vegetation cover and only 26% show a significant overlap with protected areas or indigenous reserves. Moreover, 40% of the microbasins overlap with hydrodams (see Section 27.6.1 and Chapter 3) or have few protected areas and high rates of habitat loss (Nogueira et al., 2010).

The faster and more severe the rate of climate change, the more severe the biological consequences such as species decline (Brook et al., 2008). Vertebrate fauna in North and South America is projected to suffer species losses until 2100 of at least 10%, as forecasted in more than 80% of the climate projections based on a low-emissions scenario (Lawler et al., 2009). Vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains for emission scenarios varying from low B1 to mid-high A2 (Lawler et al., 2009). Elevational specialists, that is, a small proportion of species with small geographic ranges restricted to high mountains, are most frequent in the Americas (e.g., Andes and Sierra Madre) and might be particularly vulnerable to global warming because of their small geographic ranges and high energetic and area requirements, particularly birds and mammals (Laurance et al., 2011). In Brazil, projections for Atlantic forest birds (Anciães and Peterson, 2006), endemic bird species (Marini et al., 2009), and plant species (by 2055, scenarios HHGSDX50 and HHGGAX50; Siqueira and Peterson, 2003) of the Cerrado indicate that distribution will dislocate toward the south and southeast, precisely where fragmentation and habitat loss are worse. Global climate change is also predicted to increase negative impacts worldwide, including SA, on freshwater fisheries due to alterations in physiology and life histories of fish (Ficke et al., 2007).

In addition to climate change impacts at the individual species level, biotic interactions will be affected. Modifications in phenology, structure of ecological networks, predator-prey interactions, and non-trophic interactions among organisms have been forecasted (Brooker et al., 2008; Walther, 2010). The outcome of non-trophic interactions among plants is expected to shift along with variation in climatic parameters, with more facilitative interactions in more stressful environments, and more competitive interactions in more benign environments (Brooker et al., 2008; Anthelme et al., 2012). These effects are expected to have a strong influence of community and ecosystem (re-)organization given the key engineering role played by plants on the functioning of ecosystems (Callaway, 2007). High Andean ecosystems, especially those within the tropics, are expected to face exceptionally strong warming effects during the 21st century because of their uncommonly high altitude (Bradley et al., 2006). At the same time they provide a series of crucial ecosystem services for millions of people (Buytaert et al., 2011). For these reasons shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in this region.

Although in the region biodiversity conservation is largely confined to protected areas, with the magnitude of climatic changes projected for the century, it is expected that many species and vegetational types will lose representativeness inside such protected areas (Heller and Zavaleta, 2009).

27.3.2.2. Adaptation Practices

The subset of practices that are multi-sectoral, multi-scale, and based on the premise that ecosystem services reduce the vulnerability of society to climate change are known as Ecosystem-based Adaptation (EbA; Vignola et al., 2009; see Glossary and Box CC-EA). Schemes such as the payment for environmental services (PES) and community management fit the concept of EbA that begins to spread in CA and SA (Vignola et al., 2009). The principle behind these schemes is the valuation of ecosystem services that should reflect both the economic and cultural benefits derived from the human-ecosystem interaction and the capacity of ecosystems to secure the flow of these benefits in the future (Abson and Termansen, 2011).

Because PES schemes have developed more commonly in CA and SA than in other parts of the world (Balvanera et al., 2012), this topic will be covered as a case study (see Section 27.6.2).

Ecological restoration, conservation in protected areas, and community management can all be important tools for adaptation. A meta-analysis of 89 studies by Benayas et al. (2009) (with a time scale of restoration varying from <5 to 300 years), including many in SA, showed that ecological restoration enhances the provision of biodiversity and environmental services by 44 and 25%, respectively, as compared to degraded systems. Moreover, ecological restoration increases the potential for carbon sequestration and promotes community organization, economic activities, and livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon et al., 2011; Rodrigues et al., 2011). In that sense, Locatelli et al. (2011) revised several ecosystem conservation and restoration initiatives in CA and SA that simultaneously help mitigate and adapt to climate change. Chazdon et al. (2009) also highlight the potential of restoration efforts to build ecological corridors (see Harvey et al., 2008, for an example in Central America).

The effective management of natural protected areas and the creation of new protected areas within national protected area systems and community management of natural areas are also efficient tools to adapt to climate change and to reconcile biodiversity conservation with socioeconomic development (e.g., Bolivian Andes: Hoffmann et al., 2011; Panama: Oestreicher et al., 2009). Porter-Bolland et al. (2012) compared protected areas with areas under community management in different parts of the tropical world, including CA and SA, and found that protected areas have higher deforestation rates than areas with community management. Similarly, Nelson and Chomitz (2011) found for the region that (1) protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and (2) in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas. This contrasts with the findings of Miteva et al. (2012), who found protected areas more efficient in constraining deforestation than other schemes. Other good examples of adaptive community management in the continent include community forest concessions (e.g., Guatemala: Radachowsky et al., 2012), multiple-use management of forests (Guariguata et al., 2012; see also examples in Brazil: Klimas et al., 2012, Soriano et al., 2012, and Bolivia: Cronkleton et al., 2012); and local communities where research and monitoring protocols are in place to pay the communities for collecting primary scientific data (Luzar et al., 2011).

27.3.3. Coastal Systems and Low-Lying Areas

27.3.3.1. Observed and Projected Impacts and Vulnerabilities

Climate change is altering coastal and marine ecosystems (Hoegh-Guldberg and Bruno, 2010). Coral reefs (Chapter 5; Box CC-CR), seagrass beds, mangroves, rocky reefs and shelves, and seamounts have few to no areas left in the world that remain unaffected by human influence (Halpern et al., 2008). Anthropogenic drivers associated with climate change decreased ocean productivity, altered food web dynamics, reduced the abundance of habitat-forming species, shifted species distributions, and led to a greater incidence of disease (Hoegh-Guldberg and Bruno, 2010). Coastal and marine impacts and vulnerability are often associated with collateral effects of climate change such as SLR, ocean warming, and ocean acidification (Box CC-OA). Overfishing, habitat pollution and destruction, and the invasion of species also negatively impact biodiversity and the delivery of ecosystem services (Guarderas et al., 2008; Halpern et al., 2008). Such negative impacts lead to losses that pose significant challenges and costs for societies, particularly in developing countries (Hoegh-Guldberg and Bruno, 2010). For instance, the Ocean Health Index (Halpern et al., 2012), which measures how healthy the coupling of the human-ocean system is for every coastal country (including parameters related to climate change), indicates that CA countries rank among the lowest values. For SA, Suriname stands out with one of the highest scores.

Coastal states of LA and the Caribbean have a human population of more than 610 million, three-fourths of whom live within 200 km of the coast (Guarderas et al., 2008). For instance, studying seven countries in the region (El Salvador, Nicaragua, Costa Rica, Panama, Colombia, Venezuela, Ecuador), Lacambra and Zahedi (2011) found that more than 30% of the population lives in coastal areas directly exposed to climatic events. Large coastal populations are related to the significant transformation marine ecosystems have been undergoing in the region. Fish stocks, places for recreation and tourism, and controls of pests and pathogens are all under pressure (Guarderas et al., 2008; Mora, 2008). Moreover, SLR varied from 2 to 7 mm yr^{-1} between 1950 and 2008 in CA and SA. The Western equatorial border, influenced by the ENSO phenomenon, shows a lower variation (of about 1 mm yr^{-1}) and a range of variation under El Niño events of the same order of magnitude that sustained past changes (Losada et al., 2013). The distribution of population is a crucial factor for inundation impact, with coastal areas being non-homogeneously impacted. A scenario of 1 m SLR would affect some coastal populations in Brazil and the Caribbean islands (see Figure 27-6; ECLAC, 2011a).

27.3.3.1.1. Coastal impacts

Based on trends observed and projections, Figure 27-6 shows how potential impacts may be distributed in the region. (a) *Flooding*: Since flooding probability increases with increasing sea level, one may expect a higher probability of flooding in locations showing >40% of change over the last 60 years in the 100-years total sea level (excluding hurricanes). The figure also identifies urban areas where the highest increase in flooding level has been obtained. (b) *Beach erosion*: It increases with potential sediment transport, thus locations where changes in potential sediment transport have increased over a certain threshold have a higher probability to be eroded. (c) *Sea ports and reliability of coastal structures*: The figure shows locations where, in the case of having a protection structure in place, there is a reduction in the reliability of the structures owing to the increase in the design wave height estimates (ECLAC, 2011a).

27.3.3.1.2. Coastal dynamics

Information on coastal dynamics is based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information, and satellite information. Advanced statistical techniques have been used for obtaining trends including uncertainties (Izaguirre et al., 2013; Losada et al., 2013).

(a) Coastal impacts (b) Coastal dynamics

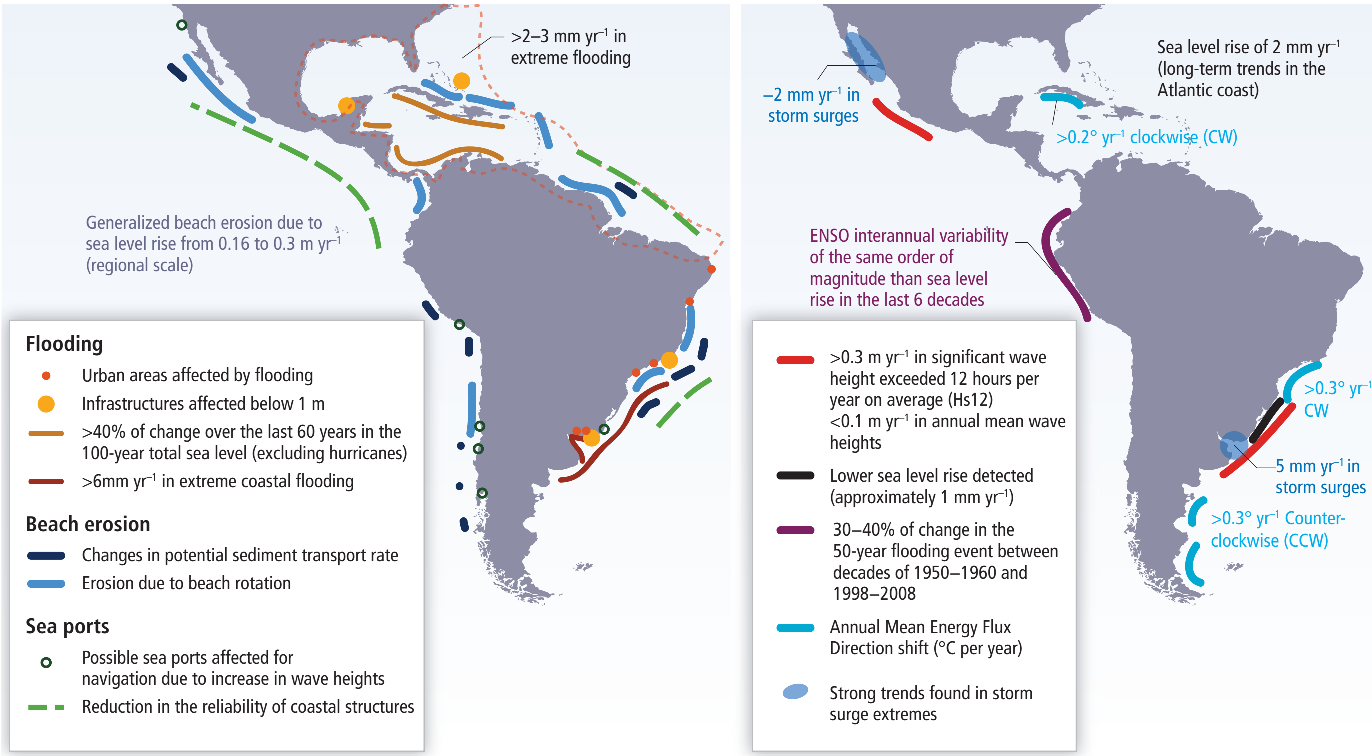

Figure 27-6 | Current and predicted coastal impacts (a) and coastal dynamics (b) in response to climate change. (a) Coastal impacts: Based on trends observed and projections, the figure shows how potential impacts may be distributed in the region (ECLAC, 2011a). ***Flooding***: Since flooding probability increases with increasing sea level, one may expect a higher probability of flooding in locations showing >40% of change over the last 60 years in 100-year total sea level (excluding hurricanes). The figure also identifies urban areas where the highest increase in flooding level has been obtained. ***Beach erosion***: Increases with potential sediment transport, and thus locations where changes in potential sediment transport have increased over a certain threshold have a higher probability of being eroded. ***Sea ports and reliability of coastal structures***: Shows locations where, in the case of having a protection structure in place, there is a reduction in the reliability of the structures due to the increase in the design wave height estimates. (b) Coastal dynamics: Information based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information, and satellite information. Advanced statistical techniques have been used for obtaining trends including uncertainties (Izaguirre et al., 2013; Losada et al., 2013).

The greatest flooding levels (hurricanes not considered) in the region are found in Rio de La Plata area, which combine a 5 mm yr^{-1} change in storm surge with SLR changes in extreme flooding levels (ECLAC, 2011a; Losada et al., 2013). Extreme flooding events may become more frequent because return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected, while at the same time beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast (ECLAC, 2011a).

The majority of the literature concerning climate change impacts for coastal and marine ecosystems considers coral reefs (see also Chapter 5; Box CC-CR), mangroves, and fisheries. Coral reefs are particularly sensitive to climate-induced changes in the physical environment (Baker et al., 2008) to an extent that one-third of the more than 700 species of reef-building corals worldwide are already threatened with extinction (Carpenter et al., 2008). Coral bleaching and mortality are often associated with ocean warming and acidification (Baker et al., 2008). If extreme sea surface temperatures were to continue, the projections using SRES scenarios (A1FI, 3°C sensitivity, and A1B with 2°C and 4.5°C sensitivity) indicate that it is possible that the Mesoamerican coral reef will collapse by mid-century (between 2050 and 2070), causing major economic losses (Vergara, 2009). Extreme high sea surface temperatures have been increasingly documented in the western Caribbean near the coast of CA and have resulted in frequent bleaching events (1993, 1998, 2005, and again in 2010) of the Mesoamerican coral reef, located along the coasts of Belize, Honduras, and Guatemala (Eakin et al., 2010). Reef and also mangrove ecosystems are estimated to contribute greatly to goods and services in economic terms. In Belize, for example, this amount is approximately US$395 to US$559 million annually, primarily through marine-based tourism, fisheries, and coastal protection (Cooper et al., 2008). In the Eastern Tropical Pacific, seascape trace abundance of cement and elevated nutrients in upwelled waters are factors that help explain high bioerosion rates of local coral reefs (Manzello et al., 2008). In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years (Francini-Filho et al., 2008). This estimate is based on coral disease prevalence and progression rate, along with growth rate of *Mussismilia braziliensis*—a major reef-building coral species that is endemic in Brazil. These authors also pointed out that coral diseases intensified between 2005 and 2007 based on qualitative observations since the 1980s and regular monitoring since 2001. They have also predicted that the studied coral species will be nearly extinct in less than a century if the current rate of mortality due to disease is not reversed.

Mangroves are largely affected by anthropogenic activities whether or not they are climate driven. All mangrove forests, along with important ecosystem goods and services, could be lost in the next 100 years if the present rate of loss continues (1 to 2% a year; Duke et al., 2007). Moreover, estimates are that climate change may lead to a maximum global loss of 10 to 15% of mangrove forest by 2100 (Alongi, 2008). In CA and SA, some of the main drivers of loss are deforestation and land conversion, agriculture, and shrimp ponds (Polidoro et al., 2010). The Atlantic and Pacific coasts of CA are some of the most endangered on the planet with regard to mangroves, as approximately 40% of present species are threatened with extinction (Polidoro et al., 2010). Approximately 75% of the global mangrove extension is concentrated in 15 countries, among which Brazil is included (Giri et al., 2011). The rate of survival of original mangroves lies between 12.8 and 47.6% in the Tumaco Bay (Colombia), resulting in ecosystem collapse, fisheries reduction, and impacts on livelihoods (Lampis, 2010). Gratiot et al. (2008) project for the current decade an increase of mean high water levels of 6 cm followed by 90 m shoreline retreat, implying flooding of thousands of hectares of mangrove forest along the coast of French Guiana.

Peru and Colombia are two of the eight most vulnerable countries to climate change impacts on fisheries, owing to the combined effect of observed and projected warming, to species and productivity shifts in upwelling systems, to the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities (Allison et al., 2009). Fisheries production systems are already pressured by overfishing, habitat loss, pollution, invasive species, water abstraction, and damming (Allison et al., 2009). In Brazil, a decadal rate of 0.16 trophic level decline (as measured by the Marine Trophic Index, which refers to the mean trophic level of the catch) has been detected through most of the northeastern coast, between 1978 and 2000, which is one of the highest rates documented in the world (Freire and Pauly, 2010).

Despite the focus in the literature on corals, mangroves, and fisheries, there is evidence that other benthic marine invertebrates that provide key services to reef systems, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change (Przeslawski et al., 2008). The same applies for seagrasses, for which a worldwide decline has accelerated from a median of 0.9% yr^{-1} before 1940 to 7% yr^{-1} since 1990, which is comparable to rates reported for mangroves, coral reefs, and tropical rainforests, and place seagrass meadows among the most threatened ecosystems on earth (Waycott et al., 2009).

A major challenge of particular relevance at local and global scales will be to understand how these physical changes will impact the biological environment of the ocean (e.g., Gutiérrez et al., 2011b), as the Humboldt Current system—flowing along the west coast of SA—is the most productive upwelling system of the world in terms of fish productivity.

27.3.3.2. Adaptation Practices

Designing marine protected areas (MPAs) that are resilient to climate change is a key adaptation strategy in coastal and marine environments (McLeod et al., 2009). By 2007, LA and the Caribbean (which includes CA and SA countries) had more than 700 MPAs established covering around 1.5% of the coastal and shelf waters, most of which allow varying levels of extractive activities (Guarderas et al., 2008). This protected area cover, however, is insufficient to preserve important habitats or connectivity among populations at large biogeographic scales (Guarderas et al., 2008).

Nevertheless, examples of adaptation in CA and SA are predominantly related to MPAs. In Brazil, a protected area type known as "Marine Extractive Reserves" currently benefits 60,000 small-scale fishermen along the coast (de Moura et al., 2009). Examples of fisheries' co-management, a form of a participatory process involving local fishermen communities, government, academia, and non-governmental organizations, are reported to favor a balance between conservation of marine fisheries, coral reefs, and mangroves on the one hand (Francini-Filho and de Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations on the other (de Moura et al., 2009; Hastings, 2011).

Significant financial and human resources are expended annually in the marine reserves to support reef management efforts. These actions, including the creation of marine reserves to protect from overfishing, improvement of watershed management, and protection or replanting of

Frequently Asked Questions

FAQ 27.2 | Can payment for ecosystem services be used as an effective way to help local communities adapt to climate change?

Ecosystems provide a wide range of basic services, such as providing breathable air, drinkable water, and moderating flood risk (*very high confidence*). Assigning values to these services and designing conservation agreements based on these (broadly known as payment for ecosystem services, or PES) can be an effective way to help local communities adapt to climate change. It can simultaneously help protect natural areas and improve livelihoods and human well-being (*medium confidence*). However, during design and planning, a number of factors need to be taken into consideration at the local level to avoid potentially negative results. Problems can arise if (1) the plan sets poor definitions about whether the program should focus just on actions to be taken or the end result of those actions, (2) many perceive the initiative as commoditization of nature and its intangible values, (3) the action is inefficient to reduce poverty, (4) difficulties emerge in building trust between various stakeholders involved in agreements, and (5) there are eventual gender or land tenure issues.

coastal mangroves, are proven tools to improve ecosystem functioning. In Mesoamerican reefs Carilli et al. (2009) found out that such actions may also actually increase the thermal tolerance of corals to bleaching stress and thus the associated likelihood of surviving future warming.

In relation to mangroves, in addition to marine protected areas that include mangroves and functionally linked ecosystems, Gilman et al. (2008) list a number of other relevant adaptation practices: coastal planning to facilitate mangrove migration with SLR, management of activities within the catchment that affect long-term trends in the mangrove sediment elevation, better management of non-climate stressors, and the rehabilitation of degraded areas. However, such types of practices are not frequent in the region.

On the other hand, the implementation of adaptation strategies to SLR or to address coastal erosion is more commonly seen in many countries in the region (Lacambra and Zahedi, 2011). For instance, redirecting new settlements to better-protected locations and to promote investments in appropriate infrastructure shall be required in the low elevation coastal zones (LECZ) of the region, particularly in lower income countries with limited resources, which are especially vulnerable. The same applies to countries with high shares of land (e.g., Brazil ranking 7th worldwide of the total land area in the LECZ) and/or population (e.g., Guyana and Suriname ranking 2nd and 5th by the share of population in the LECZ, having respectively 76 and 55% of their populations in such areas) (McGranahan et al., 2007). Adaptation will demand effective and enforceable regulations and economic incentives, all of which require political will as well as financial and human capital (McGranahan et al., 2007). Adaptive practices addressing river flooding are also being made available as in the study of Casco et al. (2011) for the low Paraná River in Argentina (see also Chapters 5 and 6 for coastal and marine adaptation).

27.3.4. Food Production Systems and Food Security

27.3.4.1. Observed and Projected Impacts and Vulnerabilities

Increases in the global demand for food and biofuels promoted a sharp increase in agricultural production in SA and CA, associated mainly with the expansion of planted areas (see Chapter 7), and this trend is predicted to continue in the future (see Section 27.2.2.1). Ecosystems are being and will be affected in isolation and synergistically by climate variability/change and land use changes, which are comparable drivers of environmental change (see Sections 27.2.2.1, 27.3.2.1). By the end of the 21st century (13 GCMs, under SRES A1B and B1) SA could lose between 1 and 21% of its arable land due to climate change and population growth (Zhang and Cai, 2011).

Optimal land management could combine efficient agricultural and biofuels production with ecosystem preservation under climate change. However, current practices are leading to a deterioration of ecosystems throughout the continent (see Section 27.3.2). In southern Brazilian Amazonia water yields (mean daily discharge (mm d^{-1})) were near four times higher in soy than in forested watersheds, and showed greater seasonal variability (Hayhoe et al., 2011). In the Argentinean Pampas current land use changes disrupt water and biogeochemical cycles and may result in soil salinization, altered carbon and nitrogen storage, surface runoff, and stream acidification (Nosetto et al., 2008; Berthrong et al., 2009; Farley et al., 2009). In central Argentina flood extension was associated with the dynamics of groundwater level, which has been influenced by precipitation and land use change (Viglizzo et al., 2009).

27.3.4.1.1. Observed impacts

The SESA region has shown significant increases in precipitation and wetter soil conditions during the 20th century (Giorgi, 2002; see Table 27-1) that benefited summer crops and pastures productivity, and contributed to the expansion of agricultural areas (Barros, 2008a; Hoyos et al., 2012). Wetter conditions observed during 1970–2000 (in relation to 1930–1960) led to increases in maize and soybean yields (9 to 58%) in Argentina, Uruguay, and southern Brazil (Magrin et al., 2007b). Even if rainfall projections estimate increases of about 25% in SESA for 2100, agricultural systems could be threatened if climate reverts to a drier situation due to inter-decadal variability. This could put at risk the viability of continuous agriculture in marginal regions of Argentina's Pampas (Podestá et al., 2009). During the 1930s and 1940s, dry and windy conditions together with deforestation, overgrazing, overcropping, and non-suitable tillage produced severe dust storms, cattle mortality, crop failure, and rural migration (Viglizzo and Frank, 2006).

At the global scale (see Chapter 7), warming since 1981 has reduced wheat, maize, and barley productivity, although the impacts were small compared with the technological yield gains over the same period (Lobell and Field, 2007). In central Argentina, simulated potential wheat yield—without considering technological improvements—has been decreasing at increasing rates since 1930 (1930–2000: –28 kg ha^{-1} yr^{-1}; 1970–2000: –53 kg ha^{-1} yr^{-1}) in response to increases in minimum temperature during October–November (1930–2000: +0.4°C per decade; 1970–2000: +0.6°C per decade) (Magrin et al., 2009). The observed changes in the growing season temperature and precipitation between 1980 and 2008 have slowed the positive yield trends due to improved genetics in Brazilian wheat, maize, and soy, as well as Paraguayan soy. In contrast, rice in Brazil and soybean in Argentina have benefited from precipitation and temperature trends (Lobell et al., 2011). In Argentina, increases in soybean yield may be associated with weather types that favor the entry of cold air from the south, reducing thermal stress during flowering and pod set, and weather types that increase the probability of dry days at harvest (Bettolli et al., 2009).

27.3.4.1.2. Projected impacts

Assessment of future climate scenarios implications to food production and food security (see Table 27-5) shows a large range of uncertainty across the spectrum of climate models and scenarios. One of the uncertainties is related to the effect of CO_2 on plant physiology. Many crops (such as soybean, common bean, maize, and sugarcane) can probably respond with an increasing productivity as a result of higher growth rates and better water use efficiency. However, food quality could decrease as a result of higher sugar contents in grain and fruits, and decreases in the protein content in cereals and legumes (DaMatta et al., 2010). Uncertainties associated with climate and crop models, as well as with the uncertainty in human behavior, potentially lead to large error bars on any long-term prediction of food output. However, the trends presented here represent the current available information.

In SESA, some crops could be benefitted until mid-21st century if CO_2 effects are considered (see Table 27-5), although interannual and decadal climate variability could provoke important damages. In Uruguay and Argentina, productivity could increase or remain almost stable until the 2030s–2050s depending on the SRES scenario (ECLAC, 2010c). Warmer and wetter conditions may benefit crops toward the southern and western zone of the Pampas (Magrin et al., 2007c; ECLAC, 2010c). In south Brazil, irrigated rice yield (Walter et al., 2010) and bean productivity (Costa et al., 2009) are expected to increase. If technological improvement is considered, the productivity of common bean and maize could increase

Table 27-5 | Impacts on agriculture.

Country/region		Activity	Time slice	Special report on Emissions Scenarios (SRES)	CO_2	Changes	Source
Southeastern South America	Uruguay	Annual crops	2030/2050/2070/2100	A2		+185/–194/–284/–508	ECLAC (2010a)[1]
			2030/2050	B2		+92/+169	
		Livestock	2030/2050/2070/2100	A2		+174/–80/–160/–287	
			2030/2050	B2		+136/+182	
		Forestry	2030/2050/2070/2100	A2		+15/+39/+52/+19	
			2030/2050/2070	B2		+6/+13/+18	
	Paraguay	Cassava	2020/2050/2080	A2		+16/+22/+22	ECLAC (2010a)
		Wheat	2020/2050/2080	A2		+4/–9/–13	
				B2		–1/+1/–5	
		Maize	2020/2050/2080	A2		+3/+3/+8	
				B2		+3/+1/+6	
		Soybean	2020/2050/2080	A2		0/–10/–15	
				B2		0/–15/–2	
		Bean	2020/2050/2080	A2		–1/+10/+16	
	Argentina	Maize	2080	A2/B2	N	–24/–15	ECLAC (2010a)
				A2/B2	Y	+1/0	
		Soybean	2080	A2/B2	N	–25/–14	
				A2/B2	Y	+14/+19	
		Wheat	2080	A2/B2	N	–16/–11	
				A2/B2	Y	+3/+3	
		Soybean	2020/2050/2080	A2	Y	+24/+42/+48	Travasso et al. (2008)
				B2	Y	+14/+30/+33	
		Maize	2020/2050/2080	A2	Y	+8/+11/+16	
				B2	Y	+5/+5/+9	
	Brazil	Rice		$2CO_2$/0ºC	Y	+60	Walter et al. (2010)
				$2CO_2$/+5ºC	Y	+30	
		Bean	2050/2080	A2	N	Up to –30%	Costa et al. (2009)[2]
			2020/2050/2080	A2+CO_2	Y	Up to: +30/+30/+45	
				A2+CO_2+T	Y	Up to: +45/+75/+90	
		Maize	2050/2080	A2	N	Up to –30%	
				A2+CO_2	Y	Near to –15%	
			2020/2050/2080	A2+CO_2+T	Y	Up to: +40/+60/+90	
		Arabica coffee		+0 to +1ºC		+1.5%	Zullo et al. (2011)[3]
				+1 to +2ºC		+15.9%	
				+2 to +3ºC		+28.6%	
				+3 to +4ºC		–12.9%	
State of São Paulo, Brazil		Sugarcane	2040	Pessimistic		+6%	Marin et al. (2009)
				Optimistic		+2%	

Continued next page →

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between 40 and 90% (Costa et al., 2009). Sugarcane production could benefit, as warming could allow the expansion of planted areas toward the south, where low temperatures are a limiting factor (Pinto et al., 2008). Increases in crop productivity could reach 6% in São Paulo state toward 2040 (Marin et al., 2009). In Paraguay the yields of soybean, maize, and wheat could have slight variations (–1.4 to +3.5%) until 2020 (ECLAC, 2010a).

In Chile and western Argentina, yields could be reduced by water limitation. In central Chile (30ºS to 42ºS) temperature increases, reduction in chilling hours, and water shortages may reduce productivity of winter crops, fruits, vines, and radiata pine. Conversely, rising temperatures, more moderate frosts, and more abundant water will *very likely* benefit all species toward the south (ECLAC, 2010a; Meza and da Silva, 2009). In northern Patagonia (Argentina) fruit and vegetable growing could be negatively affected because of a reduction in rainfall and in average flows in the Neuquén River basin. In the north of the Mendoza basin (Argentina) increases in water demand, due to population growth, may compromise the availability of subterranean water for irrigation, pushing up irrigation costs and forcing many producers out of farming toward 2030. Also, water quality could be reduced by the worsening of existing salinization processes (ECLAC, 2010a).

In CA, NEB, and parts of the Andean region (Table 27-5) climate change could affect crop yields, local economies, and food security. It is *very likely* that growing season temperatures in parts of tropical SA, east of the Andes, and CA exceed the extreme seasonal temperatures documented from 1900 to 2006 at the end of this century (23 GCMs), affecting regional agricultural productivity and human welfare (Battisti and Naylor, 2009). For NEB, declining crop yields in subsistence crops such as beans,

Table 27-5 (continued)

Country/region	Activity	Time slice	Special report on Emissions Scenarios (SRES)	CO_2	Changes	Source
Northeastern Brazil	Cassava	2020–2040		N	0 to –10	Lobell et al. (2008)
	Maize	2020–2040		N	0 to –10	
	Rice	2020–2040		N	–1 to –10	
	Wheat	2020–2040		N	–1 to –14	
	Maize				–20 to –30	Margulis et al. (2010)
	Bean				–20 to –30	
	Rice				–20 to –30	
	Cowpea bean		+1.5ºC		–26%	Silva et al. (2010)[3]
			+3.0ºC		–44%	
			+5.0ºC		–63%	
Central America	Maize	2030/2050/2070/2100	A2		0/0/–10/–30	ECLAC (2010a)
	Bean	2030/2050/2070/2100	A2		–4/–19/–29/–87	
	Rice	2030/2050/2070/2100	A2		+3/–3/–14/–63	
	Rice	2020–2040		N	0 to –10	Lobell et al. (2008)
	Wheat	2020–2040		N	–1 to –9	
Panamá	Maize	2020/2050/2080	A2	Y	–0.5/+2.4/+4.5	Ruane et al. (2011)
			B1	Y	–0.1/–0.8/+1.5	
Andean Region	Wheat	2020–2040		N	–14 to +2	Lobell et al. (2008)
	Barley	2020–2040		N	0 to –13	
	Potato	2020–2040		N	0 to –5	
	Maize	2020–2040		N	0 to –5	
Colombia	All main crops	2050	17 GCMs (A2)		80% of crops impacted in more than 60% of current cultivated areas	Ramirez et al. (2012)
Chile (34.6º to 38.5ºS)	Maize	2050	A1FI	Y	–5% to –10%	Meza and Silva (2009)
	Wheat	2050	A1FI	Y	–10% to –20%	

Notes:
Changes are expressed as differences in relative yield (%), except for [1] and [3].

N: Without considering CO_2 biological effects.
Y: Considering CO_2 biological effects.
$2CO_2$: Considering double CO_2 concentration (780 ppm CO_2).
T: Considering technological improvement (genetic changes).

[1]Gross value of production (millions of US$).
[2]Huge spatial variability; values are approximated.
[3]Changes in the percentage of areas with low climate risk.

corn, and cassava are projected (Lobell et al., 2008; Margulis et al., 2010). In addition, increases in temperature could reduce the areas currently favorable to cowpea bean (Silva et al., 2010). The highest warming foreseen for 2100 (5.8°C, under SRES A2 scenario) could make the coffee crop unfeasible in Minas Gerais and São Paulo (southeast Brazil) if no adaptation action is accomplished. Thus, the coffee crop may have to be transferred to southern regions where temperatures are lower and the frost risk will be reduced (Camargo, 2010). With +3ºC, Arabica coffee is expected to expand in the extreme south of Brazil, the Uruguayan border, and northern Argentina (Zullo Jr. et al., 2011). Brazilian potato production could be restricted to a few months in currently warm areas, which today allow potato production year-round (Lopes et al., 2011). Large losses of suitable environments for the "Pequi" tree (*Caryocar brasiliense*, an economically important Cerrado fruit tree) are projected by 2050, affecting mainly the poorest communities in central Brazil (Nabout et al., 2011). In the Amazon region soybean yields would be reduced by 44% in the worst scenario (Hadley Centre climate prediction model 3 (HadCM3) and no CO_2 fertilization) by 2050 (Lapola et al., 2011). By 2050, according to 17 GCMs under SRES A2 scenario, 80% of crops will be impacted in more than 60% of current areas of cultivation in Colombia, with severe impacts in perennial and exportable crops (Ramirez-Villegas et al., 2012).

Teixeira et al. (2013) identified hotspots for heat stress toward 2071–2100 under the A1B scenario and suggest that rice in southeast Brazil, maize in CA and SA, and soybean in central Brazil will be the crops and zones most affected by increases in temperature.

In CA, changes projected in climate could severely affect the poorest population and especially their food security, increasing the current rate of chronic malnutrition. Currently, Guatemala is the most food insecure country by percentage of the population (30.4%) and the problem has been increasing in recent years (FAO, WFP, and IFAD, 2012). The impact of climate variability and change is a great challenge in the region. As an example, the recent rust problem on the coffee sector of 2012–2013 has affected nearly 600,000 ha (55% of the total area) (ICO, 2013) and will reduce employment by 30 to 40% for the harvest 2013–2014 (FEWS NET, 2013). At least 1.4 million people in Guatemala, El Salvador, Honduras, and Nicaragua depend on the coffee sector, which is very susceptible to climate variations. In Panamá, the large interannual climate variability will continue to be the dominant influence on seasonal maize yield into the coming decades (Ruane et al., 2013). In the future, warming conditions combined with more variable rainfall are expected to reduce maize, bean, and rice productivity (ECLAC, 2010c); rice and wheat yields could decrease up to 10% by 2030 (Lobell et al., 2008; *medium confidence*). In CA, nearly 90% of agricultural production destined for internal consumption is composed by maize (70%), bean (25%), and rice (6%) (ECLAC, 2011d).

Climate change may also alter the current scenario of plant diseases and their management, having effects on productivity (Ghini et al., 2011). In Argentina, years with severe infection of late cycle diseases in soybean could increase; severe outbreaks of the Mal de Rio Cuarto virus in maize (natural vectors: *Delphacodes kuscheli* and *Delphacodes hayward*) could be more frequent; and wheat head fusariosis will increase slightly in the south of the Pampas region by the end of the century (ECLAC, 2010a). In Brazil favorable areas for soybean and coffee rusts will move toward the south, particularly for the hottest scenario of 2080 (Alves et al., 2011). Potato late blight (*Phytophtora infestans*) severity is expected to increase in Peru (Giraldo et al., 2010).

The choice of livestock species could change in the future. For example, by 2060, under a hot and dry scenario, beef and dairy cattle, pig, and chicken production choice could decrease between 0.9 and 3.2%, while sheep election could increase by 7% mainly in the Andean countries (Seo et al., 2010). Future climate could strongly affect milk production and feed intake in dairy cattle in Brazil, where substantial modifications in areas suitable for livestock, mainly in the Pernambuco region, are expected (da Silva et al., 2009). Warming and drying conditions in Nicaragua could reduce milk production, mainly among farmers who are already seriously affected under average dry season conditions (Lentes et al., 2010).

Climate change impact on regional welfare will depend not only on changes in yield, but also in international trade. According to Hertel et al. (2010), by 2030, global cereal price could change between increases of 32% (low-productivity scenario) or decreases of 16% (optimistic yield scenario). A rise in prices could benefit net exporting countries such as Brazil, where gains from terms of trade shifts could outweigh the losses due to climate change. Despite experiencing significant negative yield shocks, some countries tend to gain from higher commodity prices. However, most poor household are food purchasers and rising commodity prices tend to have a negative effect on poverty (von Braun, 2007). According to Chapter 7, increases in prices during 2007–2009 led to rising poverty in Nicaragua.

27.3.4.2. Adaptation Practices

Genetic advances and suitable soil and technological management may induce an increase in some crops' yield despite unfavorable future climate conditions. In Argentina, genetic techniques, specific scientific knowledge, and land use planning are viewed as promising sources of adaptation (Urcola et al., 2010). Adjustments in sowing dates and fertilization rates could reduce negative impacts or increase yields in maize and wheat crops in Argentina and Chile (Magrin et al., 2009; Meza and da Silva, 2009; Travasso et al., 2009b). Furthermore, in central Chile and southern Pampas in Argentina warmer climates could allow performing two crops per season, increasing productivity per unit land (Monzon et al., 2007; Meza et al., 2008). In Brazil, adaptation strategies for coffee crops include planting at high densities, vegetated soil, accurate irrigation and breeding programs, and shading management system (arborization) (Camargo, 2010). Shading is also used in Costa Rica and Colombia. In south Brazil, a good option for irrigated rice could be to plant early cultivars (Walter et al., 2010).

Water management is another option for needed better preparedness regarding water scarcity (see Section 27.3.1). In Chile, the adoption of water conservation practices depends on social capital, farm size, and land use; and the adoption of technologies that require investment depend on the access to credit and irrigation water subsidies (Jara-Rojas et al., 2012). Deficit irrigation could be an effective measure for water savings in dry areas such as the Bolivian Altiplano (quinoa), central Brazil (tomatoes), and northern Argentina (cotton) (Geerts and Raes, 2009). In rainfed crops adaptive strategies might need to look at the harvest, storage, temporal transfer, and efficient use of rainfall water. In addition, some agronomic practices such as fallowing, crop sequences, groundwater management, no-till operations, cover crops, and fertilization could improve the adaptation to water scarcity (Quiroga and Gaggioli, 2011).

One approach to adapting to future climate change is by assisting people to cope with current climate variability (Baethgen, 2010), for which the use of climatic forecasts in agricultural planning presents a measure. Increased access and improvement of climate forecast information enhances the ability of farmers in the Brazilian Amazon to cope with El Niño impacts (Moran et al., 2006). The Southern Oscillation Index for maize and the South Atlantic Sea Surface Temperature for soybean and sunflower were the best indicators of annual crop yield variability in Argentina (Travasso et al., 2009a). Another possibility to cope with extreme events consists in transferring weather-related risks by using different types of rural insurance (Baethgen, 2010). Index insurance is one mechanism that has been recently introduced to overcome obstacles to traditional agricultural and disaster insurance markets (see Chapter 15). For the support of such parametric agricultural insurance, a Central American climate database was recently established (SICA, 2013).

Local and indigenous knowledge has the potential to bring solutions even in the face of rapidly changing climatic conditions (Folke et al., 2002; Altieri and Koohafkan, 2008), although migration, climate change, and market integration are reducing indigenous capacity for dealing with weather and climate risk (Pérez et al., 2010; Valdivia et al., 2010). Crop diversification is used in the Peruvian Andes to suppress pest outbreaks and dampen pathogen transmission (Lin, 2011). In Honduras, Nicaragua, and Guatemala traditional practices have proven more resilient to erosion and runoff and have helped retain more topsoil and moisture (Holt-Gimenez, 2002). In El Salvador, if local sustainability efforts continue, the future climate vulnerability index could only slightly increase by 2015 (Aguilar et al., 2009). Studies with Indigenous farmers in highland Bolivia and Peru indicate that constraints on access to key resources must be addressed for reducing vulnerability over time (McDowell and Hess, 2012; Sietz et al., 2012). In Guatemala and Honduras adaptive response between coffees farmers is mainly related to land availability, while participation in organized groups and access to information contribute to adaptive decision making (Tucker et al., 2010). Otherwise, adaptation may include an orientation toward non-farming activities to sustain their livelihoods and be able to meet their food requirements (Sietz, 2011). In NEB increasing vulnerability related to degradation of natural resources (due to overuse of soil and water) encouraged farmers toward off-farm activities; however, they could not improve their well-being (Sietz et al., 2006, 2011). Migration is another strategy in ecosystems and regions at high risk of climate hazards (see Section 27.3.1.1). During 1970–2000 LA and the Caribbean has had a great rate of net migration per population in the dryland zones (de Sherbinin et al., 2012). In CA nearly 25% of the surveyed households reported some type of migration during the coffee crisis (Tucker et al., 2010). Some migrations—for example, Guatemala, 1960s–1990s; El Salvador, 1950s–1980s; NEB, 1960s–present—have provoked conflict in receiving areas (Reuveny, 2007).

Shifting in agricultural zoning has been an autonomous adaptation observed in SA. In Argentina., for example, increases in precipitation promoted the expansion of the agricultural frontier to the west and north of the traditional agricultural area, resulting in environmental damage that could be aggravated in the future (República Argentina, 2007; Barros, 2008b). Adjustment of production practices—like those of farmers in the semi-arid zones of mountain regions of Bolivia, which began as they noticed strong changes in the climate since the 1980s, including upward migration of crops, selection of more resistant varieties, and water capturing—presents a further adaptation measure (PNCC, 2007).

Organic systems could enhance adaptive capacity as a result of the application of traditional skills and farmers' knowledge, soil fertility-building techniques, and a high degree of diversity (ITC, 2007). As mentioned previously, crop diversity, local knowledge, soil conservation, and economic diversity are all documented strategies for managing risk in CA and SA. A controversial but important issue in relation to adaptation is the use of genetically modified plants to produce food, with biotech crops being a strategy to cope with the needed food productivity increase considering the global population trend (see Chapter 7). Brazil and Argentina are the second and third fastest growing biotech crop producers in the world after the USA (Marshall, 2012). However, this option is problematic for the small farms (Mercer et al., 2012), which are least favorable toward GMO (Soleri et al., 2008). According to Eakin and Wehbe (2009) some practices could be an adaptive option for specific farm enterprises, but may have maladaptive implications at regional scales, and over time become maladaptive for individual enterprises.

27.3.5. Human Settlements, Industry, and Infrastructure

According to the World Bank database (World Bank, 2012) CA and SA are the geographic regions with the second highest urban population (79%), behind North America (82%) and well above the world average (50%). Therefore this section focuses on assessing the literature on climate change impacts and vulnerability of urban human settlements. The information provided should be complemented with other sections of the chapter (see Sections 27.2.2.2, 27.3.1, 27.3.3, 27.3.7).

27.3.5.1. Observed and Projected Impacts and Vulnerabilities

Urban human settlements suffer from many of the vulnerabilities and impacts already presented in several sections of this chapter. The provision of critical resources and services as already discussed in the chapter—water, health, and energy—and of adequate infrastructure and housing remain determinants of urban vulnerability that are enhanced by climate change (Smolka and Larangeira, 2008; Winchester, 2008; Roberts, 2009; Romero-Lankao et al., 2012c, 2013b).

Water resource management (see Section 27.3.1) is a major concern for many cities that need to provide both drinking water and sanitation (Henríquez Ruiz, 2009). More than 20% of the population in the region are concentrated in the largest city in each country (World Bank, 2012), hence water availability for human consumption in the region's megacities (e.g., São Paulo, Santiago, Lima, Buenos Aires) is of great concern. In this context, reduction in glacier and snowmelt related runoff in the

Box 27-2 | Vulnerability of South American Megacities to Climate Change: The Case of the Metropolitan Region of São Paulo

Research in the Metropolitan Region of São Paulo (MRSP), between 2009 and 2011, represents a comprehensive and interdisciplinary project on the impacts of climate variability and change, and vulnerability of Brazilian megacities. Studies derived from this project (Nobre et al., 2011; Marengo et al., 2013b) identify the impacts of climate extremes on the occurrence of natural disasters and human health. These impacts are linked to a projected increase of 38% in the extension of the urban area of the MRSP by 2030, accompanied by a projected increase in rainfall extremes. These may induce an intensification of urban flash floods and landslides, affecting large populated areas already vulnerable to climate extremes and variability. The urbanization process in the MRSP has been affecting the local climate, and the intensification of the heat island effect to a certain degree may be responsible for the 2°C warming detected in the city during the last 50 years (Nobre et al., 2011). This warming has been further accompanied by an increase in heavy precipitation as well as more frequent warm nights (Silva Dias et al., 2012; Marengo et al., 2013b). By 2100, climate projections based on data from 1933–2010 show an expected warming between 2°C and 3°C in the MRSP, together with a possible doubling of the number of days with heavy precipitation in comparison to the present (Silva Dias et al., 2012; Marengo et al., 2013b).

With the projected changes in climate and in the extension of the MRSP (Marengo et al., 2013b) more than 20% of the total area of the city could be potentially affected by natural disasters. More frequent floods may increase the risk of leptospirosis, which, together with increasing air pollution and worsening environmental conditions that trigger the risk of respiratory diseases, would leave the population of the MRSP more vulnerable. Potential adaptation measures include a set of strategies that need to be developed by the MRSP and its institutions to face these environmental changes. These include improved building controls to avoid construction in risk areas, investment in public transportation, protection of the urban basins, and the creation of forest corridors in the collecting basins and slope regions. The lessons learned suggest that the knowledge on the observed and projected environmental changes, as well as on the vulnerability of populations living in risk areas, is of great importance for defining adaptation policies that in turn constitute a first step toward building resilient cities that in turn improve urban quality of life in Brazil.

Andes poses important adaptation challenges for many cities, for example, the metropolitan areas of Lima, La Paz/El Alto, and Santiago de Chile (Bradley et al., 2006; Hegglin and Huggel, 2008; Melo et al., 2010). Flooding is also a preoccupation in several cities. In São Paulo for example, according to Marengo et al. (2009b, 2013b) the number of days with rainfall above 50 mm were almost zero during the 1950s and now they occur between two and five times per year (2000–2010). The increase in precipitation is one of the expected risks affecting the city of São Paulo as presented in Box 27-2. Increases in flood events during 1980–2000 have been observed also in the Buenos Aires province and Metropolitan Area (Andrade and Scarpati, 2007; Barros et al., 2008; Hegglin and Huggel, 2008; Nabel et al., 2008). There are also the combined effects of climate change impacts, human settlements' features, and other stresses, such as more intense pollution events (Moreno, 2006; Nobre, 2011; Nobre et al., 2011; Romero-Lankao et al., 2013b) and more intense hydrological cycles from urban heat island effects. In terms of these combined effects, peri-urban areas and irregular settlements pose particular challenges to urban governance and risk management given their scale, lack of infrastructure, and socioeconomic fragility (Romero-Lankao et al., 2012a).

Changes in prevailing urban climates have led to changing patterns of disease vectors, and water-borne disease issues linked to water availability and subsequent quality (see Section 27.3.7). The influence of climate change on particulate matter and other local contaminants is another concern (Moreno, 2006; Romero-Lankao et al., 2013b). It is important to highlight the relationship between water and health, given the problems of water stress and intense precipitation events affecting many urban centers. Both relate to changing disease risks, as well as wider problems of event-related mortalities and morbidity, and infrastructure and property damage. These risks are compounded for low-income groups in settlements with little or no service provision, for example, waste collection, piped drinking water, and sanitation (ECLAC, 2008). Existing cases of flooding, air pollution, and heat waves reveal that not only low-income groups are at risk, but also that wealthier sectors are not spared. Factors such as high-density settlement (Barros et al., 2008) and the characteristics of some hazards explain this—for example, poor and wealthy alike are at risk from air pollution and temperature in Santiago de Chile and Bogotá (Romero-Lankao et al., 2012b, 2013b).

There are also other climate change risks in terms of economic activity location and impacts on urban manufacturing and service workers (e.g., thermal stress; Hsiang, 2010) and the forms of urban expansion or sprawl into areas where ecosystem services may be compromised and risks enhanced (e.g., floodplains). Both processes are also related to rising motorization rates that facilitate suburban development and new regional agglomerations that bring pressure to bear on land uses that favor infiltration, surface cooling, and biodiversity; the number of light vehicles in LA and the Caribbean is expected to double between 2000 and 2030, and be three times the 2000 figure by 2050 (Samaniego, 2009).

While urban populations face diverse social, political, economic, and environmental risks in daily life, climate change adds a new dimension to these risk settings (Pielke, Jr. et al., 2003; Roberts, 2009; Romero-Lankao and Qin, 2011). Because urban development remains fragile in many cases, with weak planning responses, climate change can compound existing challenges. The probabilities and magnitudes of these events in each urban center will differ significantly according to socioeconomic, institutional, and physical contexts.

27.3.5.2. Adaptation Practices

The direct and indirect effects of climate change such as flooding, heat islands, and food insecurity present cities with a set of challenges and opportunities for mainstreaming flood management, warning systems, and other adaptation responses with sustainability goals (Bradley et al., 2006; Hegglin and Huggel, 2008; Hardoy and Pandiella, 2009; Romero-Lankao, 2010, 2012a; Romero-Lankao et al., 2013a).

Urban populations, economic activities, and authorities have a long experience of responding to climate-related hazards, particularly through disaster risk management, for example, Tucuman and San Martin, Argentina (Plaza and Pasculi, 2007; Sayago et al., 2010), and land use and economic development planning to a limited extent (Barton, 2009). Climate policies can build on these. Local administrations participate in the International Council for Local Environmental Initiatives (ICLEI), Cities Climate Leadership Group (C40), Inter-American Development Bank (IDB), Emerging and Sustainable Cities Initiative (ESCI) (IDB, 2013), and other networks, demonstrating their engagement in the generation of more climate-resilient cities. In smaller settlements, there is less capacity for adequate responses, for example, climate change and vulnerability information (Hardoy and Romero-Lankao, 2011). Policies, plans, and programs are required to reduce social vulnerability, and identify and reduce potential economic effects of climate on the local economy. Rio de Janeiro, for example, with its coastline property and high dependence on tourists (and their perceptions of risk), cannot ignore these climate-related hazards (Gasper et al., 2011).

Poverty and vulnerability, as interlinked elements of the adaptation challenge in CA and SA, remain pivotal to understanding how urban climate policies can be streamlined with broader development issues and not solely the capacity to respond to climate change (Hardoy and Pandiella, 2009; Winchester and Szalachman, 2009; Hardoy and Romero-Lankao, 2011). These broader links include addressing the determinants of vulnerability (e.g., access to education, health care, and infrastructure, and to emergency response systems (Romero-Lankao, 2007a; Romero-Lankao and Qin, 2011)). Among these response options, a focus on social assets has been highlighted by Rubin and Rossing (2012), rather than a purely physical asset focus.

Much urbanization involves in-migrating or already resident, low-income groups and their location in risk-prone zones (da Costa Fereira et al., 2011). The need to consider land use arrangements, particularly urban growth on risk-prone zones, as part of climate change adaptation highlights the role of green areas that mitigate the heat island effect and reduce risks from landslides and flooding (Rodríguez Laredo, 2011; Krellenberg et al., 2013).

In the case of governance frameworks, there is clear evidence that incorporation of climate change considerations into wider city planning is still a challenge, as are more inter-sectoral and participative processes that have been linked to more effective policies (Barton, 2009, 2013; de Oliveira, 2009; Romero-Lankao et al., 2013a). Several metropolitan adaptation plans have been generated over the last 5 years, for example, Bogotá, Buenos Aires, Esmeraldas, Quito, and São Paulo, although for the most part they have been restricted to the largest conglomerations and are often included as an addition to mitigation plans (Romero-Lankao, 2007b; Carmin et al., 2009; Romero-Lankao et al., 2012b, 2013a; Luque et al., 2013).

27.3.6. Renewable Energy

27.3.6.1. Observed and Projected Impacts and Vulnerabilities

Table 27-6 shows the relevance of renewable energy in the LA energy matrix as compared to the world for 2009 according to IEA statistics (IEA, 2012). Hydropower is the most representative source of renewable energy and therefore analyzed separately (see the case study in Section 27.6.1.). Geothermal energy is not discussed, as it is assumed that there is no impact of climate change on the effectiveness of this energy type (Arvizu et al., 2011).

Hydro, wind energy, and biofuel production might be sensitive to climate change in Brazil (de Lucena et al., 2009). With the vital role that renewable energy plays in mitigating the effects of climate change, being by far the most important sources of non-hydro renewable energy in SA and CA, this sensitivity demands the implementation of renewable energy projects that will increase knowledge on the crops providing bioenergy.

For historical reasons, CA and SA developed sugarcane as bioenergy feedstock. Brazil accounts for the most intensive renewable energy production as bioethanol, which is used by the majority of the cars in the country (Goldemberg, 2008) whereas biodiesel comprises 5% of all diesel nationwide. With the continent's long latitudinal length, the expected impacts of climate change on plants will be complex owing to a wide variety of climate conditions, so that different crops would have to be used in different regions. In Brazil, most of the biodiesel comes from soybeans, but there are promising new sources such as palm oil (de Lucena et al., 2009). The development of palm oil as well as soybean are important factors that induce land use change, with a potential to influence stability of forests and biodiversity in certain key regions in SA, such as the Amazon (Section 27.2.2.1).

Biofuels can help CA and SA to decrease emissions from energy production and use. However, renewable energy might imply potential problems such as those related to positive net emissions of GHGs, threats to biodiversity, an increase in food prices, and competition for

Table 27-6 | Comparison of consumption of different energy sources in Latin America and the world (in thousand tonnes of oil equivalent on a net calorific value basis).

Energy resource		Latin America						World					
		TFC (non-electricity)		TFC (via electricity generation)		TFC (total)		TFC (non-electricity)		TFC (via electricity generation)		TFC (total)	
Fossil	Coal and peat	9008	3%	1398	2%	10,406	3%	831,897	12%	581,248	40%	1,413,145	17%
	Oil	189,313	55%	8685	13%	197,998	48%	3,462,133	52%	73,552	5%	3,535,685	44%
	Natural gas	59,440	17%	9423	14%	68,863	17%	1,265,862	19%	307,956	21%	1,573,818	19%
Nuclear		0	0%	1449	2%	1449	0%	0	0%	193,075	13%	193,075	2%
Renewable	Biofuels and waste	82,997	24%	2179	3%	85,176	21%	1,080,039	16%	20,630	1%	1,100,669	14%
	Hydropower	0	0%	45,920	66%	45,920	11%	0	0%	238,313	17%	238,313	3%
	Geothermal, solar, wind, other renewable	408	0%	364	1%	772	0%	18,265	0%	26,592	2%	44,857	1%
Total		341,166	100%	69,418	100%	410,584	100%	6,658,196	100%	1,441,366	100%	8,099,562	100%

TFC = Total final consumption.

Source: IEA (2012).

water resources (Section 27.2.3), some of which can be reverted or attenuated (Koh and Ghazoul, 2008). For example, the sugarcane agroindustry in Brazil combusts bagasse to produce electricity, providing power for the bioethanol industry and increasing sustainability. The excess heat energy is then used to generate bioelectricity, thus allowing the biorefinery to be self-sufficient in energy utilization (Amorim et al., 2011; Dias et al., 2012). In 2005–2006 the production of bioelectricity was estimated to be 9.2 kWh per tonne of sugarcane (Macedo et al., 2008). Most bioenergy feedstocks at present in production in CA and SA are grasses. In the case of sugarcane, the responses to the elevation of CO_2 concentration up to 720 ppmv have been shown to be positive in terms of biomass production and principally regarding water use efficiency (de Souza et al., 2008).

The production of energy from renewable sources such as hydro- and wind power is greatly dependent on climatic conditions and therefore may be impacted in the future by climate change. de Lucena et al. (2010a) suggest an increasing energy vulnerability of the poorest regions of Brazil to climate change together with a possible negative influence on biofuels production and electricity generation, mainly biodiesel and hydropower respectively.

Expansion of biofuel crops in Brazil might cause both direct and indirect land use changes (e.g., biofuel crops replacing rangelands, which previously replaced forests) with the direct land use changes, according to simulation performed by Lapola et al. (2010) of the effects for 2020. The same study shows that sugarcane ethanol and biodiesel derived from soybean each contribute, with about one-half of the indirect deforestation projected for 2020 (121,970 km^2) (Lapola et al., 2010). Thus, indirect land use changes, especially those causing the rangeland frontier to move further into the Amazonian forests, might potentially offset carbon savings from biofuel production.

The increase in global ethanol demand is leading to the development of new hydrolytic processes capable of converting cellulose into ethanol (dos Santos et al., 2011). The expected increase in the hydrolysis technologies is *very likely* to balance the requirement of land for biomass crops. Thus, the development of these technologies has a strong potential to diminish social (e.g., negative health effects due the burning process, poor labor conditions) and environmental impacts (e.g., loss of biodiversity, water and land uses) whereas it can improve the economic potential of sugarcane. One adaptation measure will be to increase the productivity of bioenergy crops due to planting in high productivity environments with highly developed technologies, in order to use less land. As one of the main centers of biotech agriculture application in the world (Gruskin, 2012), the region has a great potential to achieve this goal.

As the effects previously reported on crops growing in SESA might prevail (see Section 27.3.4.1), that is, that an increase in productivity may happen due to increasing precipitation, future uncertainty will have to be dealt with by preparing adapted varieties of soybean in order to maintain food and biodiesel production, mainly in Argentina, as it is one of the main producers of biodiesel from soybean in the world (Chum et al., 2011).

Other renewable energy sources—such as wind power generation—may also be vulnerable, raising the need for further research. According to de Lucena et al. (2009, 2010b), the projections of changes in wind power in Brazil may favor the use of this kind of energy in the future.

27.3.6.2. Adaptation Practices

Renewable energy will become increasingly more important over time, as this is closely related to the emissions of GHGs (Fischedick et al., 2011). Thus, renewable energy could have an important role as adaptation means to provide sustainable energy for development in the region (see also Section 27.6.1). However, the production of renewable energy requires large available areas for agriculture, which is the case of

Argentina, Bolivia, Brazil, Chile, Colombia, Peru, and Venezuela, which together represent 90% of the total area of CA and SA. However, for small countries it might not be possible to use bioenergy. Instead, they could benefit in the future from other types of renewable energy, such as geothermal, eolic, photovoltaic, and so forth, depending on policies and investment in different technologies. This is important because economic development is thought to be strongly correlated with an increase in energy use (Smil, 2000), which is itself associated with an increase in emissions (Sathaye et al., 2011).

LA is second to Africa in terms of technical potential for bioenergy production from rainfed lignocellulosic feedstocks on unprotected grassland and woodlands (Chum et al., 2011). Among the most important adaptation measures regarding renewable energy are (1) management of land use change ; and (2) development of policies for financing and management of science and technology for all types of renewable energy in the region.

If carefully managed, biofuel crops can be used as a means to regenerate biodiversity as proposed by Buckeridge et al. (2012), highlighting that the technology for tropical forest regeneration has become available and that forests could share land with biofuel crops (such as sugarcane) taking advantage of forests' mitigating potential. A possible adaptation measure could be to expand the use of reforestation technology to other countries in CA and SA.

One of the main adaptation issues is related to food versus fuel (Valentine et al., 2012). This is important because an increase in bioenergy feedstocks might threaten primary food production in a scenario expected to feed future populations with an increase of 70% in production (Gruskin, 2012; Valentine et al., 2012). This is particularly important in the region, as it has one of the highest percentages of arable land available for food production in the world (Nellemann et al., 2009). As CA and SA develop new strategies to produce more renewable energy there might be a pressure for more acreage to produce bioenergy. Because climate change will affect bioenergy and food crops at the same time, their effects, as well as the adaptation measures related to agriculture, will be similar. The main risks identified by Arvizu et al. (2011) are (1) business as usual, (2) unreconciled growth, and (3) environment and food versus fuel. Thus, the most important adaptation measures will be the ones related to the control of economic growth, environmental management, and agriculture production. The choice for lignocellulosic feedstocks (e.g., sugarcane second-generation technologies) will be an important mitigation/adaptation measure because these feedstocks do not compete with food (Arvizu et al., 2011). In the case of sugarcane, for instance, an increase of approximately 40% in the production of bioethanol is expected as a result of the implantation of second-generation technologies coupled with the first-generation ones already existent in Brazil (Dias et al., 2012; de Souza et al., 2013).

Biodiesel production has the lowest costs in LA (Chum et al., 2011) owing to the high production of soybean in Brazil and Argentina. The use of biodiesel to complement oil-derived diesel is a productive choice for adaptation measures regarding this bioenergy source. Also, the cost of ethanol, mainly derived from sugarcane, is the lowest in CA, SA, and LA (Chum et al., 2011) and as an adaptation measure, such costs, as well as the one of biodiesel, should be lowered even more by improving technologies related to agricultural and industrial production of both. Indeed, it has been reported that in LA the use of agricultural budgets by governments for investment in public goods induces faster growth, decreasing poverty and environmental degradation (López and Galinato, 2007). The pressure of soy expansion due to biodiesel demand can lead to land use change and consequently to economic teleconnections, as suggested by Nepstad et al. (2006). These teleconnections may link Amazon deforestation derived from soy expansion to economic growth in some developing countries because of changes in the demand of soy. These effects may possibly mean a decrease in jobs related to small to big farms in agriculture in Argentina (Tomei and Upham, 2009) on the one hand, and deforestation in the Amazon due to the advance of soybean cropping in the region on the other (Nepstad and Stickler, 2008).

27.3.7. Human Health

27.3.7.1. Observed and Projected Impacts and Vulnerabilities

Changes in weather extremes and climatic patterns are affecting human health (*high confidence*), by increasing morbidity, mortality, and disabilities, and through the emergence of diseases in previously non-endemic regions (*high confidence*; Winchester and Szalachman, 2009; Rodríguez-Morales, 2011). Heat waves and cold spells have increased urban mortality rates (McMichael et al., 2006; Bell et al., 2008; Hardoy and Pandiella, 2009; Muggeo and Hajat, 2009; Hajat et al., 2010). Outbreaks of vector- and water-borne diseases were triggered in CA by Hurricane Mitch in 1998 (Costello et al., 2009; Rodríguez-Morales et al., 2010), while the 2010–2012 Colombian floods caused hundreds of deaths and displaced thousands of people (Hoyos et al., 2012).

The number of cases of malaria have increased in Colombia during the last 5 decades alongside air temperatures (Poveda et al., 2011; Arevalo-Herrera et al., 2012), but also in urban and rural Amazonian regions undergoing large environmental changes (Gil et al., 2007; Tada et al., 2007; Cabral et al., 2010; da Silva-Nunes et al., 2012). Malaria transmission has reached 2300 m in the Bolivian Andes, and vectors are found at higher altitudes from Venezuela to Bolivia (Benítez and Rodríguez-Morales, 2004; Lardeux et al., 2007; Pinault and Hunter, 2011).

Although the incidence of malaria has decreased in Argentina, its vector density has increased in the northwest along with climate variables (Dantur Juri et al., 2010, 2011). El Niño drives malaria outbreaks in Colombia (Mantilla et al., 2009; Poveda et al., 2011), amidst other factors (Rodríguez-Morales et al., 2006; Osorio et al., 2007; Restrepo-Pineda et al., 2008). Linkages between ENSO and malaria are also reported in Ecuador and Peru (Anyamba et al., 2006; Kelly-Hope and Thomson, 2010), French Guiana (Hanf et al., 2011), Amazonia (Olson et al., 2009), and Venezuela (Moreno et al., 2007).

Unlike malaria, dengue fever and its hemorrhagic variant are mostly urban diseases whose vector is affected by climate conditions. Their incidence have risen in tropical America in the last 25 years, causing annual economic losses of US$2.1+ (1 to 4) billion (Torres and Castro, 2007; Tapia-Conyer et al., 2009; Shepard et al., 2011). Environmental and climatic variability affect their incidence in CA (Fuller et al., 2009; Rodríguez-Morales et al., 2010; Mena et al., 2011), in Colombia

(Arboleda et al., 2009), and in French Guiana alongside malaria (Carme et al., 2009; Gharbi et al., 2011). In Venezuela, dengue fever increases during La Niña (Rodríguez-Morales and Herrera-Martinez, 2009; Herrera-Martinez and Rodríguez-Morales, 2010). Weather and climate variability are also associated with dengue fever in southern SA (Honório et al., 2009; Costa et al., 2010; de Carvalho-Leandro et al., 2010; Degallier et al., 2010; Lowe et al., 2011), involving also demographic and geographic factors in Argentina (Carbajo et al., 2012). In Rio de Janeiro a 1°C increase in monthly minimum temperature led to a 45% increase of dengue fever in the next month, and 10 mm increase in rainfall to a 6% increase (Gomes et al., 2012). Despite large vaccination campaigns, the risk of yellow fever outbreaks has increased mostly in tropical America's densely populated poor urban settings (Gardner and Ryman, 2010), alongside climate conditions (Jentes et al., 2011).

Schistosomiasis is endemic in rural areas of Suriname, Venezuela, the Andean highlands, and rural and peripheral urbanized regions of Brazil (Barbosa et al., 2010; Kelly-Hope and Thomson, 2010; Igreja, 2011). It is *highly likely* that schistosomiasis will increase in a warmer climate (Mangal et al., 2008; Mas-Coma et al., 2009; Lopes et al., 2010). Vegetation indices are associated with human fascioliasis in the Andes (Fuentes, 2004).

Hantaviruses have been recently reported throughout the region (Jonsson et al., 2010; MacNeil et al., 2011), and El Niño and climate change augment their prevalence (Dearing and Dizney, 2010). Variation in hantavirus reservoirs in Patagonia is strongly dependent on climate and environmental conditions (Andreo et al., 2012; Carbajo et al., 2009). In Venezuela, rotavirus is more frequent and more severe in cities with minimal seasonality (Kane et al., 2004). The peak of rotavirus in Guatemala occurs in the dry season, causing 60% of total diarrhea cases (Cortes et al., 2012).

In spite of its rapid decline, climate-sensitive Chagas disease is still a major public health issue (Tourre et al., 2008; Moncayo and Silveira, 2009; Abad-Franch et al., 2009; Araújo et al., 2009; Gottdenker et al., 2011). Climate also affects the most prevalent mycosis (Barrozo et al., 2009), and ENSO is associated with outbreaks of bartonellosis in Peru (Payne and Fitchett, 2010).

The high incidence of cutaneous leishmaniasis in Bolivia is exacerbated during La Niña (Gomez et al., 2006; García et al., 2009). Cutaneous leishmaniasis is affected in Costa Rica by temperature, forest cover, and ENSO (Chaves et al., 2008), and in Colombia by land cover, altitude, climatic variables, and El Niño (Cárdenas et al., 2006, 2007, 2008; Valderrama-Ardila et al., 2010), and decreases during La Niña in Venezuela (Cabaniel et al., 2005). Cutaneous leishmaniasis in Suriname peaks during the March dry season (35%; van der Meide et al., 2008), and in French Guiana is intensified after the October-December dry season (Rotureau et al., 2007). The incidence of visceral leishmaniasis has increased in Brazil (highest in LA) in association with El Niño and deforestation (Ready, 2008; Cascio et al., 2011; Sortino-Rachou et al., 2011), as in Argentina, Paraguay, and Uruguay (Bern et al., 2008; Dupnik et al., 2011; Salomón et al., 2011; Fernández et al., 2012). Visceral leishmaniasis transmission in Venezuela is associated with rainfall seasonality (Feliciangeli et al., 2006; Rodríguez-Morales et al., 2007). The incidence of skin cancer in Chile has increased in recent years, concomitantly with climate and geographic variables (Salinas et al., 2006).

Onchocerciasis (river blindness) vector exhibits seasonal biting rates (Botto et al., 2005; Rodríguez-Pérez et al., 2011), and leptospirosis is prevalent in CA's warm-humid tropical regions (Valverde et al., 2008). Other climate-driven infectious diseases are ascariasis and gram-positive cocci in Venezuela (Benítez et al., 2004; Rodríguez-Morales et al., 2010) and Carrion's disease in Peru (Huarcaya et al., 2004).

Seawater temperature affects the abundance of cholera bacteria (Koelle, 2009; Jutla et al., 2010; Marcheggiani et al., 2010; Hofstra, 2011), which explains the outbreaks during El Niño in Peru, Ecuador, Colombia, and Venezuela (Cerda Lorca et al., 2008; Martínez-Urtaza et al., 2008; Salazar-Lindo et al., 2008; Holmner et al., 2010; Gavilán and Martínez-Urtaza, 2011; Murugaiah, 2011).

The worsening of air quality and higher temperatures in urban settings are increasing chronic respiratory and cardiovascular diseases, and morbidity from asthma and rhinitis (Grass and Cane, 2008; Martins and Andrade, 2008; Gurjar et al., 2010; Jasinski et al., 2011; Rodriguez et al., 2011), but also atherosclerosis, pregnancy-related outcomes, cancer, cognitive deficit, otitis, and diabetes (Olmo et al., 2011). Dehydration

Frequently Asked Questions

FAQ 27.3 | Are there emerging and reemerging human diseases as a consequence of climate variability and change in the region?

Human health impacts have been exacerbated by variations and changes in climate extremes. Climate-related diseases have appeared in previously non-endemic regions (e.g., malaria in the Andes, dengue in CA and southern SA) (*high confidence*). Climate variability and air pollution have also contributed to increase the incidence of respiratory and cardiovascular, vector- and water-borne and chronic kidney diseases, hantaviruses and rotaviruses, pregnancy-related outcomes, and psychological trauma (*very high confidence*). Health vulnerabilities vary with geography, age, gender, ethnicity, and socioeconomic status, and are rising in large cities. Without adaptation measures (e.g., extending basic public health services), climate change will exacerbate future health risks, owing to population growth rates and existing vulnerabilities in health, water, sanitation and waste collection systems, nutrition, pollution, and food production in poor regions (*medium confidence*).

from heat waves increases hospitalizations for chronic kidney diseases (Kjellstrom et al., 2010), affecting construction, sugarcane, and cotton workers in CA (Crowe et al., 2009, 2010; Kjellstrom and Crowe, 2011; Peraza et al., 2012).

Extreme weather/climate events affect mental health in Brazil (depression, psychological distress, anxiety, mania, and bipolar disorder), in particular in drought-prone areas of NEB (Coêlho et al., 2004; Volpe et al., 2010). Extreme weather, meager crop yields, and low GDP are also associated with increased violence (McMichael et al., 2006).

Multiple factors increase the region's vulnerability to climate change: precarious health systems; malnutrition; inadequate water and sanitation services; poor waste collection and treatment systems; air, soil, and water pollution; lack of social participation; and inadequate governance (Luber and Prudent, 2009; Rodríguez-Morales, 2011; Sverdlik, 2011). Human health vulnerabilities in the region depend on geography, age (Perera, 2008; Martiello and Giacchi, 2010; Åstrom et al., 2011; Graham et al., 2011), gender (de Oliveira et al., 2011), race, ethnicity, and socioeconomic status (Diez Roux et al., 2007; Martiello and Giacchi, 2010). Neglected tropical diseases in LA cause 1.5 to 5.0 million disability-adjusted life years (DALYs) (Hotez et al., 2008).

Vulnerability of megacities (see Section 27.3.5) is aggravated by access to clean water, rapid spread of diseases (Borsdorf and Coy, 2009), and migration from rural areas forced by disasters (Campbell-Lendrum and Corvalán, 2007; Borsdorf and Coy, 2009; Hardoy and Pandiella, 2009). Human health vulnerabilities have been assessed in Brazil through composite indicators involving epidemiological variables, downscaled climate scenarios, and socioeconomic projections (Confalonieri et al., 2009; Barata et al., 2011; Barbieri and Confalonieri, 2011). The Andes and CA are among the regions of highest predicted losses (1 to 27%) in labor productivity from future climate scenarios (Kjellstrom et al., 2009).

27.3.7.2. Adaptation Strategies and Practices

Adaptation efforts in the region (Blashki et al., 2007; Costello et al., 2011) are hampered by lack of political commitment, gaps in scientific knowledge, and institutional weaknesses (Keim, 2008; Lesnikowski et al., 2011; Olmo et al., 2011; see Section 27.4.3). Research priorities and current strategies must be reviewed (Halsnæs and Verhagen, 2007; Romero and Boelaert, 2010; Karanja et al., 2011), and preventive/responsive systems must be put in place (Bell, 2011) to foster adaptive capacity (Campbell-Lendrum and Bertollini, 2010; Huang et al., 2011). Colombia established a pilot adaptation program to cope with changes in malaria transmission and exposure (Poveda et al., 2011). The city of São Paulo has implemented local pollution control measures, with the co-benefit of reducing GHG emissions (de Oliveira, 2009; Nath and Behera, 2011).

Human well-being indices must be explicitly stated as adaptation policies in LA (e.g., Millennium Development Goals; Franco-Paredes et al., 2007; Halsnæs and Verhagen, 2007; Mitra and Rodriguez-Fernandez, 2010). South–south cooperation and multidisciplinary research are required to design relevant adaptation and mitigation strategies (Tirado et al., 2010; Team and Manderson, 2011).

27.4. Adaptation Opportunities, Constraints, and Limits

27.4.1. Adaptation Needs and Gaps

During the last few years, the study of adaptation to climate change has progressively switched from an impact-focused approach (mainly climate-driven) to include a vulnerability-focused vision (Boulanger et al., 2011). As a consequence, the development and implementation of systemic adaptation strategies, involving institutional, social, ecosystem, environmental, financial, and capacity components (see Chapter 14) to cope with present climate extreme events is a key step toward climate change adaptation, especially in SA and CA countries. Although different frameworks and definitions of vulnerability exist, a general tendency aims at studying vulnerability to climate change, especially in SA and CA, focusing on the following aspects: urban vulnerability (e.g., Hardoy and Pandiella, 2009; Heinrichs and Krellenberg, 2011), rural community (McSweeney and Coomes, 2011; Ravera et al., 2011), rural farmer vulnerability (Oft, 2010), and sectoral vulnerability (see Section 27.3). The approach used can be holistic or systemic (Ison, 2010; Carey et al., 2012b), where climate drivers are actually few with respect to all other drivers related to human and environment interactions including physical, economic, political, and social context, as well as local characteristics such as occupations, resource uses, accessibility to water, and so forth (Manuel-Navarrete et al., 2007; Young et al., 2010).

In developing and emergent countries, there exists a general consensus that the adaptive capacity is low, strengthened by the fact that poverty is the key determinant of vulnerability in LA (to climate-related natural hazards; see Rubin and Rossing, 2012) and thus a limit to resilience (Pettengell, 2010) leading to a "low human development trap" (UNDP, 2007). However, Magnan (2009, p. 1) suggests that this analysis is biased by a "relative immaturity of the science of adaptation to explain what are the processes and the determinants of adaptive capacity." Increasing research efforts on the study of adaptation is therefore of great importance to improve understanding of the actual societal, economical, community, and individual drivers defining the adaptive capacity. Especially, a major focus on traditions and their transmission (Young and Lipton, 2006) may actually indicate potential adaption potentials in remote and economically poor regions of SA and CA. Such a potential does not dismiss the fact that the nature of future challenges may actually not be compared to past climate variability (e.g., glacier retreat in the Andes).

Coping with new situations may require new approaches such as a multi-level risk governance (Corfee-Morlot et al., 2011; Young and Lipton, 2006) associated with decentralization in decision making and responsibility. Although the multi-level risk governance and the local participatory approach are interesting frameworks for strengthening adaptation capacity, perception of local and national needs is diverging, challenging the implementation of adaptation strategies in CA/SA (Salzmann et al., 2009). At present, despite an important improvement during the last few years, there still exists a certain lack of awareness of environmental changes and their implications for livelihoods and businesses (Young et al., 2010). Moreover, considering the limited financial resources of some states in CA and SA, long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the population. This situation weakens the importance of adaptation planning to climate change in the political agenda (Carey et al., 2012b), and therefore requires international involvement as one facilitating factor in natural hazard management and climate change adaptation, with respect to sovereignty according to international conventions including the United Nations Framework Convention on Climate Change (UNFCCC). In addition, as pointed out by McGray et al. (2007), development, adaptation, and mitigation are not separate issues. Development and adaptation strategies especially should be tackled together in developing countries such as SA and CA, focusing on strategies to reduce vulnerability. The poor level of adaptation of present-day climate in SA and CA countries is characterized by the fact that responses to disasters are mainly reactive rather than preventive. Some early warning systems are being implemented, but the capacity of responding to a warning is often limited, particularly among poor populations. Finally, actions combining public communication (and education), public decision-maker capacity-building, and a synergetic development-adaptation funding will be key to sustain the adaptation process that CA and SA require to face future climate change challenges.

27.4.2. Practical Experiences of Autonomous and Planned Adaptation, Including Lessons Learned

Adaptation processes in many cases have been initiated a few years ago, and there is still a lack of literature to evaluate their efficiency in reducing vulnerability and building resilience of the society against climate change. However, experiences of effective adaptation and maladaptation are slowly being documented (see also Section 27.4.3); some lessons have already been learned from these first experiences (see Section 27.3); and tools, such as the Index of Usefulness of Practices for Adaptation (IUPA) to evaluate adaptation practices, have been developed for the region (Debels et al., 2009). Evidenced by these practical experiences, there is a wide range of options to foster adaptation and thus adaptive capacity in CA and SA. In CA and SA, many societal issues are strongly connected to development goals and are often considered a priority in comparison to adaptation efforts to climate change. However, according to the 135 case studies analyzed by McGray et al. (2007), 21 of which were in CA and SA, the synergy between development and adaptation actions makes it possible to ensure a sustainable result of the development projects.

Vulnerability and disaster risk reduction may not always lead to long-term adaptive capacity (Tompkins et al., 2008; Nelson and Finan, 2009), except when structural reforms based on good governance (Tompkins et al., 2008) and negotiations (de Souza Filho and Brown, 2009) are implemented. While multi-level governance can help to create resilience and reduce vulnerability (Roncoli, 2006; Young and Lipton, 2006; Corfee-Morlot et al., 2011), capacity-building (Eakin and Lemos, 2006), good governance, and enforcement (Lemos et al., 2010; Pittock, 2011) are key components.

Autonomous adaptation experience is mainly realized at local levels (individual or communitarian) with examples found, for instance, for rural communities in Honduras (McSweeney and Coomes, 2011), Indigenous communities in Bolivia (Valdivia et al., 2010), and coffee agroforestry systems in Brazil (de Souza et al., 2012). However, such adaptation processes do not always respond specifically to climate forcing. For instance, the agricultural sector adapts rapidly to economic stressors, although, despite a clear perception of climate risks, it may last longer before responding to climate changes (Tucker et al., 2010). In certain regions or communities, such as Anchioreta in Brazil (Schlindwein et al., 2011), adaptation is part of a permanent process and is actually tackled through a clear objective of vulnerability reduction, maintaining and diversifying a large set of natural varieties of corn, allowing the farmers to diversify their planting. Another kind of autonomous adaptation is the southward displacement of agriculture activities (e.g., wine, coffee) through the purchase of lands, which will become favorable for such agriculture activities in a warmer climate. In Argentina, the increase of precipitation observed during the last 30 years contributed to a westward displacement of the annual crop frontier.

However, local adaptation to climate and non-climate drivers may undermine long-term resilience of socio-ecological systems when local, short-term strategies designed to deal with specific threats or challenges do not integrate a more holistic and long-term vision of the system at threat (Adger et al., 2011). Thus, policy should identify the sources of and conditions for local resilience and strengthen their capacities to adapt and learn (Borsdorf and Coy, 2009; Adger et al., 2011; Eakin et al., 2011), as well as to integrate new adapted tools (Oft, 2010). This sets the question of convergence between the local-scale/short-term and broad-scale/long-term visions in terms of perceptions of risks, needs to adapt, and appropriate policies to be implemented (Eakin and Wehbe, 2009; Salzmann et al., 2009). Even if funding for adaptation is available, the overarching problem is the lack of capacity and/or willingness to address the risks, especially those threatening lower income groups (Satterthwaite, 2011a). Adaptation to climate change cannot eliminate the extreme weather risks, and thus efforts should focus on disaster preparedness and post-disaster response (Sverdlik, 2011). Migration is the last resort for rural communities facing water stress problems in CA and SA (Acosta-Michlik et al., 2008).

In natural hazard management contributing to climate change adaptation, specific cases such as the one in Lake 513 in Peru (Carey et al., 2012b) clearly allowed identification of facilitating factors for a successful adaptation process (technical capacity, disaster events with visible hazards, institutional support, committed individuals, and international involvement) as well as impediments (divergent risk perceptions, imposed government policies, institutional instability, knowledge disparities, and invisible hazards). In certain cases, forward-looking learning (anticipatory process), as a contrast to learning by shock (reactive process), has been found as a key element for adaptation and resilience (Tschakert and Dietrich, 2010) and should be promoted as a tool for capacity-building at all levels (stakeholders, local and national governments). Its combination with role-playing game and agent-based models (Rebaudo et al., 2011) can strengthen and accelerate the learning process.

Planned adaptation policies promoted by governments have been strengthened by participation in international networks, where experience and knowledge can be exchanged. As an example, the C40 Cities-Climate Leadership Group or ICLEI include Bogotá (Colombia), Buenos Aires (Argentina), Caracas (Venezuela), Curitiba, Rio de Janeiro, and São Paulo (Brazil), Lima (Peru), and Santiago de Chile (Chile). Most of these cities have come up with related action and strategy plans (e.g., Action Plan

Buenos Aires 2030, Plan of Caracas 2020, or the Metropolitan Strategy to CCA of Lima) (C40 Cities, 2011).

At a regional policy level, an example of intergovernmental initiatives in SA and CA is the Ibero-American Programme on Adaptation to Climate Change (PIACC), developed by the Ibero-American Network of Climate Change Offices (RIOCC) (Keller et al., 2011b). For CA specifically, the Central American Commission for Environment and Development (CCAD) brings together the environmental ministries of the Central American Integration System (Sistema de la Integración Centroamericana (SICA)) that released its climate change strategy in 2010 (CCAD and SICA, 2010; Keller et al., 2011a).

These initiatives demonstrate that there has been a growing awareness of CA and SA governments on the need to integrate climate change and future climate risks in their policies. To date, in total, 18 regional Non-Annex countries, including Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Guyana, Panama, Paraguay, Peru, Suriname, Uruguay, and Venezuela, have already published their first and/or second National Communication to the UNFCCC (see UNFCCC, 2012), making it possible to measure the country's emissions and to assess its present and future vulnerability.

27.4.3. Observed and Expected Barriers to Adaptation

Adaptation is a dynamic process, which to be efficient requires a permanent evolution and even transformation of the vulnerable system. Such a transformation process can be affected by several constraints, including constraints affecting the context of adaptation as well as the implementation of policies and measures (see Section 16.3.2).

Major constraints related to the capacity and resources needed to support the implementation of adaptation policies and processes include: access to (Lemos et al., 2010) and exchange of knowledge (e.g., adaptive capacity can be enhanced by linking indigenous and scientific knowledge; Valdivia, 2010); access to and quality of natural resources (López-Marrero, 2010); access to financial resources, especially for poor households (Satterthwaite, 2011b; Hickey and Weis, 2012; Rubin and Rossing, 2012), as well as for institutions (Pereira et al., 2009); access to technological resources (López-Marrero, 2010) and technical assistance (Guariguata, 2009; Eakin et al., 2011), as well as the fostering of public-private technology transfer (La Rovere et al., 2009; Ramirez-Villegas et al., 2012) and promotion of technical skills (Hickey and Weis, 2012); and social asset-based formation at the local level (Rubin and Rossing, 2012).

In terms of framing adaptation, as a constraint to affect the adaptation context, it is usually considered that a major barrier to adaptation is the perception of risks, and many studies focused on such an issue (e.g., Schlindwein et al., 2011). New studies (Adger et al., 2009) identified social limits to possible adaptation to climate change in relation with issues of values and ethics, risk, knowledge, and culture, even though such limits can evolve in time. Indeed, while being a necessary condition, perception may not be the main driver for initiating an adaptation process. As pointed out by Tucker et al. (2010) with a specific focus on CA, exogenous factors (economic, land tenure, cost, etc.) may actually strongly constrain the decision-making process involved in a possible adaptation process. In that sense, efficient governance and management are key components in the use of climate and non-climate information in the decision-making and adaptation process. As a consequence, it is difficult to describe adaptation without defining at which level it is thought. Indeed, though much effort is invested in national and regional policy initiatives, most of the final adaptation efforts will be local. National and international (transborder) governance is key to build adaptive capacity (Engle and Lemos, 2010) and therefore to strengthen (or weaken) local adaptation through efficient policies and delivery of resources. At a smaller scale (Agrawal, 2008), local institutions can strongly contribute to vulnerability reduction and adaptation. However, at all levels, the efficiency in national and local adaptation activities strongly depend on the capacity-building and information transmission to decision makers (Eakin and Lemos, 2006).

27.5 Interactions between Adaptation and Mitigation

Synergies between adaptation and mitigation strategies on the local level can be reached as a result of self-organization of communities in cooperatives (see, e.g., "The SouthSouthNorth Capacity Building Module on Poverty Reduction" (SSN Capacity Building Team, 2006), which manages recycling or renewable energy production, leading to an increase in energy availability, thus production capacity, and therefore new financial resources). Moreover, Venema and Cisse (2004) also support the development of decentralized renewable energy solutions for the growth of renewable energy in CA and SA (see also Section 27.3.6) next to a large infrastructure project (see their case studies for Argentina and Brazil).

In spite of their smaller size (individual or communitarian), these solutions offer adaptation and mitigation benefits. On one hand, fossil-based energy consumption is reduced, while energy availability is increased. On the other hand, reduction of energy precariousness is key in any development strategy. Thus, it allows local community and individuals to grow socially and economically, and therefore to reduce vulnerability, avoiding the poverty trap (UNDP, 2007), and to initiate an adaptation process based on non-fossil fuel energy sources. Such initiatives also depend on local and organizational leaderships (UN-HABITAT, 2011).

Such integrated strategies of income generation as adaptation measures as well as production of renewable energy are also identified for vulnerable, small farmers diversifying their crops toward crops for vegetable oil and biodiesel production in Brazil. Barriers identified concern capacity-building and logistical requirements, making policy tools, credit mechanism, and organization into cooperatives, and fostering necessary research (La Rovere et al., 2009). Other promising interactions of mitigation and adaptation are identified, for example, for the management of Brazilian tropical natural and planted forest (Guariguata, 2009).

At national and regional scales, CA and SA countries will require the allocation of human and financial resources to adapt to climate change. While resources are limited, too large an economic dependence of these countries to fossil fuels will reduce their adaptive capacity. The reduction in energy consumption and the integration of renewable energies in their energetic matrix is therefore a key issue for all these countries to sustain their development and growth and therefore increase their adaptive capacity (see also Section 27.3.6).

Reforestation and avoided deforestation are important practices that contribute to both mitigation and adaptation efforts in the region as in other parts of the world. Maintaining forest cover can provide a suite of environmental services including local climate regulation, water regulation, and reduced soil erosion—all of which can reduce the vulnerability of communities to variable climate (see Section 27.3.2.2; Vignola et al., 2009).

27.6. Case Studies

27.6.1. Hydropower

Hydropower is the main source of renewable energy in CA and SA (see Section 27.3.6). The region is second only to Asia in terms of hydropower energy generation in the world, displaying a 20% share of total annual generation and an average regional capacity factor of greater than 50% (SRREN Table 5-1; IPCC, 2011). As a result, the region has by far the largest proportion of electricity generated through hydropower facilities (Table 27-6). The hydropower proportion of total electricity production is greater than 40% in the region, and in some cases is near or close to 80%, as in the case of Brazil, Colombia, and Costa Rica (IEA, 2012). Although there is debate, especially in tropical environments, about GHG emissions from hydropower reservoirs (Fearnside and Pueyo, 2012), this form of electricity generation is often seen as a major contributor to mitigating GHG emissions worldwide (see IPCC, 2011; Kumar et al., 2011). But, on the other hand, hydropower is a climate-related sector, thus making it prone to the potential effects of changing climate conditions (see Section 27.3.1.1). In this regard the CA and SA region constitutes a unique example to study these relations between climate change mitigation and adaptation in relation to hydropower generation.

Diverse studies have analyzed the potential impacts of climate change on hydropower generation (Table 27-4). Maurer et al. (2009) studied future conditions for the Lempa River (El Salvador, Honduras, and Guatemala), showing a potential reduction in hydropower capacity of 33 to 53% by 2070–2099. A similar loss is expected for the Sinú-Caribe basin in Colombia where, despite a general projection of increased precipitation, losses due to evaporation enhancement reduce inflows to hydroelectric systems, thus reducing electricity generation up to 35% (Ospina Noreña et al., 2009a). Further studies (Ospina Noreña et al., 2011a,b) have estimated vulnerability indices for the hydropower sector in the same basin, and identified reservoir operation strategies to reduce this vulnerability. Overall reductions in hydropower generation capacity are also expected in Chile for the main hydropower generation river basins (Maule, Laja, and Biobio (ECLAC, 2009a; McPhee et al., 2010; Stehr et al., 2010)), and also in the Argentinean Limay River basin (Seoane and López, 2007). Ecuador, on the other hand, faces an increase in generation capacity associated with an increment in precipitation on its largest hydroelectric generator, the Paute River basin (Buytaert et al., 2010). Brazil, although being the country with the largest installed hydroelectric capacity in the region, still has unused generation capacity in sub-basins of the Amazon River (Soito and Freitas, 2011). However, future climate conditions plus environmental concerns pose an important challenge for the expansion of the system (Freitas and Soito, 2009; Andrade et al., 2012; Finer and Jenkins, 2012). According to de Lucena et al. (2009), hydropower systems in southern Brazil (most significantly the Parana River system) could face a slight increase in energy production under an A2 scenario. However, the rest of the country's hydropower system, especially those in NEB, could face a reduction in power generation, thus reducing the reliability of the whole system (de Lucena et al., 2009).

An obvious implication of the mentioned impacts is the need to replace the energy lost through alternative (see Section 27.3.6.2) or traditional sources. Adaptation measures have been studied for Brazil (de Lucena et al., 2010a), with results implying an increase in natural gas and sugarcane bagasse electricity generation on the order of 300 TWh, increase in operation costs on the order of US$7 billion annually, and US$50 billion in terms of investment costs by 2035. In Chile, the study by ECLAC (2009a) assumed that the loss in hydropower generation, on the order of 18 TWh for the 2011–2040 period (a little over 10% of actual total hydropower generation capacity) would be compensated by the least operating cost source available, coal-fired power plant, implying an increase of 2 MT CO_2-eq of total GHG emissions (emissions for the electricity sector in Chile totaled 25 MT CO_2-eq in 2009). Ospina Noreña (2011a,b) studied some adaptation options, such as changes in water use efficiency or demand growth that could mitigate the expected impacts on hydropower systems in the Colombian Sinú-Caribe River basin. Changes in seasonality and total availability could also increase complexities in the management of multiple-use dedicated basins in Peru (Juen et al., 2007; Condom et al., 2012), Chile (ECLAC, 2009a), and Argentina (Seoane and López, 2007), that could affect the relationship between different water users within a basin. It is worth noting that those regions that are projected to face an increase in streamflow and associated generation capacity, such as Ecuador or Costa Rica, also share difficulties in managing deforestation, erosion, and sedimentation which limits the useful life of reservoirs (see Section 27.3.1.1). In these cases it is important to consider these effects in future infrastructure operation (Ferreira and Teegavarapu, 2012) and planning, and also to enhance the ongoing process of recognizing the value of the relation between ecosystem services and hydropower system operations (Leguía et al., 2008) (see more on PES in Sections 27.3.2.2, 27.6.2).

27.6.2. Payment for Ecosystem Services

Payment for ecosystem services (PES) is commonly described as a set of transparent schemes for securing a well-defined ecosystem service (or a land use capable to secure that service) through conditional payments or compensations to voluntary providers (Engel et al., 2008; Tacconi, 2012). Van Noordwijk et al. (2012) provides a broader definition to PES by arguing that it encompasses three complementary approaches: (1) the one above, that is, commodification of predefined ecosystem services so that prices can be negotiated between buyers and sellers; plus (2) compensation for opportunities forgone voluntarily or by command and control decisions; and (3) coinvestment in environmental stewardships. Therefore, the terms *conservation agreements*, *conservation incentives*, and *community conservation* are often used as synonyms or as something

Table 27-7 | Cases of government-funded physiological-ecological simulation (PES) schemes in Central America and South America.

Countries	Level	Start	Name	Benefits	References
Brazil	Sub-national (Amazonas state)	2007	Bolsa Floresta	By 2008, 2700 traditional and indigenous families already benefitted: financial compensation and health assistance in exchange for zero deforestation in primary forests.	Viana (2008)
Costa Rica	National	1997	Fondo Nacional de Financiamiento Forestal	PES is a strong incentive for reforestation and, for agroforestry ecosystems alone, more than 7000 contracts have been set since 2003 and nearly 2 million trees planted.	Montagnini and Finney (2011)
Ecuador	National	2008	Socio-Bosque	By 2010, the program already included more than half a million hectares of natural ecosystems protected and has more than 60,000 beneficiaries.	De Koning et al. (2011)
Guatemala	National	1997	Programa de Incentivos Forestales	By 2009, the program included 4174 beneficiaries, who planted 94,151 hectares of forest. In addition, 155,790 hectares of natural forest were under protection with monetary incentives.	INE (2011)

different or broader than PES (Milne and Niesten, 2009; Cranford and Mourato, 2011). For simplicity, we refer to PES in its broadest sense (van Noordwijk et al., 2012).

Services subjected to such types of agreements often include regulation of freshwater flows, carbon storage, provision of habitat for biodiversity, and scenic beauty (de Koning et al., 2011; Montagnini and Finney, 2011). Because the ecosystems that provide the services are mostly privately owned, policies often aim at supporting landowners to maintain the provision of services over time (Kemkes et al., 2010). Irrespective of the debate as to whether payments or compensations should be designed to focus on actions or results (Gibbons et al., 2011), experiences in Colombia, Costa Rica, and Nicaragua show that PES can finance conservation, ecosystem restoration, and better land use practices (Montagnini and Finney, 2011; see also Table 27-5). However, based on examples from Ecuador and Guatemala, Southgate et al. (2010) argue that uniformity of payment for beneficiaries can be inefficient if recipients accept less compensation in return for conservation measures, or if recipients that promote greater environmental gains receive only the prevailing payment. Other setbacks to PES schemes might include cases where there is a perception of commoditization of nature and its intangible values (e.g., Bolivia, Cuba, Ecuador, and Venezuela); other cases where mechanisms are inefficient to reduce poverty; and slowness to build trust between buyers and sellers, as well as gender and land tenure issues that might arise (Asquith et al., 2008; Peterson et al., 2010; Balvanera et al., 2012; van Noordwijk et al., 2012). Table 27-7 lists select examples of PES schemes in Latin America, with a more complete and detailed list given in Balvanera et al. (2012).

The PES concept (or "fishing agreements") also applies to coastal and marine areas, although only a few cases have been reported. Begossi (2011) argues that this is due to three factors: origin (the mechanism was originally designed for forests), monitoring (marine resources such as fish are more difficult to monitor than terrestrial resources), and definition of resource boundaries in offshore water. One example of a compensation mechanism in the region is the so-called *defeso*, in Brazil. It consists of a period (reproductive season) when fishing is forbidden by the government and fishermen receive a financial compensation. It applies to shrimp, lobster, and both marine and freshwater fisheries (Begossi et al., 2011).

27.7. Data and Research Gaps

The scarcity of and difficulty in obtaining high-resolution, high quality, and continuous climate, oceanic, and hydrological data, together with availability of only very few complete regional studies, pose challenges for the region to address changes in climate variability and the identification of trends in extremes, in particular for CA. This situation hampers studies on frequency and variability of extremes, as well as impacts and vulnerability analyses of the present and future climates, and the development of vulnerability assessments and adaptation actions.

Related to observed impacts in most sectors, there is an imbalance in information availability among countries. While more studies have been performed for Brazil, southern SA, and SESA region, much less are available for CA and for some regions of tropical SA. An additional problem is poor dissemination of results in peer-reviewed publications because most information is available only as grey literature. There is a need for studies focused on current impacts and vulnerabilities across sectors throughout CA and SA, with emphasis on extremes to improve risk management assessments.

The complex interactions between climate and non-climate drivers make the assessment of impacts and projections difficult, as is the case for water availability and streamflows owing to current and potential deforestation, overfishing and pollution regarding the impacts on fisheries, or impacts on hydroenergy production. The lack of interdisciplinary integrated studies limits our understanding of the complex interactions between natural and socioeconomic systems. In addition, accelerating deforestation and land use changes, as well as changes in economic conditions, impose a continuous need for updated and available data sets that feed basic and applied studies.

To address the global challenge of food security and food quality, both important issues in CA and SA, investment in scientific agricultural knowledge needs to be reinforced, mainly with regard to the integration of agriculture with organic production, and the integration of food and bioenergy production. It is necessary to consider ethical aspects when the competition for food and bioenergy production is analyzed to identify which activity is most important at a given location and time and whether bioenergy production would affect food security for a particular population.

SLR and coastal erosion are also relevant issues; the lack of comparable measurements of SLR in CA and SA make the present and future integrated assessment of the impacts of SLR in the region difficult. Of local and global importance will be improving our understanding of the physical oceanic processes, in particular of the Humboldt Current system flowing along the west coast of SA, which is one of the most productive systems worldwide.

More information and research about the impacts of climate variability and change on human health is needed. One problem is the difficulty in accessing health data that are not always archived and ready to be used in integrated studies. Another need refers to building the necessary critical mass of transdisciplinary scientists to tackle the climate change-human health problems in the region. The prevailing gaps in scientific knowledge hamper the implementation of adaptation strategies, thus demanding a review of research priorities toward better disease control. With the aim of further studying the health impacts of climate change and identifying resilience, mitigation, and adaptation strategies, South-South cooperation and multidisciplinary research are considered to be relevant priorities.

In spite of the uncertainty that stems from global and regional climatic projections, the region needs to act in preparation for a possible increase in climate variability and in extremes. It is necessary to undertake research activities leading to public policies to assist societies in coping with current climate variability, such as, for example, risk assessment and risk management. Another important aspect since AR4 is the improvement of climate modeling and the generation of high-resolution climate scenarios, which in countries in CA and SA resulted in the first integrated regional studies on impacts and vulnerability assessments of climate change focusing on sectors such as agriculture, energy, and human health.

Research on adaptation and the scientific understanding of the various processes and determinants of adaptive capacity is also mandatory for the region, with particular emphasis on increasing adaptation capacity involving the traditional knowledge of ancestral cultures and how this knowledge is transmitted. Linking indigenous knowledge with scientific knowledge is important. The concept of "mother earth" (madre tierra in Spanish) as a living system has been mentioned in recent years, as a key sacred entity on the view of indigenous nations and as a system that may be affected and also resilient to climate change. Although some adaptation processes have been initiated in recent years dealing with this and other indigenous knowledge, there is only very limited scientific literature discussing these subjects so far.

The research agenda needs to address vulnerability and foster adaptation in the region, encompassing an inclusion of the regions' researchers and focusing also on governance structures and action-oriented research that addresses resource distribution inequities.

Regional and international partnerships, and research networks and programs, have allowed linking those programs with local strategies for adaptation and mitigation, also providing opportunities to address research gaps and exchange among researchers. Examples are the European Union funded projects CLARIS LPB (La Plata Basin) in SESA, and AMAZALERT in Amazonia. Other important initiatives come from the Interamerican Institute for Global Change Research (IAI), World Health Organization (WHO), Global Environment Facility (GEF), Inter-American Development Bank (IDB), Economic Commission for Latin America and the Caribbean (ECLAC, CEPAL), La Red, and BirdLife International, among others. The same holds for local international networks such as the International Council for Local Environmental Initiatives (ICLEI) or C40, of which CA and SA cities form part. The weADAPT initiative is a good example on how CA and SA practitioners, researchers, and policy makers can have access to credible, high-quality information and to share experiences and lessons learned in other regions of the world.

27.8. Conclusions

CA and SA harbor unique ecosystems and maximum biodiversity, with a variety of eco-climatic gradients rapidly changing from development initiatives. Agricultural and beef production as well as bioenergy crops are on the rise, mostly by expanding agricultural frontiers. Poverty and inequality are decreasing, but at a slow pace. Socioeconomic development shows a high level of heterogeneity and a very unequal income distribution, resulting in high vulnerability to climatic conditions. There is still a high and persistent level of poverty in most countries (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade.

The IPCC AR4 and SREX reports contain ample evidence of increase in extreme climate events in CA and SA. During 2000–2013, 613 weather and climate extreme events led to 13,883 fatalities and 53.8 million people affected, with estimated losses of US$52.3 billion. During 2000–2009, 39 hurricanes occurred in the CA-Caribbean basin compared to 15 and 9 in the decade of 1980 and 1990, respectively. In SESA, more frequent and intense rainfall extremes have favored an increase in the occurrence of flash floods and landslides. In Amazonia extreme droughts were reported in 2005 and 2010, and record floods were observed in 2009 and 2012. In 2012–2013 an extreme drought affected NEB.

While warming occurred in most of CA and SA, cooling was detected off the coast of southern Peru and Chile. There is growing evidence that Andean glaciers (both tropical and extratropical) are retreating in response to warming trends. Increases in precipitation were registered in SESA, CA, and the NAMS regions, while decreases were observed in southern Chile, and a slight decrease in NEB after the middle 1970s. In CA a gradual delay of the beginning of the rainfall season has been observed. SLR varied from 2 to 7 mm yr^{-1} between 1950 and 2008 in CA and SA, which is a reason for concern because a large proportion of the population of the region lives by the coast.

Land use and land cover change are key drivers of regional environmental change in SA and CA. Natural ecosystems are affected by climate variability/change and land use change. Deforestation, land degradation, and biodiversity loss are attributed mainly to increased extensive agriculture for traditional export activities and bioenergy crops. Agricultural expansion has affected fragile ecosystems, causing severe environmental degradation and reducing the environmental services provided by these ecosystems. Deforestation has intensified the process of land degradation, increasing the vulnerability of communities exposed to floods, landslides, and droughts. Plant species are rapidly declining in CA and SA, with a high percentage of rapidly declining amphibian species. However, the region has still large extensions of natural vegetation cover, with the Amazon being the main example. Ecosystem-based adaptation practices, such as the establishment of protected areas and their effective management, conservation agreements, community management of natural areas, and payment for ecosystem services are increasingly more common across the region.

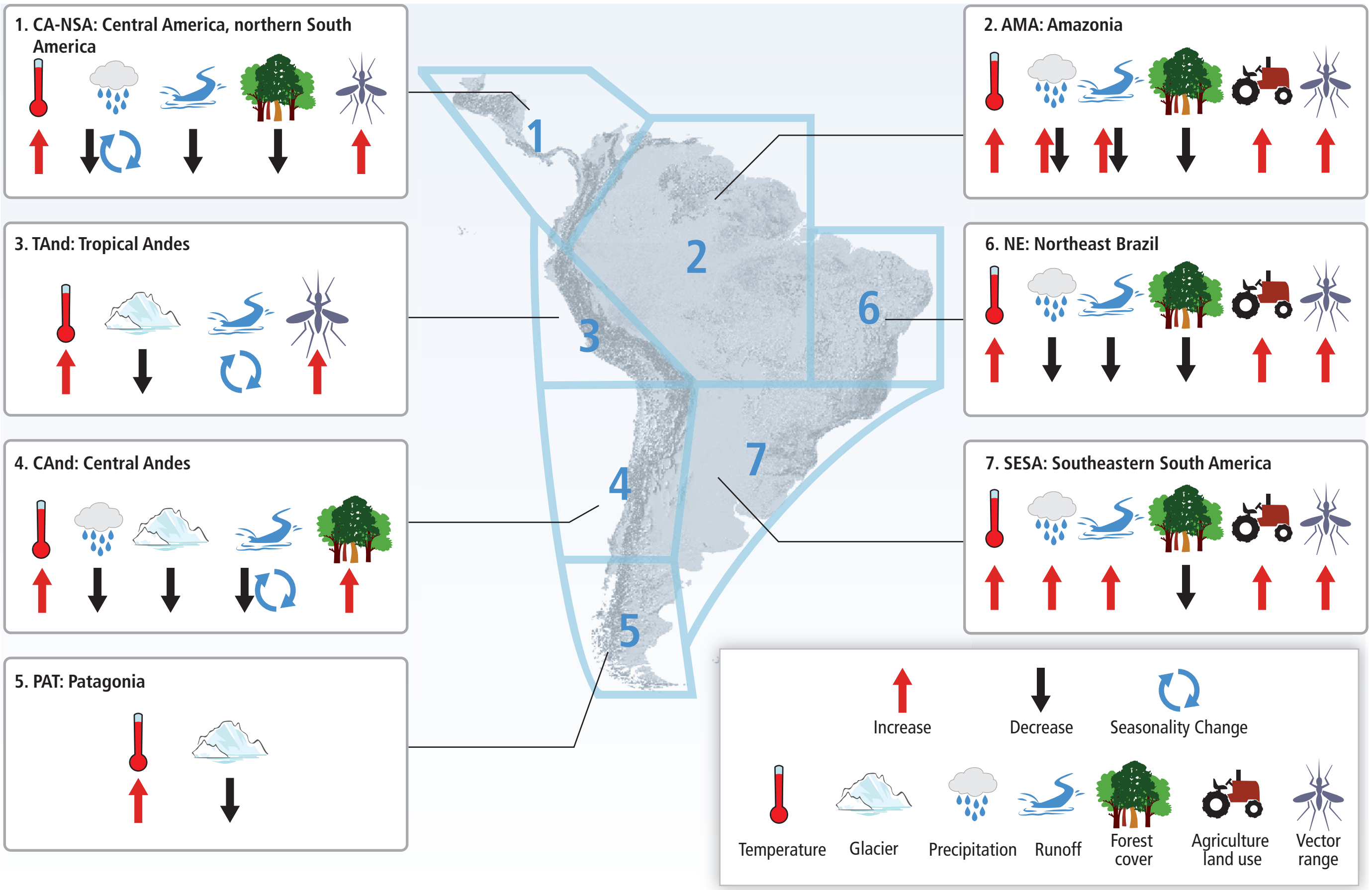

Figure 27-7 | Summary of observed changes in climate and other environmental factors in representative regions of Central and South America. The boundaries of the regions in the map are conceptual (neither geographic nor political precision). Information and references to changes provided are presented in different sections of the chapter.

Figure 27-7 summarizes of some of the main observed trends in global environmental change drivers across different representative regions of CA and SA. Changes in climate and non-climate drivers have to be compounded with other socioeconomic related trends, such as the rapid urbanization experienced in the region.

Some observed impacts on human and natural systems can be directly or indirectly attributed to human influences (see also Figure 27-8):

- Changes in river flow variability in the Amazon River during the last 2 decades, robust positive trends in streamflow in sub-basins of the La Plata River basin, and increased dryness for most of the river basins in west coast of South America during the last 50 years
- Reduction in tropical glaciers and ice fields in extratropical and tropical Andes over the second half of the 20th century that can be attributed to an increase in temperature
- Coastal erosion, bleaching of coral reefs in the coast of CA, and reduction in fisheries stock
- Increase in agricultural yield in SESA, and shift in agricultural zoning (significant expansion of agricultural areas, mainly in climatically marginal regions)
- Increase in frequency and extension of dengue fever, yellow fever, and malaria.

However, for some impacts the number of concluding studies is still insufficient, leading to low levels of confidence for attribution to human influences.

By the end of the century, the CMIP5-derived projections for RCP8.5 yielded: CA – mean annual warming of 2.5°C (range: 1.5°C to 5.0°C), mean rainfall reduction of 10% (range: –25% to +10%), and reduction in summertime precipitation; SA – mean warming of 4°C (range: 2.0°C to 5.0°C), with rainfall reduction up to 15% in tropical SA east of the Andes, and an increase of about 15 to 20% in SESA and in other regions of the continent, and increases in warm days and nights *very likely* to occur in most of SA; SESA – increases in heavy precipitation, and increases in dry spell in northeastern SA. However, there is some degree of uncertainty in climate change projections for regions, particularly for rainfall in CA and tropical SA.

Current vulnerability in terms of water supply in the semi-arid zones and the tropical Andes is expected to increase even further due to climate change. This would be exacerbated by the expected glacier retreat, precipitation reduction, and increased evapotranspiration demands as expected in the semi-arid regions of CA and SA. These scenarios would affect water supply for large cities, small communities, food production, and hydropower generation. There is a need for reassessing current practices to reduce the mismatch between water supply and demand to reduce future vulnerability, and to implement constitutional and legal reforms toward more efficient and effective water resources management.

SLR due to climate change and human activities on coastal and marine ecosystems pose threats to fish stocks, corals, mangroves, recreation

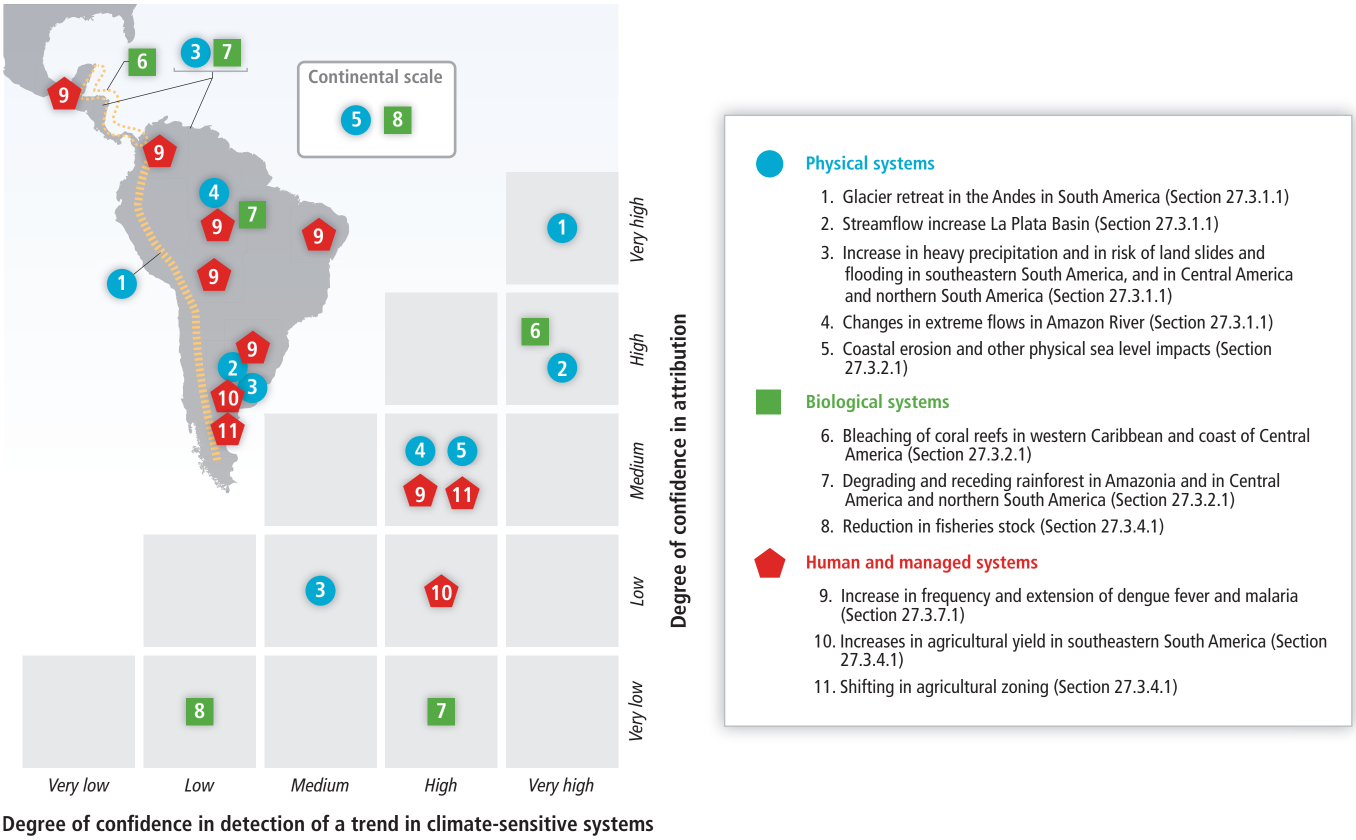

Figure 27-8 | Observed impacts of climate variations and attribution of causes to climate change in Central and South America.

and tourism, and diseases control in CA and SA. Coral reefs, mangroves, fisheries, and other benthic marine invertebrates that provide key ecosystem services, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change. It is possible that the Mesoamerican coral reef will collapse by mid-century (between 2050 and 2070), causing major economic and environmental losses. In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years. In the Rio de La Plata area extreme flooding events may become more frequent because return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected. Beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast.

Urban populations in CA and SA face diverse social, political, economic, and environmental risks in daily life, and climate change will add a new dimension to these risks. Because urban development remains fragile in many cases, with weak planning responses, climate change can compound existing challenges, for example, water supply in cities from glacier, snowmelt, and paramos related runoff in the Andes (Lima, La Paz/El Alto, Santiago de Chile, Bogotá), flooding in several cities such as São Paulo and Buenos Aires, and health-related challenges in many cities of the region.

Climate change will affect individual species and biotic interactions. Vertebrate fauna will suffer major species losses especially in high-altitude areas; elevational specialists might be particularly vulnerable because of their small geographic ranges and high energetic requirements. Freshwater fisheries can suffer alterations in physiology and life histories. In addition, modifications in phenology, structure of ecological networks, predator-prey interactions, and non-trophic interactions among organisms will affect biotic interactions. Shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in High Andean ecosystems. Although in the region biodiversity conservation is largely confined to protected areas, it is expected that many species and vegetational types will lose representativeness inside such protected areas.

Changes in food production and food security are expected to have great spatial variability, with a wide range of uncertainty mainly related to climate and crop models. In SESA average productivity could be sustained or increased until the mid-century, although interannual and decadal climate variability is *likely* to impose important damages. In other regions such as NEB, CA, and some Andean countries agricultural productivity could decrease in the short term, threatening the food security of the poorest population. The expansion of pastures and croplands is expected to continue in the coming years, particularly from an increasing global demand for food and biofuels. The great challenge for CA and SA will be to increase the food and bioenergy production and at the same time sustain the environmental quality in a scenario of climate change.

Renewable energy provides great potential for adaptation and mitigation. Hydropower is currently the main source of renewable energy in CA and SA, followed by biofuels. SESA is one of the main sources of production of the feedstocks for biofuel production, mainly with sugarcane and soybean, and future climate conditions may lead to an increase in productivity and production. Advances in second-generation biofuels will be important as a measure of adaptation, as they have the potential to increase biofuel productivity. In spite of the large amount of arable land available, the expansion of biofuels might have some direct and indirect land use change effects, producing teleconnections that could lead to deforestation of native tropical forests and loss of employment in some countries. This might also affect food security.

Changes in weather and climatic patterns are negatively affecting human health in CA and SA, by increasing morbidity, mortality, and disabilities, and through the emergence of diseases in previously non-endemic regions. Multiple factors increase the region's vulnerability to climate change: precarious health systems; malnutrition; inadequate water and sanitation services; population growth; poor waste collection and treatment systems; air, soil, and water pollution; food in poor regions; lack of social participation; and inadequate governance. Vulnerabilities vary with geography, age, gender, race, ethnicity, and socioeconomic status, and are rising in large cities. Climate change and variability may exacerbate current and future risks to health.

Climate change will bring modifications to environmental conditions in space and time, and the frequency and intensity of weather and climate processes. In many CA and SA countries, a first step toward adaptation to climate change is to reduce the vulnerability to present climate, taking into account future potential impacts, particularly of weather and climate extremes. Long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the CA and SA population. Such conditions weaken the importance of adaptation planning to climate change on the political agenda. Currently, there are few experiences on synergies between development, adaptation, and mitigation planning, which can help local communities and governments to allocate available resources in the design of strategies to reduce vulnerability and develop adaptation measures. Facing a new climate system and, in particular, the exacerbation of extreme events, will call for new ways to manage human and natural systems for achieving sustainable development.

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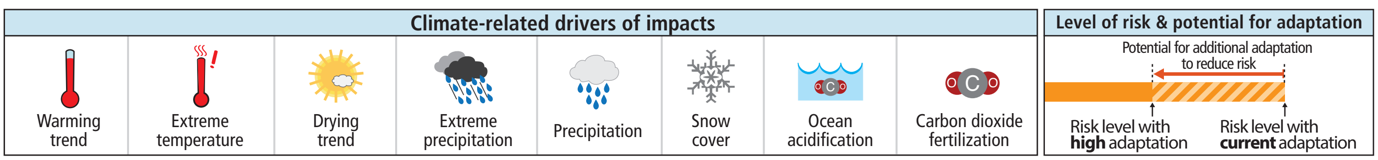
Table 27-8 | Key risks from climate change and the potential for risk reduction through mitigation and adaptation.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Water availability in semi-arid and glacier-melt-dependent regions and Central America; flooding and landslides in urban and rural areas due to extreme precipitation (*high confidence*) [27.3]	• Integrated water resource management • Urban and rural flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control			Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	
			4°C	
CA coral reef bleaching (*high confidence*) [27.3.3]	Limited evidence for autonomous genetic adaptation of corals; other adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing.			Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	
			4°C	
Decreased food production and food quality (*medium confidence*) [27.3]	• Development of new crop varieties more adapted to climate change (temperature and drought) • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land-use change • Strengthening traditional indigenous knowledge systems and practices			Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	
			4°C	
Spread of vector-borne diseases in altitude and latitude (*high confidence*) [27.3]	• Development of early warning systems for disease control and mitigation based on climatic and other relevant inputs. Many factors augment vulnerability. • Establishing programs to extend basic public health services			Very low / Medium / Very high
			Present	
			Near term (2030–2040)	
			Long term (2080–2100) 2°C	not available
			4°C	not available

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28

Polar Regions

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Frequently Asked Questions

Executive Summary

Additional and stronger scientific evidence has accumulated since the AR4 that reinforces key findings made in the Fourth Assessment Report (AR4).

The impacts of climate change, and the adaptations to it, exhibit strong spatial heterogeneity in the polar regions because of the high diversity of social systems, biophysical regions, and associated drivers of change (*high confidence*). {28.2.2} For example, the tree line has moved northward and upward in many, but not all, Arctic areas (*high confidence*) and significant increases in tall shrubs and grasses have been observed in many places (*very high confidence*). {28.2.3.1.2}

Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the polar regions (*medium confidence*). The response rate and the spatial extent of the shifts will differ by species based on their vulnerability to change and their life history. {28.2.2, 28.3.2} Loss of sea ice in summer and increased ocean temperatures are expected to impact secondary pelagic production in some regions of the Arctic Ocean, with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). These changes are expected to alter the species composition of zooplankton in some regions, with associated impacts on some fish and shellfish populations (*medium confidence*). {28.2.2.1} Also, changes in sea ice and the physical environment to the west of the Antarctic Peninsula are altering phytoplankton stocks and productivity, and krill (*high confidence*). {28.2.2.2}

Climate change is impacting terrestrial and freshwater ecosystems in some areas of Antarctica and the Arctic. This is due to ecological effects resulting from reductions in the duration and extent of ice and snow cover and enhanced permafrost thaw (*very high confidence*), and through changes in the precipitation-evaporation balance (*medium confidence*). {28.2.1, 28.2.3}

The primary concern for polar bears over the foreseeable future is the recent and projected loss of annual sea ice cover, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent. {28.2.2.1.2, 28.3.2.2.2}

Rising temperatures, leading to the further thawing of permafrost, and changing precipitation patterns have the potential to affect infrastructure and related services in the Arctic (*high confidence*). {28.3.4.3} Particular concerns are associated with damage to residential buildings resulting from thawing permafrost, including Arctic cities; small, rural settlements; and storage facilities for hazardous materials. {28.2.4-5}

In addition, there is new scientific evidence that has emerged since the AR4.

The physical, biological, and socioeconomic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by drivers other than climate change but also demography, culture, and economic development. Climate change has compounded some of the existing vulnerabilities caused by these other factors (*high confidence*). {28.2.4-5, 28.4} For example, food security for many Indigenous and rural residents in the Arctic is being impacted by climate change, and in combination with globalization and resource development food insecurity is projected to increase in the future (*high confidence*). {28.2.4}

The rapid rate at which climate is changing in the polar regions will impact natural and social systems (*high confidence*) and may exceed the rate at which some of their components can successfully adapt (*low* to *medium confidence*). {28.2.4, 28.4} The decline of Arctic sea ice in summer is occurring at a rate that exceeds most of the earlier generation model projections (*high confidence*), and evidence of similarly rapid rates of change is emerging in some regions of Antarctica. {WGI AR5 Chapters 4, 5, 9} In the future, trends in polar regions of populations of marine mammals, fish, and birds will be a complex response to multiple stressors and indirect effects (*high confidence*). {28.3.2} Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea level rise, and increased weather intensity are forcing relocation of some Indigenous communities in Alaska (*high confidence*). {28.2.4.2, 28.2.5, 28.3.4}

Shifts in the timing and magnitude of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival of dependent species (*medium confidence*). If the timing of primary and secondary production is no longer matched to the timing of spawning or egg release, survival could be impacted, with cascading implications to higher trophic levels. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). {28.2.2, 28.3.2} Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species, the majority likely to arrive through direct human assistance (*high confidence*).

Ocean acidification has the potential to inhibit embryo development and shell formation of some zooplankton and krill in the polar regions, with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Embryos of Antarctic krill have been shown to be vulnerable to increased concentrations of carbon dioxide (CO_2) in the water (*high confidence*). As well, there is increasing evidence that pelagic molluscs (pteropods) are vulnerable to ocean acidification (*medium confidence*). {28.2.2, 28.3.2}

There is increased evidence that climate change will have large effects on Arctic communities, especially where narrowly based economies leave a smaller range of adaptive choices. {28.2.6.1, 28.4} Some commercial activities will become more profitable while others will face decline. Increased economic opportunities are expected with increased navigability in the Arctic Ocean and the expansion of some land- and freshwater-based transportation networks. {28.2.6.1.3, 28.3.4.3} The informal, subsistence-based economy will be impacted (*high confidence*). There is *high confidence* that changing sea ice conditions may result in more difficult access for hunting marine mammals. {28.2.6.1.6} Although Arctic residents have a history of adapting to change, the complex interlinkages among societal, economic, and political factors and climatic stresses represent unprecedented challenges for northern communities, particularly if the rate of change will be faster than the social systems can adapt (*high confidence*). {28.2.5, 28.4}

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase—especially for many Indigenous peoples (*high confidence*). {28.2.4} These impacts are expected to vary among the diverse settlements, which range from small, remote, predominantly Indigenous communities to large cities and industrial settlements (*high confidence*), especially those in highly vulnerable locations along ocean and river shorelines. {28.2.4}

28.1. Introduction

Several recent climate impact assessments on polar regions have been undertaken, including the synthesis report on Snow, Water, Ice and Permafrost in the Arctic (AMAP, 2011a), the State of the Arctic Coast 2010 (2011) reports, the Antarctic Climate and the Environment (Turner et al., 2009, 2013), Arctic Resilience Interim Report 2013 (2013), and the findings of the International Polar Year (IPY; Krupnick et al., 2011). These reports draw a consistent pattern of climate-driven environmental, societal, and economic changes in the polar regions in recent decades. In this chapter, we use the scientific literature, including these reports, to consolidate the assessment of the impacts of climate change on polar regions from 2007, advance new scientific evidence of impacts, and identify key gaps in knowledge on current and future impacts. Previous IPCC reports define the Arctic as the area within the Arctic Circle (66°N), and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58°S (IPCC, 2007). For the purpose of this report we use the conventional IPCC definitions as a basis, while incorporating a degree of flexibility when describing the polar regions in relation to particular subjects.

Changes in the physical and chemical environments of the polar regions are detailed in the WGI contribution to the AR5. There is evidence that Arctic land surface temperatures have warmed substantially since the mid-20th century, and the future rate of warming is expected to exceed the global rate. Sea ice extent at the summer minimum has decreased significantly in recent decades, and the Arctic Ocean is projected to become nearly ice free in summer within this century. The duration of snow cover extent and snow depth are decreasing in North America while increasing in Eurasia. Since the late 1970s, permafrost temperatures have increased between 0.5°C and 2°C. In the Southern Hemisphere, the strongest rates of atmospheric warming are occurring in the western Antarctic Peninsula (WAP, between 0.2°C and 0.3°C per decade) and the islands of the Scotia Arc, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration. Warming, although less than WAP, has also occurred in the continental margins near the Bellingshausen Sea, Prydz Bay, and the Ross Sea, with areas of cooling in between. Land regions have experienced glacial recession and changes in the ice and permafrost habitats in the coastal margins. The Southern Ocean continues to warm, with increased freshening at the surface due to precipitation leading to increased stratification. In both polar regions, as a result of acidification, surface waters will become seasonally corrosive to aragonite within decades, with some regions being affected sooner than others (see Box CC-OA; WGI AR5 Chapter 6). Observations and models indicate that the carbon cycle of the Arctic and Southern Oceans will be impacted by climate change and increased carbon dioxide (CO_2).

28.2. Observed Changes and Vulnerability under Multiple Stressors

28.2.1. Hydrology and Freshwater Ecosystems

28.2.1.1. Arctic

Arctic rivers and lakes continue to show pronounced changes to their hydrology and ecology. Previously noted increases in Eurasian Arctic

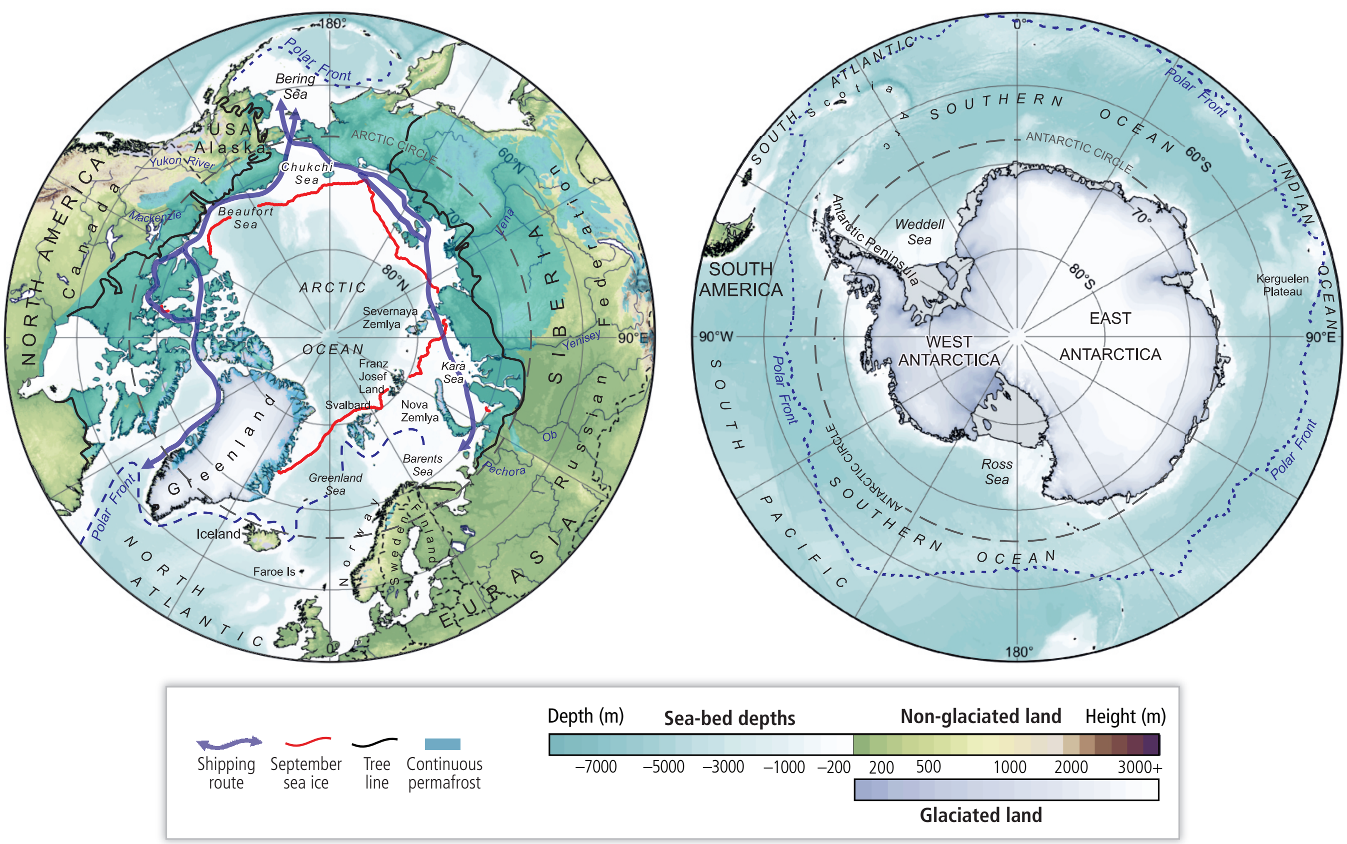


Figure 28-1| Location maps of the north and south polar regions (courtesy of P. Fretwell, British Antarctic Survey).

river flow (1936–1999; Peterson et al., 2002) could not, for a similar period (1951–2000), be attributed with certainty to precipitation changes (Milliman et al., 2008) but has been, including more recent extreme increases (2007), attributed to enhanced poleward atmospheric moisture transport (Zhang et al., 2013). By contrast, decreased flow in high-latitude Canadian rivers (1964–2000; average –10%) does match that for precipitation (Déry and Wood, 2005). Recent data (1977–2007) for 19 circumpolar rivers also indicate an area-weighted average increase of +9.8% (–17.1 to 47.0%; Overeem and Syvitski, 2010) accompanied by shifts in flow timing, with May snowmelt increasing (avg. 66%) but flow in the subsequent month of peak discharge decreasing (~7%). Across the Russian Arctic, dates of spring maximum discharge have also started to occur earlier, particularly in the most recent (1960–2001) period analyzed (average –5 days; range for four regions +0.2 to –7.1 days), but no consistent trend exists for magnitude (average –1%; range +21 to –24%; Shiklomanov et al., 2007). Earlier timing was most pronounced in eastern, colder continental climates, where increases in air temperature have been identified as the dominant control (Tan et al., 2011).

Increases have also occurred in winter low flows for many Eurasian and North American rivers (primarily in the late 20th century; Smith et al., 2007; Walvoord and Striegl, 2007; St. Jacques and Sauchyn, 2009; Ye et al., 2009), the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm et al., 2010). Most such studies suggest permafrost thaw (WGI AR5 Chapter 4) has increased winter flow, whereas others suggest increases in net winter precipitation minus evapotranspiration (Rawlins et al., 2009a,b; Landerer et al., 2010). Insufficient precipitation stations preclude deciphering the relative importance of these factors (WGI AR5 Section 2.5.1).

The surface-water temperatures of large water bodies has warmed (1985–2009; Schneider and Hook, 2010), particularly for mid- and high latitudes of the Northern Hemisphere, with spatial patterns generally matching those for air temperature. Where water bodies warmed more rapidly than air temperature, decreasing ice cover was suggested as enhancing radiative warming. Paleolimnological evidence indicates that the highest primary productivity was associated with warm, ice-free summer conditions and the lowest with periods of perennial ice (Melles et al., 2007). Increasing water temperatures affect planktonic and benthic biomass and lead to changes in species composition (Christoffersen et al., 2008; Heino et al., 2009, Jansson et al., 2010). Reduced ice cover with higher air temperatures and evaporation are responsible for the late-20th to early-21st century desiccation of some Arctic ponds (Smol and Douglas, 2007).

Changes have occurred in the size and number of permafrost lakes over the last half-century (Hinkel et al., 2007; Marsh et al., 2009), but their patterns and rates of change are not consistent because of differing thawing states, variations in warming, and effects of human activities (Hinket et al., 2007; Prowse and Brown, 2010a). Thawing permafrost affects the biogeochemistry of water entering lakes and rivers (Frey and McClelland, 2009; Kokelj et al., 2009) and their ecological structure and function (Lantz and Kokelj, 2008; Thompson et al., 2008; Mesquita et al., 2010), such as enhancing eutrophication by a shift from pelagic to benthic-dominated production (Thompson et al., 2012).

The aquatic ecosystem health and biodiversity of northern deltas is dependent on combined changes in the elevation of spring river ice-jam floods and sea level (Lesack and Marsh, 2007, 2010). Diminishing ice shelves (last half-century) have also caused a decline in the number of freshwater epishelf lakes that develop behind them (Veillette et al., 2008; Vincent et al., 2009). Although such biophysical dependencies have been established, temporal trends in such river-delta and epishelf lake impacts and their linkages to changing climate remain to be quantified precisely.

An interplay of freshwater-marine conditions also affects the timing, growth, run size, and distribution of several Arctic freshwater and anadromous fish. Key examples include the timing of marine exit of Yukon River Chinook salmon (*Oncorhynchus tshawytscha*; 1961–2009) varied with air and sea temperatures and sea ice cover (Mundy and Evenson, 2011); the growth of young-of-year Arctic cisco (*Coregonus autumnalis*; 1978–2004) varied in response to lagged sea ice concentration and Mackenzie River discharge, also indicating that decreased sea ice concentration and increased river discharge enhanced marine primary production, leading to more favorable foraging conditions (von Biela et al., 2011); and factors that influence the water level and freshening of rivers, as well as the strength, duration, and directions of prevailing coastal winds, affect survival of anadromous fishes during coastal migration and their subsequent run size (Fechhelm et al., 2007).

28.2.1.2. Antarctic

Biota of Antarctic freshwater systems (lakes, ponds, short streams, and seasonally wetted areas) are dominated by benthic microbial communities of cyanobacteria and green algae in a simple food web. Mosses occur in some continental lakes with higher plants absent. Planktonic ecosystems are typically depauperate and include small algae, bacteria, and colorless flagellates, with few metazoans and no fish (Quesada and Velázquez, 2012). Recent compilations of single-year data sets have reinforced previous conclusions on the changing freshwater habitats in Antarctica (Verleyen et al., 2012). In regions where the climate has warmed, the physical impacts on aquatic ecosystems include loss of ice and perennial snow cover, increasing periods of seasonal open water, increased water column temperatures, and changes in water column stratification. In some areas, a negative water balance has occurred as a result of increased temperature and changes in wind strength driving enhanced evaporation and sublimation and leading to increased salinity in lakes in recent decades (Hodgson et al., 2006a). In other areas, especially glacial forelands, increased temperatures have led to greater volumes of seasonal meltwater in streams and lakes together with increased nutrient fluxes (*high confidence*). In both cases, the balance between precipitation and evaporation can have detectable effects on lake ecosystems (*medium confidence*) through changes in water body volume and lake chemistry (Lyons et al., 2006; Quesada et al., 2006). Non-dilute lakes with a low lake depth to surface area ratio are most susceptible to interannual and inter-decadal variability in the water balance, as measured by changes in specific conductance (*high confidence*; Verleyen et al., 2012). Warming in the northwestern Antarctic Peninsula region has resulted in permafrost degradation in the last approximately 50 years, impacting surface geomorphology and hydrology (Bockheim et al., 2013) with the potential to increase soil biomass.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

28.2.2.1.1. Marine plankton, fish, and other invertebrates

WGI documented the expected physical and chemical changes that will occur in Arctic marine ecosystems (WGI AR5 Chapters 4, 6, 11). Naturally occurring interannual, decadal, and multi-decadal variations in climate will continue to influence the Arctic Ocean and its neighboring high-latitude seas (Chapter 5). In recent years (2007–2012), ocean conditions in the Bering Sea have been cold (Stabeno et al., 2012a), while the Barents Sea has been warm (Lind and Ingvaldsen, 2012).

In this section, we build on previous reviews of observed species responses to climate (Wassman et al., 2011) to summarize the current evidence of the impact of physical and chemical changes in marine systems on the phenology, spatial distribution, and production of Arctic marine species. For each type of response, the implications for phytoplankton, zooplankton, fish, and shellfish are discussed. The implications of these changes on marine ecosystem structure and function will be the result of the synergistic effects of all three types of biological responses.

Phenological response

The timing of spring phytoplankton blooms is a function of seasonal light, hydrographic conditions, and the timing of sea ice breakup (Wassman, 2011). In addition to the open water phytoplankton bloom, potentially large ice algal blooms can form under the sea ice (Arrigo, 2012). During the period 1997–2009, a trend toward earlier phytoplankton blooms was detected in approximately 11% of the area of the Arctic Ocean (Kahru et al., 2011). This advanced timing of annual phytoplankton blooms coincided with decreased sea ice concentration in early summer. Brown and Arrigo (2013) studied the timing and intensity of spring blooms in the Bering Sea from 1997 to 2010 and found that in northern regions sea ice consistently retreated in late spring and was associated with ice-edge blooms, whereas in the southern regions the timing of sea ice retreat varied, with ice-edge blooms associated with late ice retreat, and open water blooms associated with early ice retreat. Given the short time series and limited studies, there is *medium confidence* that climate variability and change has altered the timing and the duration of phytoplankton production.

The life cycles of calanoid copepods in the Arctic Ocean and Barents Sea are timed to utilize ice algal and phytoplankton blooms (Falk-Petersen et al., 2009; Søreide et al., 2010; Darnis et al., 2012). Based on a synthesis of existing data, Hunt, Jr. et al. (2011) hypothesized that, in the southeastern Bering Sea, ocean conditions and the timing of sea ice retreat influences the species composition of dominant zooplankton, with lipid-rich copepods being more abundant in cold years.

There is ample evidence that the timing of spawning and hatching of some fish and shellfish is aligned to match larval emergence with seasonal increases in prey availability (Gjosaeter et al., 2009; Vikebø et al., 2010; Bouchard and Fortier, 2011; Drinkwater et al., 2011). These regional phenological adjustments to local conditions occurred over many generations (Ormseth and Norcross, 2009; Geffen et al., 2011; Kristiansen et al., 2011). There is *medium* to *high confidence* that climate-induced disruptions in this synchrony can result in increased larval or juvenile mortality or changes in the condition factor of fish and shellfish species in the Arctic marine ecosystems.

Observed spatial shifts

Spatial heterogeneity in primary production has been observed (Lee et al., 2010; Grebmeier, 2012). Simulation modeling studies show that spatial differences in the abundance of four species of copepod can be explained by regional differences in the duration of the growing season and temperature (Ji et al., 2012). Retrospective studies based on surveys from 1952 to 2005 in the Barents Sea revealed that changes in the species composition, abundance, and distribution of euphausiids were related to climate-related changes in oceanographic conditions (Zhukova et al., 2009).

Retrospective analysis of observed shifts in the spatial distribution of fish and shellfish species along latitudinal and depth gradients showed observed spatial shifts were consistent with expected responses of species to climate change (Simpson et al., 2011; Poloczanska et al., 2013; see also Box CC-MB). Retrospective studies from the Bering Sea, Barents Sea, and the northeast Atlantic Ocean and Icelandic waters showed that fish shift their spatial distribution in response to climate variability (i.e., interannual, decadal, or multi-decadal changes in ocean temperature; Mueter and Litzow, 2008; Sundby and Nakken, 2008; Hátún et al., 2009; Valdimarsson et al., 2012; Kotwicki and Lauth, 2013). There are limits to the movement potential of some species. Vulnerability assessments indicate that the movement of some sub-Arctic fish and shellfish species into the Arctic Ocean may be impeded by the presence of water temperatures on the shelves that fall below their thermal tolerances (Hollowed et al., 2013; Hunt, Jr. et al., 2013). Coupled biophysical models have reproduced the observed spatial dynamics of some the species in the Bering and Barents Seas, and are being used to explain the role of climate variability and change on the distribution and abundance of some species (Huse and Ellingsen, 2008; Parada et al., 2010). In summary, there is *medium* to *high confidence* based on observations and modeling that some fish and shellfish have shifted their distribution in response to climate impacts on the spatial distribution and volume of suitable habitat.

Observed variations in production

Seasonal patterns in light, sea ice cover, freshwater input, stratification, and nutrient exchange act in concert to produce temporal cycles of ice algal and phytoplankton production in Arctic marine ecosystems (Perrette et al., 2011; Wassmann, 2011; Tremblay et al., 2012). Satellite observations and model estimates for the period 1988–2007 showed that phytoplankton productivity increased in the Arctic Ocean in response to a downward trend in the extent of summer sea ice (Zhang et al., 2010). Satellite data provided evidence of a 20% increase in annual net primary production in the Arctic Ocean between 1998 and 2009 in response to extended ice-free periods (Arrigo and van Dijken, 2011). Regional trends in primary production will differ in response to the amount of open water area in summer (Arrigo and van Dijken, 2011). Other studies showed gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad et al., 2011). A recent 5-year study (2004–2008) in the Canada Basin showed that smaller phytoplankton densities were higher than larger phytoplankton densities in years when sea surface temperatures (SSTs) were warmer, the water column was more stratified, and nutrients were more depleted during the Arctic summer (Li et al., 2009; Morán et al., 2010). Additional observations will help to resolve observed differences between *in situ* and satellite-derived estimates of primary production (Matrai et al., 2013). In conclusion, based on recent observations and modeling, there is *medium* to *high confidence* that primary production has increased in the Arctic Ocean in response to changes in climate and its impact on the duration and areal extent of ice-free periods in summer.

Regional differences in zooplankton production have been observed. During a period of ocean warming (1984–2010), Dalpadado et al. (2012) observed an increase in the biomass of lipid-rich euphausiids in the Barents Sea and relatively stable levels of biomass and production of *Calanus finmarchicus*. In the Bering Sea, observations over the most recent decade in the southeast Bering Sea showed *C. marshallae* were more abundant in cold than in warm years (Coyle et al., 2011).

There is strong evidence that climate variability impacts the year-class strength of Arctic marine fish and shellfish through its influence on predation risk; the quality, quantity, and availability of prey; and reproductive success (Mueter et al., 2007; Bakun 2010; Drinkwater et al., 2010). Regional differences in the species responses to climate change will be a function of the exposure of the species to changing environmental conditions, the sensitivity of the species to these changes (Beaugrand and Kirby, 2010), and the abilities of species to adapt to changing conditions (Pörtner and Peck, 2010; Donelson et al., 2011). There is *high confidence* that shifts in ocean conditions have impacted the abundance of fish and shellfish in Arctic regions. Observed trends in the abundance of commercial fish and shellfish may also be influenced by historical patterns of exploitation (Vert-pre et al., 2013).

28.2.2.1.2. Marine mammals, polar bears, and seabirds

Studies on responses of Arctic and subarctic marine mammals to climate change are limited and vary according to insight into their habitat requirements and trophic relationships (Laidre et al., 2008). Many Arctic and sub-Arctic marine mammals are highly specialized, have long life spans, and are poorly adapted to rapid environmental change (Moore and Huntington, 2008), and changes may be delayed until significant sea ice loss has occurred (Freitas et al., 2008; Laidre et al., 2008).

Climate change effects on Arctic and sub-Arctic marine mammal species will vary by life history, distribution, and habitat specificity (*high confidence*). Climate change will improve conditions for a few species, have minor negative effects for others, and some will suffer major negative effects (Laidre et al., 2008; Ragen et al., 2008). Climate change resilience will vary and some ice-obligate species should survive in regions with sufficient ice and some may adapt to ice-free conditions (Moore and Huntington, 2008). Less ice-dependent species may be more adaptable but an increase in seasonally migrant species could increase competition (Moore and Huntington, 2008).

Climate change vulnerability was associated with feeding specialization, ice dependence, and ice reliance for prey access and predator avoidance (Laidre et al., 2008). There is *medium agreement* on which species' life histories are most vulnerable. Hooded seals (*Cystophora cristata*) and narwhal (*Monodon monoceros*) were identified as most at risk and ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*) as least sensitive (Laidre et al., 2008). Kovacs et al. (2010) shared concern for hooded seals and narwhal but had concerns for ringed seals and bearded seals. Narwhal may have limited ability to respond to habitat alteration (Williams et al., 2011). Species that spend only part of the year in the Arctic (e.g., gray whale (*Eschrichtius robustus*), killer whale (*Orcinus orca*)) may benefit from reduced ice (Laidre et al., 2008; Moore, 2008; Higdon and Ferguson, 2009; Matthews et al., 2011; Ferguson et al., 2012). Killer whale expansion into the Arctic could cause a trophic cascade (Higdon and Ferguson, 2009), although there is *limited evidence* at this time.

There is *limited evidence* although *medium agreement* that generalists and pelagic feeding species may benefit from increased marine productivity from reduced ice while benthic feeding species near continental shelf habitats may do poorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary or habitat specialists will do poorly with reduced ice. Reduction of summer/autumn ice was the primary extrinsic factor affecting Pacific walrus (*Odobenus rosmarus*), with predictions of distribution changes, reduced calf recruitment, and longer term predictions of high extinction probability (Cooper et al., 2006; MacCracken, 2012). Summer ice retreat may make migration to such habitats energetically unprofitable for ringed seals (Freitas et al., 2008). Ice loss threatens Baltic ringed seals (Kovacs and Lydersen, 2008). In Hudson Bay, earlier spring break-up and changes in snow cover over lairs have reduced ringed seal recruitment (Ferguson et al., 2005). Changes in snowfall over the 21st century were projected to reduce ringed seal habitat for lairs by 70% (Hezel et al., 2012). Similarly, harp seal (*Pagophilus groenlandicus*) breeding habitat was affected by changing ice conditions that could reduce pup survival (Bajzak et al., 2011). Although there is *limited evidence*, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, shipping, and development; Burek et al., 2008).

Empirical studies provide direct insight into the mechanisms of climate change impact on polar bears (*Ursus maritimus*) but modeling allows predictive capacity (Amstrup et al., 2010; Hunter et al., 2010; Durner et al., 2011; Castro de la Guardia et al., 2013).

Polar bears are highly specialized and use annual ice over the continental shelves as their preferred habitat (Durner et al., 2009; Miller et al., 2012). The recent and projected loss of annual ice over continental shelves, decreased ice duration, decreased ice thickness, and habitat fragmentation are causing reduced food intake, increased energy expenditure, and increased fasting in polar bears (*high confidence*; Stirling and Parkinson, 2006; Regehr et al., 2007; Durner et al., 2009; Amstrup et al., 2010; Hunter et al., 2010; Derocher et al., 2011; Rode et al., 2012; Sahanatien and Derocher, 2012; Castro de la Guardia et al., 2013).

Subpopulation response varies geographically. Only 2 of the 19 subpopulations—Western Hudson Bay (Regehr et al., 2007) and the southern Beaufort Sea (Regehr et al., 2010; Rode et al., 2010a)—have data series adequate for clear identification of abundance effects related to climate change. Many other subpopulations show characteristics associated with decline but some remain stable. Declining ice is causing lower body condition, reduced individual growth rates, lower fasting endurance, lower reproductive rates, and lower survival (*high confidence*; Regehr et al., 2007, 2010; Rode et al., 2010a, 2012; Molnar et al., 2011). Condition is a precursor to demographic change (*very high confidence*; Hunter et al., 2010; Regehr et al., 2010; Rode et al., 2010a; Robinson et al., 2011). The decline in the subpopulation in Western Hudson Bay by 21% between 1987 and 2004 was related to climate change (*medium confidence*; Regehr et al., 2007). Replacement of multi-year ice by annual ice could increase polar bear habitat (*low confidence*; Derocher et al., 2004). Increasing the distance to multi-year ice and terrestrial refugia at maximal melt may result in drowning, cub mortality, and increased energetic costs (Monnett and Gleason, 2006; Durner et al., 2011; Pagano et al., 2012). There is *robust evidence* of changes in sea ice conditions changing polar bear distribution including den areas (*high confidence*; Fischbach et al., 2007; Schliebe et al., 2008; Gleason and Rode, 2009; Towns et al., 2010; Derocher et al., 2011). The number of human-bear interactions is projected to increase with warming (*high confidence*; Stirling and Parkinson, 2006; Towns et al., 2009).

Use of terrestrial resources by polar bears was suggested as adaptive (Dyck et al., 2007, 2008; Dyck and Romberg, 2007; Armstrong et al., 2008; Dyck and Kebreab, 2009; Rockwell and Gormezano, 2009; Smith et al., 2010). Polar bears cannot adapt to terrestrial foods (Stirling et al., 2008b; Amstrup et al., 2009; Rode et al., 2010b; Slater et al., 2010), and will most likely not be able to adapt to climate change and reduced sea ice extent (*very high confidence*). Changing ice conditions are linked to cannibalism (Amstrup et al., 2006), altered feeding (Cherry et al., 2009), unusual hunting behavior (Stirling et al., 2008a), and diet change (Iverson et al., 2006; Thiemann et al., 2008) (*medium confidence*).

Upwelling or subsurface convergence areas found in frontal zones and eddies, and the marginal ice zone, are associated with high marine productivity important to Arctic seabirds (e.g., Irons et al., 2008). Long-term or permanent shifts in convergence areas and the marginal ice-edge zone induced by climate change may cause mismatch between the timing of breeding and the peak in food availability, and thus potentially have strong negative impacts on seabird populations (*medium confidence*; Gaston et al., 2005, 2009; Moline et al., 2008; Grémillet and Boulinier, 2009).

The contrasting results from the relatively few studies of impacts of climate change on Arctic seabirds demonstrate that future impacts will be highly variable between species and between populations of the same species (*medium confidence*). Retreating sea ice and increasing SSTs have favored some species and disadvantaged others (Gaston et al., 2005; Byrd et al., 2008; Irons et al., 2008; Karnovsky et al., 2010; Fredriksen et al., 2013). Some species of seabirds respond to a wide range of sea surface temperatures via plasticity of their foraging behavior, allowing them to maintain their fitness levels (Grémillet et al., 2012). Phenological changes and changes in productivity of some breeding colonies have been observed (Byrd et al., 2008; Gaston and Woo, 2008; Moe et al., 2009). Negative trends in population size, observed over the last few decades for several species of widespread Arctic seabirds, may be related to over-harvesting and pollution as well as climate change effects (Gaston, 2011). For those species whose distribution is limited by sea ice and cold water, polar warming could be beneficial (Mehlum, 2012).

A major ecosystem shift in the northern Bering Sea starting in the mid-1990s caused by increased temperatures and reduced sea ice cover had a negative impact on benthic prey for diving birds, and these populations have declined in the area (Grebmeier et al., 2006). More recently, the Bering Sea has turned colder again.

28.2.2.2. Antarctica

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry, and vertical mixing (Massom and Stammerjohn, 2010; Boyd et al., 2012; Murphy et al., 2012a). Moreover, there is large-scale regional variability in habitats (Grant et al., 2006) and their responses to climate change. Antarctic krill, *Euphausia superba* (hereafter, krill), is the dominant consumer, eating diatoms, and, in turn, is the main prey of fish, squid, marine mammals, and seabirds. Krill is dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean (Rogers et al., 2012). In the East Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the Antarctic Circumpolar Current (Nicol et al., 2000a,b) while to the north copepods and myctophid fish are most important (Rogers et al., 2012). Further west, where the Weddell Sea exerts an influence, krill are found as far north as the Sub-Antarctic Circumpolar Current Front (Jarvis et al., 2010). Where sea ice dominates for most of the year, ice-obligate species (e.g., *Euphausia crystallorophias* and *Peluragramma antarcticum*) are most important (Smith et al., 2007).

Few studies were available in AR4 to document and validate the changes in these systems resulting from climate change. Those studies reported increasing abundance of benthic sponges and their predators, declining populations of krill, Adélie and emperor penguins, and Weddell seals, and a possible increase in salps, noting some regional differences in these trends. The importance of climate processes in generating these changes could not be distinguished from the indirect consequences of the recovery of whale and seal populations from past over-exploitation (Trathan and Reid, 2009; Murphy et al., 2012a,b).

28.2.2.2.1. Marine plankton, krill, fish, and other invertebrates

Distributions of phytoplankton and zooplankton have moved south with the frontal systems (Hinz et al., 2012; Mackey et al., 2012), including range expansion into the Southern Ocean from the north by the coccolithophorid *Emiliania huxleyi* (Cubillos et al., 2007) and the red-tide dinoflagellate *Noctiluca scintillans* (McLeod et al., 2012) (*medium confidence*). There is insufficient evidence to determine whether other range shifts are occurring.

Collapsing ice shelves are altering the dynamics of benthic assemblages by exposing areas previously covered by ice shelves, allowing increased primary production and establishment of new assemblages (e.g., collapse of the Larson A/B ice shelves) (*medium confidence*; Peck et al., 2009; Gutt et al., 2011). More icebergs are grounding, causing changes in local oceanography and declining productivity that consequently affects productivity of benthic assemblages (*low confidence*; Thrush and Cummings, 2011). Iceberg scour on shallow banks is also increasing, disrupting resident benthic assemblages (*medium confidence*; Barnes and Souster, 2011; Gutt et al., 2011).

Primary production is changing regionally in response to changes in sea ice, glacial melt, and oceanographic features (*medium confidence*; Arrigo et al., 2008; Boyd et al., 2012). Off the west Antarctic Peninsula, phytoplankton stocks and productivity have decreased north of 63°S, but increased south of 63°S (*high confidence*; Montes-Hugo et al., 2009; Chapter 6). This study (based on time series of satellite-derived and measured chlorophyll concentrations) also indicated a change from diatom-dominated assemblages to ones dominated by smaller phytoplankton (Montes-Hugo et al., 2009). The reduced productivity in the north may be tempered by increased inputs of iron through changes to ocean processes in the region (*low confidence*; Dinniman et al., 2012).

Since the 1980s, Antarctic krill densities have declined in the Scotia Sea (Atkinson et al., 2004), in parallel with regional declines in the extent and duration of winter sea ice (Flores et al., 2012). Uncertainty remains over changes in the krill population because this decline was observed using net samples and is not reflected in acoustic abundance time series (Nicol and Brierley, 2010); the observed changes in krill density may have been partly a result of changes in distribution (Murphy et al., 2007). Nevertheless, given its dependence on sea ice (Nicol et al., 2008), the krill population may already have changed and will be subject to further alterations (*high confidence*).

The response of krill populations is probably a complex response to multiple stressors. Decreases in recruitment of post-larval krill across the Scotia Sea have been linked to declines in sea ice extent in the Antarctic Peninsula region (*medium confidence*; Wiedenmann et al., 2009) but these declines may have been offset by increased growth arising from increased water temperature in that area (Wiedenmann et al., 2008). However, near South Georgia krill productivity may have declined as a result of the increased metabolic costs of increasing temperatures (*low confidence*; Hill et al., 2013). The combined effects of changing sea ice, temperature, and food have not been investigated.

28.2.2.2.2. Marine mammals and seabirds

In general, many Southern Ocean seals and seabirds exhibit strong relationships to a variety of climate indices, and many of these relationships are negative to warmer conditions (*low confidence*; Trathan et al., 2007; Barbraud et al., 2012; Forcada et al., 2012). Regional variations in climate change impacts on habitats and food will result in a mix of direct and indirect effects on these species. For example, Adélie penguin colonies are declining in recent decades throughout the Antarctic Peninsula while the reduction in chinstrap penguins is more regional (Lynch et al., 2012) and related to reductions in krill availability (Lima and Estay, 2013). In contrast, gentoo penguins are increasing in that region and expanding south (*high confidence*; Lynch et al., 2012). This may be explained by the reduced sea ice habitats and krill availability in the north, resulting in a southward shift of krill predators, particularly those dependent on sea ice (Forcada et al., 2012) and the replacement of these predators in the north by species that do not depend on sea ice, such as gentoo penguins and elephant seals (*low confidence*; Costa et al., 2010; Trivelpiece et al., 2011; Ducklow et al., 2012; Murphy et al., 2013). A contrasting situation is in the Ross Sea, where Adélie penguin populations have increased (Smith, Jr. et al., 2012). The mechanisms driving these changes are currently under review and may be more than simply sea ice (Lynch et al., 2012; Melbourne-Thomas et al., 2013). For example, too much or too little sea ice may have negative effects on the demography of Adélie and emperor penguins (see Barbraud et al., 2012, for review). Also, increased snow precipitation that accumulates in breeding colonies can decrease survival of chicks of Adélie penguins when accompanied by reduced food supply (Chapman et al., 2011).

Changes elsewhere are less well known. Some emperor penguin colonies have decreased in recent decades (*low confidence*; Barbraud et al., 2008; Jenouvrier et al., 2009), and one breeding site has been recorded as having been vacated (Trathan et al., 2011). However, there is insufficient evidence to make a global assessment of their current trend. In the sub-Antarctic of the Indian sector, reductions in seal and seabird populations may indicate a region-wide shift to a system with lower productivity (*low confidence*; Weimerskirch et al., 2003; Jenouvrier et al., 2005a,b) but commercial fishing activities may also play a role.

Where frontal systems are shifting south, productive foraging areas also move to higher latitudes. In the Indian sector, this is thought to be causing declines in king penguin colonies on sub-Antarctic islands (*low confidence*; Péron et al., 2010), while the shift in wind patterns may be causing changes to the demography of albatross (*low confidence*; Weimerskirch et al., 2012).

As identified in the WGII AR4, some species' populations may suffer as a result of fisheries while others are recovering from past over-exploitation, either of which may confound interpretation of the response of these species and their food webs to climate change. The recovery of Antarctic fur seals on some sub-Antarctic islands has been well documented, and their populations may now be competing with krill-eating macaroni penguins (Trathan et al., 2012). More recently, there has been confirmation that populations of some Antarctic whales are recovering, such as humpbacks (Nicol et al., 2008; Zerbini et al., 2010), suggesting that food is currently not limiting. In contrast, a number of albatross and petrel populations are declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall et al., 2012).

28.2.3. Terrestrial Ecosystems

28.2.3.1. Arctic

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 130,000 years), mainly driven by natural climate change. Significant altitudinal and latitudinal advances and retreats in tree line have been common, animal species have gone extinct, and animal populations have fluctuated significantly throughout this period (e.g., Lorenzen et al., 2011; Salonen et al., 2011; Mamet and Kershaw, 2012).

28.2.3.1.1. Phenology

Phenological responses attributable to warming are apparent in most Arctic terrestrial ecosystems (*medium confidence*). They vary from earlier onset and later end of season in western Arctic Russia (Zeng et al., 2013), to little overall trend in plant phenology in the Swedish sub-Arctic (Callaghan et al., 2010), to dramatic earlier onset of phenophases in Greenland (Høye et al., 2007; Post et al., 2009a; Callaghan et al., 2011a; see Figure 28-2).

28.2.3.1.2. Vegetation

The latest assessment of changes in Normalized Difference Vegetation Index (NDVI), a proxy for plant productivity, from satellite observations between 1982 and 2012 shows that about a third of the Pan-Arctic has substantially greened, less than 4% browned, and more than 57% did not change significantly (Xu et al., 2013; Figure 28-3). The greatest increases reported in recent years were in the North American high Arctic, along the Beaufort Sea and the east European Arctic (Zhang et al., 2008; Pouliot et al., 2009; Bhatt et al., 2010; Forbes et al., 2010; Walker et al., 2011; Epstein et al., 2012; Macias-Fauria et al., 2012; Xu et al., 2013).

The positive trends in NDVI are associated with increases in the summer warmth index (sum of the monthly mean temperatures above freezing expressed as degrees Celsius per month) that have increased on average by 5°C per month for the Arctic as a whole (Xu et al., 2013). However, the even greater 10°C to 12°C per month increase for the land adjacent to the Chukchi and Bering Seas (Figure 28-3) was associated with decreases in NDVI. On the Yamal Peninsula in Russia the pattern of NDVI is partly due to surface disturbance, such as landslide activity (Walker et al., 2009). Small rodent cycles reduce NDVI in sub-Arctic Sweden, by decreasing biomass and changing plant species composition (Olofsson et al., 2012). The changing NDVI signal should therefore generally be interpreted with care.

In common with tree line trees and herbs, the abundance and biomass of deciduous shrubs and graminoids (grasses and grass-like plants) have

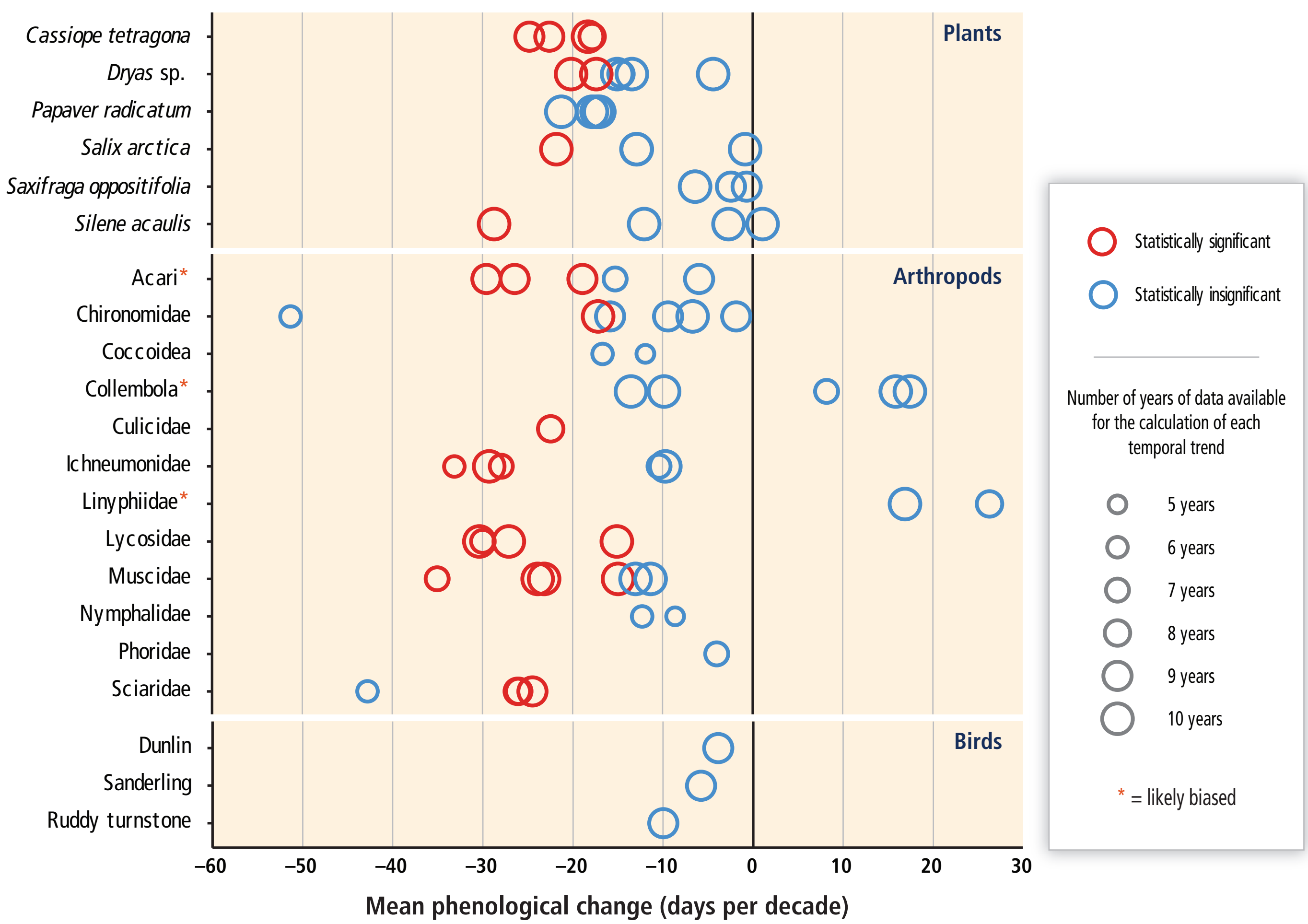


Figure 28-2 | Temporal change in onset of flowering (plants), median date of emergence (arthropods), and clutch initiation dates (birds) estimated from weekly sampling in permanents plots (plants and arthropods) and near-daily surveys through the breeding period in a 19 km^2 census area (birds) during 1996–2005 in high-Arctic Greenland. Trends based on 5 to 10 years of observations are red circles when statistically significant and otherwise blue. Trends in arthropod taxa marked by asterisks (*) are likely to be biased (Høye et al., 2007).

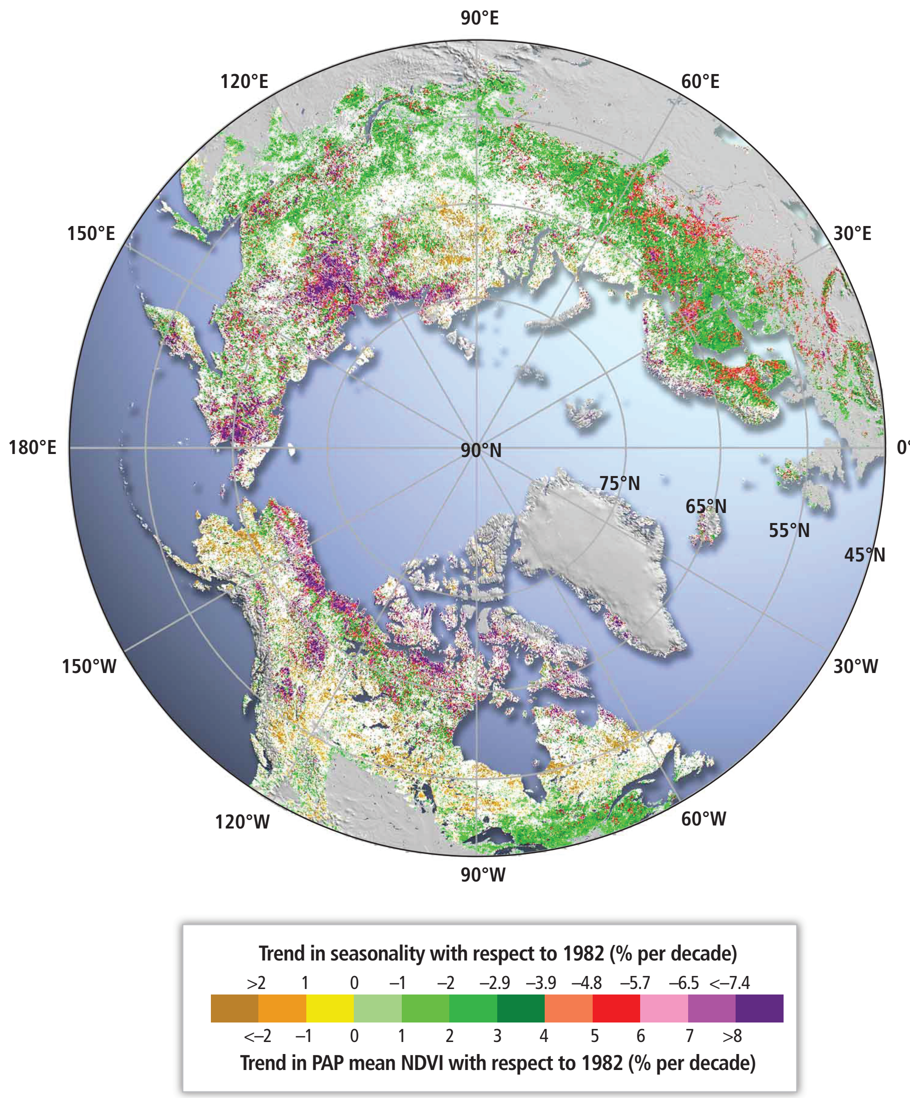


Figure 28-3 | Significant changes ($p < 0.01$) in photosynthetically active period (PAP) Normalized Difference Vegetation Index (NDVI) between 1982 and 2012 (Xu et al., 2013).

increased substantially in certain parts of the Arctic tundra in recent years, but remained stable or decreased in others (*very high confidence*). Attribution for the increases and decreases in deciduous shrubs and graminoids is heterogeneous, with drivers varying among different regions (*very likely*), including Arctic warming, differences in herbivory, industrial development, legacies from past land use, and changes in moisture (Post and Pedersen, 2008; Forbes et al., 2009, 2010; Kitti et al., 2009; Olofsson et al., 2009; Callaghan et al., 2011b, 2013; Kumpula et al., 2011, 2012; Myers-Smith et al., 2011; Elmendorf et al., 2012b; Gamon et al., 2013).

Shrubs have generally expanded their ranges and/or growth over the last 20 years (Danby and Hik, 2007; Hudson and Henry, 2009; Forbes et al., 2010; Hallinger et al., 2010; Callaghan et al., 2011b; Hedenås et al., 2011; Hill and Henry, 2011; Myers-Smith et al., 2011a,b; Rundqvist et al., 2011; Elmendorf et al., 2012a,b; Macias-Fauria et al., 2012), and have varied from dramatic, that is, 200% area increase in study plots (Rundqvist et al., 2011) in sub-Arctic Sweden, to early invasion of a fell field community on west Greenland by low shrubs (Callaghan et al., 2011a).

A synthesis (61 sites; Elmendorf et al., 2012a) of experimental warming studies of up to 20 years duration in tundra sites worldwide showed, overall, increased growth of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness. Elmendorf et al. (2012a) point out that the groups that increased most in abundance under simulated warming were graminoids in cold regions and primarily shrubs in warm regions of the tundra. However, strong heterogeneity in responses to the experimental warming suggested that other factors could moderate the effects of climate warming significantly, such as herbivory, differences in soil nutrients and pH, precipitation, winter temperatures and snow cover, and species composition and density.

Snow bed habitats have decreased in sub-Arctic Sweden (Björk and Molau, 2007; Hedenås et al., 2011). In other plant communities, changes have been less dramatic, ranging from small increases in species richness in the south west Yukon of the Canadian sub-Arctic (Danby et al., 2011), through subtle changes in plant community composition in west and southeast Greenland (Callaghan et al., 2011a; Daniëls and De Molenaar, 2011) to 70-year stability of a plant community on Svalbard (Prach et al., 2010).

The responses to Arctic warming of lichen and bryophyte (mosses) diversity have been heterogeneous, varying from consistent negative effects to significant increases in recent years (Hudson and Henry, 2009; Tømmervik et al., 2009, 2012). Forbes and Kumpula (2009) recorded long-term and widespread lichen degradation in northern Finland attributed more to trampling of dry lichens by reindeer in summer than to winter consumption as forage.

Palaeorecords of vegetation change indicate that the northern tree line should extend upward and northward during current climate warming (Callaghan et al., 2005) because tree line is related to summer warmth (e.g., Harsch et al., 2009). Although the tree line has moved northward and upward in many Arctic areas, it has not shown a general circumpolar expansion in recent decades (*high confidence*).

Model projections that suggest a displacement of between 11 and 50% of tundra by forest by 2100 (see references in Callaghan et al., 2005) and shifts upslope by 2 to 6 m yr^{-1} (Moen et al., 2004) and northwards by 7.4 to 20 km yr^{-1} (Kaplan and New, 2006) might be overestimating rate of tree line advance by a factor of up to 2000 (Van Bogaert et al., 2011). The fastest upslope shifts of tree lines recorded during 20th century warming are 1 to 2 m yr^{-1} (Shiyatov et al., 2007; Kullman and Öberg, 2009) whereas the fastest so-far recorded northward-migrating tree line replaces tundra by taiga at a rate of 3 to 10 m yr^{-1} (Kharuk et al., 2006). In some areas, the location of the tree line has not changed or has changed very slowly (Payette, 2007; MacDonald et al., 2008). A global study by Harsch et al. (2009) showed that only 52% of 166 global tree line sites studied had advanced over the past 100 years. In many cases the tree line has even retreated (Cherosov et al., 2010). At the small scale, the tree line has shown increase, decrease, and stability in neighboring locations (Lloyd et al., 2011; Van Bogaert et al., 2011).

Evidence for densification of the forest at the sub-Arctic tree line is robust and consistent within Fennoscandia (Tømmervik et al., 2009; Hedenås et al., 2011; Rundqvist et al., 2011) and Canada (Danby and Hik, 2007). Dendroecological studies indicate enhanced conifer recruitment during the 20th century in the northern Siberian taiga (Briffa et al., 2008). Some of the changes are dramatic, such as an increase in area of mountain birch in study plots in northern Sweden by 600% between 1977/1998 and 2009/2010 (Rundqvist et al., 2011) and a doubling of tree biomass in Finnmarksvidda in northern Norway since 1957 (Tømmervik et al., 2009). However, model projections of displacement of deciduous forest by evergreen forest (Wolf et al., 2008; Wramneby et al., 2010) have not so far been validated.

Where the mountain birch tree line has increased in elevation and shrub (e.g., willow, dwarf birch) abundance has increased, the response can be an interaction between climate warming, herbivory pressure, and earlier land use (Olofsson et al., 2009; Hofgaard et al., 2010; Van Bogaert et al., 2011). In Fennoscandia and Greenland, heavy grazing by large herbivores may significantly check deciduous low erect shrub (e.g., dwarf shrub and willow) growth (Post et al., 2008; Kitti et al., 2009; Olofsson et al., 2009).

Less moisture from snow and more rain now favors broadleaf trees over conifers and mosses in some areas (Juday, 2009) while moisture deficits are reducing the growth of some northern forests (Goetz et al., 2005; Verbyla, 2008; Yarie, 2008) and making them more susceptible to insect pest outbreaks (see references in Callaghan et al., 2011c). Death of trees through drought stress or insect pest activity will increase the probability of fire, which will have positive feedbacks (increase warming) on the climate (Mack et al., 2011).

28.2.3.1.3. Changes in animal populations

The documented collapse or dampening of population cycles of voles and lemmings over the last 20 to 30 years in parts of Fennoscandia and Greenland (Schmidt et al., 2012) can be attributed with *high confidence* to climate change (Ims et al., 2007, 2011; Gilg et al., 2009; Kausrud et al., 2009). A shortening of the snow season and more thaw and/or rain events during the winter will have an effect on the subnivean space, which provides thermal insulation, access to food, and protection from predators (Berg et al., 2008; Kausrud et al., 2009; Johansson et al., 2011). However, the causes of the changes in the lemming and vole cycles are still being debated as factors other than climate change may also be of importance (Brommer et al., 2010; Krebs, 2011).

Climate-mediated range expansion both in altitude and latitude of insect pests, and increased survival due to higher winter temperatures, has been documented for bark beetles in North America (Robertson et al., 2009) and for geometrid moths in Fennoscandia (Jepsen et al., 2008, 2011; Callaghan et al., 2010), causing more extensive forest damage than before. Outbreaks of insect pests such as geometrid moths can even reduce the strengths of CO_2 sinks in some areas (Heliasz et al., 2011).

The decline in wild reindeer and caribou (both *Rangifer tarandus*) populations in some regions of about 30% over the last 10 to 15 years has been linked both to climate warming and anthropogenic landscape changes (Post et al., 2009a; Vors and Boyce, 2009; Russell and Gunn, 2010). Even though most of the Arctic has warmed, the decline in the populations has not been uniform. Some of the North American large, wild herds have, for example, declined by 75 to 90%, while other wild herds and semi-domestic herds in Fennoscandia and Russia have been stable or even increased (Forbes et al., 2009; Gunn et al., 2009; Vors and Boyce, 2009; Forbes, 2010; Joly et al., 2011; Kumpula et al., 2012).

The expected and partially observed increased primary productivity of Arctic tundra may potentially increase the supply of food for Arctic ungulates. However, the overall quality of forage may decline during warming, for example, if the nitrogen content of key fodder species for ungulates were to drop during warming (Turunen et al., 2009; Heggberget et al., 2010), while lichen biomass, an important winter fodder for reindeer, is decreasing over parts of the Arctic region. Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes and their impacts on ungulate populations (van Der Wal et al., 2007; Turunen et al., 2009).

More frequent rain-on-snow icing events and thicker snowpacks caused by warmer winters and increased precipitation may restrict access to vegetation and may have profound negative influences on the population dynamics of Arctic ungulates (Berg et al., 2008; Forchhammer et al., 2008; Miller and Barry, 2009; Stien et al., 2010, 2012; Hansen et al., 2011). Such events have caused heavy mortality in some semi-domestic reindeer herds and musk oxen in recent years (Grenfell and Putkonen, 2008; Forbes, 2009; Bartsch et al., 2010), and have also been shown to synchronize the dynamics of a resident vertebrate community (small mammals, reindeer, and Arctic fox) in Svalbard (Hansen et al., 2013). In contrast, Tyler et al. (2008) and Tyler (2010) suggested that generally warmer winters enhance the abundance of reindeer populations.

It has been suggested that warming-induced trophic mismatches between forage availability and quality and timing of calving have a role in the decline of circumpolar reindeer and caribou populations (Post and Forchhammer, 2008; Post et al., 2009a,b), although such trophic mismatch has been disputed (Griffith et al., 2010).

Adjustment via phenotypic plasticity instead of adaptation by natural selection is expected to dominate vertebrate responses to rapid Arctic climate change, and many such adjustments have already been documented (Gilg et al., 2012).

28.2.3.1.4. Long-term trends and event-driven changes

Long-term climate change impacts on vegetation and animal populations are accelerated when tipping points are triggered by events such as extreme weather, fire, insect pest, and disease outbreaks. The impacts of winter thaw events on ecosystems are now well documented (e.g., Bokhorst et al., 2011) but studies of the severe impacts of tundra fires on vegetation and biospheric feedbacks are recent (Mack et al., 2011). Results from experimental winter thaws were validated by a natural event in northern Norway and Sweden in 2007 that reduced NDVI by almost 30% over at least 1400 km^2 (Bokhorst et al., 2009). Studies on relationships between climate change and plant disease are rare, but Olofsson et al. (2011) showed that increased snow accumulation led to a higher incidence of fungal growth on sub-Arctic vegetation.

28.2.3.2. Antarctica

Antarctic terrestrial ecosystems occur in 15 biologically distinct areas (Terauds et al., 2012), with those in the maritime and sub-Antarctic islands experiencing the warmest temperatures, reduced extreme seasonality and greatest biodiversity (Convey, 2006). In the cooler conditions on the continent, species must be capable of exploiting the short periods where temperature and moisture availability are above physiological and biochemical thresholds. In many areas, there is no visible vegetation, with life being limited, at the extreme, to endolithic (within rock) communities of algae, cyanobacteria, fungi, bacteria, and lichens (Convey, 2006).

Few robust studies are available of biological responses to observed climatic changes in natural Antarctic terrestrial ecosystems. The rapid population expansion and local-scale colonization by two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in maritime Antarctica (Parnikoza et al., 2009) remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. Radiocarbon dating of moss peat deposits has shown that growth rates and microbial productivity have risen rapidly on the Antarctic Peninsula since the 1960s, consistent with temperature changes, and are unprecedented in the last 150 years (Royles et al., 2013). In east Antarctica, moss growth rates over the last 50 years have been linked to changes in wind speed and temperature and their influence on water availability (Clarke et al., 2012). A contributing factor is that air temperatures have increased past the critical temperature at which successful sexual reproduction (seed set) can now take place, changing the dominant mode of reproduction and increasing the potential distance for dispersal (*low confidence*; Convey, 2011). Similar changes in the local distribution and development of typical cryptogamic vegetation of this region have been reported (Convey, 2011), including the rapid colonization of ice-free ground made available through glacial retreat and reduction in extent of previously permanent snow cover (Olech and Chwedorzewska, 2011). As these vegetation changes create new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonize them (*low confidence*).

28.2.4. Health and Well-being of Arctic Residents

The warming Arctic and major changes in the cryosphere are significantly impacting the health and well-being of Arctic residents and projected to increase, especially for many Indigenous peoples. Although impacts are expected to vary among the diverse settlements that range from small, remote, predominantly Indigenous to large cities and industrial settlements, this section focuses more on health impacts of climate change on Indigenous, isolated, and rural populations because they are especially vulnerable to climate change owing to a strong dependence on the environment for food, culture, and way of life; their political and economic marginalization; existing social, health, and poverty disparities; as well as their frequent close proximity to exposed locations along ocean, lake, or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen et al., 2010; Cochran et al., 2013).

28.2.4.1. Direct Impacts of a Changing Climate on the Health of Arctic Residents

Direct impacts of climate changes on the health of Arctic residents include extreme weather events, rapidly changing weather conditions, and increasingly unsafe hunting conditions (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts) (*high confidence*; Revich, 2008; AMAP, 2009; IPCC, 2012). Intense precipitation events and rapid snowmelt are expected to impact the magnitude and frequency of slumping and active layer detachment, resulting in rock falls, debris flow, and avalanches (Kokelj et al., 2009; Ford et al., 2010). Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration, and/or rapid onset of extreme weather events, storms, and inundation by large storm surges, which, in turn, may create risks to safe travel or subsistence activities, loss of access to critical supplies and services to rural or isolated communities (e.g., food, telecommunications, fuel), and risk of being trapped outside one's own community (*high confidence*; Laidre et al., 2008; Parkinson, 2009; Brubaker et al., 2011b,c). Changing river and sea ice conditions affect the safety of travel for

Indigenous populations especially, and inhibit access to critical hunting, herding, and fishing areas (Andrachuk and Pearce, 2010; Derksen et al., 2012; Huntington and Watson, 2012).

Cold exposure has been shown to increase the frequency of certain injuries (e.g., hypothermia, frostbite), accidents, and diseases (respiratory, circulatory, cardiovascular, musculoskeletal) (Revich and Shaposhmikov, 2010). Studies in northern Russia have indicated an association between low temperatures and social stress and cases of cardiomyopathy (Revich and Shaposhnikov, 2010). It is expected that winter warming in the Arctic will reduce winter mortality rates, primarily through a reduction in respiratory and cardiovascular deaths (Shaposhnikov et al., 2010). Researchers project that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, studies are showing respiratory and cardiac stress associated with extreme warm summer days and that rising temperatures are accompanied by increased air pollution and mortality, especially in Russian cities with large pollution sources (Revich, 2008; Revich and Shaposhnikov, 2012).

28.2.4.2. Indirect Impacts of Climate Change on the Health of Arctic Residents

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion) (*high confidence*; Maynard and Conway, 2007; Parkinson and Evengård, 2009; Brubaker et al., 2011a; see also Chapter 11).

In addition to the climate change impacts and processes are the complicated impacts from contaminants such as persistent organic pollutants (POPs), radioactivity, and heavy metals (e.g., mercury), which create additional and/or synergistic impacts on the overall health and well-being of all Arctic communities (Armitage et al., 2011; UNEP and AMAP, 2011; Teran et al., 2012). Ambient temperature variability and temperature gradients directly affect the volatilization, remobilization, and transport pathways of mercury and POPs in the atmosphere, ocean currents, sea ice, and rivers. Transport pathways, inter-compartmental distribution, and bioaccumulation and transformation of environmental contaminants such as POPs, mercury, and radionuclides in the Arctic may consequently be affected by climate change (*high confidence*; AMAP 2011b; Ma et al., 2011; UNEP and AMAP 2011; Teng et al., 2012). Ma et al. (2011) and Hung et al. (2010) demonstrated that POPs are already being remobilized into the air from sinks in the Arctic region as a result of decreasing sea ice and increasing temperatures.

Contaminants and human health in the Arctic are tightly linked to the climate and Arctic ecosystems by factors such as contaminant cycling and climate (increased transport to and from the Arctic), and the related increased risks of transmission to residents through subsistence life ways (Maynard, 2006; AMAP, 2010; Armitage et al., 2011; UNEP and AMAP, 2011; Teran et al., 2012). The consumption of traditional foods by Indigenous peoples places these populations at the top of the Arctic food chain and through biomagnification, therefore, they may receive some of the highest exposures in the world to certain contaminants (Armitage et al., 2011; UNEP and AMAP, 2011). Contaminants such as POPs are known for their adverse neurological and medical effects on humans, particularly the developing fetus, children, women of reproductive age, and the elderly; thus it is important to include contaminants as a significant part of any climate impact assessment (UNEP and AMAP, 2011).

Radioactivity in the Arctic is also a concern because there are many potential and existing radionuclide sources in some parts of the Arctic, and contamination can remain for long periods of time in soils and some vegetation, creating potentially high exposures for people (AMAP, 2010). Climate changes can mobilize radionuclides throughout the Arctic environment, and also potentially impact infrastructure associated with nuclear activities by changes in permafrost, precipitation, erosion, and extreme weather events (AMAP, 2010).

Warming temperatures are enabling increased overwintering survival and distribution of new insects that sting and bite as well as many bird, animal, and insect species that can serve as disease vectors and, in turn, causing an increase in human exposure to new and emerging infectious diseases (Parkinson et al., 2008; Epstein and Ferber, 2011). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia and Canada (Ogden et al., 2010; Tokarevich et al., 2011) and Sweden (Lindgren and Gustafson, 2001) and *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean (Hughes-Hanks et al., 2005). It is also expected that temperature increases will increase the incidence of zoonotic diseases as relocations of animal populations occur (Revich et al., 2012; Hueffler et al., 2013).

Harmful algal blooms (HABs), whose biotoxins can be a serious health hazard to humans or animals (paralysis, death), are increasing globally and expected to increase in the Arctic, and HABs are influenced directly by climate change-related factors such as temperature, winds, currents, nutrients, and runoff (Portier et al., 2010; Epstein and Ferber, 2011; Walsh et al., 2011; see also Chapters 6, 11). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, caused by *Vibrio parahaemolyticus*, in Alaskan oysters (McLaughlin et al., 2005). In addition, warmer temperatures raise the possibility of anthrax exposure in Siberia from permafrost thawing of historic cattle burial grounds (Revich and Podolnaya, 2011).

The impacts of climate change on food security and basic nutrition are critical to human health because subsistence foods from the local environment provide Arctic residents, especially Indigenous peoples, with unique cultural and economic benefits necessary to well-being and contribute a significant proportion of daily requirements of nutrition, vitamins, and essential elements to the diet (Ford, 2009; Ford and Berrang-Ford, 2009). However, climate change is already an important threat because of the decrease in predictability of weather patterns, low water levels and streams, timing of snow, and ice extent and stability, impacting the opportunities for successful hunting, gathering, fishing, and access to food sources and increasing the probability of accidents (*high confidence*; Ford and Furgal, 2009; Ford et al., 2010). In recent years, populations of marine and land mammals, fish, and water fowl are also being reduced or displaced, thus reducing the traditional food supply (Gearheard et al., 2006; West and Hovelsrud, 2010; Lynn et al., 2013).

Traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by warming temperatures, thus further reducing food available to the community (Brubaker et al., 2011b,c). For example, food contamination caused by thawing of permafrost "ice cellars" is occurring and increasingly wet conditions make it harder to dry food for storage (Hovelsrud et al., 2011). Indigenous people increasingly have to abandon their semi-nomadic lifestyles, limiting their overall flexibility to access traditional foods from more distant locations (www.arctichealthyukon.ca). These reductions in the availability of traditional foods plus general globalization pressures are forcing Indigenous communities to increasingly depend on expensive, non-traditional, and often less healthy Western foods, increasing the rates of modern diseases associated with processed food and its packaging, such as cardiovascular diseases, diabetes, dental caries, and obesity (Armitage et al., 2011; Berrang-Ford et al., 2011; Brubaker et al., 2011b,c).

Climate change is beginning to threaten community and public health infrastructure, often in communities with no central water supply and treatment sources. This is especially serious in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada) through increased river and coastal flooding and erosion, increased drought, and thawing of permafrost, resulting in loss of reservoirs, damage to landfill sites, or sewage contamination (GAO, 2009; Bronen, 2011). Saltwater intrusion and bacterial contamination may also be threatening community water supplies (Parkinson et al., 2008; Virginia and Yalowitz, 2012). Quantities of water available for drinking, basic hygiene, and cooking are becoming limited owing to damaged infrastructure, drought, and changes in hydrology (Virginia and Yalowitz, 2012). Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure spreads sewage in villages with no municipal water supply. This can result in higher rates of hospitalization for pneumonia, influenza, skin infections, and respiratory viral infections (Parkinson and Evengård, 2009; Virginia and Yalowitz, 2012). Compounding these impacts in rural areas as well as cities are respiratory and other illnesses caused by air-borne pollutants (e.g., contaminants, microbes, dust, mold, pollen, smoke) (Revich, 2008; Rylander and Schilling, 2011; Revich and Shaposhnikov, 2012).

It is now well documented that the many climate-related impacts on Arctic communities are causing significant psychological and mental distress and anxiety among residents (Levintova, 2010; Portier et al., 2010; Coyle and Susteren, 2012; see also Chapter 11). For example, changes in the physical environment (e.g., through thawing permafrost and erosion) that may lead to forced or voluntary relocation of residents out of their villages or loss of traditional subsistence species are causing mental health impacts among Indigenous and other vulnerable, isolated populations (Curtis et al., 2005; Albrecht et al., 2007; Coyle and Susteren, 2012; Maldonado et al, 2013). Special concern has been expressed by many communities about the unusually high and increasing numbers of suicides in the Arctic, especially among Indigenous youth, and efforts are underway to try to develop a thorough assessment as well as establish effective intervention efforts (Albrecht et al., 2007; Portier et al., 2010; USARC, 2010).

28.2.5. Indigenous Peoples and Traditional Knowledge

Indigenous populations in the Arctic—the original Native inhabitants of the region—are considered especially vulnerable to climate change because of their close relationship with the environment and its natural resources for physical, social, and cultural well-being (Nuttall et al., 2005; Parkinson, 2009; Cochran et al., 2013). Although there are wide differences in the estimates, including variations in definitions of the Arctic region, Arctic Indigenous peoples are estimated to number between 400,000 and 1.3 million (Bogoyavlensky and Siggner, 2004; Galloway-McLean, 2010). According to 2010 census data, there are approximately 68,000 Indigenous people living in the Russian Arctic. These Arctic residents depend heavily on the region's terrestrial, marine, and freshwater renewable resources, including fish, mammals, birds, and plants; however, the ability of Indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by the unprecedented rate of climate change (*high confidence*; Nakashima et al., 2012; Cochran et al., 2013). In habitats across the Arctic, climate changes are affecting these livelihoods through decreased sea ice thickness and extent, less predictable weather, severe storms, sea level rise, changing seasonal melt/freeze-up of rivers and lakes, changes in snow type and timing, increasing shrub growth, permafrost thaw, and storm-related erosion, which, in turn, are causing such severe loss of land in some regions that a number of Alaskan coastal villages are having to relocate entire communities (Oskal, 2008; Forbes and Stammler, 2009; Mahoney et al., 2009; Bartsch et al., 2010; Weatherhead et al., 2010; ,Bronen, 2011; Brubaker et al., 2011b,c; Eira et al., 2012; Huntington and Watson, 2012; McNeeley, 2012; Maldonado et al., 2013). In addressing these climate impacts, Indigenous communities must at the same time consider multiple other stressors such as resource development (oil and gas, mining); pollution; changes in land use policies; changing forms of governance; and the prevalence in many Indigenous communities of poverty, marginalization, and resulting health disparities (Abryutina, 2009; Forbes et al., 2009; Reinert et al., 2009; Magga et al., 2011; Vuojala-Magga et al., 2011; Nakashima et al., 2012; Mathiesen et al., 2013).

Traditional knowledge is the historical knowledge of Indigenous peoples accumulated over many generations and it is increasingly emerging as an important knowledge base for more comprehensively addressing the impacts of environmental and other changes as well as development of appropriate adaptation strategies for Indigenous communities (WGII AR4 Chapter 15; Oskal, 2008; Reinert et al., 2008; Wildcat, 2009; Magga et al., 2011; Vuojala-Magga et al., 2011; Nakashima et al., 2012; Vogesser et al, 2013). For example, Saami reindeer herders have specialized knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter, and spring reindeer rangelands (Roturier and Roue, 2009; Eira et al., 2012; Vikhamar-Schuler et al., 2013) and traditional governance systems for relating to natural environments (Sara, 2013). Increasingly, traditional knowledge is being combined with Western scientific knowledge to develop more sustainable adaptation strategies for all communities in the changing climate.

For example, at Clyde River, Nunavut, Canada, Inuit experts and scientists both note that wind speed has increased in recent years and that wind direction changes more often over shorter periods (within a day) than it did during the past few decades (Gearheard et al., 2010; Overland et al., 2012). In Norway, Sámi reindeer herders and scientists are both observing direct and indirect impacts to reindeer husbandry such as changes in snow and ice cover, forage availability, and timing of river freeze-thaw patterns from increasing temperatures (Eira et al., 2012). On the Yamal Peninsula in western Siberia, detailed Nenets observations and recollections of iced-over autumn and winter pastures due to rain-on-snow events have proven suitable for calibrating the satellite-based microwave sensor SeaWinds (Bartsch et al., 2010) and NASA's AMSR-E sensor.

28.2.6. Economic Sectors

28.2.6.1. Arctic

28.2.6.1.1. Agriculture and forestry

Climate change presents benefits and costs for forestry and agriculture (Aaheim et al., 2009; Hovelsrud et al., 2011). In Iceland, for example, tree limits are found at higher altitudes than before, and productivity of many plants has increased (Björnsson et al., 2011). Grain production in Iceland has increased in the last 2 decades, and work on soil conservation and forestry has benefited from warming (Sigurdsson et al., 2007; Björnsson et al., 2011), but also the number of new insect pests on trees and shrubs has increased in the past 20 years. A strong relationship between rate of new insect pest colonization and outbreak intensity in forests exists with changes in annual temperature during the past century (Halldórsson et al., 2013). Climate change impacts on species change and fire frequency have potential impact on commercial forest harvesting activity. Vulnerability of forestry to changes that affect road conditions and thus accessibility during thawing periods has been found in Sweden (Keskitalo, 2008). A case study on Greenland found challenges for plant diseases in potatoes and grass fields, with pathogens and pests present in agricultural cropping systems, for example, black scurf (*Rhizoctonia*) and common scab (*Streptomyces* scabies) (Neergaard et al., 2009).

28.2.6.1.2. Open and freshwater fisheries

Current commercial fisheries are sharply divided between regions of high-yield and value (e.g., commercial fisheries in the southern Bering Sea, Baffin Bay, the east and west Greenland Seas, the Iceland Shelf Sea, the deep Norwegian/Greenland Sea, and the Barents Sea) and subsistence fisheries in the coastal regions of the Arctic Ocean. The relative absence of commercial fishing activity in the Arctic Ocean results from a combination of fisheries policy, the abundance of the resource, the lack of infrastructure for capturing and processing fish, and the difficulties in accessing fishing grounds, especially during winter. In most regions, fisheries management strategies have been developed to build sustainable fisheries and rebuild overfished stocks (Froese and Proelß, 2010; Livingston et al., 2011). Recently observed changes in the spatial distribution and abundance of mackerel (*Scomber scombrus*) has challenged existing international agreements for shared resources in the North Atlantic (Arnason, 2012; Astthorsson et al., 2012). Although loss of sea ice in summer is allowing greater access to fisheries resources in the Arctic Ocean, some nations have prohibited commercial fishing within their exclusive economic zones until there is sufficient understanding of stock status to ensure that proposed fisheries would be managed sustainably (Stram and Evans, 2009; Wilson and Ormseth, 2009).

Several Arctic coastal sea-run fishes are targeted for subsistence and commercial use in the Arctic. Commercial transactions from fishing are typically for local markets; however, the socioeconomic and cultural importance of these fishes to Indigenous peoples far outweighs their monetary value. Reist et al. (2006) and Fechhelm et al. (2007) found that climate-related factors that influenced the water level and freshening of rivers were related to run size of Arctic cisco (*Coregonus autumnalis*). Similarly, a recent study based on Chinook salmon (*Oncorhynchus tshawytscha*) run timing for the period 1961–2009 showed that success in the fishery was dependent on the timing of the marine exit, which was tightly coupled to environmental conditions that were linked to climate (Mundy and Evenson, 2011).

28.2.6.1.3. Marine transportation

Observations and climate models indicate that in the period between 1979–1988 and 1998–2007 the number of days with ice-free conditions (less than 15% ice concentration) increased by 22 days along the Northern Sea Route (NSR) in the Russian Arctic, and by 19 days in the Northwest Passage (NWP) in the Canadian Arctic, while the average duration of the navigation season in the period 1980–1999 was 45 and 35 days, respectively (Mokhow and Khon, 2008). Increased shipping associated with the opening of the NSR will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific. The future status of marine, terrestrial, and freshwater biota may be negatively affected as a result of substantial coastal infrastructure to facilitate offshore developments (Meschtyb et al., 2005). Also, the frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season for fish and marine mammals, which is the late spring/summer, when these resources can be found throughout the NSR area (Østreng, 2006).

28.2.6.1.4. Infrastructure

Much of the physical infrastructure in the Arctic relies on and is adapted to local sea ice conditions, permafrost, and snow (Huntington et al., 2007; Sundby and Nakken, 2008; Sherman et al., 2009; West and Hovelsrud, 2010; Forbes, 2011). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower poses major economic costs and risks, which are more closely linked to the design of the structure than with thawing permafrost. Current engineering practices are designed to help minimize the impacts (Prowse et al., 2009). Much of the infrastructure has been built with weather conditions in mind, but remains vulnerable and inadequate to respond to environmental emergencies, natural disasters, and non-environmental accidents (NRTEE, 2009). Northern safety, security, and environmental integrity are much dependent on transportation infrastructure. Ice as a provisioning system provides a transportation corridor and a platform for a range of activities and access to food sources in the Arctic (Eicken et al., 2009).

In northern Canada climate warming presents an additional challenge for northern development and infrastructure design. While the impacts of climate change become increasingly significant over the longer time scales, in the short term of greater significance will be the impacts associated with ground disturbance and construction (Smith and Risebrough, 2010).

Climate change impacts have increased the demand for improved communication infrastructure and related services and community infrastructure for the safety and confidence in drinking water (NRTEE, 2009). The access, treatment, and distribution of drinking water is generally dependent on a stable platform of permafrost for pond or lake retention. Several communities have reported the need for more frequent water-quality testing of both municipal systems and untreated water sources to ensure its suitability for drinking (Furgal, 2008).

28.2.6.1.5. Resource exploration

The Arctic has large reserves of minerals (Lindholt, 2006; Harsem et al., 2011; Peters et al., 2011) and potentially large reserves of undiscovered sources of raw minerals and oil and gas. Predicted new access to offshore energy resources is hypothesized to be a significant share of the global supply of oil and gas (Gautier et al., 2009; Berkman, 2010). The socioeconomic impacts of oil and gas exploration activity may be positive or negative (Duhaime et al., 2004; Huntington et al., 2007; Forbes, 2008; Forbes et al., 2009; Kumpula et al., 2011; Harsem et al., 2011).

Climatic warming is accelerating access to northern lands for development (Forbes et al., 2009). Yamal in Western Siberia has approximately 90% of Russia's gas reserves, but at the same time represents the largest area of reindeer herding in the world (Jernsletten and Klokov, 2002; Stammler, 2005; Forbes and Kumpula, 2009). Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to loss of "available room for adaptation" for reindeer husbandry (Nuttall et al., 2005; Oskal, 2008; Forbes et al., 2009). Sharp increases in future oil and gas and other resource development in the Russian north and other Arctic regions are anticipated—along with associated infrastructure, pollution, and other development byproducts—which will reduce the availability of pasturelands for reindeer and use by Indigenous communities (Derome and Lukina, 2011; Degteva and Nellermann, 2013).

28.2.6.1.6. Informal, subsistence-based economy

Hunting, gathering, herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Nuttall et al., 2005; Poppel and Kruse, 2009; Crate et al., 2010; Larsen and Huskey, 2010). In the early 1990s—initially in western Canada, and later elsewhere—Indigenous communities started reporting climate change impacts (Berkes and Armitage, 2010). According to some herders, whalers, and walrus hunters, non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes and Stammler, 2009; Forbes et al., 2009; Ignatowski and Rosales, 2013).

The Inuit and Saami have expressed strong concern about the effects of climate warming on their livelihoods (Forbes and Stammler, 2009; Magga et al., 2011). For the Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn; earlier melt-out and faster sea ice retreat in spring; and thinner, less predictable ice in general (Krupnik and Jolly, 2002; Cochran et al., 2013). Diminished sea ice translates into more difficult access for hunting marine mammals, and greater risk for the long-term viability of subsistence species such as polar bear populations (*high confidence*; Laidre et al., 2008). Most Inuit communities depend to some extent on marine mammals for nutritional and cultural reasons, and many benefit economically from polar bear and narwhal hunting. A reduction in these resources represents a potentially significant economic loss (Hovelsrud et al., 2008). Among Fennoscandian Saami, the economic viability of reindeer herding is threatened by competition with other land users coupled with strict agricultural norms (Forbes, 2006; Magga et al., 2011). Reindeer herders are concerned that more extreme weather may exacerbate this situation (Oskal, 2008).

Climate change is affecting reindeer herding communities through greater variability in snow melt/freeze, ice, weather, winds, temperatures, and precipitation, which, in turn are affecting snow quality and quantity—the most critical environmental variables for reindeer sustainability (Bartsch et al., 2010; Magga et al., 2011; Eira et al., 2012). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow that then block the animals' access to their forage and subsequent starvation (Bartsch, 2010; Maynard et al., 2011; Eira et al., 2012).

28.2.6.2. Antarctica and the Southern Ocean

Economic activities in the Antarctic have been limited to fishing and tourism (IPCC, 2007). Ship-based tourism is a significant industry in Antarctica but does not involve permanent shore-based infrastructure. Over recent decades, the number of tourists landing in Antarctica has risen from 7322 in 1996/1997 to 32,637 in 2007/2008 (IAATO, 2012). Visits generally coincide with the times when wildlife are breeding and are often restricted because of the presence of fast ice, sea ice, or icebergs. They are expected to continue to increase, with an increasing chance of terrestrial alien species being introduced from tourism and other vectors as ice-free areas increase from climate change (Chown et al., 2012). Scientific activity by a number of nations is also taking place and has the potential to impact upon local ecologies. Mineral resource activity is prohibited south of 60°S under the Protocol on Environmental Protection to the Antarctic Treaty.

Fisheries in Antarctica, primarily through fisheries for Antarctic krill, could amount to approximately 6% of existing global marine capture fisheries (Nicol et al., 2012). The pattern of the krill fishery has been affected by changes in the sea ice extent around the Antarctic Peninsula, where the fishery has been taking advantage of the ice-free conditions and taking more of its catch during winter in that region (*high confidence*; Kawaguchi et al., 2009). Ecosystem-based management of krill fisheries by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) has yet to include procedures to account for climate change impacts, although the need to do so has been identified (Trathan and Agnew, 2010; Constable, 2011).

28.3. Key Projected Impacts and Vulnerabilities

28.3.1. Hydrology and Freshwater Ecosystems

28.3.1.1. Arctic

Accompanying projected increases in high-latitude river flow (Section 3.4.5; WGI AR5 Section 12.4.5.4) are earlier spring runoff (Pohl et al., 2007; Dankers and Middelkoop, 2008; Hay and McCabe, 2010), greater spring snowmelt (Adam et al., 2009), and increases in spring sediment fluxes (Lewis and Lamoureux, 2010). Enhanced permafrost thaw (WGI AR5 Section 12.4.6.2) will continue to affect the dynamics of thermokarst lakes and related ecological effects (Section 28.2.1.1). Thawing permafrost and changes in the hydrological regime of the Arctic rivers, particularly those traversing regions affected by industrial developments, will increase the contaminant flow (Nikanorov et al., 2007). Loss of glacier ice masses will alter runoff hydrographs; sediment loads; water chemistry; thermal regimes; and related channel stability, habitat, and biodiversity (Milner et al., 2009; Moore et al., 2009). Although snow, freshwater ice, and permafrost affect the morphology of arctic alluvial channels, their future combined effects remain unclear (McNamara and Kane, 2009). For small permafrost streams, however, longer projected periods of flowing water will modify nutrient and organic matter processing (Greenwald et al., 2008; Zarnetske et al., 2008) but long-term negative impacts of increased sediment load on biological productivity could outweigh any positive effects from increased nutrient loading (Bowden et al., 2008).

Changes to river-ice flooding are also projected to occur as a result of changes in (1) hydraulic gradients for near-coastal locations because of sea level rise, (2) streamwise air-temperature gradients, and (3) the timing and magnitude of spring snowmelt (Prowse et al., 2011). Synergistic/antagonistic effects among these factors, however, require detailed site-specific analyses for accurate projections of future conditions (Beltaos and Prowse, 2009). Reduced (increased) ice-jam flooding will have positive (negative) benefits for river-side northern communities/infrastructure but could also alter delta-riparian (Lesack and Marsh, 2010) and coastal marine (Emmerton et al., 2008) ecosystems. The quality of river water entering the marine environment will also be affected by the reduction or loss of stamukhi lakes that process river inputs (Dumas et al., 2006; Galand et al., 2008).

Future changes to lake ice regimes will include delayed freeze-up, advanced break-up, thinner ice and changes in cover composition (especially white ice in areas of enhanced winter precipitation), increased water temperature, and earlier and longer-lasting summer stratification (Dibike et al., 2011), all of which will affect a range of aquatic processes, including secondary productivity (Borgstrøm and Museth, 2005; Prowse et al., 2007; Prowse and Brown, 2010b). Patterns of species richness and diversity are also projected to change with alterations to ice duration—increased open-water periods favoring the development of new trophic levels, colonization of new aquatic species assemblages (Vincent et al., 2009), greater atmosphere-water gas exchange, and a decrease in winter kill of resident fish with cascading effects on lower trophic levels (Balayla et al., 2010). The loss of ice, however, can also decrease key habitat availability and quality (Vincent et al., 2008). Geochemical responses of Arctic lakes will also be altered. As observed for thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production (Metje and Frenzel, 2007; Laurion et al., 2010). Because temperature sensitivity has a stronger control over methane production than oxidation (Duc et al., 2010), elevated water temperatures will enhance methanogenesis, causing increased methane release from sediments. The net balance of these two processes operating under a broad range of future changing environmental factors, however, remains to be quantified (Walter et al., 2007a,b, 2008; Laurion et al., 2010).

As well as methane, increased water temperatures are projected to lead to reduced organic carbon (OC) burial. Projections, based on a range of six climate warming scenarios (IPCC, 2007), indicate that there will be a 4 to 27% decrease (0.9 to 6.4 TgC yr^{-1}) in OC burial across lakes of the northern boreal zone by the end of the 21st century as compared to rates for the approximately last half-century (Gudasz et al., 2010). Although these estimates assume that future OC delivery will be similar to present-day conditions, even with enhanced supply from thawing permafrost, higher water temperatures will increase OC mineralization and thereby lower burial efficiency. The amount of burial also depends on lake depth and mixing regimes. For non-thermally stratified shallow lakes, there will be a greater opportunity for water-sediment mixing, and hence greater carbon recycling back into the water column. By contrast, for lakes that become increasingly thermally stratified, carbon sinking below the thermocline will tend not to return to the surface until an increasing later fall turnover, thereby decreasing the probability of sediment-stored carbon being returned to the water column (Flanagan et al., 2006).

Changes in ice cover, thermal regimes, and stratification patterns will also affect the fate of contaminants in northern lakes. Higher water temperatures can enhance the methylation of mercury and modify food web and energy pathways, such as through enhanced algal scavenging (a major food web entry pathway for mercury), resulting in increased mercury bioavailability to higher trophic levels (Outridge et al., 2007; Carrie et al., 2010).

28.3.1.2. Antarctica

This assessment reinforces conclusions of AR4. Increased temperatures will impact aquatic ecosystems in Antarctica (*high confidence*), but the exact nature of these impacts will vary regionally. The most vulnerable freshwater systems are in the northern Antarctic Peninsula and maritime Antarctic islands, where a small increase in temperature can have widespread ecosystem impacts because the average temperature is within a few degrees of the melting point (*high confidence*; Quesada and Velázquez, 2012). Potential impacts are expected to range from immediate catastrophic impacts such as loss of bounding ice masses causing drainage of freshwater and epishelf lakes (Smith et al., 2006; Hodgson, 2011), to more gradual impacts on changes in the amount and duration of catchment ice and snow cover; accelerated glacier melting; declining volumes of precipitation falling as snow; permafrost; and active layer and hydrological changes, such as water retention times (*medium confidence*; e.g., Vieira et al., 2010; Quesada and Velázquez, 2012; Bockheim et al., 2013).

Changes in the thickness and duration of seasonal ice cover, longer melt seasons, and larger volumes of water flowing into the lakes are expected in the future (*medium confidence*; Lyons et al., 2006) but the ecological effects will vary between lakes, depending on their depth to surface area ratio, with insufficient evidence to fully assess future changes in these systems. Longer ice-free seasons may cause physical conditions to be more favorable for primary production (Hodgson and Smol, 2008) but very high irradiances experienced during summer in some systems can substantially inhibit algal blooms under ice-free conditions (Tanabe et al., 2007), which would favor the growth of benthic cyanobacteria species (Hodgson et al., 2005). In other lakes, increases in meltwater supply may increase suspended solids and reduce light penetration and may offset the increases in the underwater light regime predicted as a result of extended ice-free periods (Quesada et al., 2006).

Under a warming climate an increase in microbial biomass is expected because of the increased water supply from glacial melt and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved OC delivery to lakes (Velázquez et al., 2013). This organic supply will promote growth and reproduction in the benthos and plankton and imbalances in population dynamics (Quesada and Velázquez, 2013). Nutrient enrichment of some freshwater habitats in the vicinity of fur seal colonies will increase because of expanding fur seal populations (*high confidence*; Quayle et al., 2013).

Away from glacial forelands, increasing aridity will occur in the long term in some areas of the continent (Hodgson et al., 2006b) and on sub-Antarctic islands (*medium confidence*; Smith, Jr. et al., 2012). Closed basin lakes can dry up completely causing local extinctions or retreat into cryptic or resistant life-cycle stages, as experienced in Arctic lakes (Smol and Douglas, 2007b). Other effects include desiccation of moss banks due to increased evaporation and sublimation rates (*medium confidence*; Wasley et al., 2006). Studies have also shown that warming of once cold freshwater habitats in Antarctica will allow the sub- and maritime Antarctic species to re-invade and establish self-maintaining populations on the Antarctic continent, particularly where human vectors are involved (*medium confidence*; Barnes et al., 2006; Hodgson et al., 2006b). For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman et al., 2010), with a possibility that surface Antarctic lakes contain endemic species that are relics of Gondwana (cf. Convey and Stevens, 2007) and that would become extinct should they be lost from these lakes as a result of climate change.

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Ocean Acidification in the Arctic and Antarctic

The effects of ocean acidification on polar marine food webs can have considerable implications (*medium confidence*). For example, if some regions in the Arctic become understaturated with respect to aragonite (the primary structural component of the shells of some marine calcifiers such as molluscs and urchins), the growth and survial of these organisms will be impacted (WGI AR5 Figure 6.28; Chierici and Fransson, 2009; Fabry et al., 2009; Yamamoto-Kawai et al., 2009). In laboratory experiments, Arctic pteropods (*Limacina helicina*, a small planktonic mollusc) held under conditions consistent with projected ocean warming and acidification in the Arctic Ocean in early spring were able to extend their shells in corrosive waters but dissolution marks were observed (Comeau et al., 2010, 2012). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on *Limacina helicina* and other vulnerable species (Orr et al., 2009). At the current time there are insufficient data to fully assess the ecosystem consequences of acidification on pteropods because it is unclear whether other species, with a similar nutritive value, will replace pteropods.

In the Southern Ocean, foraminifera have thinner shells than in the Holocene and there is evidence for shell thickness to be related to atmospheric CO_2, supporting the hypothesis that ocean acidification will affect this abundant protozoan in this region (Moy et al., 2009). Similarly, shells are thinner from sediment traps in aragonite undersaturated water (below the aragonite saturation horizon (ASH)) compared to those captured above the ASH in sub-Antarctic waters, but there is no time series of data related to change in the ASH (Roberts et al., 2011). Shell dissolution has been observed in surface waters in the Atlantic sector as a result of both upwelling and atmospheric changes in CO_2 (*medium confidence*; Bednarsek et al., 2012). Other impacts of acidification on Southern Ocean organisms are currently uncertain, but short-term negative impacts need to be considered together with an organism's capacity to adapt in the longer term (Watson et al., 2012).

Only a few studies have been conducted on commercially exploited polar species on ocean acidification. Antarctic krill embryonic development (Kawaguchi et al., 2011) and post-larval krill metabolic physiology (Saba et al., 2012) may be impeded by elevated CO_2 concentrations, which may negatively impact the reproductive success of krill more generally under emission scenarios used in Coupled Model Intercomparison Project Phase 5 (CMIP5) (*medium confidence*; Kawaguchi et al., 2013). Long et al. (2013) examined the effects of acidification on red king crab (*Paralithodes camtschaticus*) and found animals exposed to reduced pH exhibited increased hatch duration, decreased egg yolk, increased larval size, and decreased larval survival. In contrast, Hurst et al. (2012) conducted laboratory experiments at levels of elevated CO_2 predicted to be present in the Gulf of Alaska and Bering Sea in the next century and found that juvenile walleye pollock (*Gadus chalcogrammus*) exhibited a general resiliency of growth energetics to the direct effects of CO_2 changes.

28.3.2.2. Arctic

28.3.2.2.1. Marine plankton, fish, and other invertebrates

Phenological response

Projected changes in the timing, spatial distribution, and intensity of spring blooms may result in mismatches with the timing of the emergence of Arctic grazers (Søreide et al., 2010). Based on past experience, some species will adapt to local conditions by shifting key life cycle events (hatch date, maturity schedule, and reproductive timing) or diet to accommodate differences in the regional timing and availability of prey and environmental conditions (Ormseth and Norcross, 2007; Sundby and Nakken, 2008; Vikebø et al., 2010; Darnis et al., 2012). For example, loss of sea ice cover in spring is expected to change fish behavior in ice-bound areas (Mundy and Evenson, 2011). It is uncertain whether endemic animals will be able to alter key phenologies fast enough to keep pace with the projected rates of change in the Arctic Ocean.

Projected spatial shifts

Simulation studies revealed that a 2-week longer growing season and a 2°C increase in temperature would not be sufficient to allow expatriate species (*Calanus finmarchicus* or *C. marshallae*) to invade the Arctic Ocean (Ji et al., 2012). Ellingsen et al. (2008) projected future zooplankton distribution and abundance in the Barents Sea for the period 1995–2059 using a regional climate model that was forced with climate model output based on the *Special Report on Emission Scenarios* (SRES) B2 scenario. They projected that by 2059, Atlantic origin zooplankton will increase and Arctic origin zooplankton will decrease in the Barents Sea.

The literature is mixed with respect to the potential for future movement of fish and shellfish into the Arctic Ocean. Modeling studies project that marine fish stocks potentially will shift their distributions into the Arctic Ocean, resulting in an increase in biodiversity in the region (Cheung et al., 2009, 2011; see also Box CC-MB). However, other studies show the persistence of cold seawater temperatures on the shelf regions of the Arctic Ocean and northern Bering Sea will restrict or retard movement of several sub-Arctic fish and shellfish species into the Arctic Ocean (Sigler et al., 2011; Stabeno et al., 2012b; Hunt, Jr. et al., 2013). In waters off the coasts of Europe there is a potential for increased fish production because of the combined effects of intrusion of Atlantic water over the relatively broader shelf regions and advective corridors for larval drift and range expansion of spawners. Huse and Ellingsen (2008) forced a spatially explicit coupled biophysical model for the Barents Sea with future climate scenarios to project the implications of climate change on the spawning distribution of capelin (*Mallotus villosus*). Projections show that the spawning distribution of capelin will shift to the east and new spawning grounds will be colonized. A key factor governing this expansion will be the availability of pelagic prey. In the southeast Bering Sea, there is evidence that planktivorous species such as walleye pollock will shift their distribution in response to shifts in ocean temperature (Kotwicki and Lauth, 2013). In summary, the spatial distribution of some fish and shellfish in the Barents and southeast Bering Seas will shift in response to climate change (*high confidence*).

Projected impacts on production

In the deep basins of the Arctic Ocean the number of ice-free days in summer are expected to result in longer productive seasons (*high confidence*; Slagstad et al., 2011). Ellingsen et al. (2008) projected that annual primary production would increase by 2059 in the Barents Sea. Tremblay et al. (2012) hypothesized that longer ice-free periods in summer in the Arctic Ocean could provide for more opportunities for episodic nutrient pulses that would enhance secondary production through the growing season. However, in the Arctic Ocean, these changes in primary production may be offset later in the year by increased zooplankton grazing (Olli et al., 2007) or nutrient depletion due to stronger stratification and shifts in the mixed layer depth (Wassmann, 2011; Tremblay et al., 2012). Therefore, there is *medium confidence* that annual phytoplankton production will increase in the central Arctic Ocean.

In the few cases where future abundance of fish has been projected using climate change scenarios, species exhibited different trends related to their vulnerability. Forward extrapolation of observed responses suggests that increased summer sea surface temperatures in the Bering and Barents Seas will cause a decrease in the abundance of energy-rich copepods and euphausiids (Coyle et al., 2011; Slagstad et al., 2011). This change in prey quality is expected to lower survival of walleye pollock in the eastern Bering Sea by 2050 (Mueter et al., 2011). Climate-enhanced stock projection models showed time trends in cross-shelf transport of juvenile northern rock sole (*Lepidopsetta polyxystra*) to nursery areas will not be substantially altered by climate change (Wilderbuer et al., 2012).

28.3.2.2.2. Marine mammals, polar bears, and seabirds

The effects of the projected reduction in sea ice extent in this century (Wang and Overland, 2009) on Arctic marine mammals and seabirds will vary spatially and temporally (Laidre et al., 2008). Many ice-associated marine mammals and seabirds will be affected by ice loss, with altered species distributions, migration patterns, behavior, interspecific interactions, demography, population changes, and vulnerability to extinction but there is *limited evidence* of changes for most species (*high confidence*).

The polar bear population of the southern Beaufort Sea is projected to decline by 99% by 2100, with a probability estimated at 0.80 to 0.94 under A1B (Hunter et al., 2010). The northern Beaufort Sea population is stable although decline is predicted with warming (Stirling et al., 2011). Projected extirpation of approximately two-thirds of the world's polar bears was predicted for mid-century under A1B (Amstrup et al., 2008). Aspects of this study were criticized (Armstrong et al., 2008) but refuted (Amstrup et al., 2009). The two-thirds decline is consistent with other studies and has *robust evidence* with *medium agreement*. Projected extinction of polar bears is *unlikely*. There is *very high confidence* of subpopulation extirpation.

It is *likely* that the high Arctic seabird species partly or completely dependent on the sympagic ecosystem or the cold Arctic waters close to the ice edge will be negatively impacted if the projected changes in these physical parameters occur (*medium confidence*). A general increase in sea surface temperatures, retreat of the ice cover, and earlier break up of fast ice may improve the environmental conditions and food abundance for seabird species that have their range in the southern part of the Arctic or south of the Arctic (*medium confidence*). A poleward expansion of the range of these species is expected during a continued warming (*medium confidence*).

Several factors other than climate influence seabird population dynamics (Regular et al., 2010), and projections of changes with a continued Arctic warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA, 2005). At present, the resolution of Atmosphere-Ocean General Circulation Models are not detailed enough to project spatial changes in mesoscale oceanographic features such as frontal zones and eddies of importance to Arctic seabirds.

28.3.2.3. Antarctica and the Southern Ocean

Continued rising temperatures in the Southern Ocean will result in increased metabolic costs in many ectothermic pelagic species, southward movement of temperate species, and contraction of the range of polar species (*medium confidence*). Southward movement of ocean fronts and associated biota that are prey of sub-Antarctic island-based predators will result in energetic inefficiencies for some of those predators (*low confidence*; Péron et al., 2012; Weimerskirch et al., 2012).

For Antarctic krill, insufficient evidence is available to predict what will happen to circumpolar productivity because of regional variability of the effects of climate change on the different factors (positive and negative) that affect krill, directly and indirectly. For example, increased metabolic and growth rates from warming may be countered by a reduced food supply and the effects of ocean acidification (Sections 28.2.2.2, 28.3.2.1). Also, areas that are already warm may result in slower growth with further warming, such as could happen in the northern Scotia Arc (Wiedenmann et al., 2008; Hill et al., 2013). Models of recruitment and population dynamics indicate that the biomass of krill will decline if surface warming continues, but preliminary projections incorporating a range of factors are uncertain (*low confidence*; Murphy et al., 2007, 2012b). Physiological and behavioral responses might also ameliorate impacts. For example, krill are now known to exploit the full depth of the ocean, which could provide escapes from further warming (Schmidt et al., 2011) as well as refuge from air-breathing predators.

The strong dependence of species in more southern regions (e.g., southern west Antarctic Peninsula and Ross Sea region) on sea ice means that changes in sea ice distribution will cause spatial shifts in the structure of ice-obligate food webs (*low confidence*; Murphy et al., 2012b). Projections show that loss of summer sea ice from the west Antarctic Peninsula is expected to result in ice-dependent seals declining and being replaced by other seal species that are not dependent on sea ice (*low confidence*; Siniff et al., 2008; Costa et al., 2010). There is insufficient evidence to determine whether there will be a mismatch in phenologies of different species as a result of changes in the winter sea ice season (timing and winter extent), such as might occur if the timing of sea ice melt was not at a time of optimal growing conditions for phytoplankton (Trathan and Agnew, 2010).

Reductions in krill abundance in the marine food webs around the South Atlantic islands may result in a shift in their structure toward a more fish-centered ecosystem as observed in the Indian Sector (*low confidence*; Trathan, et al., 2007, 2012; Shreeve et al., 2009; Waluda et al., 2010; Murphy et al., 2012a,b). Also, salps have been postulated to be competitors with krill for phytoplankton around the Antarctic Peninsula when oceanic conditions displace shelf and near-shelf waters during times of low sea ice (Ducklow et al., 2012). In the absence of krill, longer food chains have lower trophic efficiency (Muprhy et al., 2013), and the long-term implications of this for higher trophic levels are unknown.

Coastal environments will be impacted by the dynamics of fast ice, ice shelves, and glacier tongues. These factors will positively affect local primary production and food web dynamics (Peck et al., 2009) but negatively affect benthic communities (*low confidence*; Barnes and Souster, 2011). Projections of the response of emperor penguins and Southern Ocean seabirds based on AR4 model outputs for sea ice and temperature in east Antarctica indicate that general declines in these populations are to be expected if sea ice habitats decline in the future (*low confidence*; Barbraud et al., 2011; Jenouvrier et al., 2012). However, these responses are also expected to be regionally specific because of the regional differences in expectations of change in the ice habitats (*high confidence*). Additional studies at other sites are needed to improve confidence levels of predictions.

28.3.3. Terrestrial Environment and Related Ecosystems

28.3.3.1. Arctic

The boreal forest is generally projected by models to move northward under a warming climate, which will displace between 11 and 50% of the tundra within 100 years (Callaghan et al., 2005; Wolf et al., 2008; Tchebakova et al., 2009; Wramneby et al., 2010) in a pattern similar to that which occurred during the early Holocene climatic warming (*high confidence*). Pearson et al. (2013) projected that at least half of vegetated Arctic areas will shift to a different physiognomic class, and woody cover will increase by as much as 52%, in line with what has been occurring in northwest Eurasia (Macias-Fauria et al., 2012).

Dynamic vegetation models applied to Europe and the Barents Region project a general increase in net annual primary production by climate warming and CO_2 fertilization (Wolf et al., 2008; Wramneby et al., 2010; Anisimov et al., 2011). Boreal needle-leaved evergreen coniferous forest replaces tundra and expands into the mountain areas of Fennoscandia, but this advance may be delayed or prevented in regions already occupied by clonal deciduous shrubs whose *in situ* growth has increased significantly in recent decades (Macias-Fauria et al., 2012).

In contrast to these expected results, shrubs, currently expanding in area in many Arctic locations, were modeled to decrease in extent over the next 100 years after an initial increase (Wolf et al., 2008). Also, counterintuitively, tundra areas increased in the projections. This was a result of changes at the highest latitudes that opened land for colonization at a rate exceeding displacement of tundra by shrubs in the south.

Several studies have calculated the magnitude of the effects of vegetation change in the Arctic on negative feedbacks of CO_2 sequestration and increased evapotranspiration and the positive feedback of decreased albedo (Swann et al., 2010; Wramneby et al., 2010; Wolf et al., 2010; Pearson et al., 2013). It is *likely* that vegetation changes will result in an overall positive feedback on the climate.

Recent changes and results of climate change simulation experiments in the field have shown that there are considerable uncertainties in the projected rates of change (e.g., Van Bogaert et al., 2010). Furthermore, the models do not yet include vertebrate and invertebrate herbivory, extreme events such as tundra fire, and extreme winter warming damage or changes in land use that either reduce the rate of vegetation change or open up niches for rapid change. Projections suggest increases in the ranges of the autumn and winter months that have outbreaks in populations resulting in the defoliation of birch forest (Jepsen et al., 2008, 2011) and a general increase in the "background" (non-outbreak) invertebrate herbivores (Wolf et al., 2008).

Animal terrestrial biodiversity is generally projected to increase in the Arctic during warming by immigration of new species from the south, vegetation changes, and indirectly by introduction of invasive species caused by increased human activities and increased survival of such species (*high confidence*; Post et al., 2009; Gilg et al., 2012; CAFF, 2013). Many native Arctic species will *likely* be increasingly threatened during this century.

28.3.3.2. Antarctica

Projected effects of climate change on Antarctic terrestrial species are limited to knowledge of their ecophysiological tolerances to changes in air temperature, wind speed, precipitation (rain and snowfall), permafrost thaw, and exposure of new habitat through glacial/ice retreat. The climate is expected to become more tolerable to a number of species, leading to increases in biomass and extent of existing ecological communities.

The frequency with which new potential colonizing plant and animal species arrive in Antarctica (particularly the Antarctic Peninsula region) from lower latitudes, and the subsequent probability of their successful establishment, will increase with regional climate warming and associated environmental changes (*high confidence*; Chown et al., 2012). Human-assisted transfers of biota may be more important by two orders of magnitude than natural introductions (Frenot et al., 2005) as the transfer is faster and avoids extreme environments such as altitude or oceans (Barnes et al., 2006). The potential for anthropogenic introduction of non-indigenous species to Antarctic terrestrial areas, which could have devastating consequences to the local biodiversity, will increase (*high confidence*; Convey et al., 2009; Hughes and Convey, 2010; Convey, 2011; Braun et al., 2012). At present, established non-indigenous species in the sub- and maritime Antarctic are very restricted in their distributions (Frenot et al., 2005). Climate change could result in a greater rate of spread of invasive species through colonization of areas exposed by glacial retreat, as has occurred at South Georgia (Cook et al., 2010) and in the maritime Antarctic (Olech and Chwedorzewska, 2011). Biosecurity measures may be needed to help control dispersal of established non-indigenous species to new locations, particularly given the expected increase in human activities in terrestrial areas (Hughes and Convey, 2010; Convey et al., 2011). An important gap in understanding is the degree to which climate change may facilitate some established but localized alien species to become invasive and widespread (Frenot et al., 2005; Convey 2010; Hughes and Convey, 2010; Cowan et al., 2011), which has been shown for the sub-Antarctic (Chown et al., 2012).

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic islands, along with the continued increased presence of Antarctic fur seals, are likely to have far greater importance over the time scale under consideration than are those attributable to climate change itself (Convey and Lebouvier, 2009; Turner et al., 2009; Convey, 2010).

28.3.4. Economic Sectors

Projections of economic costs of climate change impacts for different economic sectors in the Arctic are limited, but current assessments suggest that there will be both benefits and costs (AMAP, 2011a; Forbes, 2011). Non-Arctic actors are likely to receive most of the benefits from increased shipping and commercial development of renewable and non-renewable resources, while Indigenous peoples and local Arctic communities will have a harder time maintaining their way of life (Hovelsrud et al., 2011).

Contributing to the complexity of measuring the future economic effects of climate change is the uncertainty in future predictions and the rapid speed of change, which are linked with the uncertainty of the technological and ecological effects of such change (NorAcia, 2010). Communities within the same eco-zone may experience different effects from identical climate-related events because of marked local variations in site, situation, culture, and economy (Clark et al., 2008).

Economic cost estimates have been made for the case of the Alaskan economy, for example, which suggest that a heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). Some Alaskan villages such as Shishmaref, Kivalina, and Newtok have already lost critical infrastructure and services and are becoming unlivable because of permafrost thaw, storm damage, and coastal erosion but the high costs and limitations of government mechanisms are significant barriers to the actual relocation of these communities (Bronen, 2011; Brubaker et al., 2011c; Cochran et al., 2013; Maldonado et al., 2013).

28.3.4.1. Fisheries

Climate change will impact the spatial distribution and catch of some open ocean fisheries in the Barents and Bering Seas (*high confidence*); however, the future of commercial fisheries in the Arctic Ocean is uncertain. There is strong evidence and considerable data showing links between climate-driven shifts in ocean conditions and shifts in the spatial distribution and abundance of commercial species in the Bering and Barents Seas (Section 28.3.2.2.1). In limited cases, coupled biophysical models or climate-enhanced stock projection models have been used to predict future commercial yield or shifts in fishing locations. However, these predictions are uncertain (Huse and Ellingsen, 2008; Ianelli et al., 2011; Wilderbuer et al., 2012). Cheung et al. (2011) used projections from an Earth System Model to estimate shifts in bio-climatic windows that included climate change effects on biogeochemistry (oxygen and acidity) and primary production to project future catch potential of 120 demersal fish and invertebrates. Results from their model suggested that the catch potential will increase in the Barents and Greenland Seas and regions at greater than 70° north latitude (Cheung et al., 2011). In contrast, vulnerability analysis suggests that only a few species are expected to be abundant enough to support viable fisheries in the Arctic Ocean (Hollowed et al., 2013). Potential fisheries for snow crab (*Chionoecetes opilio*) on shelf areas of the Arctic Ocean may be limited by the associated impacts of ocean acidification. If fisheries develop in the Arctic Ocean, adoption of sustainable strategies for management will be a high priority (Molenaar, 2009). The moratorium on fishing in the US portion of the Chukchi and Beaufort Seas would prevent fishing until sufficient data become available to manage the stock sustainably (Wilson and Ormseth, 2009).

Predicting how harvesters will respond to changing economic, institutional, and environmental conditions under climate change is difficult. Current techniques track fishers' choices based on revenues and costs associated with targeting a species in a given time and area with a particular gear given projected changes in the abundance and spatial distribution of target species (Haynie and Pfeiffer, 2012). However, estimates of future revenues and costs will depend, in part, on future demand for fish, global fish markets, and trends in aquaculture practices (Rice and Garcia, 2011; Merino et al., 2012).

28.3.4.2. Forestry and Farming

Climate change is *likely* to have positive impacts for agriculture, including extended growing season (*medium* to *high confidence*; Falloon and Betts, 2009; Grønlund, 2009; Tholstrup and Rasmussen, 2009), although variations across regions are expected (Hovelsrud et al., 2011), and the importance of impacts to the Arctic economy will likely remain minor (Eskeland and Flottorp, 2006). Potential positive effects of climatic warming for forestry include decreased risk of snow damage. Kilpeläinen et al. (2010) estimate a 50% decrease in snow damage in Finland toward the end of the century. A warmer climate is likely to impact access conditions and plant diseases for forestry and farming. Grønlund (2009) found in the case of northern Norway—where about half of the arable land area is covered by forest and 40% by marshland—that the potential harnessing of arable land for farming will be at the cost of forestry production, or dried-up marshlands, which may contribute to more greenhouse emissions. Larger field areas may contribute to land erosion through rainfall and predicted unstable winters, and may increase conditions for plant diseases and fungal infections (Grønlund, 2009). If the winter season continues to shorten due to climate change (Xu et al., 2013), accessibility to logging sites will be negatively affected. Accessibility is higher when frozen ground makes transportation possible in sensitive locations or areas that lack road. If weather changes occur when logging has taken place, sanding of roads may be necessary which carries significant economic costs. Impact on carrying capacity of ground or road accessibility will thus affect forestry economically. Challenges may include limited storage space for wood (Keskitalo, 2008).

28.3.4.3. Infrastructure, Transportation, and Terrestrial Resources

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much of the infrastructure in the North is dependent on the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines, and provide access to remote communities in the winter (*high confidence*; Huntington et al., 2007; Furgal and Prowse, 2008; Sundby and Nakken, 2008; Sherman et al., 2009; West and Hovelsrud, 2010; Forbes, 2011). In the long-term, marine and freshwater transportation will need to shift reliance from ice routes to open-water or land-based transportation systems. Relocation remains one community-based adaptation to deal with projections of persistent flooding and bank erosion (Furgal, 2008; NRTEE, 2009). Changing sea ice (multi-year) conditions are expected to have a regulating impact on marine shipping and coastal infrastructure (i.e., via introduced hazards; Eicken et al., 2009).

By adapting transportation models to integrate monthly climate model (Community Climate System Model 3 (CCSM3)) predictions of air temperature—combined with data sets on land cover, topography, hydrography, built infrastructure, and locations of human settlements—estimates have been made of changes to inland accessibility for landscapes northward of 40°N by the mid-21st century (Stephenson et al., 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000-kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000–2014) for eight circumpolar countries was projected to be –14%, varying from –11 to –82%. In absolute terms, Canada and Russia (both at –13%) account for the majority of declining winter-road potential with approximately 1×10^6 km^2 being lost (see Table 28-1). The winter road season has decreased since the 1970s on the Alaskan North Slope, from as much as 200 to 100 days in some areas (Hinzman, et al., 2005).

Climate change is expected to lead to a nearly ice-free Arctic Ocean in late summer and increased navigability of Arctic marine waters within this century. New possibilities for shipping routes and extended use of existing routes may result from increased melting of sea ice (*high confidence*; Corbett et al., 2010; Khon et al., 2010; Paxian et al., 2010; Peters et al., 2011; Stephenson et al., 2011).

Table 28-1 | Annually averaged changes in inland and maritime transportation accessibility by mid-century (2045–2059) versus baseline (2000–2014).

	Change (%) in winter road-accessible land area (km^2) (2000-kg GVWR vehicle)	Change (%) in maritime-accessible ocean area (km^2) (type A vessel)—current EEZ
Canada	–13	19
Finland	–41	0
Greenland	–11	28
Iceland	–82	<1
Norway	–51	2
Russia	–13	16
Sweden	–46	0
USA (Alaska)	–29	5
High seas	n/a	406
Total	–14	23

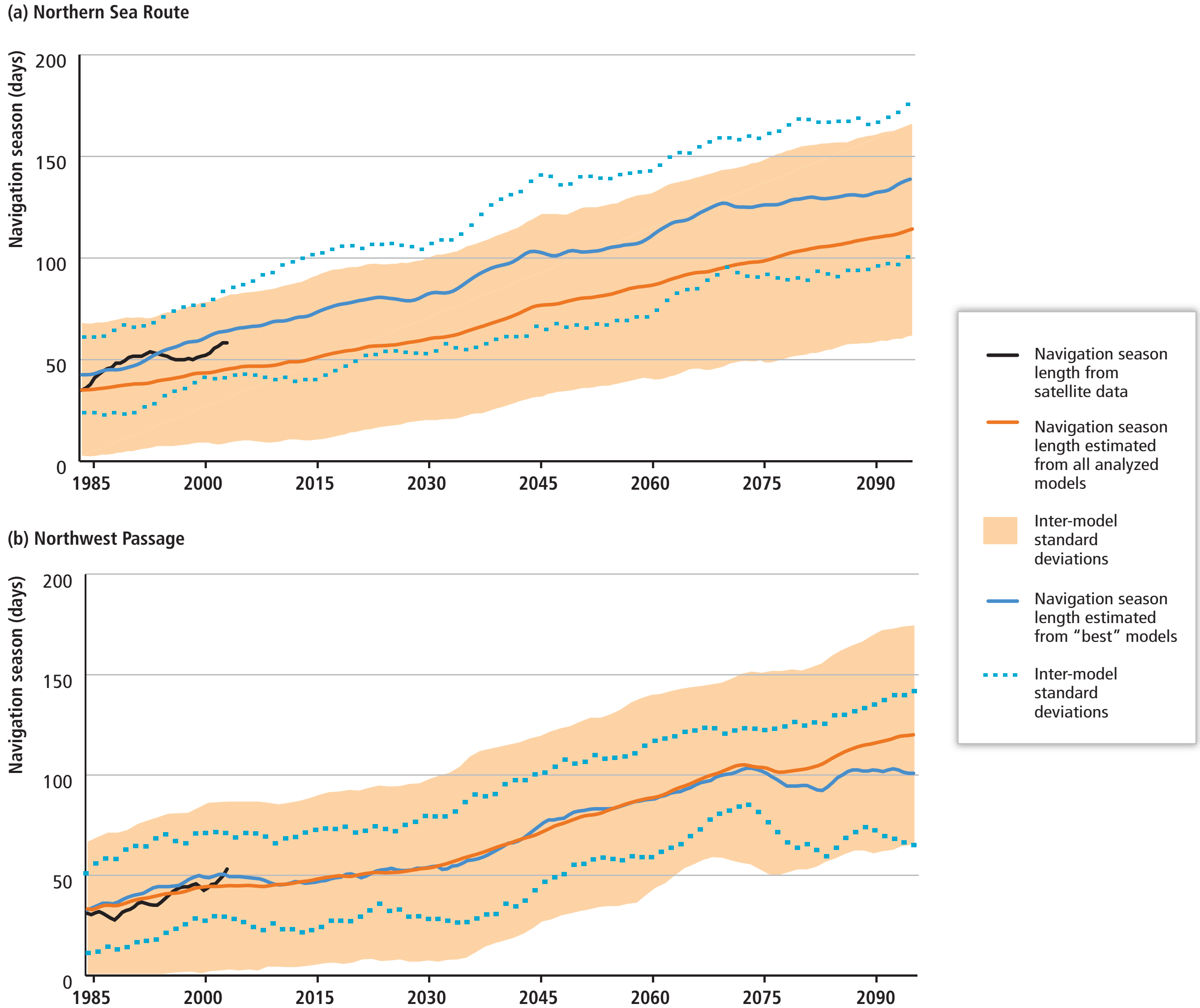


Figure 28-4 | Projected duration of the navigation period (days) over the Northwest Passage and Northern Sea Route (Khon et al., 2010).

Projections made by Stephenson et al. (2011) suggest that all five Arctic littoral states will gain increased maritime access to their current exclusive economic zones, especially Greenland (+28%, relative to baseline), Canada (+19%), Russia (+16%), and the USA (+15%). In contrast, Iceland, Norway, Sweden, and Finland display little or no increase in maritime accessibility (Table 28-1; Stephenson et al., 2011).

General Circulation Models (GCMs) developed for the AR4 generally have underestimated the duration of the ice-free period in the Arctic Ocean and simulate slower changes than those observed in the past decades (Stroeve et al., 2007). Mokhow and Khon (2008) used a subset of climate models that better reproduce observed sea ice dynamics than other GCMs to project the duration of the navigation season along the NSR and through the NWP under the moderate SRES A1B emission scenario. According to their results, by the end of the 21st century, the NSR may be open for navigation 4.5 ± 1.3 months per year, while the NWP may be open 2 to 4 months per year (see Figure 28-4). The models did not predict any significant changes of the ice conditions in the NWP until the early 2030s.

An increase in the length of the summer shipping season, with sea ice duration expected to be 10 days shorter by 2020 and 20 to 30 days shorter by 2080, is likely to be the most obvious impact of changing climate on Arctic marine transportation (Prowse et al., 2009). Reduction in sea ice and increased marine traffic could offer opportunities for economic diversification in new service sectors supporting marine shipping. Loss of sea ice may open up waterways and opportunities for increased cruise traffic (e.g., Glomsrød and Aslaksen, 2009), and add to an already rapid increase in cruise tourism (Howell et al., 2007; Stewart et al., 2007, 2010). Climate change has increased the prevalence of cruise tourism throughout Greenland, Norway, Alaska, and Canada because of decreasing sea ice extent.

Projected declines in sea ice cover leading to development of integrated land and marine transportation networks in northern Canada may stimulate further mine exploration and development (Prowse et al., 2009). These possibilities, however, also come with challenges including their predicted contribution to the largest change in contaminant movement into or within the Arctic, as well as their significant negative impacts on the traditional ways of life of northern residents (Furgal and Prowse, 2008). Added shipping and economic activity will increase the amount of black carbon and reinforce warming trends in the region (Lack and Corbett, 2012), leading to additional economic activity.

A longer shipping season and improved access to ports may lead to increased petroleum activities, although possible increased wave activity and coastal erosion may increase costs related to infrastructure and technology. Peters et al. (2011) find by using a bottom-up shipping model and a detailed global energy market model to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050—and based on estimated sea ice extent—that there will be rapid growth in transit shipping; oil and gas production will be moving into locations requiring more ship transport; and this will lead to rapid growth in emissions from oil and gas transport by ship.

The Arctic contains vast resources of oil, which is hard to replace as transportation fuel, and vast resources of gas, a more climate-benign fuel than coal. Petroleum resources are unevenly distributed among Arctic regions and states. Arctic resources will play a growing role in the world economy, but increased accessibility is expected to create challenges for extraction, transport, engineering, search-and-rescue needs, and responses to accidents (Hovelsrud et al., 2011), and climatic change presents the oil and gas industry with challenges in terms of planning and predictions (Harsem et al., 2011). Increased emissions due to rapid growth in Arctic Ocean transportation of oil and gas are projected (Peters et al., 2011). Owing to high costs and difficult access conditions, the impact on future oil and gas production in the Arctic remains unclear (Peters et al., 2011; Lindholdt and Glomsrød, 2012).

28.4. Human Adaptation

There is general agreement that both Indigenous and non-Indigenous people in the Arctic have a history of adapting to natural variability in the climate and natural resource base, as well as recent socioeconomic, cultural, and technological changes (*high confidence*; Forbes and Stammler, 2009; Wenzel, 2009; Ford and Pearce, 2010; West and Hovelsrud, 2010; Bolton et al., 2011; Cochran et al., 2013). Climate change exacerbates the existing stresses faced by Arctic communities (*high confidence*; Crate and Nuttall, 2009; Rybråten and Hovelsrud, 2010), and is only one of many important factors influencing adaptation (Berrang-Ford et al., 2011). Climate adaptation needs to be seen in the context of these interconnected and mutually reinforcing factors (Tyler et al., 2007; Hovelsrud and Smit, 2010). The challenges faced today by communities in the Arctic are complex and interlinked and are testing their traditional adaptive capacity (*low* to *medium confidence*).

Climatic and other large-scale changes have potentially large effects on Arctic communities, in particular where simple economies leave a narrower range of adaptive choices (Berkes et al., 2003; Anisimov et al., 2007; Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford et al., 2010; Forbes, 2011). There is considerable evidence that changing weather patterns, declining sea ice and river as well as lake ice, thawing permafrost, and plant and animal species' abundance and composition have consequences for communities in the Arctic (see Sections 28.2.4, 28.2.5.2, and 28.3.4). Sea ice is particularly important for coastal communities that rely upon it for transportation to and from hunting areas (Krupnik et al., 2010). Changes in the duration and condition of sea ice and the consequent changes to country food availability significantly impact the well-being of communities (Furgal and Seguin, 2006; Ford and Berrang-Ford, 2009; Ford et al., 2010), outdoor tourism (Dawson et al., 2010), and hunting and fishing (*high confidence*; Wiig et al., 2008; Brander, 2010).

Adaptation to climate change is taking place at the local and regional levels where impacts are often felt most acutely and the resources most readily available (Oskal, 2008; Hovelsrud and Smit, 2010). Current experiences and projections of future conditions often lead to technological adaptation responses such as flood and water management and snow avalanche protection (Hovelsrud and Smit, 2010; West and Hovelsrud, 2010) rather than policy responses (Hedensted Lund et al., 2012; Rudberg et al., 2012). Climate variability and extreme events are found to be salient drivers of adaptation (Amundsen et al., 2010; Berrang-Ford et al., 2011; Dannevig et al., 2012).

The lack of local scale climate projections, combined with uncertainties in future economic, social, and technological developments, often act as barriers to adaptation. These barriers, together with other societal determinants such as ethics, cultures, and attitudes toward risk, may cause inaction (Adger et al., 2009; West and Hovelsrud, 2010). Resolving divergent values across and within different communities poses a challenge for governance regimes. A determining factor in building adaptive capacity is the flexibility of enabling institutions to develop robust options (Forbes et al., 2009; Keskitalo et al., 2009; Hovelsrud and Smit, 2010; Ford and Goldhar, 2012; Whyte, 2013). Refer to Table 28-2 for key climate-related risks and potential adaptation practices. In the North American and Scandinavian context, adaptive co-management responses have been developed through land claims settlements and/or multi-scale institutional cooperation to foster social learning (Armitage et al., 2008; Berkes, 2009).

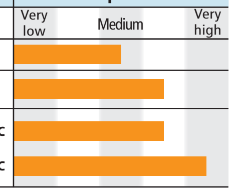
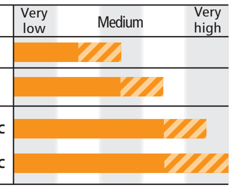
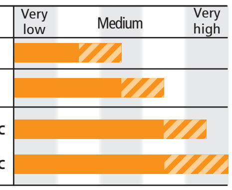
Indigenous Peoples

Although Arctic indigenous peoples with traditional lifestyles are facing unprecedented impacts to their ways of life from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they are already implementing creative ways of adapting (*high confidence*; Cruikshank, 2001; Forbes et al., 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Alexander et al., 2011; Cullen-Unsworth et al., 2011).

While many of these adaptation activities tend to be short term or reactive in nature (e.g., dealing with other issues such as disaster response planning), some Indigenous communities are beginning to develop more formal adaptation plans (Galloway-McLean, 2010; Brubaker et al., 2011b,c; Nakashima et al., 2012). Comprehensive adaptation planning must take into account underlying social issues of some Indigenous populations when addressing the new challenges from climate and development. Indigenous communities are especially vulnerable to climate change because of their strong dependence on the environment for food, culture, and way of life; their political and economic marginalization; the social, health, and poverty disparities; and community locations

Table 28-2 | Key climate-related risks in the Arctic and Antarctic, and potential adaptation practices.

Climate-related drivers of impacts			Level of risk & potential for adaptation
Warming trend	Snow cover	Ocean acidification	Potential for additional adaptation to reduce risk Risk level with **high** adaptation — Risk level with **current** adaptation

Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Risks for freshwater and terrestrial ecosystems (*high confidence*) and marine ecosystems (*medium confidence*), due to changes in ice, snow cover, permafrost, and freshwater/ocean conditions, affecting species´ habitat quality, ranges, phenology, and productivity, as well as dependent economies [28.2-4]	• Improved understanding through scientific and indigenous knowledge, producing more effective solutions and/or technological innovations • Enhanced monitoring, regulation, and warning systems that achieve safe and sustainable use of ecosystem resources • Hunting or fishing for different species, if possible, and diversifying income sources	Warming trend, Snow cover, Ocean acidification	Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Risks for the health and well-being of Arctic residents, resulting from injuries and illness from the changing physical environment, food insecurity, lack of reliable and safe drinking water, and damage to infrastructure, including infrastructure in permafrost regions (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Shifting resource bases, land use, and/or settlement areas	Warming trend, Snow cover	Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	
Unprecedented challenges for northern communities due to complex inter-linkages between climate-related hazards and societal factors, particularly if rate of change is faster than social systems can adapt (*high confidence*) [28.2-4]	• Co-production of more robust solutions that combine science and technology with indigenous knowledge • Enhanced observation, monitoring, and warning systems • Improved communications, education, and training • Adaptive co-management responses developed through the settlement of land claims	Warming trend, Snow cover	Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	

along exposed ocean, lake, or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen et al., 2010; Cochran et al., 2013).

The adaptive capacity of Arctic Indigenous peoples is largely due to an extensive traditional knowledge and cultural repertoire, and flexible social networks (*medium confidence*; Williams and Hardison, 2013; see Section 12.3). The dynamic nature of traditional knowledge is valuable for adapting to current conditions (Kitti et al., 2006; Tyler et al., 2007; Eira et al., 2012). The sharing of knowledge ensures rapid responses to crises (Ford et al., 2007). In addition, cultural values such as sharing, patience, persistence, calmness, and respect for elders and the environment are important. Some studies suggest that traditional knowledge may not always be sufficient to meet the rapid changes in climate (see Chapter 12) and it may be perceived to be less reliable because the changing conditions are beyond the current knowledge range (Ingram et al., 2002; Ford et al., 2006; Hovelsrud et al., 2010; Valdivia et al., 2010).

Over the last half-century, the adaptive capacity in some Indigenous communities has been challenged by the transition from semi-nomadic hunting groups to permanent settlements, accompanied by impacts to health and well-being from loss of connection to the land, traditional foods, and culture (Ford et al., 2010; Galloway-McLean, 2010). Forced or voluntary migration as an adaptation response can have deep cultural impacts (Shearer, 2011, 2012; Maldonado et al., 2013). On the other hand, the establishment of permanent communities, particularly those associated with new industrial development, can also lead to increasing employment opportunities and income diversification for Indigenous peoples. The intergenerational transfers of knowledge and skills through school curricula, land camps, and involvement in community-based monitoring programs may strengthen adaptive capacity (Forbes 2007; Ford et al., 2007; Hovelsrud and Smit, 2010; Bolton et al., 2011).

Examples of Indigenous adaptation strategies have included changing resource bases; shifting land use and/or settlement areas; combining technologies with traditional knowledge; changing timing and location of hunting, gathering, herding, and fishing areas; and improving communications and education (Galloway-McLean, 2010). Protection of grazing land will be the most important adaptive strategy for reindeer herders under climate change (Forbes et al., 2009; Magga et al., 2011; Kumpula et al., 2012; Degteva and Nellemann, 2013; Mathiesen et al., 2013). Renewable resource harvesting remains a significant component of Arctic livelihoods, and with climate change hunting and fishing has become a riskier undertaking and many communities are already adapting (Gearheard et al., 2011; Laidler et al., 2011). Adaptation includes taking more supplies when hunting, constructing permanent shelters on land as refuges from storms, improved communications infrastructure, greater use of global positioning systems (GPS) for navigation, synthetic aperture radar (SAR) to provide estimates of sea ice conditions (Laidler et al., 2011), and the use of larger or faster vehicles (Ford et al., 2010). Avoiding dangerous terrain can result in longer and time-consuming journeys that can be inconvenient to those with wage-earning employment (Ford et al., 2007).

Reindeer herders have developed a wide range of adaptation strategies in response to changing pasture conditions. These include moving herds to better pastures (Bartsch et al., 2010), providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009), retaining a few castrated reindeer males to break through heavy ice crust (Oskal, 2008; Reinert et al., 2008), ensuring an optimal herd size (Tyler et al., 2007;

Forbes et al., 2009), and creating multicultural initiatives combining traditional with scientific knowledge (Vuojala-Magga et al., 2011). Coastal fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud et al., 2010).

In some Arctic countries Indigenous peoples have successfully negotiated land claims rights and have become key players in addressing climate change (Abele et al., 2009). In some instances, this has given rise to tensions over land/water use between traditional livelihoods and new opportunities, for example, tourism and natural resource development (Forbes et al., 2006; Hovelsrud and Smit, 2010). Some territorial governments in northern Canada have promoted adaptation by providing hunter support programs (Ford et al., 2006, 2010).

Health of many Indigenous people is being affected by the interaction of changes in the climate with ongoing changes in human, economic, and biophysical systems (Donaldson et al., 2010). The distribution of traditional foods between communities and the use of community freezers in the Canadian Arctic has improved food security, an important factor for health (Ford et al., 2010). Although wage employment may enhance the possibilities for adaptive capacity, greater involvement in full-time jobs can threaten social and cultural cohesion and mental well-being by disrupting the traditional cycle of land-based practices (Berner et al., 2005; Furgal, 2008).

28.5. Research and Data Gaps

There remains a poor knowledge of coupling among, and thresholds within, biogeophysical and socioeconomic processes to fully assess the effects of a changing climate, and to separate them from those due to other environmental stressors:

- Existing integrative models are either lacking or insufficiently validated to project and to assess the cascading effects on, and feedbacks from, the systems in the polar regions, in particular socioeconomic systems.
- There is a need to enhance or establish a coordinated network of long-term representative sites for monitoring and assessment of climate change detection and attribution studies in the polar regions. Regional differences and confounding variables will need to be

Frequently Asked Questions

FAQ 28.1 | What will be the net socioeconomic impacts of change in the polar regions?

Climate change will have costs and benefits for polar regions. Climate change, exacerbated by other large-scale changes, can have potentially large effects on Arctic communities, where relatively simple economies leave a narrower range of adaptive choices.

In the Arctic, positive impacts include new possibilities for economic diversification, marine shipping, agricultural production, forestry, and tourism. The Northern Sea Route is predicted to have up to 125 days per year suitable for navigation by 2050, while the heating energy demand in the populated Arctic areas is predicted to decline by 15%. In addition, there could be greater accessibility to offshore mineral and energy resources although challenges related to environmental impacts and traditional livelihoods are possible.

Changing sea ice condition and permafrost thawing may cause damage to bridges, pipelines, drilling platforms, hydropower, and other infrastructure. This poses major economic costs and human risks, although these impacts are closely linked to the design of the structure. Furthermore, warmer winter temperatures will shorten the accessibility of ice roads that are critical for communications between settlements and economic development and have implications for increased costs. Statistically, a long-term mean increase of 2°C to 3°C in autumn and spring air temperature produces an approximately 10- to 15-day delay in freeze-up and advance in break-up, respectively.

Particular concerns are associated with projected increase in the frequency and severity of ice-jam floods on Siberian rivers. They may have potentially catastrophic consequences for the villages and cities located in the river plain, as exemplified by the 2001 Lena River flood, which demolished most of the buildings in the city of Lensk.

Changing sea ice conditions will impact Indigenous livelihoods, and changes in resources, including marine mammals, could represent a significant economic loss for many local communities. Food security and health and well-being are expected to be impacted negatively.

In the Antarctic, tourism is expected to increase, and risks exist of accidental pollution from maritime accidents, along with an increasing likelihood of the introduction of alien species to terrestrial environments. Fishing for Antarctic krill near the Antarctic continent is expected to become more common during winter months in areas where there is less winter sea ice.

Frequently Asked Questions

FAQ 28.2 | Why are changes in sea ice so important to the polar regions?

Sea ice is a dominant feature of polar oceans. Shifts in the distribution and extent of sea ice during the growing season impacts the duration, magnitude, and species composition of primary and secondary production in the polar regions. With less sea ice many marine ecosystems will experience more light, which can accelerate the growth of phytoplankton, and shift the balance between the primary production by ice algae and water-borne phytoplankton, with implications for Arctic food webs. In contrast, sea ice is also an important habitat for juvenile Antarctic krill, providing food and protection from predators. Krill is a basic food source for many species in polar marine ecosystems.

Changes in sea ice will have other impacts, beyond these "bottom-up" consequences for marine food webs. Mammals and birds utilize sea ice as haul-outs during foraging trips (seals, walrus, and polar bears in the Arctic and seals and penguins in the Antarctic). Some seals (e.g., bearded seals in the Arctic and crab eater and leopard seals in the Antarctic) give birth and nurse pups in pack ice. Shifts in the spatial distribution and extent of sea ice will alter the spatial overlap of predators and their prey. According to model projections, within 50 to 70 years, loss of hunting habitats may lead to elimination of polar bears from seasonally ice-covered areas, where two-thirds of their world population currently live. The vulnerability of marine species to changes in sea ice will depend on the exposure to change, which will vary by location, as well as the sensitivity of the species to changing environmental conditions and the adaptive capacity of each species. More open waters and longer ice-free periods in the northern seas enhance the effect of wave action and coastal erosion, with implications for coastal communities and infrastructure.

Although the overall sea ice extent in the Southern Ocean has not changed markedly in recent decades, there have been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc.

considered in designing field and modeling studies. Standardized methods and approaches of biophysical and socioeconomic analysis along with coordinated sampling in more regions will be necessary.

There are more specific research gaps, including:

- Many mechanisms of how climate change and ocean acidification may be affecting polar ecosystems have been proposed but few studies of physiological tolerances of species, long-term field studies of ecosystem effects, and ecosystem modeling studies are available to be able to attribute with high confidence current and future change in these ecosystems to climate change.
- More comprehensive studies including long-term monitoring on the increasing impacts from climate changes on Arctic communities (urban and rural) and their health, well-being, traditional livelihoods, and life ways are needed. There is a need to assess more fully vulnerabilities and to develop response capacities at the local and regional levels.

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29 Small Islands

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Frequently Asked Questions

Executive Summary

Current and future climate-related drivers of risk for small islands during the 21st century include sea level rise (SLR), tropical and extratropical cyclones, increasing air and sea surface temperatures, and changing rainfall patterns (*high confidence*; *robust evidence*, *high agreement*). {WGI AR5 Chapter 14; Table 29-1} Current impacts associated with these changes confirm findings reported on small islands from the Fourth Assessment Report (AR4) and previous IPCC assessments. The future risks associated with these drivers include loss of adaptive capacity {29.6.2.1, 29.6.2.3} and ecosystem services critical to lives and livelihoods in small islands. {29.3.1-3}

SLR poses one of the most widely recognized climate change threats to low-lying coastal areas on islands and atolls (*high confidence*; *robust evidence*, *high agreement*). {29.3.1} It is *virtually certain* that global mean SLR rates are accelerating. {WGI AR5 13.2.2.1} Projected increases to the year 2100 (RCP4.5: 0.35 m to 0.70 m) {WGI AR5 13.5.1; Table 29-1} superimposed on extreme sea level events (e.g., swell waves, storm surges, El Niño-Southern Oscillation) present severe sea flood and erosion risks for low-lying coastal areas and atoll islands (*high confidence*). Likewise, there is *high confidence* that wave over-wash of seawater will degrade fresh groundwater resources {29.3.2} and that sea surface temperature rise will result in increased coral bleaching and reef degradation. {29.3.1.2} Given the dependence of island communities on coral reef ecosystems for a range of services including coastal protection, subsistence fisheries, and tourism, there is *high confidence* that coral reef ecosystem degradation will negatively impact island communities and livelihoods.

Given the inherent physical characteristics of small islands, the AR5 reconfirms the high level of vulnerability of small islands to multiple stressors, both climate and non-climate (*high confidence*; *robust evidence*, *high agreement*). However, the distinction between observed and projected impacts of climate change is often not clear in the literature on small islands (*high agreement*). {29.3} There is evidence that this challenge can be partly overcome through improvements in baseline monitoring of island systems and downscaling of climate-model projections, which would heighten confidence in assessing recent and projected impacts. {WGI AR5 9.6; 29.3-4, 29.9}

Small islands do not have uniform climate change risk profiles (*high confidence*). Rather, their high diversity in both physical and human attributes and their response to climate-related drivers means that climate change impacts, vulnerability, and adaptation will be variable from one island region to another and between countries in the same region. {Figure 29-1; Table 29-3} In the past, this diversity in potential response has not always been adequately integrated in adaptation planning.

There is increasing recognition of the risks to small islands from climate-related processes originating well beyond the borders of an individual nation or island. Such transboundary processes already have a negative impact on small islands (*high confidence*; *robust evidence*, *medium agreement*). These include air-borne dust from the Sahara and Asia, distant-source ocean swells from mid to high latitudes, invasive plant and animal species, and the spread of aquatic pathogens. For island communities the risks associated with existing and future invasive species and human health challenges are projected to increase in a changing climate. {29.5.4}

Adaptation to climate change generates larger benefit to small islands when delivered in conjunction with other development activities, such as disaster risk reduction and community-based approaches to development (*medium confidence*). {29.6.4} Addressing the critical social, economic, and environmental issues of the day, raising awareness, and communicating future risks to local communities {29.6.3} will *likely* increase human and environmental resilience to the longer term impacts of climate change. {29.6.1, 29.6.2.3; Figure 29-5}

Adaptation and mitigation on small islands are not always trade-offs, but can be regarded as complementary components in the response to climate change (*medium confidence*). Examples of adaptation-mitigation interlinkages in small islands include energy supply and use, tourism infrastructure and activities, and functions and services associated with coastal wetlands. The alignment of these sectors for potential emission reductions, together with adaptation, offer co-benefits and opportunities in some small islands. {29.7.2, 29.8} Lessons learned from adaptation and mitigation experiences in one island may offer some guidance to other small island states, though there is *low confidence* in the success of wholesale transfer of adaptation and mitigation options when the local lenses through which they are viewed differ from one island state to the next, given the diverse cultural, socioeconomic, ecological, and political values. {29.6.2, 29.8}

The ability of small islands to undertake adaptation and mitigation programs, and their effectiveness, can be substantially strengthened through appropriate assistance from the international community (*medium confidence*). However, caution is needed to ensure such assistance is not driving the climate change agenda in small islands, as there is a risk that critical challenges confronting island governments and communities may not be addressed. Opportunities for effective adaptation can be found by, for example, empowering communities and optimizing the benefits of local practices that have proven to be efficacious through time, and working synergistically to progress development agendas. {29.6.2.3, 29.6.3, 29.8}

29.1. Introduction

It has long been recognized that greenhouse gas (GHG) emissions from small islands are negligible in relation to global emissions, but that the threats of climate change and sea level rise (SLR) to small islands are very real. Indeed, it has been suggested that the very existence of some atoll nations is threatened by rising sea levels associated with global warming. Although such scenarios are not applicable to all small island nations, there is no doubt that on the whole the impacts of climate change on small islands will have serious negative effects especially on socioeconomic conditions and biophysical resources—although impacts may be reduced through effective adaptation measures.

The small islands considered in this chapter are principally sovereign states and territories located within the tropics of the southern and western Pacific Ocean, central and western Indian Ocean, the Caribbean Sea, and the eastern Atlantic off the coast of West Africa, as well as in the more temperate Mediterranean Sea.

Although these small islands nations are by no means homogeneous politically, socially, or culturally, or in terms of physical size and character or economic development, there has been a tendency to generalize about the potential impacts on small islands and their adaptive capacity. In this chapter we attempt to strike a balance between identifying the differences between small islands and at the same time recognizing that small islands tend to share a number of common characteristics that have distinguished them as a particular group in international affairs. Also in this chapter we reiterate some of the frequently voiced and key concerns relating to climate change impacts, vulnerability, and adaptation while emphasizing a number of additional themes that have emerged in the literature on small islands since the IPCC Fourth Assessment Report (AR4). These include the relationship among climate change policy, activities, and development issues; externally generated transboundary impacts; and the implications of risk in relation to adaptation and the adaptive capacity of small island nations.

29.2. Major Conclusions from Previous Assessments

Small islands were not given a separate chapter in the IPCC First Assessment Report (FAR) in 1990 though they were discussed in the chapter on "World Oceans and Coastal Zones" (Tsyban et al., 1990). Two points were highlighted. First, a 30- to 50-cm SLR projected by 2050 would threaten low islands, and a 1-m rise by 2100 "would render some island countries uninhabitable" (Tegart et al., 1990, p. 4). Second, the costs of protection works to combat SLR would be extremely high for small island nations. Indeed, as a percentage of gross domestic product (GDP), the Maldives, Kiribati, Tuvalu, Tokelau, Anguilla, Turks and Caicos, Marshall Islands, and Seychelles were ranked among the 10 nations with the highest protection costs in relation to GDP (Tsyban et al., 1990). More than 20 years later these two points continue to be emphasized. For instance, although small islands represent only a fraction of total global damage projected to occur as a result of a SLR of 1.0 m by 2100 (*Special Report on Emission Scenarios* (SRES) A1 scenario) the actual damage costs for the small island states is enormous in relation to the size of their economies, with several small island nations being included in the group of 10 countries with the highest relative impact projected for 2100 (Anthoff et al., 2010).

The Second Assessment Report (SAR) in 1995 confirmed the vulnerable state of small islands, now included in a specific chapter titled "Coastal Zones and Small Islands" (Bijlsma et al., 1996). However, importantly, the SAR recognized that both vulnerability and impacts would be highly variable between small islands and that impacts were "likely to be greatest where local environments are already under stress as a result of human activities" (Bijlsma et al., 1996, p. 291). The report also summarized results from the application of a common methodology for vulnerability and adaptation analysis that gave new insights into the socioeconomic implications of SLR for small islands including: negative impacts on virtually all sectors including tourism, freshwater resources, fisheries and agriculture, human settlements, financial services, and human health; protection is likely to be very costly; and adaptation would involve a series of trade-offs. It also noted that major constraints to adaptation on small islands included lack of technology and human resource capacity, serious financial limitations, lack of cultural and social acceptability, and uncertain political and legal frameworks. Integrated coastal and island management was seen as a way of overcoming some of these constraints.

The Third Assessment Report (TAR) in 2001 included a specific chapter on "Small Island States." In confirming previously identified concerns of small island states two factors were highlighted, the first relating to sustainability, noting that "with limited resources and low adaptive capacity, these islands face the considerable challenge of meeting the social and economic needs of their populations in a manner that is sustainable" (Nurse et al., 2001, p. 845). The second noted that there were other issues faced by small island states, concluding that "for most small islands the reality of climate change is just one of many serious challenges with which they are confronted" (Nurse et al., 2001, p. 846). In the present chapter, both of these themes are raised again and assessed in light of recent findings.

Until the AR4 in 2007, SLR had dominated vulnerability and impact studies of small island states. Whilst a broader range of climate change drivers and geographical spread of islands was included in the "Small Islands" chapter, Mimura et al. (2007) prefaced their assessment by noting that the number of "independent scientific studies on climate change and small islands since the TAR" had been quite limited and in their view "the volume of literature in refereed international journals relating to small islands and climate change since publication of the TAR is rather less than that between the SAR in 1995 and TAR in 2001" (Mimura et al., 2007, p. 690).

Since AR4, the literature on small islands and climate change has increased substantially. A number of features distinguish the literature we review here from that included in earlier assessments. First, the literature appears more sophisticated and does not shirk from dealing with the complexity of small island vulnerability, impacts, and adaptation or the differences between islands and island states. Second, and related to the first, the literature is less one-dimensional, and deals with climate change in a multidimensional manner as just one of several stressors on small island nations. Third, the literature also critiques some aspects of climate change policy, notably in relation to critical present-day development and security needs of small islands (Section 29.3.3.1) as well as the possibility that some proposed adaptation measures may prove to be maladaptive (Section 29.8). Fourth, many initiatives have been identified in recent times that will reduce vulnerability and enhance resilience of small islands to ongoing global change including improving risk knowledge and island resource management while also strengthening socioeconomic systems and livelihoods (Hay, 2013).

29.3. Observed Impacts of Climate Change, Including Detection and Attribution

The distinction between observed impacts of climate change and projected impacts is often unclear in the small islands literature and discussions. Publications frequently deal with both aspects of impacts interchangeably, and use observed impacts from, for instance an extreme event, as an analogy to what may happen in the future as a result of climate change (e.g., Lo-Yat et al., 2011). The key climate and ocean drivers of change that impact small islands include variations in air and ocean temperatures; ocean chemistry; rainfall; wind strength and direction; sea levels and wave climate; and particularly the extremes such as tropical cyclones, drought, and distant storm swell events. All have varying impacts, dependent on the magnitude, frequency, and temporal and spatial extent of the event, as well as on the biophysical nature of the island (Figure 29-1) and its social, economic, and political setting.

29.3.1. Observed Impacts on Island Coasts and Marine Biophysical Systems

29.3.1.1. Sea Level Rise, Inundation, and Shoreline Change

SLR poses one of the most widely recognized climate change threats to low-lying coastal areas (Cazenave and Llovel, 2010; Nicholls and Cazenave, 2010; Church and White, 2011). This is particularly important in small islands where the majority of human communities and infrastructure is located in coastal zones with limited on-island relocation opportunities, especially on atoll islands (Woodroffe, 2008) (Figure 29-1). Over much of the 20th century, global mean sea level rose at a rate between 1.3 and 1.7 mm yr^{-1} and since 1993, at a rate between 2.8 and 3.6 mm yr^{-1} (WGI AR5 Table 13.1), and acceleration is detected in longer records since 1870 (Merrifield et al., 2009; Church and White, 2011; see also WGI AR5 Section 13.2.2.1). Rates of SLR, however, are not uniform across the globe and large regional differences have been detected including in the Indian Ocean and tropical Pacific, where in some parts rates have been significantly higher than the global average (Meyssignac et al., 2012; see also Section 5.3.2.2). In the tropical western Pacific, where a large number of small island communities exist, rates up to four times the global average (approximately 12 mm yr^{-1}) have been reported between 1993 and 2009. These are generally thought to describe short-term variations associated with natural cyclic climate phenomena such as El Niño-Southern Oscillation (ENSO), which has a strong modulating effect on sea level variability with lower/higher-than-average sea level during El Niño/La Niña events of the order of ±20 to 30 cm (Cazenave and Remy, 2011; Becker et al., 2012). Large interannual variability in sea level has also been demonstrated from the Indian Ocean (e.g., Chagos Archipelago; Dunne et al., 2012) while Palanisamy et al. (2012) found that over the last 60 years the mean rate of SLR in the Caribbean region was similar to the global average of approximately 1.8 mm yr^{-1}.

There are few long-term sea level records available for individual small island locations. Reported sea flooding and inundation is often associated with transient phenomena, such as storm waves and surges, deep ocean swell, and predicted astronomical tidal cycles (Vassie et al., 2004; Zahibo et al., 2007; Komar and Allan, 2008; Haigh et al., 2011). For example, high spring tide floods at Fongafale Island, Funafuti Atoll, Tuvalu, have been well publicized, and areas of the central portion of Fongafale are

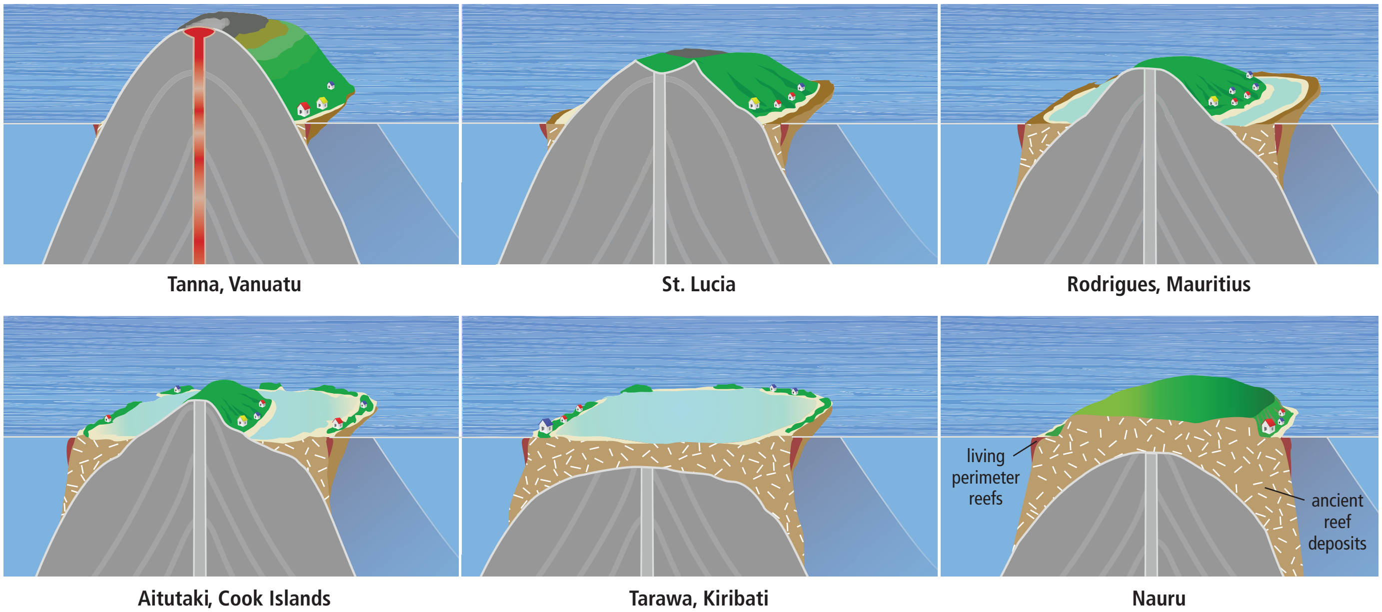

Figure 29-1 | Representative tropical island typologies. From top left: A young, active volcanic island (with altitudinal zonation) and limited living perimeter reefs (red zone at outer reef edge), through to an atoll (center bottom), and raised limestone island (bottom right) dominated by ancient reef deposits (brown + white fleck). Atolls have limited, low-lying land areas but well developed reef/lagoon systems. Islands composed of continental rocks are not included in this figure, but see Table 29-3.

Frequently Asked Questions

FAQ 29.1 | Why is it difficult to detect and attribute changes on small islands to climate change?

In the last 2 or 3 decades many small islands have undergone substantial changes in human settlement patterns and in socioeconomic and environmental conditions. Those changes may have masked any clear evidence of the effects of climate change. For example, on many small islands coastal erosion has been widespread and has adversely affected important tourist facilities, settlements, utilities, and infrastructure. But specific case studies from islands in the Pacific, Indian, and Atlantic Oceans and the Caribbean have shown that human impacts play an important role in this erosion, as do episodic extreme events that have long been part of the natural cycle of events affecting small islands. So although coastal erosion is consistent with models of sea level rise resulting from climate change, determining just how much of this erosion might have been caused by climate change impacts is difficult. Given the range of natural processes and human activities that could impact the coasts of small islands in the future, without more and better empirical monitoring the role of climate change-related processes on small islands may continue to be difficult to identify and quantify.

already below high spring tide level. However, rates of relative SLR at Funafuti between 1950 and 2009 have been approximately three times higher than the global average (Becker et al., 2012), and saline flooding of internal low-lying areas occurs regularly and is expected to become more frequent and extensive over time (Yamano et al., 2007).

Documented cases of coastal inundation and erosion often cite additional circumstances such as vertical subsidence, engineering works, development activities, or beach mining as the causal process. Four examples can be cited. First, on the Torres Islands, Vanuatu communities have been displaced as a result of increasing inundation of low-lying settlement areas owing to a combination of tectonic subsidence and SLR (Ballu et al., 2011). Second, on Anjouan Island, Comores in the Indian Ocean, Sinane et al. (2010) found beach aggregate mining was a major contributing factor influencing rapid beach erosion. Third, the intrinsic exposure of rapidly expanding settlements and agriculture in the low-lying flood prone Rewa Delta, Fiji, is shown by Lata and Nunn (2012) to place populations in increasingly severe conditions of vulnerability to flooding and marine inundation. Fourth, Hoeke et al. (2013) describe a 2008 widespread inundation event that displaced some 63,000 people in Papua New Guinea and Solomon Islands alone. That event was caused primarily by remotely generated swell waves, and the severity of flooding was greatly increased by anomalously high regional sea levels linked with ENSO and ongoing SLR. Such examples serve to highlight that extreme events superimposed on a rising sea level baseline are the main drivers that threaten the habitability of low-lying islands as sea levels continue to rise.

Since the AR4 a number of empirical studies have documented historical changes in island shorelines. Historical shoreline position change over 20 to 60 years on 27 central Pacific atoll islands showed that total land area remained relatively stable in 43% of islands, while another 43% had increased in area, and the rest showed a net reduction in land area (Webb and Kench, 2010). Dynamic responses were also found in a 4-year study of 17 relatively pristine islands on two other central Pacific atolls in Kiribati by Rankey (2011), who concluded that SLR was not likely to be the main influencing factor in these shoreline changes. Similarly in French Polynesia, Yates et al. (2013) showed mixed shoreline change patterns over the last 40 to 50 years with examples of both erosion and accretion in the 47 atoll islands assessed. SLR did not appear to be the primary control on shoreline processes on these islands. On uninhabited Raine Island on the Great Barrier Reef, Dawson and Smithers (2010) also found that shoreline processes were dynamic but that island area and volume increased 6 and 4%, respectively, between 1967 and 2007. Overall, these studies of observed shoreline change on reef islands conclude that for rates of change experienced over recent decades, normal seasonal erosion and accretion processes appear to predominate over any long-term morphological trend or signal at this time. Ford's (2013) investigation of Wotje Atoll, Marshall Islands, also found shoreline variability between 1945 and 2010 but that overall accretion had been more prevalent than erosion up until 2004. From 2004 to the present, 17 out of 18 islands became net erosive, potentially corresponding to the high sea levels in the region over the last 10 years. On the high tropical islands of Kauai and Maui, Hawaii, Romine and Fletcher (2013) found shoreline change was highly variable over the last century but that recently chronic erosion predominated with over 70% of beaches now being erosive. Finally, it is important to note the majority of these studies warn that (1) past changes cannot be simply extrapolated to determine future shoreline responses; and (2) rising sea level will incrementally increase the rate and extent of erosion in the future.

In many locations changing patterns of human settlement and direct impacts on shoreline processes present immediate erosion challenges in populated islands and coastal zones (Yamano et al., 2007; Novelo-Casanova and Suarez, 2010; Storey and Hunter, 2010) and mask attribution to SLR. A study of Majuro atoll (Marshall Islands) found that erosion was widespread but attribution to SLR was obscured by pervasive anthropogenic impacts to the coastal system (Ford, 2012; see Section 5.4.4). Similarly a study of three islands in the Rosario Archipelago (Colombia) reported shoreline retreat over a 50- to 55-year period and found Grande, Rosario, and Tesoro Islands had lost 6.7, 8.2, and 48.7% of their land area, respectively. Erosion was largely attributed to poor management on densely settled Grande Island, while SLR and persistent northeast winds enhanced erosion on uninhabited Rosario and Tesoro (Restrepo et al., 2012). Likewise, Cambers (2009) reported average beach erosion rates of 0.5 m yr^{-1} in eight Caribbean islands from 1985 to 2000. Although the study could not quantify the extent of attribution it noted that greater erosion rates were positively correlated with the number of hurricane events. Alternately, Etienne and Terry (2012) found a Category 4 tropical cyclone that passed within 30 km of Taveuni Island (Fiji) nourished shorelines with fresh coralline sediments despite localized storm damage. Although these studies contribute to improved understanding of island shoreline processes and change since AR4, the warning of increased vulnerability of small island shores and low-lying areas to inundation and erosion in response to SLR and other potential climate change stressors is not diminished.

29.3.1.2. Coastal Ecosystem Change on Small Islands: Coral Reefs and Coastal Wetlands

Coral reefs are an important resource in small tropical islands, and the well-being of many island communities is linked to their ongoing function and productivity. Reefs play a significant role in supplying sediment to island shores and in dissipating wave energy, thus reducing the potential foreshore erosion. They also provide habitat for a host of marine species on which many island communities are dependent for subsistence foods as well as underpinning beach and reef-based tourism and economic activity (Perch-Nielsen, 2010; Bell et al., 2011). The documented sensitivity of coral reef ecosystems to climate change is summarized elsewhere (see Chapter 5; Box CC-CR).

Increased coral bleaching and reduced reef calcification rates due to thermal stress and increasing carbon dioxide (CO_2) concentration are expected to affect the functioning and viability of living reef systems (Hoegh-Guldberg et al., 2007; Eakin et al., 2009). Some studies already implicate thermal stress in reduced coral calcification rates (Tanzil et al., 2009) and regional declines in calcification of corals that form reef framework (De'ath et al., 2009; Cantin et al., 2010). Unprecedented bleaching events have been recorded in the remote Phoenix Islands (Kiribati), with nearly 100% coral mortality in the lagoon and 62% mortality on the outer leeward slopes of the otherwise pristine reefs of Kanton Atoll during 2002–2003 (Alling et al., 2007). Similar patterns of mortality were observed in four other atolls in the Phoenix group and temperature-induced coral bleaching was also recorded in isolated Palmyra Atoll during the 2009 ENSO event (Williams et al., 2010). In 2005 extensive bleaching was recorded at 22 sites around Rodrigues Island in the western Indian Ocean, with up to 75% of the dominant species affected in some areas (Hardman et al., 2007). Studies of the severe 1998 El Niño bleaching event in the tropical Indian Ocean showed reefs in the Maldives, Seychelles, and Chagos Islands were among the most impacted (Cinner et al., 2012; Tkachenko, 2012). In 2005 a reef survey around Barbados following a Caribbean regional bleaching event revealed the most severe bleaching ever recorded, with approximately 70% of corals impacted (Oxenford et al., 2008). Globally, the incidence and implications of temperature-related coral bleaching in small islands is well documented, and combined with the effects of increasing ocean acidification these stressors could threaten the function and persistence of island coral reef ecosystems (see Chapter 5; Box CC-OA).

Island coral reefs have limited defenses against thermal stress and acidification. However, studies such as Cinner et al. (2012) and Tkachenko (2012) highlight that although recovery from bleaching is variable, some reefs show greater resilience than others. There is also some evidence to show that coral reef resilience is enhanced in the absence of other environmental stresses such as declining water quality. In Belize chronologies of growth rates in massive corals (*Montastraea faveolata*) over the past 75 to 150 years suggest that the bleaching event in 1998 was unprecedented and its severity appeared to stem from reduced thermal tolerance related to human coastal development (Carilli et al., 2010). Likewise a study over a 40-year period (1960s–2008) in the Grand Recif of Tulear, Madagascar, concluded that severe degradation of the reef was mostly ascribed to direct anthropogenic disturbance, despite an average 1°C increase in temperature over this period (Harris et al., 2010). Coral recovery following the 2004 bleaching event in the central Pacific atolls of Tarawa and Abaiang (Kiribati) was also noted to be improved in the absence of direct human impacts (Donner et al., 2010), and isolation of bleached reefs was shown by Gilmour et al. (2013) to be less inhibiting to reef recovery than direct human disturbance.

The loss of coral reef habitat has detrimental implications for coastal fisheries (Pratchett et al., 2009) in small islands where reef-based subsistence and tourism activities are often critical to the well-being and economies of islands (Bell et al., 2011). In Kimbe Bay, Papua New Guinea, 65% of coastal fish are dependent on living reefs at some stage in their life cycle and there is evidence that fish abundance declined following degradation of the reef (Jones et al., 2004). Even where coral reef recovery has followed bleaching, reef-associated species composition may not recover to its original state (Pratchett et al., 2009; Donner et al., 2010). Sea surface temperature (SST) anomaly events can be associated with a lag in the larval supply of coral reef fishes, as reported by Lo-Yat et al. (2011) between 1996 and 2000 at Rangiroa Atoll, French Polynesia. Higher temperatures have also been implicated in negatively affecting the spawning of adult reef species (Munday et al., 2009; Donelson et al., 2010).

Like coral reefs, mangroves and seagrass environments provide a range of ecosystem goods and services (Waycott et al., 2009; Polidoro et al., 2010) and both habitats play a significant role in the well-being of small island communities. Mangroves in particular serve a host of commercial and subsistence uses as well as providing natural coastal protection from erosion and storm events (Ellison, 2009; Krauss et al., 2010; Waycott et al., 2011).

SLR is reported as the most significant climate change threat to the survival of mangroves (Waycott et al., 2011). Loss of the seaward edge of mangroves at Hungry Bay, Bermuda, has been reported by Ellison (1993), who attributes this process to SLR and the inability of mangroves to tolerate increased water depth at the seaward margin. Elsewhere in the Caribbean and tropical Pacific, observations vary in regard to the potential for sedimentation rates in mangroves forests to keep pace with SLR (Krauss et al., 2003; McKee et al., 2007). In Kosrae and Pohnpei Islands (Federated States of Micronesia), Krauss et al. (2010) found significant variability in mangrove average soil elevation changes due to deposition from an accretion deficit of 4.95 mm yr^{-1} to an accretion surplus of 3.28 mm yr^{-1} relative to the estimated rate of SLR. Such surpluses are generally reported from high islands where additional sediments can be delivered from terrestrial runoff. However, Rankey (2011) described natural seaward migration (up to 40 m) of some mangrove areas between 1969 and 2009 in atolls in Kiribati, suggesting sediment accretion can also occur in sediment-rich reefal areas and in the absence of terrigenous inputs.

The response of seagrass to climate change is also complex, regionally variable, and manifest in quite different ways. A study of seven species of seagrasses from tropical Green Island, Australia, highlighted the variability in response to heat and light stress (Campbell et al., 2006). Light reduction may be a limiting factor to seagrass growth due to increased water depth and sedimentation (Ralph et al., 2007). Ogston and Field (2010) observed that a 20-cm rise in sea level may double the suspended sediment loads and turbidity in shallow waters on fringing reefs of Molokai, Hawaiian Islands, with negative implications to photosynthetic species such as seagrass. Otherwise, temperature stress is most commonly reported as the main expected climate change impact on seagrass (e.g., Campbell et al., 2006; Waycott et al., 2011). Literature on seagrass diebacks in small islands is scarce but research in the Balearic Islands (Western Mediterranean) has shown that over a 6-year study, seagrass shoot mortality and recruitment rates were negatively influenced by higher temperature (Marbá and Duarte, 2010; see also Section 5.4.2.3 for further discussion of impacts on mangrove and seagrass communities).

29.3.2. Observed Impacts on Terrestrial Systems: Island Biodiversity and Water Resources

Climate change impacts on terrestrial biodiversity on islands, frequently interacting with several other drivers (Blackburn et al., 2004; Didham et al., 2005), fall into three general categories, namely: (1) ecosystem and species horizontal shifts and range decline; (2) altitudinal species range shifts and decline mainly due to temperature increase on high islands; and (3) exotic and pest species range increase and invasions mainly due to temperature increase in high-latitude islands. Owing to the limited area and isolated nature of most islands, these effects are generally magnified compared to continental areas and may cause species loss, especially in tropical islands with high numbers of endemic species. For example, in two low-lying islands in the Bahamas, Greaver and Sternberg (2010) found that during periods of reduced rainfall the shallow freshwater lens subsides and contracts landward and ocean water infiltrates further inland, negatively impacting on coastal strand vegetation. SLR has also been observed to threaten the long-term persistence of freshwater-dependent ecosystems within low-lying islands in the Florida Keys (Goodman et al., 2012). On Sugarloaf Key, Ross et al. (2009) found pine forest area declined from 88 to 30 ha from 1935 to 1991 due to increasing salinization and rising groundwater, with vegetation transitioning to more saline-tolerant species such as mangroves.

Although there are many studies that report observations associated with temperature increases in mid- and high-latitude islands, such as the Falkland Islands and Marion Islands in the south Atlantic and south Indian Ocean respectively (Le Roux et al., 2005; Bokhorst et al., 2007, 2008) and Svalbard in the Arctic (Webb et al., 1998), there are few equivalent studies in tropical small islands. A recent study of the tropical Mauritius kestrel indicates changing rainfall conditions in Mauritius over the last 50 years have resulted in this species having reduced reproductive success due to a mismatch between the timing of breeding and peak food abundance (Senapathi et al., 2011).

Increasing global temperatures may also lead to altitudinal species range shifts and contractions within high islands, with an upward creep of the tree line and associated fauna (Benning et al., 2002; Krushelnycky et al., 2013). For instance, in the central mountain ranges of the subtropical island of Taiwan, Province of China, historical survey and resurvey data from 1906 to 2006 showed that the upper altitudinal limits of plant distributions had risen by about 3.6 m yr^{-1} during the last century in parallel with rising temperatures in the region (Jump et al., 2012). Comparable effects also occur in the tropics such as in Hawaii Volcano National Park, where comparison of sample plots over a 40-year period from 1966/1967 to 2008 show fire-adapted grasses expanded upward along a warming tropical elevation gradient (Angelo and Daehler, 2013). Reduction in the numbers and sizes of endemic populations caused by such habitat constriction and changes in species composition in mountain systems may result in the demise and possibly extinction of endemic species (Pauli et al., 2007; Chen et al., 2009; Sekercioglu et al., 2008; Krushelnycky et al., 2013). Altitudinal temperature change has also been reported to influence the distribution of disease vectors such as mosquitoes, potentially threatening biota unaccustomed to such vectors (Freed et al., 2005; Atkinson and LaPointe, 2009).

Freshwater supply in small island environments has always presented challenges and has been an issue raised in all previous IPCC reports. On high volcanic and granitic islands, small and steep river catchments respond rapidly to rainfall events, and watersheds generally have restricted storage capacity. On porous limestone and low atoll islands, surface runoff is minimal and water rapidly passes through the substrate into the groundwater lens. Rainwater harvesting is also an important contribution to freshwater access, and alternatives such as desalination have had mixed success in small island settings owing to operational costs (White and Falkland, 2010).

Rapidly growing demand, land use change, urbanization, and tourism are already placing significant strain on the limited freshwater reserves in small island environments (Emmanuel and Spence, 2009; Cashman et al., 2010; White and Falkland, 2010). In the Caribbean, where there is considerable variation in the types of freshwater supplies utilized, concern over the status of freshwater availability has been expressed for at least the past 30 years (Cashman et al., 2010). There have also been economic and management failures in the water sector not only in the Caribbean (Mycoo, 2007) but also in small islands in the Indian (Payet and Agricole, 2006) and Pacific Oceans (White et al., 2007; Moglia et al., 2008a,b).

These issues also occur on a background of decreasing rainfall and increasing temperature. Rainfall records averaged over the Caribbean region for 100 years (1900–2000) show a consistent 0.18 mm yr^{-1} reduction in rainfall, a trend that is projected to continue (Jury and Winter, 2010). In contrast, analysis of rainfall data over the past 100 years from the Seychelles has shown substantial variability related to ENSO. Nevertheless an increase in average rainfall from 1959 to 1997 and an increase in temperature of approximately 0.25°C per decade have occurred (Payet and Agricole, 2006). Long-term reduction in streamflow (median reduction of 22 to 23%) has been detected in the Hawaiian Islands over the period 1913–2008, resulting in reduced freshwater availability for both human use and ecological processes (Bassiouni and Oki, 2013). Detection of long-term statistical change in precipitation is an important prerequisite toward a better understanding the impacts of climate change in small island hydrology and water resources.

There is a paucity of empirical evidence linking saline (seawater) intrusion into fresh groundwater reserves due simply to incremental SLR at this time (e.g., Rozell and Wong, 2010). However, this dynamic must be the subject of improved research given the importance of groundwater aquifers in small island environments. White and Falkland's (2010) review of existing small island studies indicates that a sea level increase of up to 1 m would have negligible salinity impacts on atoll island groundwater lenses so long as there is adequate vertical accommodation space, island shores remain intact, rainfall patterns do not change, and direct human impacts are managed. However, wave overtopping and wash-over can be expected to become more frequent with SLR, and this has been shown to impact freshwater lenses dramatically. On Pukapuka Atoll, Cook Islands, storm surge over-wash occurred in 2005. This caused the freshwater lenses to become immediately brackish and took 11 months to recover to conductivity levels appropriate for human use (Terry and Falkland, 2010). The ability of the freshwater lens to float upward within the substrate of an island in step with incremental SLR also means that in low-lying and central areas of many atoll islands the lens may pond at the surface. This phenomenon already occurs in central areas of Fongafale Island, Tuvalu, and during extreme high "king" tides large areas of the inner part of the island become inundated with brackish waters (Yamano et al., 2007; Locke, 2009).

29.3.3. Observed Impacts on Human Systems in Small Islands

29.3.3.1. Observed Impacts on Island Settlements and Tourism

While traditional settlements on high islands in the Pacific were often located inland, the move to coastal locations was encouraged by colonial and religious authorities and more recently through the development of tourism (Barnett and Campbell, 2010). Now the majority of settlement, infrastructure, and development are located on lowlands along the coastal fringe of small islands. In the case of atoll islands, all development and settlement is essentially coastal. It follows that populations, infrastructure, agricultural areas, and fresh groundwater supplies are all vulnerable to extreme tides, wave and surge events, and SLR (Walsh et al., 2012). Population drift from outer islands or from inland, together with rapid population growth in main centers and lack of accommodation space, drives growing populations into ever more vulnerable locations (Connell, 2012). In addition, without adequate resources and planning, engineering solutions such as shoreline reclamation also place communities and infrastructure in positions of increased risk (Yamano et al., 2007; Duvat, 2013).

Many of the environmental issues raised by the media relating to Tuvalu, the Marshall Islands, and Maldives are primarily relevant to the major population center and its surrounds, which are Funafuti, Majuro, and Male, respectively. As an example, Storey and Hunter (2010) indicate the "Kiribati" problem does not refer to the whole of Kiribati but rather to the southern part of Tarawa atoll, where preexisting issues of severe overcrowding, proliferation of informal housing and unplanned settlement, inadequate water supply, poor sanitation and solid waste disposal, pollution, and conflict over land ownership are of concern. They argue that these problems require immediate resolution if the vulnerability of the South Tarawa community to the "real and alarming threat" of climate change is to be managed effectively (Storey and Hunter, 2010).

On Majuro atoll, rapid urban development and the abandonment of traditional settlement patterns has resulted in movement from less vulnerable to more vulnerable locations on the island (Spennemann, 1996). Likewise, geophysical studies of Fongafale Island, the capital of Tuvalu, show that engineering works during World War II, and rapid development and population growth since independence, have led to the settlement of inappropriate shoreline and swampland areas, leaving communities in heightened conditions of vulnerability (e.g., Yamano et al., 2007). Ascribing direct climate change impacts in such disturbed environments is problematic owing to the existing multiple lines of stress on the island's biophysical and social systems. However, it is clear that such preexisting conditions of vulnerability add to the threat of climate change in such locations. Increased risk can also result from lack of awareness, particularly in communities in rural areas and outer islands ("periphery") of archipelagic countries such as Cook Islands, Fiji, Kiribati, and Vanuatu, whose climate change knowledge often contrasts sharply with that of communities in the major centers ("core"). In the core, communities tend to be better informed and have higher levels of awareness about the complex issues associated with climate change than in the periphery (Nunn et al., 2013).

The issue of "coastal squeeze" remains a concern for many small islands as there is a constant struggle to manage the requirements for physical development against the need to maintain ecological balance (Fish et al., 2008; Gero et al., 2011; Mycoo, 2011). Martinique in the Caribbean exemplifies the point, where physical infrastructure prevents the beach and wetlands from retreating landward as a spontaneous adaptation response to increased rates of coastal erosion (Schleupner, 2008). Moreover, intensive coastal development in the limited coastal zone, combined with population growth and tourism, has placed great stress on the coast of some islands and has resulted in dense aggregations of infrastructure and people in potentially vulnerable locations.

Tourism is an important weather and climate-sensitive sector on many small islands and has been assessed on several occasions, including in previous IPCC assessments. There is currently no evidence that observed climatic changes in small island destinations or source markets have permanently altered patterns of demand for tourism to small islands, and the complex mix of factors that actually determines destination choices under a changing climate still need to be fully evaluated (Scott et al., 2012a). However, there are cases reported that clearly show severe weather-related events in a destination country (e.g., heavy, persistent rainfall in Martinique: Hubner and Gössling, 2012; hurricanes in Anguilla: Forster et al., 2012) can significantly influence visitors' perception of the desirability of the location as a vacation choice.

Climate can also impact directly on environmental resources that are major tourism attractions in small islands. Widespread resource degradation challenges such as beach erosion and coral bleaching have been found to negatively impact the perception of destination attractiveness in various locations, for example, in Martinique (Schleupner, 2008), Barbados, and Bonaire (Uyarra et al., 2005). Similarly, dive tourists are well aware of coral bleaching, particularly the experienced diver segment (Gössling et al., 2012a; Klint et al., 2012). Therefore more acute impacts are felt by tourism operators and resorts that cater to these markets. Houston (2002) and Buzinde et al. (2010) also indicate that beach erosion may similarly affect accommodation prices in some destinations. Consequently, some countries have begun to invest in a variety of resource restoration initiatives including artificial beach nourishment, coral and mangrove restoration, and the establishment of marine parks and protected areas (McClanahan et al., 2008; Mycoo and Chadwick, 2012). There is no analysis of how widespread such investments are or their capability to cope effectively with future climate change. The tourism industry and investors are also beginning to consider the climate risk of tourism operations (Scott et al., 2012b), including those associated with the availability of freshwater. Freshwater is limited on many small islands, and changes in its availability or quality during drought events linked to climate change have adverse impacts on tourism operations (UNWTO, 2012). Tourism is a seasonally significant water user in many island destinations, and in times of drought concerns over limited supply for residents and other economic activities become heightened (Gössling et al., 2012b). The increasing use of desalination plants is one adaptation to reduce the risk of water scarcity in tourism operations.

29.3.3.2. Observed Impacts on Human Health

Globally, the effects of climate change on human health will be both direct and indirect, and are expected to exacerbate existing health risks, especially in the most vulnerable communities, where the burden of disease is already high (refer to Sections 11.3, 11.5, 11.6.1). Many small island states currently suffer from climate-sensitive health problems, including morbidity and mortality from extreme weather events, certain vector- and food- and water-borne diseases (Lozano, 2006; Barnett and Campbell, 2010; Cashman et al., 2010; Pulwarty et al., 2010; McMichael and Lindgren, 2011). Extreme weather and climate events such as tropical cyclones, storm surges, flooding, and drought can have both short- and long-term effects on human health, including drowning, injuries, increased disease transmission, and health problems associated with deterioration of water quality and quantity. Most small island nations are in tropical areas with weather conducive to the transmission of diseases such as malaria, dengue, filariasis, and schistosomiasis.

The linkages between human health, climate variability, and seasonal weather have been demonstrated in several recent studies. The Caribbean has been identified as a "highly endemic zone for leptospirosis," with Trinidad and Tobago, Barbados, and Jamaica representing the highest annual incidence (12, 10, and 7.8 cases per 100,000, respectively) in the world, with only the Seychelles being higher (43.2 per 100,000 population) (Pappas et al., 2008). Studies conducted in Guadeloupe demonstrated a link between El Niño occurrence and leptospirosis incidence, with rates increasing to 13 per 100,000 population in El Niño years, as opposed to 4.5 cases per 100,000 inhabitants in La Niña and neutral years (Herrmann-Storck et al., 2008). In addition, epidemiological studies conducted in Trinidad reviewed the incidence of leptospirosis during the period 1996–2007 and showed seasonal patterns in the occurrence of confirmed leptospirosis cases, with significantly ($P < 0.001$) more cases occurring in the wet season, May to November (193 cases), than during the dry season, December to May (66 cases) (Mohan et al., 2009). Recently changes in the epidemiology of leptospirosis have been detected, especially in tropical islands, with the main factors being climatic and anthropogenic ones (Pappas et al., 2008). These factors may be enhanced with increases in ambient temperature and changes in precipitation, vegetation, and water availability as a consequence of climate change (Russell, 2009).

In Pacific islands the incidence of diseases such as malaria and dengue fever has been increasing, especially endemic dengue in Samoa, Tonga, and Kiribati (Russell, 2009). Although studies conducted so far in the Pacific have established a direct link only between malaria, dengue, and climate variability, these and other health risks including from cholera are projected to increase as a consequence of climate change (Russell, 2009; see also Sections 11.2.4-5 for detailed discussion on the link between climate change and projected increases in the outbreak of dengue and cholera). Dengue incidence is also a major health concern in other small island countries, including Trinidad and Tobago, Singapore, Cape Verde, Comoros, and Mauritius (Koh et al., 2008; Chadee, 2009; Van Kleef et al., 2010; Teles, 2011). In the specific cases of Trinidad and Tobago and Singapore the outbreaks have been significantly correlated with rainfall and temperature, respectively (Chadee et al., 2007; Koh et al., 2008).

Previous IPCC assessments have consistently shown that human health on islands can be seriously compromised by lack of access to adequate, safe freshwater and adequate nutrition (Nurse et al., 2001; Mimura et al., 2007). Lovell (2011) notes that in the Pacific many of the anticipated health effects of climate change are expected to be indirect, connected to the increased stress and declining well-being that comes with property damage, loss of economic livelihood, and threatened communities. There is also a growing concern in island communities in the Caribbean Sea and Pacific and Indian Oceans that freshwater scarcity and more intense droughts and storms could lead to a deterioration in standards of sanitation and hygiene (Cashman et al., 2010; McMichael and Lindgren, 2011). In such circumstances, increased exposure to a range of health risks including communicable (transmissible) diseases would be a distinct possibility.

Ciguatera fish poisoning (CFP) occurs in tropical regions and is the most common non-bacterial food-borne illness associated with consumption of fish. Distribution and abundance of the organisms that produce these toxins, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with water temperature. Consequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of CFP in the island regions of the Caribbean (Morrison et al., 2008; Tester et al., 2010), Pacific (Chan et al., 2011; Rongo and van Woesik, 2011), the Mediterranean (Aligizaki and Nikolaidis, 2008; see also Section 29.5.5), and the Canary Islands in the Atlantic (Pérez-Arellano et al., 2005). A recent Caribbean study sought to characterize the relationship between SSTs and CFP incidence and to determine the effects of temperature on the growth rate of organisms responsible for CFP. Results from this work show that in the Lesser Antilles high rates occur in areas that experience the warmest water temperatures and that show the least temperature variability (Tester et al., 2010). There are also high rates in the Pacific in Tokelau, Tuvalu, Kiribati, Cook Islands, and Vanuatu (Chan et al., 2011).

The influence of climatic factors on malaria vector density and parasite development is well established (Chaves and Koenraadt, 2010; Béguin et al., 2011). Previous studies have assessed the potential influence of climate change on malaria, using deterministic or statistical models (Martens et al., 1999; Pascual et al., 2006; Hay et al., 2009; Parham and Michael, 2010). Although the present incidence of malaria on small islands is not reported to be high, favorable environmental and social circumstances for the spread of the disease are present in some island regions and are expected to be enhanced under projected changes in climate in Papua New Guinea, Guyana, Suriname, and French Guyana (Michon et al., 2007; Figueroa, 2008; Rawlins et al., 2008). In the Caribbean, the occurrence of autochthonous malaria in non-endemic island countries in the last 10 years suggests that all of the essential malaria transmission conditions now exist. Rawlins et al. (2008) call for enhanced surveillance, recognizing the possible impact of climate change on the spread of the *Anopheles* mosquito vector and malaria transmission.

29.3.3.3. Observed Impacts of Climate Change on Relocation and Migration

Evidence of human migration as a response to climate change is scarce for small islands. Although there is general agreement that migration is usually driven by multiple factors (Black et al., 2011), several authors highlight the lack of empirical studies of the effect of climate-related factors, such as SLR, on island migration (Mortreux and Barnett, 2009; Lilleør and Van den Broeck, 2011). Furthermore, there is no evidence of any government policy that allows for climate "refugees" from islands to be accepted into another country (Bedford and Bedford, 2010). This finding contrasts with the early desk-based estimates of migration under climate change such as the work of Myers (2002). These early studies have been criticized as they fail to acknowledge the reality of climate impacts on islands, the capacity of islands and islanders to adapt, or the actual drivers of migration (Barnett and O'Neill, 2012).

Studies of island migration commonly reveal the complexity of a decision to migrate and rarely identify a single cause. For example, when looking at historical process of migration within the Mediterranean, it appears that rising levels of income, coupled with a decreased dependence on subsistence agriculture, has left the Mediterranean less vulnerable to all environmental stressors, resulting in a reduced need for mobility to cope with environmental or climatic change (de Haas, 2011). Studies from the Pacific have also shown that culture, lifestyle, and a connection to place are more significant drivers of migration than climate (Barnett and Webber, 2010). For example, a Pacific Access Category of migration has been agreed between New Zealand and Tuvalu that permits 75 Tuvaluans to migrate to New Zealand every year (Kravchenko, 2008). Instead of enabling climate-driven migration, this agreement is designed to facilitate economic and social migration as part of the Pacific Island lifestyle (Shen and Gemenne, 2011). To date there is no unequivocal evidence that reveals migration from islands is being driven by anthropogenic climate change.

There is, however, some evidence that environmental change has played a role in Pacific Island migration in the past (Nunn, 2007). In the Pacific, environmental change has been shown to affect land use and land rights, which in turn have become drivers of migration (Bedford and Bedford, 2010). In a survey of 86 case studies of community relocations in Pacific Islands, Campbell et al. (2005) found that environmental variability and natural hazards accounted for 37 communities relocating. In the Pacific, where land rights are a source of conflict, climate change could increase levels of stress associated with land rights and impact on migration (Campbell, 2010; Weir and Virani, 2011). Although there is not yet a climate fingerprint on migration and resettlement patterns in all small islands, it is clear that there is the potential for human movement as a response to climate change. To understand better the impact of climate change on migration there is an urgent need for robust methods to identify and measure the effects of the drivers of migration on migration and resettlement.

29.3.3.4. Observed Impacts on Island Economies

The economic and environmental vulnerabilities of small islands states are well documented (Briguglio et al., 2009, Bishop, 2012). Such vulnerabilities, which render the states at risk of being harmed by economic and environmental conditions, stem from intrinsic features of these vulnerable states, and are not usually governance induced. However, governance does remain one of the challenges for island countries in the Pacific in the pursuit of sustainable development through economic growth (Prasad, 2008). Economic vulnerability is often the result of a high degree of exposure to economic conditions often outside the control of small island states, exacerbated by dependence on a narrow range of exports and a high degree of dependence on strategic imports, such as food and fuel (Briguglio et al., 2009). This leads to economic volatility, a condition that is harmful for the economy of the islands (Guillaumont, 2010).

There are other economic downsides associated with small size and insularity. Small size leads to high overhead cost per capita, particularly in infrastructural outlays. This is of major relevance to climate change adaptation that often requires upgrades and redesign of island infrastructure. Insularity leads to high cost of transport per unit, associated with purchases of raw materials and industrial supplies in small quantities, and sales of local produced products to distant markets. These disadvantages are associated with the inability of small islands to reap the benefits of economies of scale, resulting in a high cost of doing business in small islands (Winters and Martins, 2004).

High costs are also associated with the small size of island states when impacted by extreme events such as hurricanes and droughts. On small islands such events often disrupt most of the territory, especially on single-island states, and have a very large negative impact on the state's GDP, in comparison with larger and more populous states where individual events generally only affect a small proportion of the country and have a small impact on its GDP (Anthoff et al., 2010). Moreover, the dependence of many small islands on a limited number of economic

Frequently Asked Questions

FAQ 29.2 | Why is the cost of adaptation to climate change so high in small islands?

Adaptation to climate change that involves infrastructural works generally requires large up-front overhead costs, which in the case of small islands cannot be easily downscaled in proportion to the size of the population or territory. This is a major socioeconomic reality that confronts many small islands, notwithstanding the benefits that could accrue to island communities through adaptation. Referred to as "indivisibility" in economics, the problem can be illustrated by the cost of shore protection works aimed at reducing the impact of sea level rise. The unit cost of shoreline protection per capita in small islands is substantially higher than the unit cost for a similar structure in a larger territory with a larger population. This scale-reality applies throughout much of a small island economy including the indivisibility of public utilities, services, and all forms of development. Moreover, the relative impact of an extreme event such as a tropical cyclone that can affect most of a small island's territory has a disproportionate impact on that state's gross domestic product, compared to a larger country where an individual event generally affects a small proportion of its total territory and its GDP. The result is relatively higher adaptation and disaster risk reduction costs per capita in countries with small populations and areas—especially those that are also geographically isolated, have a poor resource base, and have high transport costs.

sectors such as tourism, fisheries, and agricultural crops, all of which are climate sensitive, means that on the one hand climate change adaptation is integral to social stability and economic vitality but that government adaptation efforts are constrained because of the high cost on the other.

29.3.4. Detection and Attribution of Observed Impacts of Climate Change on Small Islands

While exceptional vulnerability of many small islands to future climate change is widely accepted, the foregoing analysis indicates that the scientific literature on observed impacts is quite limited. Detection of past and recent climate change impacts is challenging owing to the presence of other anthropogenic drivers, especially in the constrained environments of small islands. Attribution is further challenged by the strong influence of natural climate variability compared to gradual incremental change of climate drivers. Notwithstanding these limitations, a summary of the relationship between detection and attribution to climate change of several of the phenomena described in the preceding sections has been prepared. Figure 29-2 reflects the degree of confidence in the link between observed changes in several components of the coastal, terrestrial, and human systems of small islands and the drivers of climate change.

29.4. Projected Integrated Climate Change Impacts

Small islands face many challenges in using climate change projections for policy development and decision making (Keener et al., 2012). Among these is the inaction inherent in the mismatch of the short-term time scale on which government decisions are generally taken compared with the long-term time scale required for decisions related to climate change. This is further magnified by the general absence of credible regional socioeconomic scenarios relevant at the spatial scale at which most decisions are taken. Scenarios are an important tool to help decision makers disaggregate vulnerability to the direct physical impacts of the climate signal from the vulnerability associated with socioeconomic conditions and governance. There is, however, a problem in generating formal climate scenarios at the scale of small islands because they are generally much smaller than the resolution of the global climate models. This is because the grid squares in the Global Circulation Models (GCMs) used in the SRES scenarios over the last decade were between 200 and 600 km^2, which provides inadequate resolution over the land areas of most small islands. This has recently improved with the new Representative Concentration Pathway (RCP) scenario GCMs with grid boxes generally between 100 and 200 km^2 in size.

The scale problem has been usually addressed by the implementation of statistical downscaling models that relate GCM output to the historical climate of a local small island data point. The limitation of this approach is the need for observed data ideally for at least 3 decades for a number of representative points on the island, in order to establish the statistical relationships between GCM data and observations. In most small islands long-term quality-controlled climate data are generally sparse, so that in widely dispersed islands such as in the Pacific, observational records are usually supplemented with satellite observations combined with dynamical downscaling computer models (Australian Bureau of Meteorology and CSIRO, 2011a; Keener et al., 2012). However, where adequate local data are available for several stations for at least 30 years, downscaling techniques have demonstrated that they can provide projections at fine scales ranging from about 10 to 25 km^2 (e.g., Charlery and Nurse, 2010; Australian Bureau of Meteorology and CSIRO, 2011a). Even so, most projected changes in climate for the Caribbean Sea, Pacific and Indian Oceans, and Mediterranean islands generally apply to the region as a whole, and this may be adequate to determine general trends in regions where islands are close together.

29.4.1. Non-formal Scenario-based Projected Impacts

Scenarios are often constructed by using a qualitative or broad order of magnitude climate projections approach based on expected changes

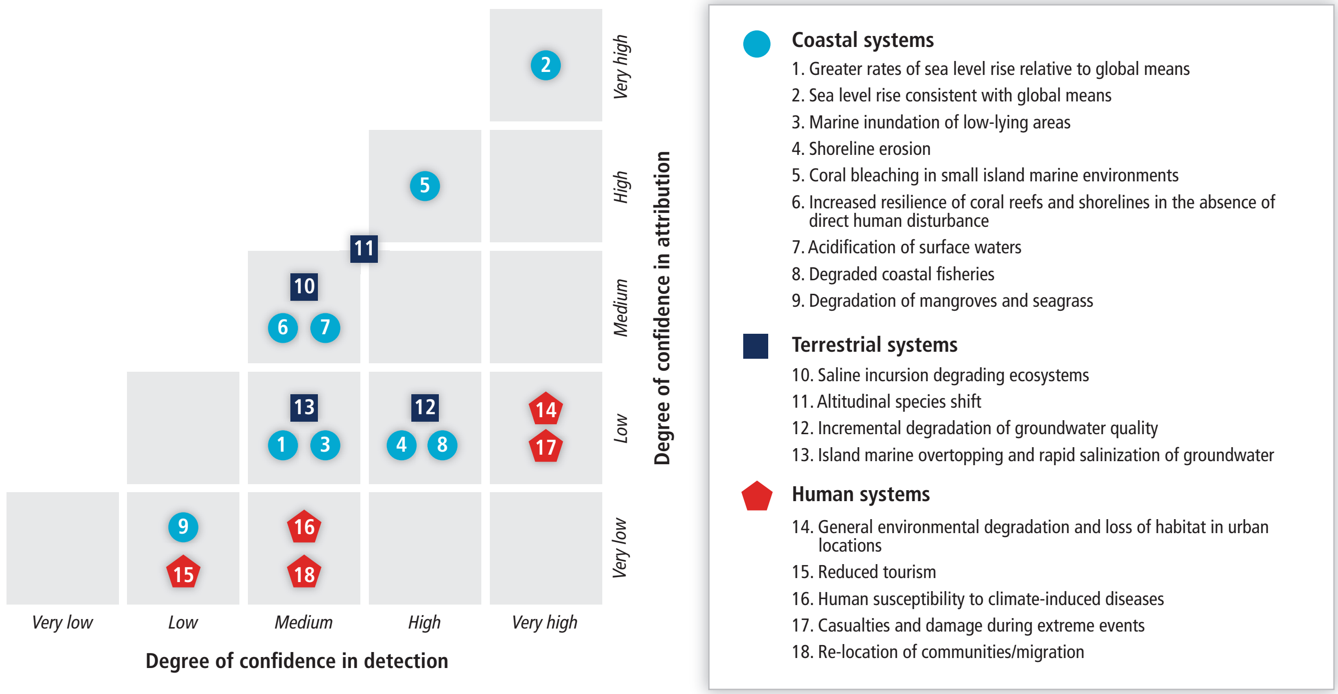

Figure 29-2 | A comparison of the degree of confidence in the detection of observed impacts of climate change on tropical small islands with the degree of confidence in attribution to climate change drivers at this time. For example, the blue symbol No. 2 (Coastal Systems) indicates there is *very high confidence* in both the detection of "sea level rise consistent with global means" and its attribution to climate change drivers; whereas the red symbol No. 17 (Human Systems) indicates that although confidence in detection of "casualties and damage during extreme events" is *very high*, there is at present *low confidence* in the attribution to climate change. It is important to note that *low confidence* in attribution frequently arises owing to the limited research available on small island environments.

in some physical climate signal from literature review rather than projections based on direct location-specific modeling. Usually this is proposed as a "what if" question that is then quantified using a numerical method. For example, in the Pacific, digital elevation models of Fiji's islands have been used to identify high risk areas for flooding based on six scenarios for SLR from 0.09 to 0.88 m in combination with six scenarios for storm surge with return intervals from 1 to 50 years (Gravelle and Mimura, 2008). Another example of qualitative modeling from the Pacific is a case study from Nauru that uses local data and knowledge of climate to assess the GCM projections. It suggests that Nauru should plan for continued ENSO variability in the future with dry years during La Niña and an overall increase in mean rainfall and extreme rainfall events. Climate adaptation concerns that arise include water security and potential changes in extreme wet events that affect infrastructure and human health (Brown et al., 2013a). Climate change also poses risks for food security in the Pacific Islands, including agriculture and fisheries (Barnett, 2011).

Projections have also been used in the islands of the Republic of Baharain to estimate proneness to inundation for SLR of 0.5, 1.0, and 1.5 m (Al-Jeneid et al., 2008). Similarly, in the Caribbean the elevation equivalent of a projected SLR of 1 m has been superimposed on topographic maps to estimate that 49 to 60% of tourist resort properties would be at risk of beach erosion damage, potentially transforming the competitive position and sustainability of coastal tourism destinations in the region (Scott et al., 2012c). This method has also been used to quantify the area loss for more than 12,900 islands and more than 3000 terrestrial vertebrates in the tropical Pacific region for three SLR scenarios. The study estimated that for SLR of 1 m, 37 island endemic species in this region risk complete inundation (Wetzel et al., 2013).

29.4.2. Projected Impacts for Islands Based on Scenario Projections

Another approach to scenario development is to use the region-specific projections more directly. It is worth noting that the broad synthesis in the AR4 of medium emissions climate scenario projections for small island regions (Mimura et al., 2007) shows concordance with the new RCP scenarios (see Table 29-1 and new RCP projections in Figure 29-3). For example, the SRES A1B medium emissions scenario suggests about a 1.8°C to 2.3°C median annual increase in surface temperature in the Caribbean Sea and Indian and Pacific Ocean small islands regions by 2100 compared to a 1980–1999 baseline, with an overall annual decrease in precipitation of about 12% in the Caribbean (WGI AR4 Table 11.1; WGI AR5 Section 14.7.4) and a 3 to 5% increase in the Indian and Pacific Ocean small island regions. Comparative projections for the new RCP4.5 scenario suggests about a 1.2°C to 2.3°C increase in surface temperature by 2100 compared to a 1986–2005 baseline and a decrease in precipitation of about 5 or 6% in the Caribbean and Mediterranean, respectively, signaling potential future problems for agriculture and water availability compared to a 1 to 9% increase in the Indian and Pacific Ocean small islands regions (Table 29-1). However, there are important spatial and high-island topography differences. Thus, for example, among the more dispersed Pacific Islands where the equatorial regions are likely to get wetter and the subtropical high pressure belts

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Table 29-1 | Climate change projections for the intermediate low (500–700 ppm CO_2e) Representative Concentration Pathway 4.5 (RCP4.5) scenario for the main small island regions. The table shows the 25th, 50th (median), and 75th percentiles for surface temperature and precipitation based on averages from 42 Coupled Model Intercomparison Project Phase 5 (CMIP5) global models (adapted from WGI AR5 Table 14.1). Mean net regional sea level change is evaluated from 21 CMIP5 models and includes regional non-scenario components (adapted from WGI AR5 Figure 13-20).

Small island region	RCP4.5 annual projected change for 2081–2100 compared to 1986–2005						
	Temperature (°C)			Precipitation (%)			Sea level (m)
	25%	50%	75%	25%	50%	75%	Range
Caribbean	1.2	1.4	1.9	–10	–5	–1	0.5–0.6
Mediterranean	2.0	2.3	2.7	–10	–6	–3	0.4–0.5
Northern tropical Pacific	1.2	1.4	1.7	0	1	4	0.5–0.6
Southern Pacific	1.1	1.2	1.5	0	2	4	0.5–0.6
North Indian Ocean	1.3	1.5	2.0	5	9	20	0.4–0.5
West Indian Ocean	1.2	1.4	1.8	0	2	5	0.5–0.6

drier (as reported by WGI AR5) in regions directly affected by the South Pacific Convergent Zone (SPCZ) and western portion of the Inter-Tropical Convergent Zone (ITCZ), the rainfall outlook is uncertain (WGI AR5 Section 14.7.13). Projections for the Mediterranean islands also differ from those for the tropical small islands. Throughout the Mediterranean region, the length, frequency, and/or intensity of warm spells or heat waves are *very likely* to increase to the year 2100 (WGI AR5 Section 14.7.6). SLR projections in the small islands regions for RCP4.5 are similar to the global projections of 0.41 to 0.71 m (WGI AR5 Section 13.5.1), ranging from 0.5 to 0.6 m by 2100 compared to 1986–2005 in the Caribbean Sea and Pacific and Indian Oceans to 0.4 to 0.5 m in the Mediterranean and north Indian Ocean (Table 29-1).

In the main regions in which most tropical or subtropical small island states are located, there are few independent peer-reviewed scientific publications providing downscaled climate data projections, and even less illustrating the experience gained from their use for policy making. A possible 2°C temperature increase by the year 2100 has potentially far-reaching consequences for sentinel ecosystems such as coral reefs that are important to tropical islands (see Section 6.2.2.4.4). This is because "degree heating months" (DHMs) greater than 2°C per month are the determining threshold for severe coral bleaching (Donner, 2009). For example, in a study of SST across all coral reef regions using GCM ensemble projections forced with five different SRES future emissions scenarios, Donner (2009) concluded that even warming in the future from the current accumulation of GHGs in the atmosphere could cause more than half of the world's coral reefs to experience harmfully frequent thermal stress by 2080. Further, this timeline could be brought forward to as early as 2030 under the A1B medium emissions scenario. He further stated that thermal adaptation of 1.5°C would delay the thermal stress forecast by only 50 to 80 years. Donner (2009) also estimated the year of likelihood of a severe mass coral bleaching event due more than once every 5 years to be 2074 in the Caribbean, 2088 in the western Indian Ocean, 2082 in the central Indian Ocean, 2065 in Micronesia, 2051 in the central Pacific, 2094 in Polynesia, and 2073 in the eastern Pacific small islands regions. Using the new RCP scenarios by comparison, van Hooidonk et al. (2013) found that the onset of annual bleaching conditions is associated with about 510 ppm CO_2-eq. The conclusion based on outputs from a wide range of emissions scenarios and models is that preserving more than 10% of coral reefs worldwide would require limiting warming to less than 1.5°C (1.3°C to 1.8°C Atmosphere-Ocean General Circulation Model (AOGCM) range) compared to pre-industrial levels (Frieler et al., 2013).

Small island economies can also be objectively shown to be at greater risk from SLR in comparison to other geographic areas because most of their population and infrastructure are in the coastal zone. This is demonstrated in a study using the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model to assess the economic impact of substantial SLR in a range of socioeconomic scenarios downscaled to the national level, including the four SRES storylines (Anthoff et al., 2010). Although this study showed that, in magnitude, a few regions will experience most of the absolute costs of SLR by 2100, especially East Asia, North America, Europe, and South Asia, these same results when expressed as percent of GDP showed that most of the top ten and four of the top five most impacted are small islands from the Pacific (Federated States of Micronesia, Palau, Marshall Islands, Nauru) and Caribbean (Bahamas). The point is made that the damage costs for these small island states are enormous in relation to the size of their economies (Nicholls and Tol, 2006) and that, together with deltaic areas, they will find it most difficult to locally raise the finances necessary to implement adequate coastal protection (Anthoff et al., 2010).

In the Caribbean, downscaled climate projections have been generated for some islands using the Hadley Centre PRECIS (Providing REgional Climates for Impact Studies) regional model (Taylor et al., 2007; Stephenson et al., 2008). For the SRES A2 and B2 scenarios, the PRECIS regional climate model projects an increase in temperature across the Caribbean of 1°C to 4°C compared to a 1960–1990 baseline, with increasing rainfall during the latter part of the wet season from November to January in the northern Caribbean (i.e., north of 22°N) and drier conditions in the southern Caribbean linked to changes in the Caribbean Low Level Jet (CLLJ) with a strong tendency to drying in the traditional wet season from June to October (Whyte et al., 2008; Campbell et al., 2011; Taylor et al., 2013). Projected lengthening seasonal dry periods, and increasing frequency of drought are expected to increase demand for water throughout the region under the SRES A1B scenario (Cashman et al., 2010). Decrease in crop yield is also projected in Puerto Rico for the SRES B1 (low), A2 (mid to high), and A1F1 scenarios during September although increased crop yield is suggested during February (Harmsen et al., 2009). Using a tourism demand model linked to the SRES A1F1, A2, B1, and B2 scenarios, the projected climate change heating and drying impacts are also linked to potential aesthetic, physical, and thermal effects that are estimated to cause a change in total regional tourist expenditure of about +321, +356, –118, and -146 million US$ from the least to the most severe emissions scenario, respectively (Moore, 2010).

In the Indian Ocean, representative downscaled projections have been generated for Australia's two Indian Ocean territories, the Cocos (Keeling) Islands and Christmas Island using the CSIRO (Commonwealth Scientific and Industrial Research Organisation) Mark 3.0 climate model with the SRES A2 high-emissions scenario (Maunsell Australia Pty Ltd., 2009). Future climate change projections for the two islands for 2070 include an approximate 1.8°C increase in air temperature by 2070, probable drier dry seasons and wet seasons, about a 40-cm rise in sea level, and a decrease in the number of intense tropical cyclones.

In the western tropical Pacific, extensive climate projections have been made for several Pacific Island countries based on downscaling from an ensemble of models (Australian Bureau of Meteorology and CSIRO, 2011b). The temperature projections in this region dominated by oceans seem less than those seen globally, ranging from +1.5 to 2.0°C for the B1 low-emissions scenario to +2.5 to 3.0°C for the A2 high-emissions scenario by the year 2090 relative to a 20-year period centered on 1990. Notably, extreme rainfall events that currently occur once every 20 years on average are generally simulated to occur four times per 20-year period, on average, by 2055 and seven times per 20-year period, on average, by 2090 under the A2 (high-emissions) scenario (Australian Bureau of Meteorology and CSIRO, 2011b). The results are not very different from the tropical Pacific RCP4.5 projections, with projected temperature increases of about +1.2 to 1.4°C by 2100 and an increase in rainfall of about 4% (Table 29-1). A comprehensive assessment of the vulnerability of the fisheries and aquaculture sectors to climate change in 22 Pacific island countries and territories focused on two future time frames (2035 and 2100) and two SRES emissions scenarios, B1 (low emissions) and A2 (high emissions) (Bell et al., 2013). Many anticipated changes in habitat and resource availability such as coral reef-based fisheries are negative. By contrast, projected changes in tuna fisheries and freshwater aquaculture/fisheries can be positive with implications for government revenue and island food security (Bell et al., 2013). Simulation studies on changes in stocks of skipjack and bigeye tuna in the tropical Pacific area summarized in Table 29-2 and also discussed in Sections 7.4.2.1 and 30.6.2.1.1. Some of these projected changes may favor the large international fishing fleets that can shift operations over large distances compared to local, artisanal fishers (Polovina et al., 2011).

In the Mediterranean islands of Mallorca, Corsica, Sardinia, Crete, and Lesvos, Gritti et al. (2006) simulated the terrestrial vegetation biogeography and distribution dynamics under the SRES A1F1 and B1 scenarios to the year 2050. The simulations indicate that the effects of climate change are expected to be negligible within most ecosystems except for mountainous areas. These areas are projected to be eventually occupied by exotic vegetation types from warmer, drier conditions. Cruz et al. (2009) report similar results for the terrestrial ecosystems of Madeira Island in the Atlantic. Downscaled SRES A2 and B2 scenarios for the periods 2040–2069 and 2070–2099 suggest that the higher altitude native humid forest, called the Laurissilva, may expand upward in altitude, which could lead to a severe reduction of the heath woodland which because it has little upward area to shift may reduce in range or disappear at high altitudes, resulting in the loss of rare and endemic species within this ecosystem.

Table 29-2 | Summary of projected percentage changes in tropical Pacific tuna catches by 2036 and 2100 relative to 1980–2000 for SRES scenarios A2 and B1, and the estimated resulting percentage change to government revenue (after Tables 12.7 and 12.9 of Bell et al., 2011).

Tuna fishery		Change in catch (%)		
		2035: B1/A2	2100: B1	2100: A2
Skipjack tuna	Western fishery	+11	–0.2	–21
	Eastern fishery	+37	+43	+27
	Total	+19	+12	–7
Bigeye tuna	Western fishery	–2	–12	–34
	Eastern fishery	+3	–4	–18
	Total	+0.3	–9	–27
Country		**Change in government revenue (%)**		
		2035: B1/A2	**2100: B1**	**2100: A2**
Federated States of Micronesia		+1 to +2	0 to +1	–1 to –2
Solomon Islands		0 to +0.2	0 to –0.3	0 to +0.8
Kiribati		+11 to +18	+13 to +21	+7 to +12
Tuvalu		+4 to +9	+4 to +10	+2 to +6

29.4.3. Representative Concentration Pathway Projections and Implications for Small Islands

Utilizing updated historical GHG emissions data the scientific community has produced future projections for four plausible new global RCPs to explore a range of global climate signals up to the year 2100 and beyond (e.g., Moss et al., 2010). Typical model ensemble representations of low, intermediate low, intermediate high, and high RCP projections for annual temperature and precipitation in some small islands regions are presented in Figure 29-3. Highlighted in Figure 29-3 is the ensemble mean of each RCP. A more comprehensive compilation of quarterly global RCP projections can be found in the WGI AR5 Annex I: Atlas of Global and Regional Climate Projections.

During negotiations toward a new multilateral climate change regime Small Island Developing States (SIDS) have advocated that any agreement should be based on Global Mean Surface Temperature (GMST) increase "well below" 1.5°C above pre-industrial levels (Hare et al., 2011; Riedy and McGregor, 2011). Inspection of column 1 in Figure 29-3 suggests that for the Caribbean, Indian Ocean, and Pacific SIDS in the tropics, the median projected regional increase is in the range 0.5°C to 0.9°C by 2100 compared to 1986–2005. This, together with the temperature change that has already occurred since the Industrial Revolution, suggests that a temperature "well below" 1.5°C is unlikely to be achieved with the lowest RCP2.6 projection (Peters et al., 2013). By comparison, temperature projections for the intermediate low RCP4.5 scenario (Table 29-1; Figure 29-3) suggest possible 1.2°C to 1.5°C temperature increases in Caribbean, Indian Ocean, and Pacific SIDS by 2100 compared to 1986–2005. Similarly, the projections for the Mediterranean would be about a 2.3°C increase by 2100 compared to 1986–2005 that would represent a 2.7°C increase compared to pre-industrial temperatures. Associated with this change, the Caribbean and Mediterranean regions may experience a noticeable decrease in mean rainfall while the Indian and Pacific Ocean SIDS may experience increased rainfall. These trends accelerate moderately for RCP6.0 and steeply for RCP8.5 (Table 29-1).

29.5. Inter- and Intra-regional Transboundary Impacts on Small Islands

Available literature since AR4 has highlighted previously less well understood impacts on small islands that are generated by processes originating in another region or continent well beyond the borders of an individual archipelagic nation or small island. These are inter-regional transboundary impacts. Intra-regional transboundary impacts originate from a within-region source (e.g., the Caribbean). Some transboundary processes may have positive effects on the receiving small island or nation, though most that are reported have negative impacts. Deciphering a climate change signal in inter- and intra-regional transboundary impacts on small islands is not easy and usually involves a chain of linkages tracing back from island-impact to a distant climate or climate-related bio-physical or human process. Some examples are given below.

29.5.1. Large Ocean Waves from Distant Sources

Unusually large deep ocean swells, generated from sources in the mid- and high latitudes by extratropical cyclones (ETCs) cause considerable damage on the coasts of small islands thousands of kilometers away in the tropics. Impacts include sea flooding and inundation of settlements, infrastructure, and tourism facilities as well as severe erosion of beaches (see also Section 5.4.3.4). Examples from small islands in the Pacific and Caribbean are common, though perhaps the most significant instance, in terms of a harbinger of climate change and SLR, occurred in the

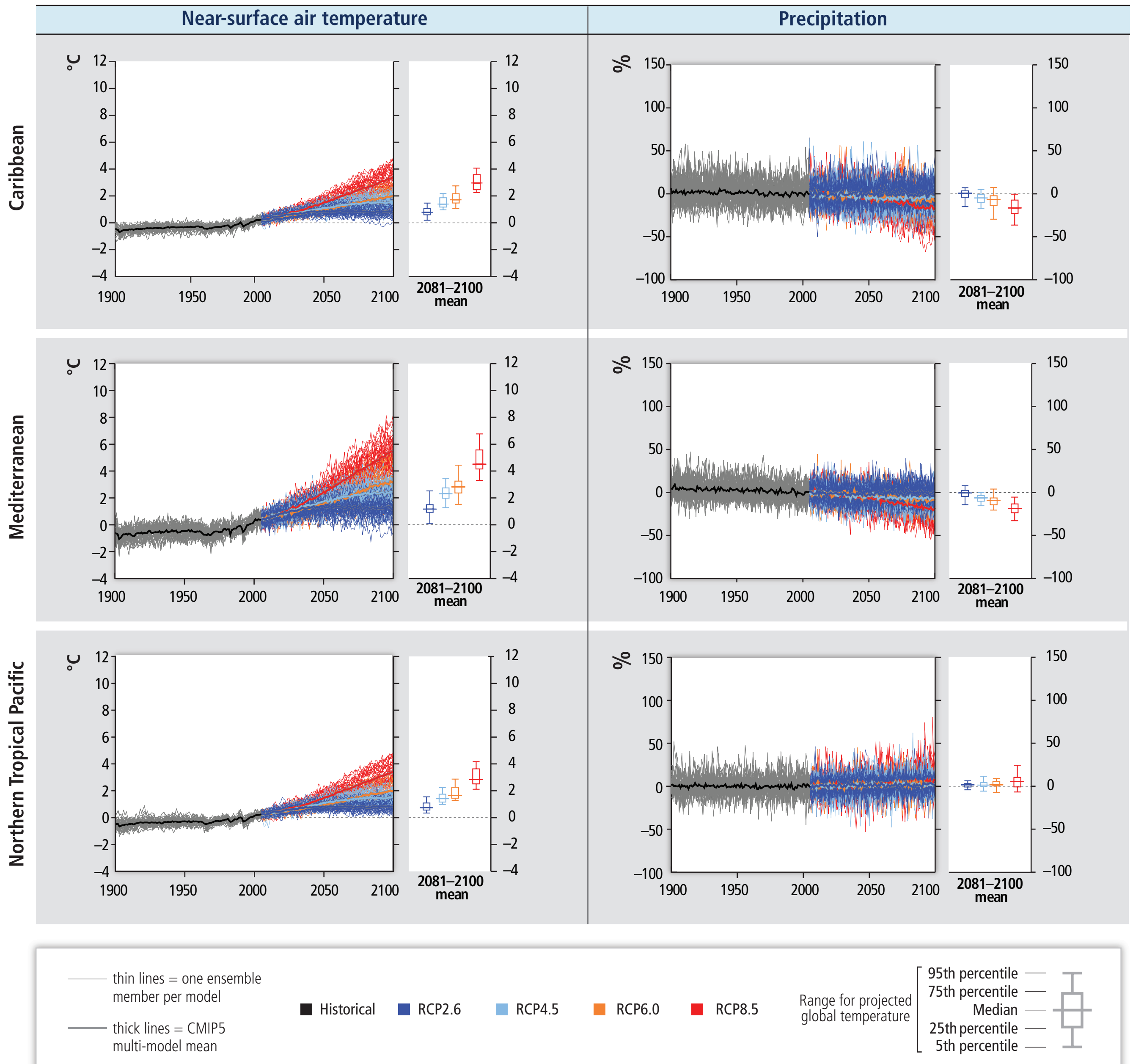

Figure 29-3 | Time series of Representative Concentration Pathway (RCP) scenarios annual projected temperature and precipitation change relative to 1986–2005 for six small islands regions (using regions defined in WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections). Thin lines denote one ensemble member per model, and thick lines the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model mean. On the righthand side, the 5th, 25th, 50th (median), 75th, and 95th percentiles of the distribution of 20-year mean changes are given for 2081–2100 in the four RCP scenarios. Note that the model ensemble averages in the figure are for grid points over wide areas and encompass many different climate change signals.

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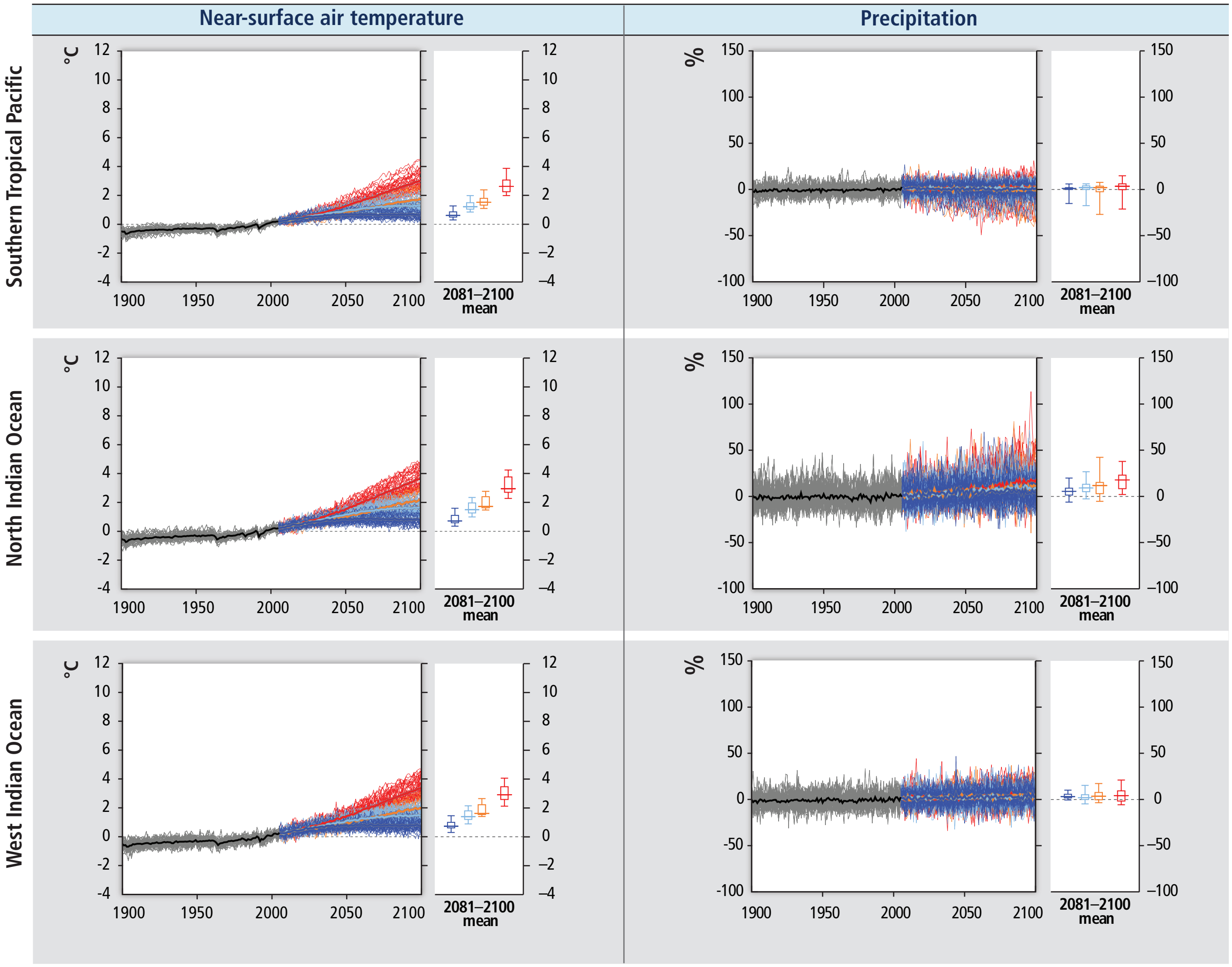
Figure 29-3 (continued)



Maldives in April 1987 when long period swells originating from the Southern Ocean some 6000 km away caused major flooding, damage to property, destruction of sea defenses, and erosion of reclaimed land and islands (Harangozo, 1992). The Maldives and several other island groups in the Indian Ocean have been subject to similar ocean swell events more recently, most notably in May 2007 (Maldives Department of Meteorology, 2007).

In the Caribbean, northerly swells affecting the coasts of islands have been recognized as a significant coastal hazard since the 1950s (Donn and McGuinness, 1959). They cause considerable seasonal damage to beaches, marine ecosystems, and coastal infrastructure throughout the region (Bush et al., 2009; Cambers, 2009). These high-energy events manifest themselves as long period high-amplitude waves that occur during the Northern Hemisphere winter and often impact the normally sheltered, low-energy leeward coasts of the islands. Such swells have even reached the shores of Guyana on the South American mainland as illustrated by a swell event in October 2005 that caused widespread flooding and overtopping and destruction of sea defenses (van Ledden et al., 2009).

Distant origin swells differ from the "normal" wave climate conditions experienced in the Caribbean, particularly with respect to direction of wave approach, wave height, and periodicity and in their morphological impact (Cooper et al., 2013). Swells of similar origin and characteristics also occur in the Pacific (Fletcher et al., 2008; Keener et al., 2012). These events frequently occur in the Hawaiian Islands, where there is evidence of damage to coral growth by swell from the north Pacific, especially during years with a strong El Niño signal (Fletcher et al., 2008).

Hoeke et al. (2013) describe inundation from mid- to high-latitude north and south Pacific waves respectively at Majuro (Marshall Islands) in November and December 1979 and along the Coral Coast (Fiji) in May 2011. They also describe in detail an inundation event in December 2008 that was widespread throughout the western and central Pacific and resulted in waves surging across low-lying islands causing severe damage to housing and infrastructure and key natural resources that affected about 100,000 people across the region. The proximate cause of this event was swell generated in mid-latitudes of the North Pacific Ocean, more than 4000 km from the farthest affected island (Hoeke et al., 2013).

Whereas the origin of the long period ocean swells that impact small islands in the tropical regions come from the mid- and high latitudes in the Pacific, Indian, and Atlantic Oceans, there are also instances of unusually large waves generated from tropical cyclones that spread into the mid- and high latitudes. One example occurred during 1999 when tide gauges at Ascension and St. Helena Islands in the central south Atlantic recorded unusually large deep-ocean swell generated from distant Hurricane Irene (Vassie et al., 2004). The impacts of increasing incidence or severity of storms or cyclones is generally considered from the perspective of direct landfall of such systems, whereas all of these instances serve to show "the potential importance of swells to communities on distant, low-lying coasts, particularly if the climatology of swells is modified under future climate change" (Vassie et al., 2004, p. 1095). From the perspective of those islands that suffer damage from this coastal hazard on an annual basis, this is an area that warrants further investigation. Projected changes in global wind-wave climate to 2070–2100, compared to a base period 1979–2009, show considerable regional and seasonal differences with both decreases and increases in annual mean significant wave height. Of particular relevance in the present context is the projected increase in wave activity in the Southern Ocean, which influences a large portion of the global ocean as swell waves propagate northward into the Pacific, Indian, and Atlantic Oceans (Hemer et al., 2013).

Deep ocean swell waves and elevated sea levels resulting from ETCs are examples of inter-regional transboundary processes; locally generated tropical cyclones (TCs) provide examples of intra-regional transboundary processes. Whereas hurricane force winds, heavy rainfall, and turbulent seas associated with TCs can cause massive damage to both land and coastal systems in tropical small islands, the impacts of sea waves and inundation associated with far distant ETCs are limited to the coastal margins. Nevertheless both storm types result in a range of impacts covering island morphology, natural and ecological systems, island economies, settlements, and human well-being (see Figure 29-4).

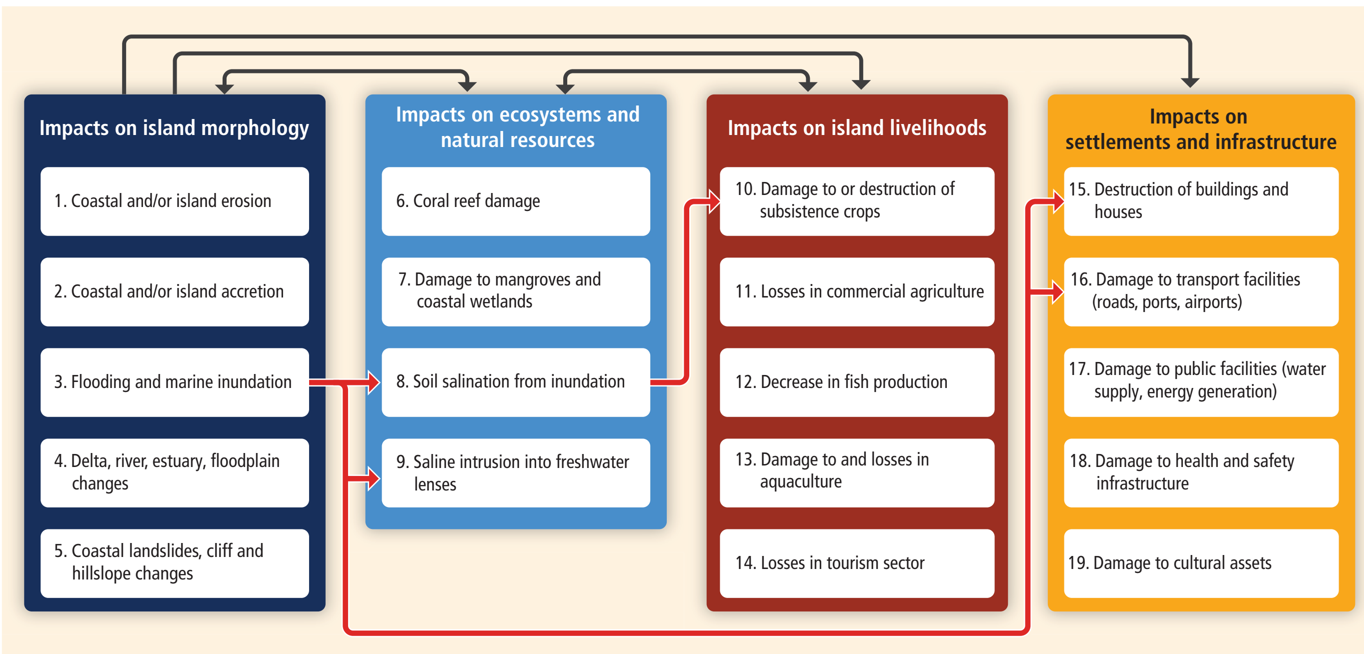


Figure 29-4 | Tropical and extratropical cyclone (ETC) impacts on the coasts of small islands. Four types of impacts are distinguished here, with black arrows showing the connections between them, based on the existing literature. An example of the chain of impacts associated with two ETCs centered to the east of Japan is illustrated by the red arrows. Swell waves generated by these events in December 2008 reached islands in the southwest Pacific and caused extensive flooding (3) that impacted soil quality (8) and freshwater resources (9), and damaged crops (10), buildings (15), and transport facilities (16) in the region (example based on Hoeke et al., 2013).

Examples of tropical cyclone impacts on small island coasts (with reference):
1. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 2. Taveuni, Fiji, March 2010 (Etienne and Terry, 2012); 3. Cook Islands (de Scally, 2008); Society and Autral Islands, French Polynesia, February 2010 (Etienne, 2012); 4. Viti Levu, Fiji, March 1997 (Terry et al., 2002); 5. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 6. Curacao, Bonaire, Netherlands Antilles, November 1999 (Scheffers and Scheffers, 2006); Hawaiian Islands (Fletcher et al., 2008); 7. Bay Islands, Honduras, October 1998 (Cahoon et al., 2003); 8. Marshall Islands, June 1905 (Spennemann, 1996); 9. Pukapuka atoll, Cook Islands, February 2005 (Terry and Falkland, 2010); 10. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 11. 12. 13. Tuamotu Islands, French Polynesia, 1982–1983 (Dupon, 1987); 14. Grenada, September 2004 (OECS, 2004); 15. Grenada, September 2004 (OECS, 2004); Tubuai, Austral Islands, French Polynesia, February 2010 (Etienne, 2012); 16. Vanuatu, February 2004 (Richmond and Sovacool, 2012); Guadeloupe Island, October 2008 (Dorville and Zahibo, 2010); 17. Bora Bora, Raiatea, Maupiti, Tahaa, Huahine, Society Islands, February 2010 (Etienne, 2012); 18. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 19. Tuamotu, French Polynesia, 1982–1983 (Dupon, 1987).

Examples of ETC impacts on small island coasts (with reference):
1. Maldives, April 1987 (Harangozo, 1992); 2. Maldives, January 1955 (Maniku, 1990); 3. Maldives, April 1987 (Harangozo, 1992); 9. Solomon Islands, December 2008 (Hoeke et al., 2013); 10. Chuck, Pohnpei, Kosrae, Federated States of Micronesia, December 2008 (Hoeke et al., 2013); 15. Majuro, Marshall Islands, November 1979 (Hoeke et al., 2013); 16. Coral Coast, Viti Levu, Fiji, May 2011 (Hoeke et al., 2013); 17. Majuro, Kwajalein, Arno, Marshall Islands, December 2008 (Hoeke et al., 2013); 18. Bismark Archipelago, Papua New Guinea, December 2008 (Hoeke et al., 2013).

29.5.2. Transcontinental Dust Clouds and Their Impact

The transport of airborne Saharan dust across the Atlantic and into the Caribbean has engaged the attention of researchers for some time. The resulting dust clouds are known to carry pollen, microbes, insects, bacteria, fungal spores, and various chemicals and pesticides (Prospero et al., 2005; Garrison et al., 2006; Middleton et al., 2008; Monteil, 2008; López-Villarrubia et al., 2010). During major events, dust concentrations can exceed 100 µg m^{-3} (Prospero, 2006). Independent studies using different methodologies have all found a strong positive correlation between dust levels in the Caribbean and periods of drought in the Sahara, while concentrations show a marked decrease during periods of higher rainfall. Consequently, it is argued that higher dust emissions due to increasing aridity in the Sahel and other arid areas could enhance climate change effects over large areas, including the eastern Caribbean and the Mediterranean (Prospero and Lamb, 2003). Similar findings have been reported at Cape Verde where dust emission levels were found to be a factor of nine lower during the decade of the 1950s when rainfall was at or above normal, compared to the 1980s, a period of intense drought in the Sahel region (Nicoll et al., 2011). Dust from the Sahara has also reached the eastern Mediterranean (e.g., Santese et al., 2010) whilst dust from Asia has been transported across the Pacific and Atlantic Oceans and around the world (Uno et al., 2009).

There is also evidence that the transboundary movement of Saharan dust into the island regions of the Caribbean, Pacific, and Mediterranean is associated with various human health problems (Griffin, 2007) including asthma admissions in the Caribbean (Monteil, 2008; Prospero et al., 2008; Monteil and Antoine, 2009) and cardiovascular morbidity in Cyprus in the Mediterranean (Middleton et al., 2008), and is found to be a risk factor in respiratory and obstructive pulmonary disease in the Cape Verde islands (Martins et al., 2009). These findings underscore the need for further research into the link among climate change, airborne aerosols, and human health in localities such as oceanic islands far distant from the continental source of the particulates.

29.5.3. Movement and Impact of Introduced and Invasive Species across Boundaries

Invasive species are colonizer species that establish populations outside their normal distribution ranges. The spread of invasive alien species is regarded as a significant transboundary threat to the health of biodiversity and ecosystems, and has emerged as a major factor in species decline, extinction, and loss of biodiversity goods and services worldwide. This is particularly true of islands, where both endemicity and vulnerability to introduced species tend to be high (Reaser et al., 2007; Westphal et al., 2008; Kenis et al., 2009; Rocha et al., 2009; Kueffer et al., 2010). The extent to which alien invasive species successfully establish themselves at new locations in a changing climate will be dependent on many variables, but non-climate factors such as ease of access to migration pathways, suitability of the destination, ability to compete and adapt to new environments, and susceptibility to invasion of host ecosystems are deemed to be critical. This is borne out, for example, by Le Roux et al. (2008), who studied the effect of the invasive weed *Miconia calvescens* in New Caledonia, Society Islands, and Marquesas Islands; by Gillespie et al. (2008) in an analysis of the spread of *Leucaena leucocephala*, *Miconia calvescens*, *Psidium* sp., and *Schinus terebinthifolius* in the Hawaiian Islands; and by Christenhusz and Toivonen (2008), who showed the potential for rapid spread and establishment of the oriental vessel fern, *Angiopteris evecta*, from the South Pacific throughout the tropics. Mutualism between an invasive ant and locally honeydew-producing insects has been strongly associated with damage to the native and functionally important tree species *Pisonia grandis* on Cousine Island, Seychelles (Gaigher et al., 2011).

While invasive alien species constitute a major threat to biodiversity in small islands, the removal of such species can result in recovery and return of species richness. This has been demonstrated in Mauritius by Baider and Florens (2011), where some forested areas were weeded of alien plants and after a decade the forest had recovered close to its initial condition. They concluded, given the severity of alien plant invasion in Mauritius, that their example can "be seen as a relevant model for a whole swath of other island nations and territories around the world particularly in the Pacific and Indian Oceans" (Baider and Florens, 2011, p. 2645).

The movement of aquatic and terrestrial invasive fauna within and across regions will almost certainly exacerbate the threat posed by climate change in island regions, and could impose significant environmental, economic, and social costs. Recent research has shown that the invasion of the Caribbean Sea by the Indo-Pacific lionfish (*Pterois volitans*), a highly efficient and successful predator, is a major contributor to observed increases in algal dominance in coral and sponge communities in the Bahamas and elsewhere in the region. The consequential damage to these ecosystems has been attributed to a significant decline in herbivores due to predation by lionfish (Albins and Hixon, 2008; Schofield, 2010; Green et al., 2011; Lesser and Slattery, 2011). Although there is no evidence that the lionfish invasion is climate-related, the concern is that when combined with preexisting stress factors the natural resilience of Caribbean reef communities will decrease (Green et al., 2012; Albins and Hixon, 2013), making them more susceptible to climate change effects such as bleaching. Englund (2008) has documented the negative effects of invasive species on native aquatic insects on Hawaii and French Polynesia, and their potential role in the extirpation of native aquatic invertebrates in the Pacific. Similarly, there is evidence that on the island of Oahu introduced slugs appear to be "skewing species abundance in favour of certain non-native and native plants," by altering the "rank order of seedling survival rates," thereby undermining the ability of preferred species (e.g., the endangered *C. superba*) to compete effectively (Joe and Daehler, 2008, p. 253).

29.5.4. Spread of Aquatic Pathogens within Island Regions

The mass mortality of the black sea urchin, *Diadema antillarum*, in the Caribbean basin during the early 1980s demonstrates the ease with which ecological threats in one part of a region can be disseminated to other jurisdictions thousands of kilometers away. The die-off was first observed in the waters off Panama around January 1983, and within 13 months the disease epidemic had spread rapidly through the Caribbean Sea, affecting practically all island reefs, as far away as Tobago some 2000 km to the south and Bermuda some 4000 km to the east. The diadema population in the wider Caribbean declined by more than 93% as a consequence of this single episode (Lessios, 1988, 1995) As *D. antillarum* is one of the principal grazers that removes macroalgae from reefs and thus promotes juvenile coral recruitment, the collateral damage was severe, as the region's corals suffered from high morbidity and mortality for decades thereafter (Carpenter and Edmunds, 2006; Idjadi et al., 2010).

There are other climate-sensitive diseases such as yellow, white, and black band; white plague; and white pox that travel across national boundaries and infect coral reefs directly. This is variously supported by examples from the Indo-Pacific and Caribbean relating to the role of bacterial infections in white syndrome and yellow band disease (Piskorska et al., 2007; Cervino et al., 2008); the impact of microbial pathogens as stressors on benthic communities in the Mediterranean associated with warming seawater (Danovaro et al., 2009); and an increasing evidence of white, yellow, and black band disease associated with Caribbean and Atlantic reefs (Brandt and McManus, 2009; Miller, J. et al., 2009; Rosenberg et al., 2009; Weil and Croquer, 2009; Weil and Rogers, 2011).

29.5.5. Transboundary Movements and Human Health

For island communities the transboundary implications of existing and future human health challenges are projected to increase in a changing climate. For instance, the aggressive spread of the invasive giant African snail, *Achatina fulica*, throughout the Caribbean, Indo-Pacific Islands, and Hawaii is not only assessed to be a severe threat to native snails and other fauna (e.g., native gastropods), flora, and crop agriculture, but is also identified as a vector for certain human diseases such as meningitis (Reaser et al., 2007; Meyer et al., 2008; Thiengo et al., 2010).

Like other aquatic pathogens, ciguatoxins that cause ciguatera fish poisoning may be readily dispersed by currents across and within boundaries in tropical and subtropical waters. Ciguatoxins are known to be highly temperature-sensitive and may flourish when certain seawater temperature thresholds are reached, as has been noted in the South Pacific (Llewellyn, 2010), Cook Islands (Rongo and van Woesik, 2011), Kiribati (Chan et al., 2011), the Caribbean and Atlantic (Otero et al., 2010; Tester et al., 2010), and Mediterranean (Aligizaki and Nikolaidis, 2008; see also Section 29.3.3.2).

29.6. Adaptation and Management of Risks

Islands face risks from both climate-related hazards that have occurred for centuries, as well as new risks from climate change. There have been extensive studies of the risks associated with past climate-related hazards and adaptations to these, such as tropical cyclones, drought, and disease, and their attendant impacts on human health, tourism, fisheries, and other areas (Bijlsma et al., 1996; Cronk 1997; Solomon and Forbes 1999; Pelling and Uitto 2001). There have also been many studies that have used a variety of vulnerability, risk, and adaptation assessment methods particularly in the Pacific that have recently been summarized by Hay et al. (2013). But for most islands, there is very little published literature documenting the probability, frequency, severity, or consequences of climate change risks such as SLR, ocean acidification, and salinization of freshwater resources—or associated adaptation measures. Projections of future climate change risks are limited by the lack of model skill in projecting the climatic variables that matter to small islands, notably tropical cyclone frequency and intensity, wind speed and direction, precipitation, sea level, ocean temperature, and ocean acidification (Brown et al., 2013b); inadequate projections of regional sea levels (Willis and Church, 2012); and a lack of long-term baseline monitoring of changes in climatic risk, or to ground-truth models (Voccia, 2012), such as risk of saline intrusion, risk of invasive species, risk of biodiversity loss, or risk of large ocean waves. In their absence, qualitative studies have documented perceptions of change in current risks (Fazey et al., 2011; Lata and Nunn, 2012), reviewed effective coping mechanisms for current stressors (Bunce et al., 2009; Campbell et al., 2011) and have considered future scenarios of change (Weir and Virani, 2011). These studies highlight that change is occurring, but they do not quantify the probability, speed, scale, or distribution of future climate risks. The lack of quantitative published assessments of climate risk for many small islands means that future adaptation decisions have to rely on analogs of responses to past and present weather extremes and climate variability, or assumed/hypothesized impacts of

Table 29-3 | Types of island in the Pacific region and implications for hydro-meteorological hazards (after Campbell, 2009).

Island type and size		Island elevation, slope, rainfall	Implications for hazard
Continental	• Large • High biodiversity • Well-developed soils	• High elevations • River flood plains • Orographic rainfall	River flooding more likely to be a problem than in other island types. In Papua New Guinea, high elevations expose areas to frost (extreme during El Niño).
Volcanic high islands	• Relatively small land area • Barrier reefs • Different stages of erosion	• Steep slopes • Less well-developed river systems • Orographic rainfall	Because of size, few areas are not exposed to tropical cyclones. Streams and rivers are subject to flash flooding. Barrier reefs may ameliorate storm surge.
Atolls	• Very small land area • Small islets surround a lagoon • Larger islets on windward side • Shore platform on windward side • No or minimal soil	• Very low elevations • Convectional rainfall • No surface (fresh) water • Ghyben–Herzberg (freshwater) lens	Exposed to storm surge, "king" tides, and high waves. Narrow resource base. Exposed to freshwater shortages and drought. Water problems may lead to health hazards.
Raised limestone islands	• Concave inner basin • Narrow coastal plains • No or minimal soil	• Steep outer slopes • Sharp karst topography • No surface water	Depending on height, may be exposed to storm surge. Exposed to freshwater shortages and drought. Water problems may lead to health hazards.

climate change based on island type (see Table 29-3). Differences in island type and differences in exposure to climate forcing and hazards vary with island form, providing a framework for consideration of vulnerability and adaptation strategies. Place-based understanding of island landscapes and of processes operating on individual islands is critical (Forbes et al., 2013).

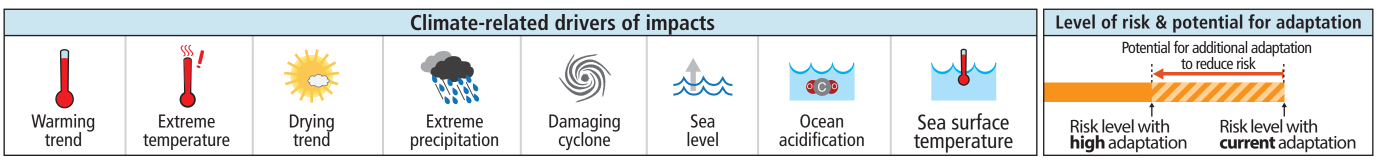
29.6.1. Addressing Current Vulnerabilities on Small Islands

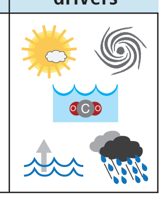
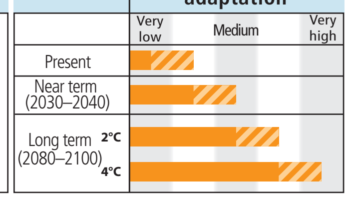
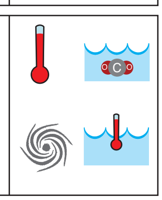
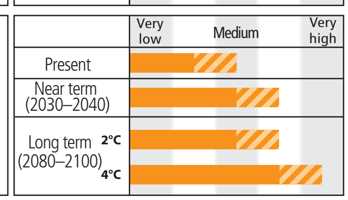
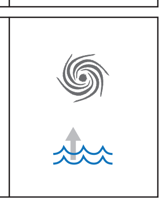
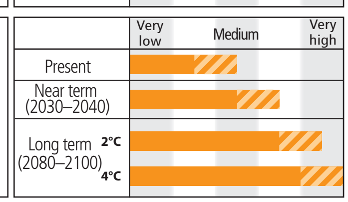
Islands are heterogeneous in geomorphology, culture, ecosystems, populations, and hence also in their vulnerability to climate change. Vulnerabilities and adaptation needs are as diverse as the variety of islands between regions and even within nation states (e.g., in Solomon Islands; Rasmussen et al., 2011), often with little climate adaptation occurring in peripheral islands, for example, in parts of the Pacific (Nunn et al., 2013). Quantitative comparison of vulnerability is difficult owing to the paucity of vulnerability indicators. Generic indices of national level vulnerability continue to emerge (Cardona, 2007) but only a minority are focused on small islands (e.g., Blancard and Hoarau, 2013). The island-specific indicators that exist often suffer from lack of data (Peduzzi et al., 2009; Hughes et al., 2012), use indicators that are not relevant in all islands (Barnett and Campbell, 2010), or use data of limited quality for islands, such as SLR (as used in Wheeler, 2011). As a result indicators of vulnerability for small islands often misrepresent actual vulnerability. Recent moves toward participatory approaches that link scientific knowledge with local visions of vulnerability (see Park et al., 2012) offer an important way forward to understanding island vulnerability in the absence of certainty in model-based scenarios.

Island vulnerability is often a function of four key stressors: physical, socioeconomic, socio-ecological, and climate-induced, whose reinforcing mechanisms are important in determining the magnitude of impacts. Geophysical characteristics of islands (see Table 29-2; Figure 29-1) create inherent physical vulnerabilities. Thus, for example the Azores (Portugal) face seismic, landslide, and tsunami risks (Coutinho et al., 2009). Socioeconomic vulnerabilities are related to ongoing challenges of managing urbanization, pollution, and sanitation, both in small island states and non-sovereign islands as highlighted by Storey and Hunter (2010) in Kiribati, López-Marrero and Yarnal (2010) in Puerto Rico, and in Mayotte, France (Le Masson and Kelman, 2011). Socio-ecological stresses, such as habitat loss and degradation, invasive species (described in Sax and Gaines, 2008), overexploitation, pollution, human encroachment, and disease can harm biodiversity (Kingsford et al., 2009; Caujape-Castells et al., 2010), and reduce the ability of socio-ecological systems to bounce back after shocks.

To understand climate vulnerability on islands, it is necessary to assess all of these dimensions of vulnerability (Rasmussen et al., 2011). For example, with individual ecosystems such as coral reef ecosystems, those already under stress from non-climate factors are more at risk from climate change than those that are unstressed (Hughes et al., 2003; Maina et al., 2011). Evidence is starting to emerge that shows the same applies at the island scale. In Majuro atoll (Marshall Islands), 34 to 37 years of aerial photography shows that socio-ecological stress is exacerbating shoreline change associated with SLR, especially on the lagoon side of islands (Ford, 2012; see also Section 29.3.1.1). Islands faced with multiple stressors can therefore be assumed to be more at risk from climate impacts.

Table 29-4 | Selected key risks and potential for adaptation for small islands from the present day to the long term.



Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe / Risk & potential for adaptation
Loss of livelihoods, coastal settlements, infrastructure, ecosystem services, and economic stability (*high confidence*) [29.6, 29.8, Figure 29-4]	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Maintenance and enhancement of ecosystem functions and services and of water and food security • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		
Decline and possible loss of coral reef ecosystems in small islands through thermal stress (*high confidence*) [29.3.1.2]	Limited coral reef adaptation responses; however, minimizing the negative impact of anthrogopenic stresses (ie: water quality change, destructive fishing practices) may increase resilience.		
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas (*high confidence*) [29.4, Table 29-1; WGI AR5 13.5, Table 13.5]	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		

Despite the limited ability of continental scale models to predict climate risks for specific islands, or the limited capacity of island vulnerability indicators, scenario based damage assessments can be undertaken. Storm surge risks have been effectively modeled for the Andaman and Nicobar Islands (Kumar et al., 2008). Rainfall-induced landslide risk maps have been produced for both Jamaica (Miller, S. et al., 2009) and the Chuuk Islands (Federated States of Micronesia; Harp et al., 2009). However, the probability of change in frequency and severity of extreme rainfall events and storm surges remains poorly understood for most small islands. Other risks, such as the climate change-driven health risks from the spread of infectious disease, loss of settlements and infrastructure, and decline of ecosystems that affect island economies, livelihoods, and human well-being also remain under-researched. Nevertheless, it is possible to consider these risks along with the threat of rising sea level and suggest a range of contemporary and future adaptation issues and prospects for small islands (see Table 29-4).

29.6.2. Practical Experiences of Adaptation on Small Islands

There is disagreement about whether islands and islanders have successfully adapted to past weather variability and climate change. Nunn (2007) argues that past climate changes have had a "crisis effect" on prehistoric societies in much of the Pacific Basin. In contrast, a variety of studies argue that past experiences of hydro-meteorological extreme events have enabled islands to become resilient to weather extremes (Barnett, 2001). Resilience appears to come from both a belief in their own capacity (Adger and Brown, 2009; Kuruppu and Liverman, 2011), and a familiarity with their environment and understanding of what is needed to adapt (Tompkins et al., 2009; Le Masson and Kelman, 2011). For example, compared to communities in the larger countries of Madagascar, Tanzania, and Kenya, the Indian Ocean islands (Seychelles and Mauritius) were found to have: comparatively high capacity to anticipate change and prepare strategies; self-awareness of human impact on environment; willingness to change occupation; livelihood diversity; social capital; material assets; and access to technology and infrastructure—all of which produced high adaptive capacity (Cinner et al., 2012). Despite this resilience, islands are assumed to be generically vulnerable to long term future climate change (Myers, 2002; Parks and Roberts, 2006).

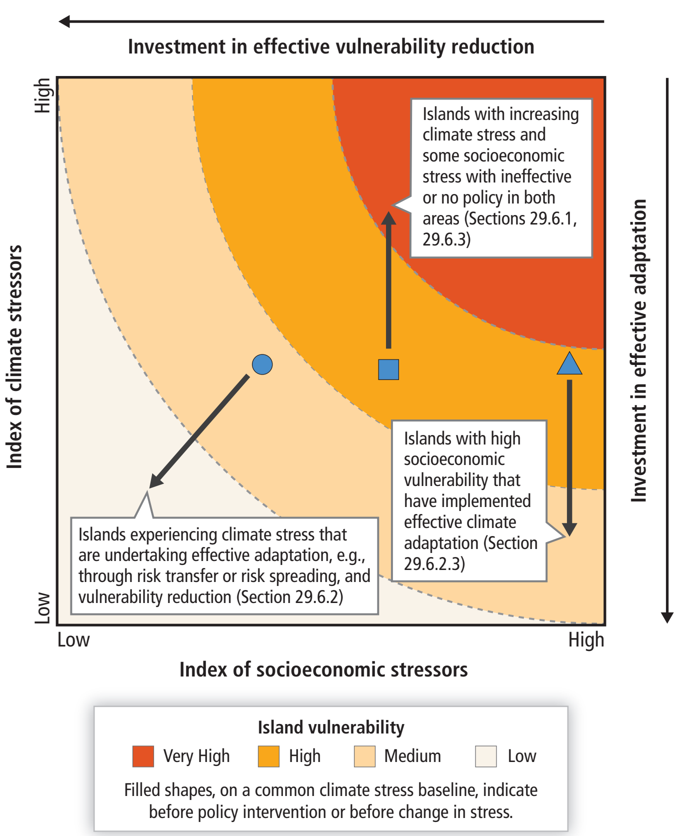


Figure 29-5 | The impact of alternative climate change adaptation actions or policies.

There are many ways in which *in situ* climate adaptation can be undertaken: reducing socioeconomic vulnerabilities, building adaptive capacity, enhancing disaster risk reduction, or building longer term climate resilience (e.g., see McGray et al., 2007; Eakin et al., 2009). Figure 29-5 highlights the implications of the various options. Not all adaptations are equally appropriate in all contexts. Understanding the baseline conditions and stresses (both climate and other) are important in understanding which climate change adaptation option will generate the greatest benefits. On small islands where resources are often limited, recognizing the starting point for action is critical to maximizing the benefits from adaptation. The following section considers the benefits of pursuing the various options.

29.6.2.1. Building Adaptive Capacity with Traditional Knowledge, Technologies, and Skills on Small Islands

As in previous IPCC assessments, there is continuing strong support for the incorporation of indigenous knowledge into adaptation planning. However, this is moderated by the recognition that current practices alone may not be adequate to cope with future climate extremes or trend changes. The ability of a small island population to deal with current climate risks may be positively correlated with the ability to adapt to future climate change, but evidence confirming this remains limited (such as Lefale, 2010). Consequently, this section focuses on evidence for adaptive capacity that reduces vulnerability to existing stressors, enables adaptation to current stresses, and supports current disaster risk management.

Traditional knowledge has proven to be useful in short-term weather forecasting (e.g., Lefale, 2010) although evidence is inconclusive on local capacity to observe long-term climate change (e.g., Hornidge and Scholtes, 2011). In Solomon Islands, Lauer and Aswani (2010) found mixed ability to detect change in spatial cover of seagrass meadows. In Jamaica, Gamble et al. (2010) reported a high level of agreement between farmers' perception of increasing drought incidence and statistical analysis of precipitation and vegetation data for the area. In this case farmers' perceptions clearly validated the observational data and vice versa. Despite some claims that vulnerability reduction in indigenous communities in small islands may be best tackled by combining indigenous and Western knowledge in a culturally compatible and sustainable manner (Mercer et al., 2007), given the small number of studies in this area, there is not sufficient evidence to determine the effectiveness and limits to the use of traditional methods of weather forecasting under climate change on small islands.

Traditional technologies and skills can be effective for current disaster risk management but there is currently a lack of supporting evidence to suggest that they will be equally appropriate under changing cultural conditions and future climate changes on islands. Campbell (2009) identified that traditional disaster reduction measures used in Pacific islands focused around maintaining food security, building community cooperation, and protecting settlements and inhabitants. Examples of actions to maintain food security include: the production and storage of food surpluses, such as yam and breadfruit buried in leaf-lined pits to ferment; high levels of agricultural diversity to minimize specific damage to any one crop; and the growth of robust famine crops, unused in times of plenty that could be used in emergencies (Campbell, 2009). Two discrete studies from Solomon Islands highlight the importance of traditional patterns of social organization within communities to support food security under social and environmental change (Reenberg et al., 2008; Mertz et al., 2010). In both studies the strategy of relying on traditional systems of organization for farming and land use management have been shown to work effectively—largely as there has been little cultural and demographic change. Nonetheless there are physical and cultural limits to traditional disaster risk management. In relation to the ability to store surplus production on atoll islands, on Rongelap in the Marshall Islands, surpluses are avoided, or are redistributed to support community bonds (Bridges and McClatchey, 2009). Further, traditional approaches that Pacific island communities have used for survival for millennia (such as building elevated settlements and resilient structures, and working collectively) have been abandoned or forgotten due to processes of globalization, colonialism, and development (Campbell, 2009). Ongoing processes of rapid urbanization and loss of language and tradition suggest that traditional approaches may not always be efficacious in longer term adaptation.

Traditional construction methods have long been identified across the Pacific as a means of reducing vulnerability to tropical cyclones and floods in rural areas. In Solomon Islands traditional practices include: elevating concrete floors on Ontong Java to keep floors dry during heavy rainfall events; building low, aerodynamic houses with sago palm leaves as roofing material on Tikopia as preparedness for tropical cyclones; and in Bellona local perceptions are that houses constructed from modern materials and practices are more easily destroyed by tropical cyclones, implying that traditional construction methods are perceived to be more resilient in the face of extreme weather (Rasmussen et al., 2009). In parallel, Campbell (2009) documents the characteristics of traditional building styles (in Fiji, Samoa, and Tonga) where relatively steep hipped roofs, well bound connections and joints, and airtight spaces with few windows or doors offer some degree of wind resistance. Traditional building measures can also reduce damages associated with earthquakes, as evidenced in Haiti (Audefroy, 2011). By reducing damage caused by other stresses (such as earthquakes), adaptive capacity is more likely to be maintained. The quality of home construction is critical to its wind resistance. If inadequately detailed, home construction will fail irrespective of method. Although some traditional measures could be challenged as potentially risky—for example, using palm leaves, rather than metal roofs as a preparation for tropical cyclone impacts—the documentation of traditional approaches, with an evaluation of their effectiveness remains urgently needed. Squatter settlements in urban areas, especially on steep hillsides in the Caribbean, often use poor construction practices frequently driven by poverty and inadequate building code enforcement (Prevatt et al., 2010).

Traditional systems appear less effective when multiple civilization-nature stresses are introduced. For example, in Reunion and Mayotte, population growth, and consequent rises in land and house prices, have led low-income families to settle closer to hazardous slopes that are prone to landslides and to river banks which are prone to flooding (Le Masson and Kelman, 2011). Traditional belief systems can also limit adaptive capacity. Thus, for example, in two Fijian villages, approximately half of survey respondents identified divine will as the cause of climate change (Lata and Nunn, 2012). These findings reinforce earlier studies in Tuvalu (Mortreux and Barnett, 2009), and more widely across the Pacific (Barnett and Campbell, 2010). The importance of taking into account local interests and traditional knowledge in adaptation in small islands is emphasized by Kelman and West (2009) and McNamara and Westoby (2011), yet evidence does not yet exist that reveals the limits to such knowledge, such as in the context of rapid socio-ecological change, or the impact of belief systems on adaptive capacity.

While there is clear evidence that traditional knowledge networks, technologies, and skills can be used effectively to support adaptation in certain contexts, the limits to these tools are not well understood. To date research in the Pacific and Caribbean dominates small island climate change work. More detailed studies on small islands in the central and western Indian Ocean, the Mediterranean, and the central and eastern Atlantic would improve understanding on this topic.

29.6.2.2. Addressing Risks on Small Islands

Relative to other areas, small islands are disproportionately affected by current hydro-meteorological extreme events, both in terms of the percentage of the population affected and losses as a percentage of GDP (Anthoff et al., 2010; Table 29-5). Under climate change the risks of damage and associated losses are expected to continue to rise (Nicholls and Cazenave, 2010). Yet much of the existing literature on climate risk in small islands does not consider how to address high future risks, but instead focuses on managing present-day risks through risk transfer, risk spreading, or risk avoidance. Risk transfer is largely undertaken through insurance; risk spreading through access to and use of common property resources, livelihood diversification, or mutual support through networks (see Section 29.6.2.3); and risk avoidance through structural engineering measures or migration (see Section 29.6.2.4).

Risk transfer through insurance markets has had limited uptake in small islands, as insurance markets do not function as effectively as they do in larger locations, in part owing to a small demand for the insurance products (Heger et al., 2008). In the case of insurance for farmers, researchers found that a lack of demand for insurance products (in their study countries: Grenada, Jamaica, Fiji, and Vanuatu) meant an under-supply of customized food insurance products, which in turn contributed to a lack of demand for insurance (Angelucci and Conforti, 2010). Alternatives exist such as index-based schemes that provide payouts based on the crossing of a physical threshold, for example, when rainfall

Table 29-5 | Top ten countries in the Asia–Pacific region based on absolute and relative physical exposure to storms and impact on GDP (between 1998 and 2009; after Tables 1.10 and 1.11 of ESCAP and UNISDR, 2010).

Rank	Absolute exposure (millions affected)	Relative exposure (% of population affected)	Absolute GDP loss (US$ billions)	Loss (% of GDP)
1	Japan (30.9)	Northern Mariana Islands (58.2)	Japan (1,226.7)	Northern Mariana Islands (59.4)
2	Philippines (12.1)	Niue (25.4)	Republic of Korea (35.6)	Vanuatu (27.1)
3	China (11.1)	Japan (24.2)	China (28.5)	Niue (24.9)
4	India (10.7)	Philippines (23.6)	Philippines (24.3)	Fiji (24.1)
5	Bangladesh (7.5)	Fiji (23.1)	Hong Kong (13.3)	Japan (23.9)
6	Republic of Korea (2.4)	Samoa (21.4)	India (8.0)	Philippines (23.9)
7	Myanmar (1.2)	New Caledonia (20.7)	Bangladesh (3.9)	New Caledonia (22.4)
8	Vietnam (0.8)	Vanuatu (18.3)	Northern Mariana Islands (1.5)	Samoa (19.2)
9	Hong Kong (0.4)	Tonga (18.1)	Australia (0.8)	Tonga (17.4)
10	Pakistan (0.3)	Cook Islands (10.5)	New Caledonia (0.7)	Bangladesh (5.9)

Note: Small islands are highlighted in yellow.

drops below a certain level, rather than on drought damage sustained (Linnerooth-Bayer and Mechler, 2009). The potential for index-based insurance for climate stressors on islands is under-researched and there remains limited evidence of the long-term effectiveness of index-based or pooled-risk insurance in supporting household level adaptation. Small island governments also face expensive climate risk insurance. The Caribbean Catastrophe Risk Insurance Facility (CCRIF), which has been operating since 2007, pools Caribbean-wide country-level risks into a central, more diversified risk portfolio—offering lower premiums for participating national governments (CCRIF, 2008). The potential for a similar scheme in the Pacific is being explored (ADB, 2009; Cummins and Mahul, 2009).

Risk can be spread socially, for example, through social networks and familial ties (see also Section 29.6.2.3), or ecologically, for example, by changing resource management approach. Social networks can be used to spread risk among households. In Fiji, after Tropical Cyclone Ami in 2003, households whose homes were not affected by the cyclone increased their fishing effort to support those whose homes were damaged (Takasaki, 2011)—mutual support formed a central pillar for community-based adaptation. In the case of natural systems, risks can be spread through enhancing representation of habitat types and replication of species, for example, through the creation of marine protected areas, around key refuges that protect a diversity of habitat, that cover an adequate proportion of the habitat and that protect critical areas such as nursery grounds and fish spawning aggregation areas (McLeod et al., 2009). Locally Managed Marine Areas—which involve the local community in the management and protection of their local marine environment—have proven to be effective in increasing biodiversity, and in reducing poverty in areas dependent on marine resources in several Pacific islands (Techera, 2008; Game et al., 2011). By creating a network of protected areas supported by local communities the risks associated with some forms of climate change can be spread and potentially reduced (Mills et al., 2010) although such initiatives may not preserve thermally sensitive corals in the face of rising SST.

Risk avoidance through engineered structures can reduce risk from some climate-related hazards (*medium evidence*, *medium agreement*). In Jamaica, recommendations to reduce rainfall-driven land surface movements resulting in landslides include: engineering structures such as soil nailing, gabion baskets (i.e., cages filled with rocks), rip rapped surfaces (i.e., permanent cover with rock), and retaining walls together with engineered drainage systems (Miller, S. et al., 2009). Engineering principles to reduce residential damage from hurricanes have been identified, tested, and recommended for decades in the Caribbean. However, expected levels of success have often not been achieved owing to inadequate training of construction workers, minimal inspection of new buildings, and lack of enforcement of building code requirements (Prevatt et al., 2010). Some island states do not even have the technical or financial capacity to build effective shore protection structures, as highlighted by a recent assessment in south Tarawa, Kiribati (Duvat, 2013).

In addition, not all engineered structures are seen as effective risk avoidance mechanisms. In the Azores archipelago, a proliferation of permanent engineered structures along the coastline to prevent erosion have resulted in a loss of natural shoreline protection against wave erosion (Calado et al., 2011). In Barbados it is recognized that seawalls can protect human assets in areas prone to high levels of erosion; however, they can also cause sediment starvation in other areas, interfere with natural processes of habitat migration, and cause coastal squeeze, which may render them less desirable for long-term adaptation (Mycoo and Chadwick, 2012; see also Section 5.4.2.1). To reduce erosion risk an approach with less detrimental downstream effects that also supports tourism is beach nourishment. This is increasingly being recommended, for example, in the Caribbean (Mycoo and Chadwick, 2012), the Mediterranean (Anagnostou et al., 2011), and western Indian Ocean (Duvat, 2009). Beach nourishment, however, is not without its challenges, as requirements such as site-specific oceanographic and wave climate data, adequate sand resources, and critical engineering design skills may not be readily available in some small islands.

29.6.2.3. Working Collectively to Address Climate Impacts on Small Islands

More attention is being focused on the relevance and application of community-based adaptation (CBA) principles to island communities, to facilitate adaptation planning and implementation (Warrick, 2009; Kelman et al., 2011) and to tackle rural poverty in resource-dependent communities (Techera, 2008). CBA research is focusing on empowerment that helps people to help themselves, for example, through marine catch monitoring (Breckwoldt and Seidel, 2012), while addressing local priorities and building on local knowledge and capacity. This approach to adaptation is being promoted as an appropriate strategy for small islands, as it is something done "with" rather than "to" communities (Warrick, 2009). Nonetheless externally driven programs to encourage community-level action have produced some evidence of effective adaptation. Both Limalevu et al. (2010) and Dumaru (2010) describe the outcomes of externally led pilot CBA projects (addressing water security and coastal management) implemented in villages across Fiji, notably more effective management of local water resources through capacity building; enhanced knowledge of climate change; and the establishment of mechanisms to facilitate greater access to technical and financial resources from outside the community. More long-term monitoring and evaluation of the effectiveness of community level action is needed.

Collaboration between stakeholders can lessen the occurrence of simple mistakes that can reduce the effectiveness of adaptation actions (*medium evidence*, *medium agreement*). Evidence from the eastern Caribbean suggests that adaptations taken by individual households to reduce landslide risk—building simple retaining walls—can be ineffective compared to community-level responses (Anderson et al., 2011). Landslide risk can be significantly reduced through better hillside drainage. In the eastern Caribbean, community groups, with input from engineers, have constructed these networks of drains to capture surface runoff, household roof water, and gray water. Case studies from Fiji and Samoa in which multi-stakeholder and multi-sector participatory approaches were used to help enhance resilience of local residents to the adverse impacts of disasters and climate change (Gero et al., 2011) further support this view. In the case of community-based disaster risk reduction (CBDRR), Pelling (2011) notes that buy-in from local and municipal governments is needed, as well as strong preexisting relationships founded on routine daily activities, to make CBDRR effective. Research from both Solomon Islands and the Cayman Islands reinforce the conclusion that drivers of community resilience to hazard maps closely onto factors driving successful governance of the commons, that is, community cohesion, effective leadership, and community buy-in to collective action (Tompkins et al., 2008; Schwarz et al., 2011). Where community organizations are operating in isolation, or where there is limited coordination and collaboration, community vulnerability is expected to increase (Ferdinand et al., 2012). Strong local networks, and trusting relationships between communities and government, appear to be key elements in adaptation, in terms of maintaining sustainable agriculture and in disaster risk management (*medium evidence*, *high agreement*).

All of these studies reinforce the earlier work of Barnett (2001), providing empirical evidence that supporting community-led approaches to disaster risk reduction and hazard management may contribute to greater community engagement with anticipatory adaptation. However, it is not yet possible to identify the extent to which climate resilience is either a coincidental benefit of island lifestyle and culture, or a purposeful approach, such as the community benefits gained from reciprocity among kinship groups (Campbell, 2009).

29.6.2.4. Addressing Long-Term Climate Impacts and Migration on Small Islands

SLR poses one of the most widely recognized climate change threats to low-lying coastal areas on islands (Section 29.3.1). However, long-term climate impacts depend on the type of island (see Figure 29-1) and the adaptation strategy adopted. Small island states have 16% of their land area in low elevation coastal areas (<10 m) as opposed to a global average of 2%, and the largest proportion of low-elevation coastal urban land area: 13% (along with Australia and New Zealand), in contrast to the global average of 8% (McGranahan et al., 2007). Statistics like these underpin the widely held view about small islands being "overwhelmed" by rising seas associated with SLR (Loughry and McAdam, 2008; Laczko and Aghazarm, 2009; Yamamoto and Esteban, 2010; Berringer, 2012; Dema, 2012; Gordon-Clark, 2012; Lazrus, 2012). Yet there remains *limited evidence* as to which regions (Caribbean, Pacific and Indian Oceans, West African islands) will experience the largest SLR (Willis and Church, 2012) and which islands will experience the worst climate impacts. Nicholls et al. (2011) have modeled impacts of 4°C warming, producing a 0.5 to 2.0 m SLR, to assess the impacts on land loss and migration. With no adaptation occurring, they estimate that this could produce displacement of between 1.2 and 2.2 million people from the Caribbean and Indian and Pacific Oceans. More research is needed to produce *robust agreement* on the impact of SLR on small islands, and on the range of adaptation strategies that could be appropriate for different island types under those scenarios. Research into the possible un-inhabitability of islands has to be undertaken sensitively to avoid short-term risks (i.e., to avoid depopulation and ultimately island abandonment) associated with a loss of confidence in an island's future (McNamara and Gibson, 2009; McLeman, 2011).

Owing to the high costs of adapting on islands, it has been suggested that there will be a need for migration (Biermann and Boas, 2010; Gemenne, 2011; Nicholls et al., 2011; Voccia 2012). Relocation and displacement are frequently cited as outcomes of SLR, salinization, and land loss on islands (Byravan and Rajan, 2006; Kolmannskog and Trebbi, 2010; see also Section 29.3.3.3). Climate stress is occurring at the same time as the growth in rural to urban migration. The latter is leading to squatter settlements that strain urban infrastructure—notably sewerage, waste management, transport, and electricity (Connell and Lea, 2002; Jones, 2005). Urban squatters on islands often live in highly exposed locations, lacking basic amenities, leaving them highly vulnerable to climate risks (Baker, 2012). However, a lack of research in this area makes it difficult to draw clear conclusions on the impact of climate change on the growing number of urban migrants in islands.

Recent examples of environmental stress-driven relocation and displacement provide contemporary analogs of climate-induced migration. Evidence of post-natural disaster migration has been documented in the Caribbean in relation to hurricanes (McLeman and Hunter, 2010) and in the Carteret Islands, Papua New Guinea, where during an exceptionally high inundation event in 2008 (see Section 29.5.1.1) islanders sought refuge on neighboring Bougainville Island (Jarvis, 2010). Drawing any strong conclusions from this literature is challenging, as there is little understanding of how to measure the effect of the environmental signal in migration patterns (Krishnamurthy, 2012; Afifi et al., 2013). Although the example of the Carteret Islands cannot be described as evidence of adaptation to climate change, it suggests that under some extreme scenarios island communities may need to consider relocating in the future (Gemenne, 2011). In reality, financial and legal barriers are expected to inhibit significant levels of international environmentally induced migration in the Pacific (Barnett and Chamberlain, 2010).

29.6.3. Barriers and Limits to Adaptation in Small Island Settings

Since publication of the SAR in 1996, significant barriers to climate change adaptation strategies in island settings have been discussed in considerable detail. Barriers include inadequate access to financial, technological, and human resources; issues related to cultural and social acceptability of measures; constraints imposed by the existing political and legal framework; the emphasis on island development as opposed to sustainability; a tendency to focus on addressing short-term climate variability rather than long-term climate change; and community preferences for "hard" adaptation measures such as seawalls instead of "soft" measures such as beach nourishment (Sovacool, 2012). Heger et al. (2008) recognized that more diversified economies have more robust responses to climate stress, yet most small islands lack economies of scale in production, thus specializing in niche markets and developing monocultures (e.g., sugar or bananas). Non-sovereign island states face additional exogenous barriers to adaptation. For example, islands such as Réunion and Mayotte benefit from the provision of social services somewhat similar to what obtains in the Metropole, but not the level of enforcement of building codes and land use planning as in France (Le Masson and Kelman, 2011). Owing to their nature and complexity, these constraints will not be easily eliminated in the short term and will require ongoing attention if their impact is to be minimized over time. Exogenous factors such as the comparatively few assessments of social vulnerability to climate change, adaptation potential, or resilience for island communities (Barnett, 2010) limit current understanding. In part this is due to the particularities of islands—both their heterogeneity and their difference from mainland locations—as well as the limitations of climate models in delivering robust science for small islands. It remains the case that, 13 years after Nurse et al. (2001) noted that downscaled global climate models do not provide a complete or necessarily accurate picture of climate vulnerabilities on islands, there is still little climate impacts research that reflects local concerns and contexts (Barnett et al., 2008).

Although lack of access to adequate financial, technological and human resources is often cited as the most critical constraint, experience has shown that endogenous factors such as culture, ethics, knowledge, and attitudes to risk are important in constraining adaptation. Translating the word "climate" into Marshallese implies cosmos, nature, and culture as well as weather and climate (Rudiak-Gould, 2012). Such cultural misunderstandings can create both barriers to action and novel ways of engaging with climate change. The lack of local support (owing to encroachment on traditional lands) for the development of new infiltration galleries to augment freshwater supply on Tarawa atoll, Kiribati, highlights the importance of social acceptability (Moglia et al., 2008a,b). Such considerations have led to the conclusion that there is still much to be learned about the drivers of past adaptation and how "mainstreaming" into national programs and policies, widely acclaimed to be a virtually indispensable strategy, can practically be achieved (Mercer et al., 2007; Adger et al., 2009; Mertz et al., 2009).

Notwithstanding the extensive and ever-growing body of literature on the subject, there is still a relatively low level of awareness and understanding at the community level on many islands about the nature of the threat posed by climate change (Nunn, 2009). Even where the threat has been identified, it is often not considered an urgent issue, or a local priority, as exemplified in Malta (Akerlof et al., 2010) and Funafuti, Tuvalu (Mortreux and Barnett, 2009). Lack of awareness, knowledge, and understanding can function as an effective barrier to the implementation and ultimate success of adaptation programs. This is borne out in both Fiji and Kiribati, where researchers found that spiritual beliefs, traditional governance mechanisms, and a short-term approach to planning were barriers to community engagement and understanding of climate change (Kuruppu, 2009; Lata and Nunn, 2012). Although widely acknowledged to be critical in small islands, few initiatives pay little more than perfunctory attention to the importance of awareness, knowledge, and understanding in climate change adaptation planning. Hence, the renewed call for adaptation initiatives to include and focus directly on these elements on an ongoing basis (e.g., Crump, 2008; Kelman and West, 2009; Kelman, 2010; Gero et al., 2011; Kuruppu and Liverman, 2011) is timely, if these barriers are to be eventually removed.

29.6.4. Mainstreaming and Integrating Climate Change into Development Plans and Policies

There is a growing body of literature that discusses the benefits and possibilities of mainstreaming or integrating climate change policies in development plans. Various mechanisms through which development agencies as well as donor and recipient countries can seek to capitalize on the opportunities to mainstream are beginning to emerge (see, e.g., Klein et al., 2007; Mertz et al., 2009). Agrawala and van Aalst (2008) provide examples, from Fiji and elsewhere, of where synergies (and trade-offs) can be found in integrating adaptation to climate change into development cooperation activities, notably in the areas of disaster risk reduction, community-based approaches to development, and building adaptive capacity. Boyd et al. (2009) support the need for more rapid integration of adaptation into development planning, to ensure that adaptation is not side-lined, or treated separately from sectoral policies. Although there are synergies and benefits to be derived from the integration of climate change and development policies, care is needed to avoid institutional overlaps, and differences in language and approach— which can give rise to conflict (Schipper and Pelling, 2006). Overall, there appears to be an emerging consensus around the views expressed by Swart and Raes (2007) that climate change and development strategies should be considered as complementary, and that some elements such as land and water management and urban, peri-urban, and rural planning provide important adaptation, development, and mitigation opportunities. Although the potential to deliver such an integrated approach may be reasonably strong in urban centers on islands, there appears to be limited capacity to mainstream climate change adaptation into local decision making in out-lying islands or peripheral areas (Nunn et al., 2013).

29.7. Adaptation and Mitigation Interactions

GHG emissions from most small islands are negligible in relation to global emissions, yet small islands will most probably be highly impacted by climate change (Srinivasan, 2010). However, many small island governments and communities have chosen to attempt to reduce their GHG emissions because of the cost and the potential co-benefits and synergies. Malta and Cyprus are obliged to do so in line with EU climate and energy policies. This section considers some of the interlinkages between adaptation and mitigation on small islands and the potential synergies, conflicts, trade-offs, and risks. Unfortunately there is relatively little research on the emissions reduction potential of small islands, and far less on the interlinkages between climate change adaptation and emissions reduction in small islands. Therefore in this section a number of assumptions are made about how and where adaptation and mitigation actions interact.

29.7.1. Assumptions/Uncertainties Associated with Adaptation and Mitigation Responses

Small islands are not homogeneous. Rather they have diverse geophysical characteristics and economic structures (see Table 29-2; Figure 29-1). Following Nunn (2009), the combination of island geography and economic types informs the extent to which adaptation and mitigation actions might interact. The geography and location of islands affect their sensitivity to hydro-meteorological and related hazards such as cyclones, floods, droughts, invasive alien species, vector-borne disease, and landslides. On the other hand, the capacity of island residents to cope is often related to income levels, resources endowment, technology, and knowledge (see Section 29.6.2).

The potential for mitigation and emissions reductions in islands depends to a large extent on their size and stage of economic development. In the small and less developed islands key "mitigation" sectors including energy, transport, industry, built environment, agriculture, forestry, or waste management sectors are generally relatively small (IPCC, 2007; Swart and Raes, 2007). Hence opportunities for emissions reductions are usually quite limited and are mostly associated with electricity generation and utilization of vehicles. More mitigation opportunities should exist in more economically advanced and larger islands that rely on forms of production that utilize fossil fuels, including manufacturing, and where vehicle usage is extensive and electricity-driven home appliances, such as air conditioners and water heaters, are extensively used.

In the absence of significant mitigation efforts at the global scale, adaptation interventions could become very costly and difficult to implement, once certain thresholds of change are reached (Birkmann, 2011; Nelson, 2011). Nicholls et al. (2011) make a similar observation with respect to coastal protection as a response to SLR. They suggest that if global mean temperatures increase by around 4°C (which may lead to sea level rise between 0.5 m and 2 m) the likelihood of successful coastal protection in some locations, such as low-lying small islands, will be low. Consequently, it is argued that the relocation of communities would be a likely outcome in such circumstances (Nicholls et al., 2011).

29.7.2. Potential Synergies and Conflicts

IPCC (2007) suggest that adaptation and mitigation interactions occur in one of four main ways: adaptations that result in GHG emissions reduction; mitigation options that facilitate adaptation; policy decisions that couple adaptation and mitigation effects; and trade-offs and synergies between adaptation and mitigation. Each of these opportunities is considered using three examples: coastal forestry, energy supply, and tourism.

Small islands have relatively large coastal zones (in comparison to land area) and most development (as well as potential mitigation and adaptation activities) are located in the coastal zone. Coastal ecosystems (coral reefs, seagrasses, and mangroves) play an important role in protecting coastal communities from wave erosion, tropical cyclones, storm surges, and even moderate tsunami waves (Cochard et al., 2008). Although coastal forests—including both endemic and exotic species, especially mangroves—are seen as effective adaptation options ("bioshields"; Feagin et al., 2010) in the coastal zones, they also play an important role in mitigation as carbon sinks (van der Werf et al., 2009). Thus, the management and conservation of mangrove forests has the potential to generate synergies between climate change adaptation and mitigation. However, despite this knowledge, population, development, and agricultural pressures have constrained the expansion of island forest carbon stocks (Fox et al., 2010) while Gilman et al. (2008) note that such pressures can also reduce the buffering capacity of coastal vegetation systems.

Renewable energy resources on small islands have only recently been considered within the context of long-term energy security (Chen et al., 2007; Praene et al., 2012). Stuart (2006) speculates that the lack of uptake of renewable technologies to date might be due to historical commitments to conventional fossil fuel-based infrastructure, and a lack of resources to undertake research and development of alternatives. Those islands that have introduced renewable energy technologies have often done so with support from international development agencies (Dornan, 2011). Despite this, there remain significant barriers to the wider institutionalization of renewable technologies in small islands. Research in Europe and the USA has shown the mitigation and cost savings benefits of Energy Service Companies (ESCOs): companies that enter into medium- to long-term performance-based contracts with energy users, invest in energy-efficiency measures in buildings and firms, and profit from the ensuing energy savings measures for the premises (see, e.g., Steinberger et al., 2009). Potential benefits exist in creating the opportunity for ESCOs to operate in small islands. Preliminary evidence from Fiji suggests that if the incentive mechanisms can be resolved, and information asymmetries between service providers and users can be aligned, ESCOs could provide an opportunity to expand renewable technologies (Dornan, 2009). IPCC (2011) presents examples of opportunities for renewable energy, including wind energy sources, as deployed in the Canary Islands.

The transition toward renewable energy sources away from fossil fuel dependence has been partly driven by economic motives, notably to avoid oil price volatility and its impact. The development of hydro-power (in Fiji, for example) necessitates protection and management of the water catchment zones, and thus could lead to improved management of the water resources—a critical adaptation consideration for areas expected to experience a decrease in average rainfall as a result of climate change. While the cost effectiveness of renewable technologies is critical, placing it within the context of water adaptation could enhance project viability (Dornan, 2009). Cost-benefit analyses have shown that in southeast Mediterranean islands photovoltaic generation and storage systems may be more cost-effective than existing thermal power stations (Kaldellis, 2008; Kaldellis et al., 2009).

Energy prices in small islands are among the highest anywhere in the world, mainly because of their dependence on imported fossil fuel, and limited ability to reap the benefits of economies of scale including bulk buying. Recent studies show that the energy sectors in small islands may be transformed into sustainable growth entities mainly through the judicious exploitation of renewable energy sources, combined with the implementation of energy-efficiency measures (van Alphen et al., 2008; Banuri, 2009; Mohanty, 2012; Rogers et al., 2012). Realizing the potential for such transformation, the countries comprising the Alliance of Small Island States (AOSIS) launched SIDS Dock, which is intended to function as a "docking station" to connect the energy sector in small island developing states with the international finance, technology, and carbon markets with the objective of pooling and optimizing energy-efficiency goods and services for the benefit of the group. This initiative seeks to decrease energy dependence in small island developing states, while generating financial resources to support low carbon growth and adaptation interventions.

Many small islands rely heavily on the foreign exchange from tourism to expand and develop their economies, including the costs of mitigation and adaptation. Tourism, particularly in small islands, often relies on coastal and terrestrial ecosystems to provide visitor attractions and accommodation space. Recognizing the relationship between ecosystem services and tourism in Jamaica, Thomas-Hope and Jardine-Comrie (2007) suggest that sustainable tourism planning should include activities undertaken by the industry, that is, tertiary treatment of waste and reuse of water, as well as composting organic material and investing in renewable energy. Gössling and Schumacher (2010) and others who have examined the linkages between GHG emissions and sustainable tourism argue that the tourism sector (operators and tourists) should pay to promote sustainable tourism, especially where they benefit directly from environmental services sustained by these investments.

29.8. Facilitating Adaptation and Avoiding Maladaptation

Although there is a clear consensus that adaptation to the risks posed by global climate change is necessary and urgent in small islands, the implementation of specific strategies and options is a complex process that requires critical evaluation of multiple factors, if expected outcomes are to be achieved (Kelman and West, 2009; Barnett and O'Neill, 2012). These considerations may include, *inter alia*, prior experience with similar or related threats, efficacy of the strategies or options and their co-benefits, costs (monetary and non-monetary), availability of alternatives, and social acceptability. In addition, previous work (e.g., Adger et al., 2005) has emphasized the relevance of scale as a critical factor when assessing the efficacy and value of adaptation strategies, as the extent to which an option is perceived to be a success, failure, or maladaptive may be conditioned by whether it is being assessed as a response to climate variability (shorter term) or climate change (longer term).

As in other regions, adaptation in islands is locally delivered and context specific (Tompkins et al., 2010). Yet, sectors and communities on small islands are often so intricately linked that there are many potential pathways that may lead to maladaptation, be it via increased GHG emissions, foreclosure of future options, or burdensome opportunity costs on local communities. There is also a concern that some types of interventions may actually be maladaptive. For example, Barnett and O'Neill (2012) suggest that strategies such as resettlement and migration should be regarded as options of "last resort" on islands, as they may actually discourage viable adaptation initiatives, by fostering over-dependence on external support. They further argue that *a priori* acceptance of adaptation as an efficacious option for places like the Pacific Islands may also act as a disincentive for reducing GHG emissions (Barnett and O'Neill, 2012).

Notwithstanding the observations of Barnett and O'Neill (2012), there is a concern that early foreclosure of this option might well prove maladaptive, if location-specific circumstances show such action to be efficacious in the longer term. For example, Bunce et al. (2009) have shown that, as an adaptive response to poverty, young fishers from Rodrigues Island periodically resort to temporary migration to the main capital island, Mauritius, where greater employment prospects exist. The case study of the residents of Nauru, who contemplated resettlement

Frequently Asked Questions

FAQ 29.3 | Is it appropriate to transfer adaptation and mitigation strategies between and within small island countries and regions?

Although lessons learned from adaptation and mitigation experiences in one island or island region may offer some guidance, caution must be exercised to ensure that the transfer of such experiences is appropriate to local biophysical, social, economic, political, and cultural circumstances. If this approach is not purposefully incorporated into the implementation process, it is possible that maladaptation and inappropriate mitigation may result. It is therefore necessary to carefully assess the risk profile of each individual island so as to ensure that any investments in adaptation and mitigation are context specific. The varying risk profiles between individual small islands and small island regions have not always been adequately acknowledged in the past.

in Australia after the collapse of phosphate mining (their only revenue source) in the 1950s, provides helpful insight into the complex social, economic, and cultural challenges associated with environmentally triggered migration (Tabucanon and Opeskin, 2011). Negotiations with the Government of Australia collapsed before a mutually acceptable agreement was reached, and the Nauruans opted to abandon the proposal to relocate (Tabucanon and Opeskin, 2011). Overall, however, it is suggested that states contemplating long-term, off-island migration may wish to consider early proactive planning, as resettlement of entire communities might prove to be socially, culturally, and economically disruptive (Campbell, 2010; McMichael et al., 2012; see also Section 29.3.3.3). A related challenge facing small islands is the need to find the middle ground between resettlement and objective assessment of other appropriate adaptation choices.

Similarly, although insurance is being promoted as an element of the overall climate change response strategy in some island regions, for example, the Caribbean, concerns have been expressed about possible linkages to maladaptation. The potential consequences include the imposition of exorbitant premiums that are beyond the capacity of resource-scarce governments as the perception of climate change risks increase, discriminatory coverage of sectors that may not align with local priorities, and tacit encouragement for the state, individuals, and the private sector to engage in behavior that is not risk-averse, for example, development in hazard-prone areas (Herweijer et al., 2009; Linnerooth-Bayer et al., 2011; Thomas and Leichenko, 2011; van Nostrand and Nevius, 2011). Likewise, although the exploitation of renewable energy is vital to the sustainable development of small islands, more attention needs to be paid to the development of energy storage technologies, if rapid transition from conventional fuels is to be achieved in an efficient manner. This is especially important in the case of intermittent energy sources (e.g., solar and wind), as the cost of current storage technologies can frustrate achievement of full conversion to renewable energy. Thus to avoid the possibility of maladaptation in the sector, countries may wish to consider engaging in comprehensive planning, including considerations relating to energy storage (Krajačić et al., 2010; Bazilian et al., 2011).

Recent studies have demonstrated that opportunities exist in island environments for avoiding maladaptation. Studies have shown that decisions about adaptation choices and their implementation are best facilitated where there is constructive engagement with the communities at risk, in a manner that fosters transparency and trust (van Aalst et al., 2008; López-Marrero, 2010). Further, some analysts argue that adaptation choices are often subjective in nature and suggest that participatory stakeholder involvement can yield valuable information about the priorities and expectations that communities attach to the sector for which adaptation is being sought.

The point is underscored by Moreno and Becken (2009), whose study of the tourism sector on the Mamanuca islands (Fiji) clearly demonstrates that approaches that explicitly integrate stakeholders into each step of the process from vulnerability assessment right through to consideration of alternatives measures can provide a sound basis for assisting destinations with the implementation of appropriate adaptation interventions. This view is supported by Dulal et al. (2009), who argue that the most vulnerable groups in the Caribbean—the poor, elderly, indigenous communities, and rural children—will be at greater risk of being marginalized, if adaptation is not informed by equitable and participatory frameworks.

Other studies reveal that new paradigms whose adoption can reduce the risk of maladaptation in island environments are emerging across various sectors. In the area of natural resource management, Hansen et al. (2010) suggest that the use of protected areas for climate refugia, reduction of non-climate stressors on ecosystems, and adoption of adaptive management approaches, combined with reduction of GHG emissions wherever possible, may prove to be more effective response strategies than traditional conservation approaches. Other strategic approaches, including the implementation of multi-sectoral and cross-sectoral measures, also facilitate adaptation in a more equitable, integrated, and sustainable manner. Similarly, "no-regret" measures such as wastewater recycling, trickle irrigation, conversion to non-fossil fuel-based energy, and transportation which offer collateral benefits with or without the threat of climate change and "low-regret" strategies, which may increase existing operational costs only marginally, are becoming increasingly attractive options to island governments (Gravelle and Mimura, 2008; Heltberg et al., 2009; Howard et al., 2010). Together, these constitute valid risk management approaches, as they are designed to assist communities in making prudent, but necessary decisions in the face of an uncertain future.

Some authors suggest that caution is needed to ensure that donors are not driving the adaptation and mitigation agenda in small islands, as there is a risk that donor-driven adaptation or mitigation may not always address the salient challenges on small islands, and may lead to inadequate adaptation or a waste of scarce resources (Nunn, 2009; Barnett, 2010). Others argue that donor-led initiatives may unintentionally cause enhanced vulnerability by supporting adaptation strategies that are externally derived, rather than optimizing the benefits of local practices that have proven to be efficacious through time (Reenberg et al., 2008; Campbell and Beckford, 2009; Kelman and West, 2009).

29.9. Research and Data Gaps

Several advances have taken place in our understanding of the observed and potential effects of climate change on small islands since the AR4. These cover a range of themes including dynamic downscaling of scenarios appropriate for small islands; impacts of transboundary processes generated well beyond the borders of an individual nation or island; barriers to adaptation in small islands and how they may be overcome; the relationships between climate change adaptation and disaster risk reduction; and the relationships between climate change adaptation, maladaptation, and sustainable development.

It is also evident that much further work is required on these themes in small island situations, especially comparative research. Important information and data gaps and many uncertainties still exist on impacts, vulnerability, and adaptation in small islands. These include:

- **Lack of climate change and socioeconomic scenarios and data at the required scale for small islands**. Although some advances have been made (Taylor et al., 2007; Australian Bureau of Meteorology and CSIRO, 2011a,b), much of the work in the

Caribbean, Pacific and Indian Oceans, and Mediterranean islands is focused at the regional scale rather than being country specific. Because most socioeconomic decisions are taken at the local level, there is a need for a more extensive database of simulations of future small island climates and socioeconomic conditions at smaller spatial scales.

- **Difficulties in detecting and attributing past impacts on small islands to climate change processes.** Further investigation of the observed impacts of weather, climate, and ocean events that may be related to climate change is required to clarify the relative role of climate change and non-climate change drivers.
- **Uncertainty in the projections is not a sufficiently valid reason to postpone adaptation planning in small islands**. In several small islands adaptation is being progressed without a full understanding of past or potential impacts and vulnerability. Although assessment of future impacts is hampered because of uncertainty in climate projections at the local island level, alternative scenarios based on a general understanding of broad trends could be used in vulnerability and sensitivity studies to guide adaptation strategies.
- **Need for a range of climate change-related projections beyond temperature and sea level**. Generally, climate-model projections of temperature and sea level have been satisfactory, but there are strong requirements for projections for other variables that are of critical importance to small islands. These include rainfall and drought, wind direction and strength, tropical storms and wave climate, and recognition that transboundary processes are also significant in a small island context. Although some such work has been undertaken for some parts of the Pacific (Australian Bureau of Meteorology and CSIRO, 2011a,b), similar work still needs to be carried out in other small island regions. In addition, the reliability of existing projections for some of the other parameters needs to be improved and the data should be in suitable formats for use in risk assessments.
- **Need to acknowledge the heterogeneity and complexity of small island states and territories**. Although small islands have several characteristics in common, neither the variety nor complexity of small islands is sufficiently reflected in the literature. Thus, transfer of data and practices from a continental situation, or from one small island state to another, needs to be done with care and in a manner that takes full cognizance of such heterogeneity and complexity.
- **Within-country and -territory differences need to be better understood**. Many of the environmental and human impacts reported in the literature on islands have been attributed to the whole country, when in fact they refer only to the major center or town or region. There is need for more work on rural areas, outer islands, and secondary communities. Several examples of such research have been cited in this chapter. Also it should be noted that some small island states are single islands and others highly fragmented multiple islands.
- **Lack of investment and attention to climate and environmental monitoring frameworks in small islands.** A fundamental gap in the ability to improve empirical understanding of present and future climate change impacts is the lack of climate and environmental monitoring frameworks that in turn hampers the level of confidence with which adaptation responses can be designed and implemented.
- **Economic and social costs of climate change impacts and adaptation options are rarely known.** In small island states and territories the costs of past weather, climate, and ocean events are poorly known and further research is required to identify such costs, and to determine the economic and societal costs of climate change impacts and the costs of adaptation options to minimize those impacts.

The foregoing list is a sample of the gaps, needs, and research agenda that urgently need to be filled for small islands. Although some countries have begun to fill these gaps, this work needs to be replicated and expanded across all island regions to improve the database available for ongoing climate change assessments. Such information would raise the level of confidence in the adaptation planning and implementation process in small islands.

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The Ocean

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Frequently Asked Questions

Executive Summary

The Ocean plays a central role in Earth's climate and has absorbed 93% of the extra energy from the enhanced greenhouse effect and approximately 30% of anthropogenic carbon dioxide (CO_2) from the atmosphere. Regional responses are addressed here by dividing the Ocean into seven sub-regions: High-Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), Coastal Boundary Systems (CBS), Equatorial Upwelling Systems (EUS), Subtropical Gyres (STG), Semi-Enclosed Seas (SES), and the Deep Sea (DS; >1000 m). An eighth region, Polar Seas, is dealt with by Chapter 28. {Figure 30-1; WGI AR5 6.3.1; WGI AR5 Boxes 3.1, 3.8}

Global average sea surface temperatures have increased since both the beginning of the 20th century and the 1950s (certain). The average sea surface temperature (SST) of the Indian, Atlantic, and Pacific Oceans has increased by 0.65°C, 0.41°C, and 0.31°C, respectively, over the period 1950–2009 (*very likely*, *p*-value ≤ 0.05). Changes in the surface temperatures of the ocean basins are consistent with temperature trends simulated by ocean-atmosphere models with anthropogenic greenhouse gas (GHG) forcing over the past century (*high confidence*). Sub-regions within the Ocean also show *robust evidence* of change, with the influence of long-term patterns of variability (e.g., Pacific Decadal Oscillation (PDO); Atlantic Multi-decadal Oscillation (AMO)) contributing to variability at regional scales, and making changes due to climate change harder to distinguish and attribute. {30.3.1; Figure 30-2e-g; Table 30-1; WGI AR5 2.4.2-3, 3.2, 10.4.1, 14}

Uptake of CO_2 has decreased ocean pH (approximately 0.1 unit over 100 years), fundamentally changing ocean carbonate chemistry in all ocean sub-regions, particularly at high latitudes (*high confidence*). The current rate of ocean acidification is unprecedented within the last 65 Ma (*high confidence*), if not the last 300 Ma (*medium confidence*). Warming temperatures, and declining pH and carbonate ion concentrations, represent risks to the productivity of fisheries and aquaculture, and the security of regional livelihoods given the direct and indirect effects of these variables on physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function) and ecosystem processes (e.g., primary productivity, reef building and erosion) (*high confidence*). {6.1.2, 6.2-3, 30.3.2, 30.6; WGI AR5 3.8.2; WGI AR5 Boxes 3.2, 5.3.1}

Regional changes observed in winds, surface salinity, stratification, ocean currents, nutrient availability, and oxygen depth profile in many regions may be a result of anthropogenic GHG emissions (*low* to *medium confidence*). Marine organisms and ecosystems are *likely* to change in response to these regional changes, although evidence is limited and responses uncertain. {6.2-3, 30.3, 30.5; WGI AR5 2.7, 3.3-8, 10.4.2, 10.4.4}

Most, if not all, of the Ocean will continue to warm and acidify, although the rates will vary regionally (*high confidence*). Differences between Representative Concentration Pathways (RCPs) are *very likely* to be minimal until 2040 (*high confidence*). Projected temperatures of the surface layers of the Ocean, however, diverge as the 21st century unfolds and will be 1°C to 3°C higher by 2100 under RCP8.5 than RCP2.6 across most ocean sub-regions. The projected changes in ocean temperature pose serious risks and vulnerabilities to ocean ecosystems and dependent human communities (*robust evidence*, *high agreement*; *high confidence*). {6.5, 30.3.1-2, 30.7.1; Figure 30-2e-g; Table 30-3; WGI AR5 11.3.3, 12.4.7; WGI AR5 Box 1.1}

Rapid changes in physical and chemical conditions within ocean sub-regions have already affected the distribution and abundance of marine organisms and ecosystems. Responses of species and ecosystems to climate change have been observed from every ocean sub-region (*high confidence*). Marine organisms are moving to higher latitudes, consistent with warming trends (*high confidence*), with fish and zooplankton migrating at the fastest rates, particularly in HLSBS regions. Changes to sea temperature have also altered the phenology, or timing of key life-history events such as plankton blooms, and migratory patterns and spawning in fish and invertebrates, over recent decades (*medium confidence*). There is *medium* to *high agreement* that these changes pose significant uncertainties and risks to fisheries, aquaculture, and other coastal activities. Ocean acidification maybe driving similar changes (*low confidence*), although there is *limited evidence* and *low agreement* at present. The associated risks will intensify as ocean warming and acidification continue. {6.3-4, 30.4-5; Table 30-3; Box CC-MB}

Regional risks and vulnerabilities to ocean warming and acidification can be compounded by non-climate related stressors such as pollution, nutrient runoff from land, and over-exploitation of marine resources, as well as natural climate variability (*high confidence*). These influences confound the detection and attribution of the impacts of climate change and ocean acidification on ecosystems yet may also represent opportunities for reducing risks through management strategies aimed at reducing their influence, especially in CBS, SES, and HLSBS. {5.3.4, 18.3.3-4, 30.1.2, 30.5-6}

Recent changes to wind and ocean mixing within the highly productive HLSBS, EBUE, and EUS are *likely* to influence energy transfer to higher trophic levels and microbial processes. There is, however, *limited evidence* and *low agreement* on the direction and magnitude of these changes and their relationship to ocean warming and acidification (*low confidence*). In cases where Net Primary Productivity (NPP) increases or is not consumed (e.g., Benguela EBUE, *low confidence*), the increased transfer of organic carbon to deep regions can stimulate microbial respiration and reduce O_2 levels (*medium confidence*). Oxygen concentrations are also declining in the tropical Pacific, Atlantic, and Indian Oceans (particularly EUS) due to reduced O_2 solubility at higher temperatures, and changes in ocean ventilation and circulation. {6.3.3, 30.3, 30.5.1-2, 30.5.5; Box CC-PP; WGI AR5 3.8.3}

Global warming will result in more frequent extreme events and greater associated risks to ocean ecosystems (*high confidence*). In some cases (e.g., mass coral bleaching and mortality), projected increases will eliminate ecosystems, and increase risks and vulnerabilities to coastal livelihoods and food security (e.g., CBS in Southeast Asia; SES, CBS, and STG in the Indo-Pacific) (*medium* to *high confidence*). Reducing stressors not related to climate change represents an opportunity to strengthen the ecological resilience within these regions, which may help them survive some projected changes in ocean temperature and chemistry. {5.4, 30.5.3-4, 30.5.6, 30.6.1; Figure 30-4; Box CC-CR; IPCC, 2012}

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The highly productive HLSBS in the Northeastern Atlantic has changed in response to warming (*medium evidence*, *high agreement*), with a range of consequences for fisheries. These ecosystems are responding to recent warming, with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganization of fish assemblages (*high confidence*). There is *medium confidence* that these changes will have both positive and negative implications depending on the particular HLSBS fishery and the time frame. {6.4.1.1, 6.5.3, 30.5.1, 30.6.2.1; Boxes CC-MB, 6-1}

EUS, which support highly productive fisheries off equatorial Africa and South America, have warmed over the past 60 years (Pacific EUS: 0.43°C, Atlantic EUS: 0.54°C; *very likely*, *p*-value ≤ 0.05). Although warming is consistent with changes in upwelling intensity, there is *low confidence* in our understanding of how EUS will change, especially in how El Niño-Southern Oscillation (ENSO) and other patterns of variability will interact in a warmer world. The risk, however, of changes to upwelling increases with average global temperature, posing significant uncertainties for dependent ecosystems, communities, and fisheries. {30.5.2; WGI AR5 14.4}

The surface waters of the SES show significant warming from 1982 and most CBS show significant warming since 1950. Warming of the Mediterranean has led to the recent spread of tropical species invading from the Atlantic and Indian Oceans. Projected warming increases the risk of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and the formation of additional hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). In some CBS, such as the East China Sea and Gulf of Mexico, these changes are further influenced by the contribution of nutrients from coastal pollution contributing to the expansion of hypoxic (low O_2) zones. These changes are *likely* to influence regional ecosystems as well as dependent industries such as fisheries and tourism, although there is *low confidence* in the understanding of potential changes and impacts. {5.3.4.3, 30.5.3-4; Table 30-1}

Coral reefs within CBS, SES, and STG are rapidly declining as a result of local stressors (i.e., coastal pollution, overexploitation) and climate change (*high confidence*). Elevated sea temperatures drive impacts such as mass coral bleaching and mortality (*very high confidence*), with an analysis of the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble projecting the loss of coral reefs from most sites globally by 2050 under mid to high rates of ocean warming (*very likely*). {29.3.1.2, 30.5.3-4, 30.5.6; Figure 30-10; Box CC-CR}

The productive EBUE and EUS involve upwelling waters that are naturally high in CO_2 concentrations and low in pH, and hence are potentially vulnerable to ocean warming and acidification (*medium confidence*). There is *limited evidence* and *low agreement* as to how upwelling systems are *likely* to change (*low confidence*). Declining O_2 and shoaling of the aragonite saturation horizon through ocean acidification increase the risk of upwelling water being low in pH and O_2, with impacts on coastal ecosystems and fisheries, as has been seen already (e.g., California Current EBUE). These risks and uncertainties are *likely* to involve significant challenges for fisheries and associated livelihoods along the west coasts of South America, Africa, and North America (*low* to *medium confidence*). {22.3.2.3, 30.3.2.2, 30.5.2, 30.5.5; Boxes CC-UP, CC-PP}

Chlorophyll concentrations measured by satellites have decreased in the STG of the North Pacific, Indian, and North Atlantic Oceans by 9%, 12%, and 11%, respectively, over and above the inherent seasonal and interannual variability from 1998 to 2010 (*high confidence*; *p*-value ≤ 0.05). Significant warming over this period has resulted in increased water column stratification, reduced mixed layer depth, and possibly decreases in nutrient availability and ecosystem productivity (*limited evidence*, *medium agreement*). The short time frame of these studies against well-established patterns of long-term variability leads to the conclusion that these changes are *about as likely as not* due to climate change. {6.3.4, 30.5.6; Table 30-1; Box CC-PP; WGI AR5 3.8.4}

The world's most abundant yet difficult to access habitat, the DS, is changing (*limited evidence*, *medium agreement*), with warming between 700 and 2000 m from 1957 to 2010 *likely* to involve a significant anthropogenic signal (*medium confidence*). Decreased primary productivity of surface waters (e.g., STG) is *likely* to reduce the availability of organic carbon to DS ecosystems. Understanding of the risks of climate change and ocean acidification to the DS is important given the size of the DS region but is limited (*low confidence*). {30.5.7; Figure 30-2; WGI AR5 3.2.4; WGI AR5 Figures 3.2, 3.9}

Changes to surface wind and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy, and mineral extraction (*medium confidence*). Risks to equipment and people may be reduced through the design and use of ocean-based infrastructure, together with the evolution of policy (*medium agreement*). Risks and uncertainties will increase with further climate change. New opportunities as well as risks for shipping, energy, and mineral extraction, and international issues over access and vulnerability, may accompany warming waters, particularly at high latitudes. {10.2.2, 10.4.4, 28.2.6, 28.3.4, 30.3.1, 30.6.2; IPCC, 2012}

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries, as well as benefits (*high agreement*). Climate change is a risk to the sustainability of capture fisheries and aquaculture development, adding to the threats of over-fishing and other non-climate stressors. In EUS and STG, shifts in the distribution and abundance of large pelagic fish stocks will have the potential to create "winners" and "losers" among island nations and economies. There has been a boost in fish stocks of high-latitude fisheries in the HLSBS of the North Pacific and North Atlantic, partly as a result of 30 years of increase in temperature. This is *very likely* to continue, although some fish stocks will eventually decline. A number of practical adaptation options and supporting international policies can minimize the risks and maximize the opportunities. {7.4.2, 7.5.1.1.2, 29.4, 30.6-7}

Adaptation strategies for ocean regions beyond coastal waters are generally poorly developed but will benefit from international legislation and expert networks, as well as marine spatial planning (*high agreement*). Fisheries and aquaculture industries with high technology and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling, and resource assessments. For smaller scale fisheries and developing nations, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. Building strategies that include climate forecasting and early-warning systems can reduce impacts of warming and ocean acidification in the short term. Overall, there is a strong need to develop ecosystem-based monitoring and adaptation strategies to mitigate rapidly growing risks and uncertainties to the coastal and oceanic industries, communities, and nations (*high agreement*). {7.5.1.1, 30.6}

Significant opportunity exists within the Ocean and its sub-regions for reducing the CO_2 flux to the atmosphere (*limited evidence*, *medium agreement*). Ecosystems such as mangroves, seagrass, and salt marsh offer important carbon storage and sequestration opportunities (e.g., Blue Carbon; *limited evidence*, *medium agreement*). Blue Carbon strategies can also be justified in terms of the ecosystem services provided by coastal vegetated habitats such as protection against coastal erosion and storm damage, and maintenance of habitats for fisheries species. Sequestration of anthropogenic CO_2 into deep ocean areas still faces considerable hurdles with respect to the expense, legality, and vulnerability of storage sites and infrastructure. There are also significant opportunities with the Ocean for the development of offshore renewable energy such as wind and tidal power. {5.5.7, 30.6.1, 30.6.4}

International frameworks for collaboration and decision making are critically important for coordinating policy that will enable mitigation and adaptation by the Ocean sectors to global climate change (e.g., United Nations Convention on the Law of the Sea (UNCLOS)). These international frameworks offer an opportunity to solve problems collectively, including improving fisheries management across national borders (e.g., reducing illegal, unreported, and unregulated (IUU) fishing), responding to extreme events, and strengthening international food security. Given the importance of the Ocean to all countries, there is a need for the international community to progress rapidly to a "whole of ocean" strategy for responding to the risks and challenges posed by anthropogenic ocean warming and acidification. {30.7.2}

30.1. Introduction

The Ocean exerts a profound influence as part of the Earth, interacting with its atmosphere, cryosphere, land, and biosphere to produce planetary conditions. It also directly influences human welfare through the provision and transport of food and resources, as well as by providing cultural and economic benefits. The Ocean also contributes to human welfare indirectly through the regulation of atmospheric gas content and the distribution of heat and water across the planet. This chapter examines the extent to which regional changes to the Ocean can be accurately detected and attributed to anthropogenic climate change and ocean acidification, building on the conclusions of Chapter 6, which focuses on the marine physiological and ecological responses to climate change and ocean acidification. Detailed assessment of the role of recent physical and chemical changes within the Ocean to anthropogenic climate change is provided in WGI AR5 (particularly Chapters 2, 3, 13, and 14). In this chapter, impacts, risks, and vulnerabilities associated with climate change and ocean acidification are assessed for seven ocean sub-regions, and the expected consequences and adaptation options for key ocean-based sectors are discussed. Polar oceans (defined by the presence of sea ice in the north and by the Polar Front in the south) are considered in Chapter 28.

Given that climate change affects coastal and low-lying sub-regions of multiple nations, detailed discussion of potential risks and consequences for these regions occurs in the relevant chapters of this report (e.g., Chapters 5 and 29, as well as other regional sections).

30.1.1. Major Sub-regions within the Ocean

The Ocean represents a vast region that stretches from the high tide mark to the deepest oceanic trench (11,030 m) and occupies 71% of the Earth's surface. The total volume of the Ocean is approximately 1.3 billion km^3, with approximately 72% of this volume being below 1000 m (Deep Sea (DS); Section 30.5.7). There are considerable challenges in assessing the regional impacts of climate change on the Ocean. Devising an appropriate structure to explore the influence of climate change across the entire Ocean region and the broad diversity of life forms and habitats is challenging. Longhurst (1998) identified more than 50 distinct ecological provinces in the Ocean, defined by physical characteristics and the structure and function of phytoplankton communities. Longhurst's scheme, however, yields far more sub-regions than could be sensibly discussed in the space allocated within AR5. Consequently, comparable principles were used with a division of the non-polar ocean into seven larger sub-regions similar to Barber (1988). It is recognized that these sub-regions do not always match physical-chemical patterns or specific geographies, and that they interact strongly with terrestrial regions through weather systems and the exchange of materials. Different ocean sub-regions may also have substantially different primary productivities and fishery catch. Notably, more than 80% of fishery catch is associated with three ocean sub-regions: Northern Hemisphere High-Latitude Spring Bloom Systems (HLSBS), Coastal Boundary Systems (CBS), and Eastern Boundary Upwelling Ecosystems (EBUE; Table SM30-1, Figure 30-1). The DS (>1000 m) is included as a separate category that overlaps with the six other ocean sub-regions dealt with in this chapter.

30.1.2. Detection and Attribution of Climate Change and Ocean Acidification in Ocean Sub-regions

The central goal of this chapter is to assess the recent literature on the Ocean as a region for changes that can be attributed to climate change and/or ocean acidification. Detailed assessments of recent physical and chemical changes in the Ocean are outlined in WGI AR5 Chapters 2, 3, 6, 10, 13, and 14. The detection and attribution of climate change and ocean acidification on marine organisms and ecosystems is addressed in Chapter 6. This chapter draws on these chapters to investigate regional changes in the physical, chemical, ecological, and socioeconomic aspects of the Ocean and the extent to which they can be attributed to climate change and ocean acidification.

Generally, successful attribution to climate change occurs when the full range of possible forcing factors is considered and those related to climate change are found to be the most probable explanation for the detected change in question (Section 18.2.1.1). Comparing detected changes with the expectations of well-established scientific evidence also plays a central role in the successful attribution of detected changes. This was attempted for seven sub-regions of the Ocean. There are a number of general limitations to the detection and attribution of impacts to climate change and ocean acidification that are discussed elsewhere (Section 18.2.1) along with challenges (Section 18.2.2). Different approaches and "best practice" guidelines are discussed in WGI AR5 Chapters 10 and 18, as well as in several other places (Hegerl et al., 2007, 2010; Stott et al., 2010). The fragmentary nature of ocean observing, structural uncertainty in model simulations, the influence of long-term variability, and confounding factors unrelated to climate change (e.g., pollution, introduced species, over-exploitation of fisheries) represent major challenges (Halpern et al., 2008; Hoegh-Guldberg et al., 2011b; Parmesan et al., 2011). Different factors may also interact synergistically or antagonistically with each other and climate change, further challenging the process of detection and attribution (Hegerl et al., 2007, 2010).

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change and ocean acidification on the Ocean as a region was not included in recent IPCC assessments, although a chapter devoted to the Ocean in the Second Assessment Report (SAR) did "attempt to assess the impacts of projected regional and global climate changes on the oceans" (Ittekkot et al., 1996). The fact that assessments for ocean and coastal systems are spread throughout previous IPCC assessment reports reduces the opportunity for synthesizing the detection and attribution of climate change and ocean acidification across the physical, chemical, ecological, and socioeconomic components of the Ocean and its sub-regions. The IPCC Fourth Assessment Report (AR4) concluded, however, that, while terrestrial sub-regions are warming faster than the oceans, "Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been taking up over 80% of the heat being added to the climate system" (AR4 Synthesis Report, p. 30). AR4 also concluded that sea levels had risen due to the thermal expansion of the Ocean but recognized that

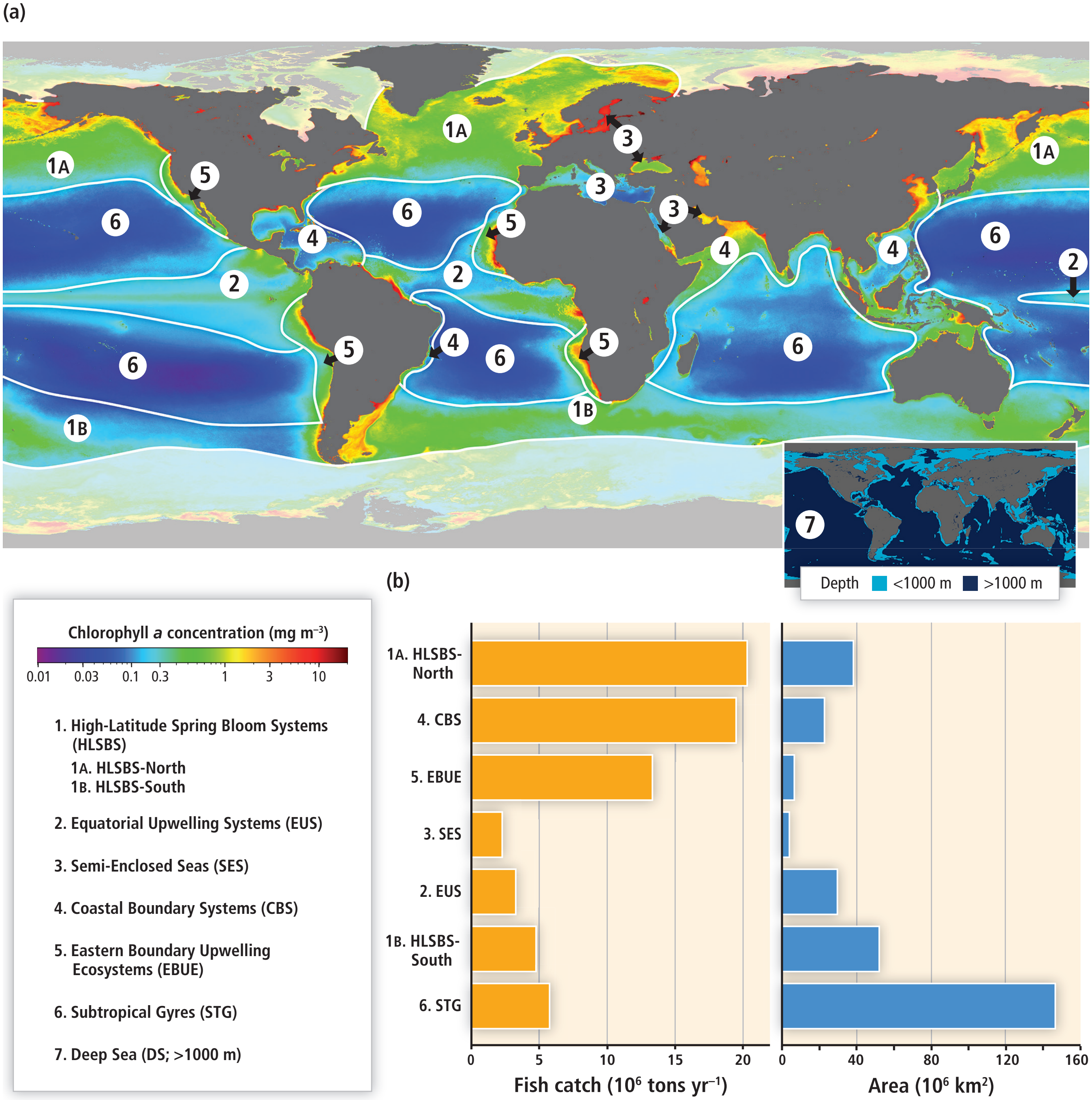

Figure 30-1 | (a) Separation of the world's oceans into seven major sub-regions (excluding an eighth area, Polar Oceans, which is considered in Chapter 28; white shaded area). The chlorophyll-*a* signal measured by SeaWiFS and averaged over the period from Sep 4, 1997 to 30 Nov 2010 (NASA) provides a proxy for differences in marine productivity (with the caveats provided in Box CC-PP). Ecosystem structure and functioning, as well as key oceanographic features, provided the basis for separating the Ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea (DS) habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). (b) Relationship between fish catch and area for each ocean subregion. Left panel: average fish catch (as millions tons yr^{-1}) for the period 1970–2006. Right panel: surface area (millions km^2). The top three bars (subregions HLSBS-North, CBS, and EBUE) cover 19% of the world oceans' area and provide 76% of the world's fish catches. Values for fish catch, area, and primary productivity of the ocean sub-regions are listed in Table SM30-1.

our understanding of the dynamics of glaciers and ice sheets was "too limited to assess their likelihood or provide a best estimate or an upper boundary for sea level rise" (WGI AR4 SPM). Changes to ocean temperature and density have been identified as having the potential to alter large-scale ocean circulation. AR4 concluded that, with respect to the Meridional Overturning Circulation (MOC), "it is *very likely* that up to the end of the 20th century the MOC was changing significantly at interannual to decadal time scales" (WGI AR4 Box 5.1, p. 397), despite limited evidence of a slowing MOC.

According to AR4, "Sea-level rise over the last 100 to150 years is probably contributing to coastal erosion in many places," including the east coast of the United States and the United Kingdom (WGII AR4 Section 1.3.3.1, p. 92). The AR4 assessment was *virtually certain* that rising atmospheric carbon dioxide (CO_2) had changed carbonate chemistry of the ocean (i.e., buffering capacity, carbonate and bicarbonate concentrations), and that a decrease in surface pH of 0.1 had occurred over the global ocean (calculated from the uptake of anthropogenic CO_2 between 1750 and 1994; Sabine et al., 2004; Raven et al., 2005; WGI AR4 Section 5.4.2.3; WGI AR4 Table 7.3). Large-scale changes in ocean salinity were also observed from 1955 to 1998 and were "characterized by a global freshening in sub-polar latitudes and salinification of shallower parts of the tropical and subtropical oceans" (WGI AR4 Chapter 5 ES, p. 387). In this case, freshening was observed in the Pacific, with increased salinity being observed in the Atlantic and Indian Oceans (WGI AR4 Sections 5.3.2-5). These changes in surface salinity were qualitatively consistent with expected changes to surface freshwater flux. Freshening of mid- and high-latitude waters together with increased salinity at low latitudes were seen as evidence "of changes in precipitation and evaporation over the oceans" (WGI AR4 SPM, p. 7).

Substantial evidence presented in AR4 indicated that changing ocean conditions have extensively influenced marine ecosystems (WGII AR4 Table 1.5). AR4 noted that there is an "accumulating body of evidence to suggest that many marine ecosystems, including managed fisheries, are responding to changes in regional climate caused predominately by warming of air and sea surface temperatures (SST) and to a lesser extent by modification of precipitation regimes and wind patterns" (WGII AR4 Section 1.3.4.2, p. 94). Observed changes in marine ecosystems and managed fisheries reported within AR4 included changes to plankton community structure and productivity, the phenology and biogeography of coastal species, intertidal communities on rocky shores, kelp forests, and the distribution of pathogens and invasive species. Changes were also observed in coral reefs (primarily increased mass coral bleaching and mortality) and migratory patterns and trophic interactions of marine birds, reptiles, and mammals, as well as of a range of other marine organisms and ecosystems (WGII AR4 Table 1.5), although a separate exercise in detection and attribution of changes due to climate change (as done for terrestrial studies) was not done as part of AR4.

30.3. Recent Changes and Projections of Future Ocean Conditions

Evidence that increasing concentrations of atmospheric CO_2 have resulted in the warming and acidification of the upper layers of the Ocean has strengthened since AR4. Understanding the full suite of physical and chemical changes to the Ocean is critical to the interpretation of the past and future responses of marine organisms and ecosystems, especially with respect to the implications for coastal and low-lying areas.

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

The Ocean has absorbed 93% of the extra heat arising from the enhanced greenhouse effect (1971–2010), with most of the warming (64%) occurring in the upper (0 to 700 m) ocean (1971–2010; WGI AR5 Section 3.2.3, Figure 3.2, Box 3.1). It is certain that global average SSTs have increased since the beginning of the 20th century, with improvements and growth of data sets and archives, and the understanding of errors and biases since AR4 (WGI AR5 Section 2.4.2). It is *virtually certain* that the upper ocean (0 to 700 m depth) has warmed from 1971 to 2010 (Figure 30-2a), while it is *likely* that the surface layers of the Ocean have warmed from the 1870s to 1971. Rates of increase in temperature are highest near the surface of the Ocean (>0.1°C per decade in the upper 75 m from 1971 to 2010) decreasing with depth (0.015°C per decade at 700 m; Figure 30-2b,c). It is *very likely* that the intensification of this warming near the surface has increased thermal stratification of the upper ocean by about 4% between 0 and 200 m depth from 1971 to 2010 in all parts of the ocean north of 40°S. It is *likely* that the Ocean has warmed between 700 and 2000 m from 1957 to 2010, with the warming signal becoming less apparent or non-existent at deeper depths (WGI AR5 Sections 3.2.1-3, Figures 3.1, 3.2, 3.9). These changes include a significant anthropogenic signal (*virtually certain*; Gleckler et al., 2012; Pierce et al., 2012), with the surface waters of all three ocean basins warming at different rates that exceed those expected if there were no changes to greenhouse gas (GHG) forcing over the past century (Figure 30-2e,f,g). In this respect, the observed record also falls within the range of historical model outputs that include increases in the concentration of GHGs as opposed to models that do not (Figure 30-2e,f,g).

Data archives such as Hadley Centre Interpolated SST 1.1 (HadISST1.1) contain SSTs reconstructed from a range of sources, allowing an opportunity to explore mean monthly, gridded, global SST from 1870 to the present (Rayner et al., 2003). The published HadISST1.1 data set (higher temporal and spatial resolution than HadSST3) was used to explore trends in historic SST within the sub-regions of the Ocean (Figure 30-1a; see definition of regions in Figure SM30-1 and Table SM30-2, column 1). The median SST for 1871–1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the UK Met Office Marine Data Bank (MDB) to produce monthly globally complete fields of SST on a 1° latitude-longitude SST grid from 1870 to the present.

The surface layers of the three ocean basins have warmed (p-value ≤ 0.05, *very likely*), with the Indian Ocean (0.11°C per decade) warming faster than the Atlantic (0.07°C per decade) and Pacific (0.05°C per decade) Oceans (*high confidence*; Table 30-1). This is consistent with the depth-averaged (0 to 700 m) temperature trend observed from 1971 to 2010 (Figure 30-2a).

While some regions (e.g., North Pacific) did not show a clear warming trend, most regions showed either significant warming in the average temperature, or significant warming in either/or the warmest and coolest months of the year, over the period 1950–2009 (HadISST1.1 data; Table 30-1). Trends in SST show considerable sub-regional variability (Table 30-1; Figure 30-2a). Notably, the average temperature of most HLSBS did not increase significantly from 1950 to 2009 (except in the Indian Ocean; Table 30-1) yet the temperatures of the warmest month (North and South Atlantic, and Southeastern Pacific) and of the coolest month (North and South Atlantic, and South Pacific) showed significant upward trends over this period (p-value ≤ 0.05; Table 30-1).

The two EUS warmed from 1950 to 2009 (Pacific EUS: 0.07°C per decade, Atlantic EUS: 0.09°C per decade; Table 30-1). The average monthly SST of the SES did not warm significantly, although the temperature of the coolest month increased significantly within the Baltic Sea (0.35°C per decade or 2.11°C from 1950 to 2009), as did the temperatures of the warmest months in the Black (0.14°C per decade or 0.83°C from 1950 to 2009), Mediterranean (0.11°C per decade or 0.66°C from 1950 to 2009), and Red (0.05°C per decade or 0.28°C from 1950 to 2009) Seas over the period 1950–2009 (*very likely*; Table 30-1). Studies over shorter periods (e.g., 1982–2006; Belkin, 2009) report significant increases in average SST of the Baltic (1.35°C), Black (0.96°C), Red (0.74°C), and Mediterranean (0.71°C) Seas. Such studies

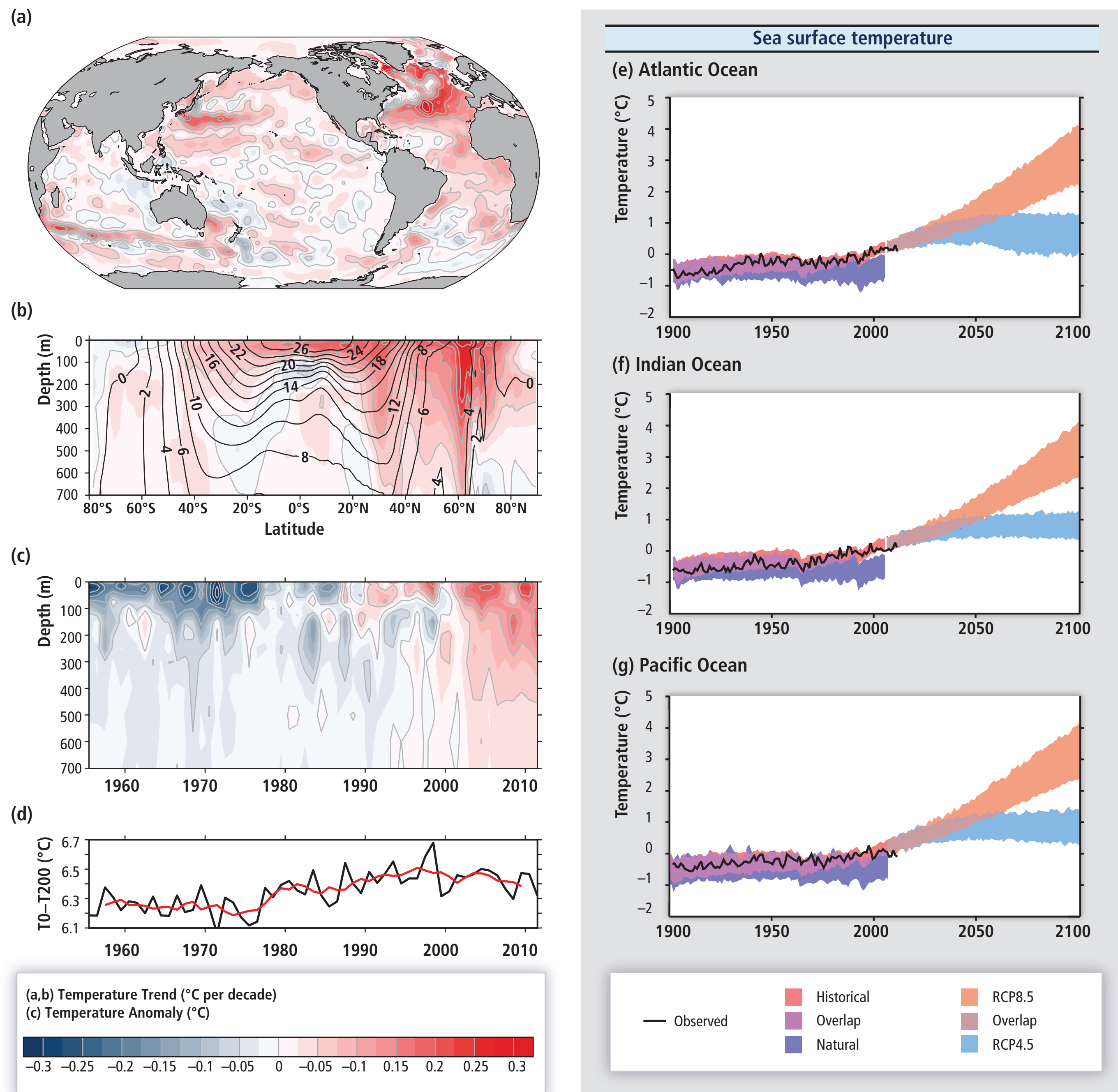

Figure 30-2 | (a) Depth-averaged 0 to 700 m temperature trend for 1971–2010 (longitude vs. latitude, colors and gray contours in degrees Celsius per decade). (b) Zonally averaged temperature trends (latitude vs. depth, colors and gray contours in degrees Celsius per decade) for 1971–2010, with zonally averaged mean temperature over plotted (black contours in degrees Celsius). (c) Globally averaged temperature anomaly (time vs. depth, colors and gray contours in degrees Celsius) relative to the 1971–2010 mean. (d) Globally averaged temperature difference between the Ocean surface and 200 m depth (black: annual values; red: 5-year running mean). [(a–d) from WGI AR5 Figure 3.1] (e)–(g) Observed and simulated variations in past and projected future annual average sea surface temperature over three ocean basins (excluding regions within 300 km of the coast). The black line shows estimates from Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1) observational measurements. Shading denotes the 5th to 95th percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (62 simulations), historical changes in "natural" drivers only (25), and the Representative Concentration Pathways (RCPs; blue: RCP4.5; orange: RCP8.5). Data are anomalies from the 1986–2006 average of the HadISST1.1 data (for the HadISST1.1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Panels (a)-(d) originally presented in WGI AR5 Fig 3.1 and Box 21-2.

Table 30-1 | Regional changes in sea surface temperature (SST) over the period 1950–2009 using the ocean regionalization specified in Figure 30-1(a) (for further details on regions defined for analysis, see Figure SM30-1 and Table SM30-2, column 1). A linear regression was fitted to the average of all 1×1 degree monthly SST data extracted from the Hadley Centre HadISST1.1 data set (Rayner et al., 2003) for each sub-region over the period 1950–2009. All SST values less than –1.8°C, together with all SST pixels that were flagged as being sea ice, were reset to the freezing point of seawater (–1.8°C) to reflect the sea temperature under the ice. Separate analyses were also done to explore trends in the temperatures extracted from the coldest-ranked and the warmest-ranked month of each year (Table SM30-2). The table includes the slope of the regression (°C per decade), the *p*-value for the slope being different from zero and the total change over 60 years (i.e., the slope of linear regression multiplied by six decades) for each category. The *p*-values that exceed 0.05 plus the associated slope and change values have an orange background, denoting the lower statistical confidence in the slope being different from zero (no slope). Note that changes with higher *p*-values may still describe informative trends although the level of confidence that the slope is different from zero is lower.

Sub-region	Area	Regression slope			Total change over 60 years			*p*-value, slope different from zero		
		°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)	Change over 60 years (coolest month)	Change over 60 years (all months)	Change over 60 years (warmest month)	°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)
1. High-Latitude Spring Bloom Systems (HLSBS)	Indian Ocean	0.056	0.087	0.145	0.336	0.522	0.870	0.000	0.003	0.000
	North Atlantic Ocean	0.054	0.073	0.116	0.324	0.438	0.696	0.001	0.15	0.000
	South Atlantic Ocean	0.087	0.063	0.097	0.522	0.378	0.582	0.000	0.098	0.000
	North Pacific Ocean (west)	0.052	0.071	0.013	0.312	0.426	0.078	0.52	0.403	0.462
	North Pacific Ocean (east)	0.016	0.04	0.016	0.096	0.24	0.096	0.643	0.53	0.444
	North Pacific Ocean	0.033	0.055	0.015	0.198	0.33	0.09	0.284	0.456	0.319
	South Pacific Ocean (west)	0.043	0.017	0.044	0.258	0.102	0.264	0.016	0.652	0.147
	South Pacific Ocean (east)	0.047	0.031	0.052	0.282	0.186	0.312	0.000	0.396	0.003
	South Pacific Ocean	0.046	0.027	0.050	0.276	0.162	0.300	0.000	0.467	0.000
2. Equatorial Upwelling Systems (EUS)	Atlantic Equatorial Upwelling	0.101	0.090	0.079	0.606	0.540	0.474	0.000	0.000	0.000
	Pacific Equatorial Upwelling	0.079	0.071	0.065	0.474	0.426	0.39	0.096	0.001	0.071
3. Semi-Enclosed Seas (SES)	Arabian Gulf	0.027	0.099	0.042	0.162	0.594	0.252	0.577	0.305	0.282
	Baltic Sea	0.352	0.165	0.06	2.112	0.99	0.36	0.000	0.155	0.299
	Black Sea	–0.004	0.053	0.139	–0.024	0.318	0.834	0.943	0.683	0.009
	Mediterranean Sea	0.035	0.084	0.110	0.21	0.504	0.660	0.083	0.32	0.006
	Red Sea	0.033	0.07	0.047	0.198	0.42	0.282	0.203	0.138	0.042
4. Coastal Boundary Systems (CBS)	Atlantic Ocean (west)	0.137	0.123	0.127	0.822	0.738	0.762	0.000	0.000	0.000
	Caribbean Sea/Gulf of Mexico	0.023	0.024	0.019	0.138	0.144	0.114	0.193	0.498	0.281
	Indian Ocean (west)	0.097	0.100	0.096	0.582	0.600	0.576	0.000	0.000	0.000
	Indian Ocean (east)	0.099	0.092	0.080	0.594	0.552	0.480	0.000	0.000	0.000
	Indian Ocean (east), Southeast Asia, Pacific Ocean (west)	0.144	0.134	0.107	0.864	0.804	0.642	0.000	0.000	0.000
5. Eastern Boundary Upwelling Ecosystems (EBUE)	Benguela Current	0.062	0.032	0.002	0.372	0.192	0.012	0.012	0.437	0.958
	California Current	0.117	0.122	0.076	0.702	0.732	0.456	0.026	0.011	0.125
	Canary Current	0.054	0.089	0.106	0.324	0.534	0.636	0.166	0.014	0.000
	Humboldt Current	0.051	0.059	0.104	0.306	0.354	0.624	0.285	0.205	0.013
6. Subtropical Gyres (STG)	Indian Ocean	0.141	0.112	0.103	0.846	0.672	0.618	0.000	0.000	0.000
	North Atlantic Ocean	0.042	0.046	0.029	0.252	0.276	0.174	0.048	0.276	0.038
	South Atlantic Ocean	0.079	0.083	0.098	0.474	0.498	0.588	0.000	0.017	0.000
	North Pacific Ocean (west)	0.065	0.071	0.059	0.390	0.426	0.354	0.000	0.018	0.000
	North Pacific Ocean (east)	0.008	0.042	0.051	0.048	0.252	0.306	0.617	0.133	0.014
	North Pacific Ocean	0.034	0.055	0.051	0.204	0.33	0.306	0.001	0.053	0.000
	South Pacific Ocean (west)	0.060	0.076	0.092	0.360	0.456	0.552	0.002	0.000	0.000
	South Pacific Ocean (east)	0.055	0.056	0.088	0.330	0.336	0.528	0.000	0.058	0.000
	South Pacific Ocean	0.056	0.060	0.089	0.336	0.360	0.534	0.000	0.027	0.000

Continued next page →

Table 30-1 (continued)

	Sub-region	Regression slope			Total change over 60 years			*p*-value, slope different from zero		
		°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)	Change over 60 years (coolest month)	Change over 60 years (all months)	Change over 60 years (warmest month)	°C per decade (coolest month)	°C per decade (all months)	°C per decade (warmest month)
Coral Reef Provinces; see Figure 30-4(b)	Caribbean Sea/Gulf of Mexico	0.026	0.024	0.023	0.156	0.144	0.138	0.107	0.382	0.203
	Coral Triangle and Southeast Asia	0.137	0.131	0.098	0.822	0.786	0.588	0.000	0.000	0.000
	Indian Ocean (east)	0.081	0.097	0.116	0.486	0.582	0.696	0.000	0.000	0.000
	Indian Ocean (west)	0.091	0.100	0.102	0.546	0.600	0.612	0.000	0.000	0.000
	Pacific Ocean (east)	0.079	0.094	0.101	0.474	0.564	0.606	0.106	0.000	0.023
	Pacific Ocean (west)	0.072	0.073	0.073	0.432	0.438	0.438	0.000	0.000	0.000
Basin Scale	North Atlantic Ocean	0.045	0.061	0.090	0.270	0.366	0.540	0.002	0.198	0.000
	South Atlantic Ocean	0.076	0.074	0.101	0.456	0.444	0.606	0.000	0.041	0.000
	Atlantic Ocean	0.060	0.068	0.091	0.360	0.408	0.546	0.000	0.000	0.000
	North Pacific Ocean	0.030	0.052	0.046	0.180	0.312	0.276	0.000	0.248	0.006
	South Pacific Ocean	0.055	0.048	0.075	0.330	0.288	0.450	0.000	0.115	0.000
	Pacific Ocean	0.043	0.052	0.046	0.258	0.312	0.276	0.000	0.000	0.006
	Indian Ocean	0.130	0.108	0.106	0.780	0.648	0.636	0.000	0.000	0.000

are complicated by the influence of patterns of long-term variability and by the small size and land-locked nature of SES. Coastal Boundary Systems (except the Caribbean and Gulf of Mexico) all showed highly significant (p-value ≤ 0.05) warming (0.09°C to 0.13°C per decade; Table 30-1). Among the EBUE, the Canary and Californian Current regions exhibited a significant rate of change in the average SST (0.09°C per decade and 0.12°C per decade, respectively; p-value ≤ 0.05), while the Benguela and Humboldt Currents did not show significant temperature changes from 1950 to 2009 (p-value ≤ 0.05; Table 30-1). There was some variability between EUBEs in terms of the behavior of the coolest and warmest months. The temperature of the coolest month increased significantly from 1950 to 2009 in the case of the Benguela and California Currents (0.06°C per decade and 0.12°C per decade, respectively; p-value ≤ 0.05), while there was a significant increase in the temperature of the warmest month in the case of the Canary and Humboldt Currents (0.11°C per decade and 0.10°C per decade, respectively; Table 30-1).

The average temperature of STG showed complex patterns with increasing temperatures (1950–2009) in the Indian, South Atlantic, and South Pacific Oceans (*very likely*; 0.11°C, 0.08°C, and 0.06°C per decade, respectively; p-value ≤ 0.05), but not in the North Atlantic or North Pacific Ocean (p-value ≤ 0.05). These rates are half the value reported over shorter periods (e.g., 1998–2010; Table 1 in Signorini and McClain, 2012) and based on NOAA_OI_SST_V2 data. Given the sensitivity of coral reefs to temperature (Eakin et al., 2010; Strong et al., 2011; Lough, 2012; Box CC-CR), trends in key coral reef regions were also examined using the World Resources Institute's Reefs at Risk report (www.wri.org) to identify HadISST1.1 grid cells containing coral reefs (Figure 30-4b). Grouping the results into six major coral reef regions, coral reef waters (with the notable exception of the Gulf of Mexico and Caribbean) were found to show strong increases in average temperature (0.07°C to 0.13°C per decade) as well as the temperature of the coolest (0.07°C to 0.14°C decade) and warmest months (*very likely*) (0.07°C to 0.12°C per decade; Table 30-1). These trends in temperature have resulted in an absolute increase in sea temperature of 0.44°C to 0.79°C from 1950 to 2009.

Given the essential role that temperature plays in the biology and ecology of marine organisms (Box CC-MB; Sections 6.2-3; Pörtner, 2002; Poloczanska et al., 2013), the speed of isotherm migration ultimately determines the speed at which populations must either move, adapt, or acclimate to changing sea temperatures (Pörtner, 2002; Burrows et al., 2011; Hoegh-Guldberg, 2012). Burrows et al. (2011) calculated the rate at which isotherms are migrating as the ratio of the rate of SST change (°C yr^{-1}) to the spatial gradient of temperature (°C km^{-1}) over the period 1960–2009 (Figure 30-3). Although many of these temperature trajectories are toward the polar regions, some are not and are influenced by features such as coastlines. This analysis and others (e.g., North Atlantic; González-Taboada and Anadón, 2012) reveals that isotherms in the Ocean are moving at high velocities (to over 200 km per decade), especially at low latitudes (*high confidence*; Figure 30-3). Other sub-regions showed smaller velocities with contracting isotherms (cooling) in some areas (e.g., the Central and North Pacific, and Atlantic Oceans; Figure 30-3). There are also changes in the timing of seasonal temperatures in both spring and fall/autumn (Burrows et al., 2011; Poloczanska et al., 2013), which, together with other variables (e.g., light, food availability, geography), are *likely* to affect biological processes such as the migration of species to higher latitudes, and the timing and synchrony of reproductive and other seasonal behaviors.

Excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) significantly affect marine organisms and ecosystems (Hoegh-Guldberg, 1999; Bensoussan et al., 2010; Crisci et al., 2011; Harley, 2011). Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly is useful in understanding recent changes to

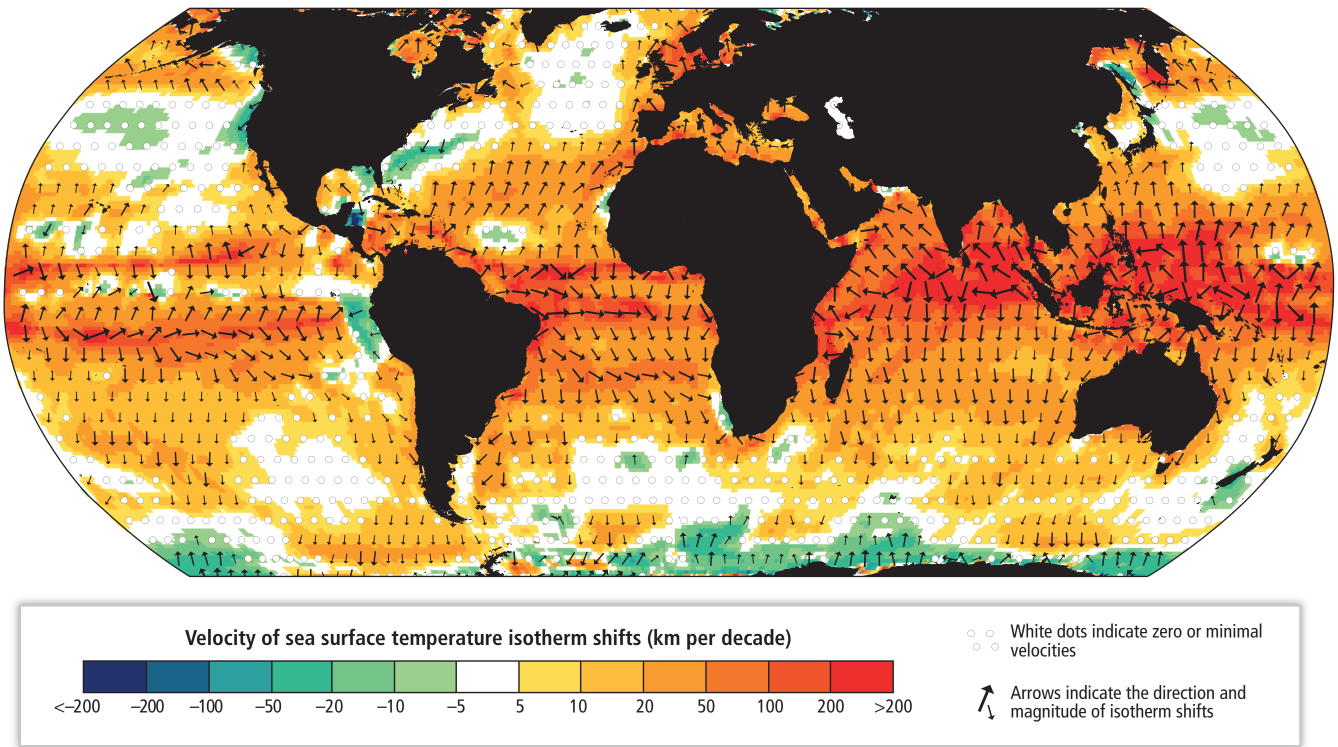

Figure 30-3 | Velocity at which sea surface temperature (SST) isotherms shifted (km per decade) over the period 1960–2009 calculated using Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1), with arrows indicating the direction and magnitude of shifts. Velocity of climate change is obtained by dividing the temperature trend in °C per decade by the local spatial gradient °C km^{-1}. The direction of movement of SST isotherms are denoted by the direction of the spatial gradient and the sign of the temperature trend: toward locally cooler areas with a local warming trend or toward locally warmer areas where temperatures are cooling. Adapted from Burrows et al., 2011.

organisms and ecosystems (e.g., coral reefs and thermal anomalies; Strong et al., 2011). The total heat stress accumulated over the period 1981–2010 was calculated using the methodology of Donner et al. (2007) and a reference climatology based on 1985–2000 in which the highest monthly SST was used to define the thermal threshold, above which accumulated thermal stress was calculated as "exposure time multiplied by stress" or Degree Heating Months (DHM) as the running total over 4 consecutive months. While most sub-regions of the Ocean experienced an accumulation of heat stress (relative to a climatology based on the period 1985–2000), equatorial and high-latitude sub-regions in the Pacific and Atlantic Oceans have the greatest levels of accumulated heat stress (Figure 30-4a). These are areas rich in thermally sensitive coral reefs (Figure 30-4b; Strong et al., 2011). There was also a higher proportion of years that have had at least one stress event (DHM > 1) in the last 30 years (1981–2010, Figure 30-4c) than in the preceding 30 years (1951–1980; Figure 30-4c,d).

The three ocean basins will continue warming under moderate (RCP4.5) to high (RCP8.5) emission trajectories (*high confidence*) and will only stabilize over the second half of the century in the case of low range scenarios such as RCP2.6 (Figure 30-2e,f,g; WGI AR5 AI.4–AI.8). Projected changes were also examined for specific ocean sub-regions using ensemble averages from Atmosphere-Ocean General Circulation Models (AOGCM) simulations available in the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive (Table SM30-3) for the four scenarios of the future (RCP2.6, RCP4.5, RCP6.0, and RCP8.5; van Vuuren et al., 2011). Ensemble averages for each RCP are based on simulations from 10 to 16 individual models (Table SM30-3). The subset of CMIP5 models were chosen because each has historic runs enabling the derivation of the maximum monthly mean (MMM) climatology from 1985 to 2000, ensuring that all anomalies were comparable across time periods and across RCPs (Figure 30-10). Model hind-cast changes matched those observed for ocean sub-regions for the period 1980–2009 (HadISST1.1; Figure 30-2), with the model ensemble slightly overestimating the extent of change across the different ocean sub-regions (slope of observed/model = 0.81, r^2 = 0.76, *p*-value ≤ 0.001). In this way, the absolute amount of change projected to occur in the ocean sub-regions was calculated for near-term (2010–2039) and long-term (2070–2099) periods (Table SM30-4). In the near term, changes in the temperature projected for the surface layers of the Ocean were largely indistinguishable between the different RCP scenarios owing to the similarity in forcing up to 2040. By the end of the century, however, SSTs across the ocean sub-regions were 1.8°C to 3.3°C higher under RCP8.5 than those projected to occur under RCP2.6 (Table SM30-4; Figure 30-2e,f,g). The implications of these projected changes on the structure and function of oceanic systems are discussed below.

30.3.1.2. Sea Level

The rate of sea level rise (SLR) since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*). Over the period 1901–2010, global mean sea level (GMSL) rose by 0.19 (0.17 to 0.21) m (WGI AR5 Figure SPM.3; WGI AR5 Sections 3.7, 5.6, 13.2). It is *very likely* that the mean rate of global averaged SLR was 1.7 (1.5 to 1.9) mm yr^{-1} between 1901 and 2010, 2.0 (1.7 to 2.3) mm yr^{-1}

between 1971 and 2010, and 3.2 (2.8 to 3.6) mm yr^{-1} between 1993 and 2010 (WGI AR5 SPM, Section 3.7). These observations are consistent with thermal expansion of the Ocean due to warming plus the addition of water from loss of mass by melting glaciers and ice sheets. Current rates of SLR vary geographically, and can be higher or lower than the GMSL for several decades at time due to fluctuations in natural variability and ocean circulation (Figure 30-5). For example, rates of SLR are up to three times higher than the GMSL in the Western Pacific and Southeast Asian region, and decreasing in many parts of the Eastern Pacific for the period 1993–2012 as measured by satellite altimetry (Figure 30-5; WGI AR5 Section 13.6.5).

SLR under increasing atmospheric GHG concentrations will continue for hundreds of years, with the extent and rate of the increase in GMSL being dependent on the emission scenario. Central to this analysis is the millennial-scale commitment to further SLR that is *likely* to arise from the loss of mass of the Greenland and Antarctic ice sheets (WGI AR5 Section 13.5.4, Figure 13.13). SLR is *very likely* to increase during the 21st century relative to the period 1971–2010 due to increased ocean warming and the continued contribution of water from loss of mass from glaciers and ice sheets. There is *medium confidence* that median SLR by 2081–2100 relative to 1986–2005 will be (5 to 95% range of process-based models): 0.44 m for RCP2.6, 0.53 m for RCP4.5, 0.55 m for RCP6.0, and 0.74 m for RCP8.5. Higher values of SLR are possible but are not backed by sufficient evidence to enable reliable estimates of the probability of specific outcomes. Many semi-empirical model projections of GMSL rise are higher than process-based model projections (up to about twice as large), but there is no consensus in the scientific community about their reliability and there is thus *low confidence* in their projections (WGI AR5 Sections 13.5.2, 13.5.3, Table 13.6, Figure 13.12).

It is considered *very likely* that increases in sea level will result in greater levels of coastal flooding and more frequent extremes by 2050 (WGI AR5 Section 13.7.2; IPCC, 2012). It is *about as likely as not* that the frequency of the most intense storms will increase in some ocean basins,

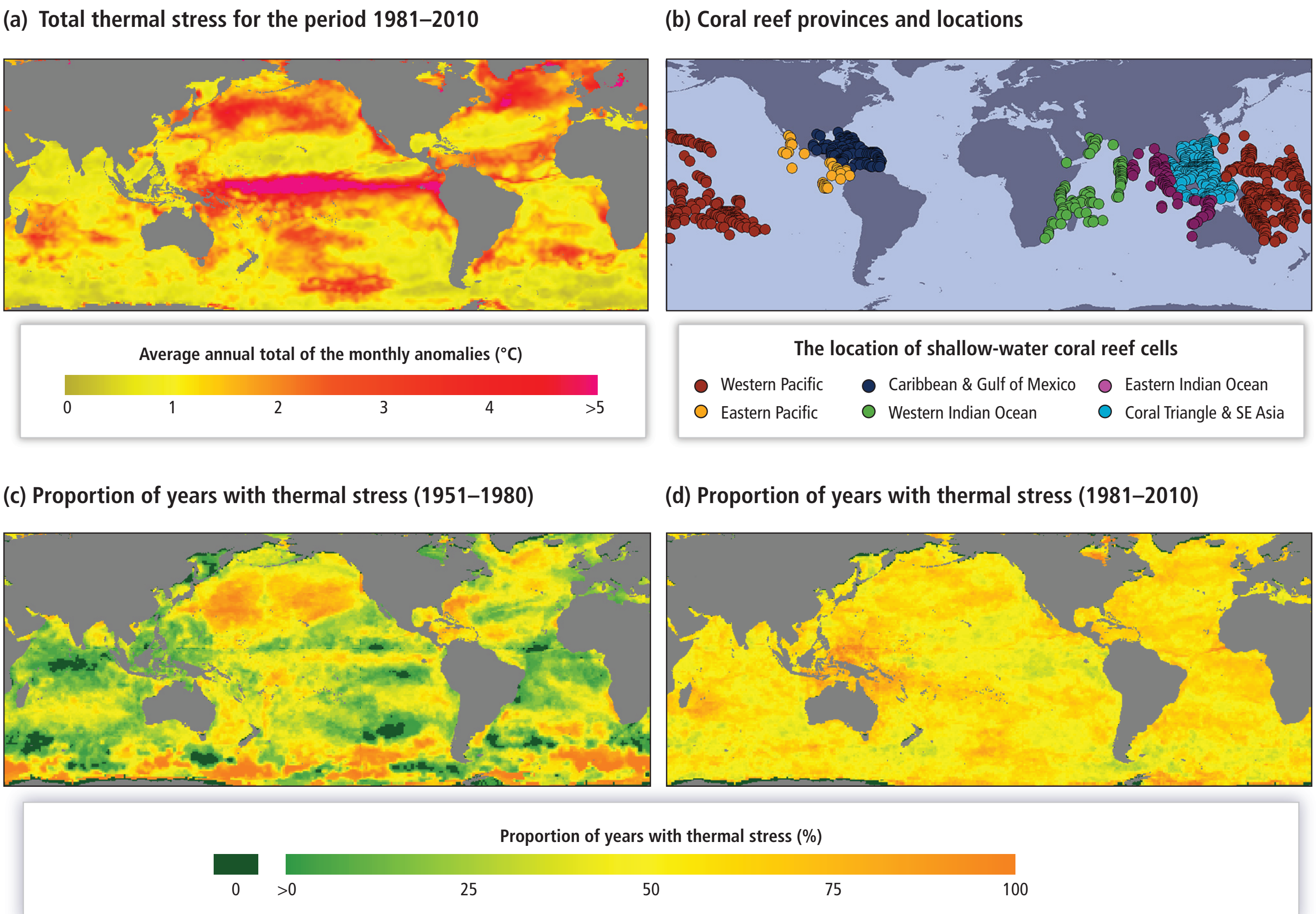

Figure 30-4 | Recent changes in thermal stress calculated using Hadley Centre Interpolated sea surface temperature data (HadISST1.1). A monthly climatology was created by averaging the HadISST monthly SST values over a reference period of 1985–2000 to create 12 averages, one for each month of the year. The Maximum Monthly Mean climatology was created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each sea surface temperature value, but allowing values to be recorded only if they were greater than zero (Donner et al., 2007). Two measures of the change in thermal stress were calculated as a result: The total thermal stress for the period 1981–2010, calculated by summing all monthly thermal anomalies for each grid cell (a); and the proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951–1980 (c) and 1981–2010 (d). The location of coral reef grid cells used in Table 30-1 and for comparison to regional heat stress is depicted in (b). Each dot is positioned over a 1 × 1 degree grid cell within which lies at least one carbonate coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's Reefs at Risk report (http://www.wri.org). The six regions are as follows: red—Western Pacific Ocean; yellow—Eastern Pacific Ocean; dark blue—Caribbean and Gulf of Mexico; green—Western Indian Ocean; purple—Eastern Indian Ocean; and light blue—Coral Triangle and Southeast Asia.

although there is *medium agreement* that the global frequency of tropical cyclones is *likely* to decrease or remain constant (WGI AR5 Sections 14.6, 14.8). Although understanding of associated risks is relatively undeveloped, coastal and low-lying areas, particularly in southern Asia, as well as the Pacific Ocean and North Atlantic regions, face increased flood risk (Sections 5.3.3.2, 8.2.3.3, 9.3.4.3). Future impacts of SLR include increasing penetration of storm surges into coastal areas and changing patterns of shoreline erosion (Section 5.3), as well as the inundation of coastal aquifers by saltwater (Sections 5.4.2.5, 29.3.2). Regionally, some natural ecosystems may reduce in extent (e.g., mangroves), although examples of habitat expansion have been reported (Brown et al., 2011). Overall, changes to sea level are *very likely* to modify coastal ecosystems such as beaches, salt marshes, coral reefs, and mangroves (Section 5.4.2; Box CC-CR), especially where rates of sea level rise are highest (e.g., Southeast Asia and the Western Pacific).

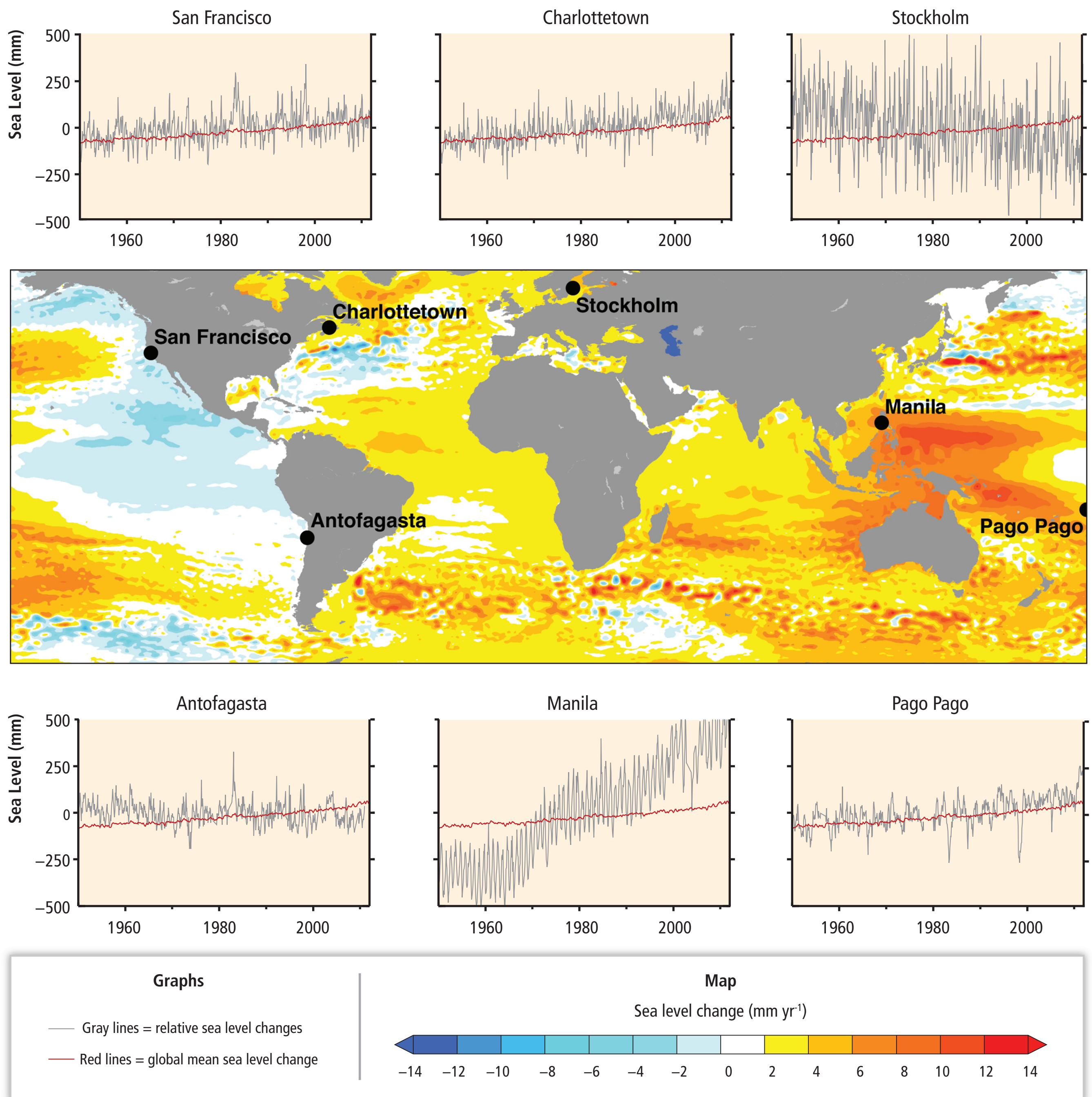

Figure 30-5 | Map of the rate of change in sea surface height (geocentric sea level) for the period 1993–2012 derived from satellite altimetry. Also shown are relative sea level changes (gray lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is shown (red lines) with each tide gauge time series. The relatively large short-term oscillations in local sea level (gray lines) are due to the natural climate variability and ocean circulation. For example, the large regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation. Figure originally presented in WGI AR5 FAQ 13.1, Figure 1.

30.3.1.3. Ocean Circulation, Surface Wind, and Waves

Circulation of atmosphere and ocean (and their interactions) drives much of the chemical, physical, and biological characteristics of the Ocean, shaping phenomena such as ocean ventilation, coastal upwelling, primary production, and biogeochemical cycling. Critical factors for transporting nutrients from deep waters to the marine primary producers in the upper layers of the ocean include wind-driven mixing and upwelling.

There has been a poleward movement of circulation features, including a widening of the tropical belt, contraction of the northern polar vortex, and a shift of storm tracks and jet streams to higher latitudes (*medium confidence*; WGI AR5 Sections 2.7.5-6, 2.7.8; WGI AR5 Box 2.5). Long-term patterns of variability (years to decades) continue to prevent robust conclusions regarding long-term changes in atmospheric circulation and winds in many cases (WGI AR5 Section 2.7.5). There is *high confidence*, however, that the increase in northern mid-latitude westerly winds from the 1950s to the 1990s, and the weakening of the Pacific Walker Circulation from the late 19th century to the 1990s, have been largely offset by recent changes (WGI AR5 Sections 2.7.5, 2.7.8; WGI AR5 Box 2.5). Wind stress has increased since the early 1980s over the Southern Ocean (*medium confidence*; WGI AR5 Section 3.4.4), and tropical Pacific since 1990 (*medium confidence*), while zonal mean wind stress may have declined by 7% in the equatorial Pacific from 1862–1990 due to weakening of the tropical Walker Circulation (*medium confidence*; WGI AR5 Section 3.4.4; Vecchi et al., 2006). For example, it is *very likely* that the subtropical gyres of the major ocean basins have expanded and strengthened since 1993. However, the short-term nature of observing means that these changes are *as likely as not* to be due to decadal variability and/or due to longer term trends in wind forcing associated with climate change (WGI AR5 Section 3.6). Other evidence of changes in ocean circulation is limited to relatively short-term records that suffer from low temporal and spatial coverage. Therefore, there is *very low confidence* that multi-decadal trends in ocean circulation can be separated from decadal variability (WGI AR5 Section 3.6.6). There is no evidence of a long-term trend in large-scale currents such as the Atlantic Meridional Overturning Circulation (AMOC), Indonesian Throughflow (ITF), the Antarctic Circumpolar Current (ACC), or the transport of water between the Atlantic Ocean and Nordic Seas (WGI AR5 Section 3.6; WGI AR5 Figures 3.10, 3.11).

Wind speeds may have increased within the regions of EBUE (*low confidence* in attribution to climate; e.g., California Current, WGI AR5 Section 2.7.2). Changing wind regimes have the potential to influence mixed layer depth (MLD) and upwelling intensity in highly productive sub-regions of the world's oceans, although there is *low agreement* as to whether or not upwelling will intensify or not under rapid climate change (Bakun, 1990; Bakun et al., 2010; Box CC-UP).

Surface waves are influenced by wind stress, although understanding trends remains a challenge due to limited data. There is *medium confidence* that significant wave height (SWH) has increased since the mid-1950s over much of the North Atlantic north of 45°N, with typical winter season trends of up to 20 cm per decade (WGI AR5 Section 3.4.5). There is *low confidence* in the current understanding of how SWH will change over the coming decades and century for most of the Ocean. It remains an important knowledge gap (WGI AR5 Section 3.4).

30.3.1.4. Solar Insolation and Clouds

Solar insolation plays a crucially important role in the biology of many marine organisms, not only as a source of energy for photosynthesis but also as a potential co-stressor in the photic zone (with temperature), as is seen during mass coral bleaching and mortality events (e.g., Hoegh-Guldberg, 1999). Global surface solar insolation (from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) Reanalysis Project; Kalnay et al., 1996) decreased by 4.3 W m^{-2} per decade from the 1950s until 1991, after which it increased at 3.3 W m^{-2} per decade until 1999 (Ohmura, 2009; Wild, 2009), matching a broad suite of evidence from many land-based sites (WGI AR5 Section 2.3.3). Although there is consistency between independent data sets for particular regions, there is substantial ambiguity and therefore *low confidence* in observations of global-scale cloud variability and trends (WGI AR5 Section 2.5.6). There is also *low confidence* in projections of how cloudiness, solar insolation, and precipitation will change as the planet warms due to the large interannual and decadal variability (El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)), short observation time series, and uneven spatial sampling, particularly in the early record (before 1950; WGI AR5 Section 2.5.8).

30.3.1.5. Storm Systems

As agents of water column mixing, storms (from small atmospheric disturbances to intense tropical cyclones) can remix nutrients from deeper areas into the photic zone of the Ocean, stimulating productivity. Storms can also reduce local sea temperatures and associated stress by remixing heat into the deeper layers of the Ocean (Carrigan and Puotinen, 2011). Large storms can destroy coastal infrastructure and coastal habitats such as coral reefs and mangrove forests, which can take decades to recover (Lotze et al., 2011; De'ath et al., 2012).

Although there is *low confidence* for long-term trends in tropical cyclone activity globally (largely due to the lack of reliable long-term data sets), it is *virtually certain* that the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (WGI AR5 Section 2.6.3). There is *medium agreement* that the frequency of the most intense cyclones in the Atlantic has increased since 1987 (WGI AR5 Section 2.6.3) and *robust evidence* of inter-decadal changes in the storm track activity within the North Pacific and North Atlantic (Lee et al., 2012). It is also *likely* that there has been a decrease in the number of land-falling tropical cyclones along the East Australian coast since the 19th century (WGI AR5 Section 2.6.3; Callaghan and Power, 2011). It is *likely* that these patterns are influenced by interannual variability such as ENSO, with land-falling tropical cyclones being twice as common in La Niña versus El Niño years (*high confidence*; Callaghan and Power, 2011). There has been an increase in the number of intense wintertime extratropical cyclone systems since the 1950s in the North Pacific. Similar trends have been reported for the Asian region, although analyses are limited in terms of the spatial and temporal coverage of reliable records (WGI AR5 Section 2.6.4). There is *low confidence*, however, in large-scale trends in storminess or storminess proxies over the last century owing to the lack of long-term data and inconsistencies between studies (WGI AR5 Section 2.6.4).

30.3.1.6. Thermal Stratification

As heat has accumulated in the Ocean there has been a 4% increase in thermal stratification of the upper layers in most ocean regions (0 to 200 m, 40-year record) north of 40°S (WGI AR5 Section 3.2.2). Increasing thermal stratification has reduced ocean ventilation and the depth of mixing in many ocean sub-regions (*medium confidence*; WGI AR5 Section 3.8.3). This in turn reduces the availability of inorganic nutrients and consequently primary productivity (*medium confidence*; Section 6.3.4). In the STG, which dominate the three major ocean basins (Section 30.5.6), satellite-derived estimates of surface chlorophyll and primary production decreased between 1999 and 2007 (Box CC-PP). In contrast, however, *in situ* observations at fixed stations in the North Pacific and North Atlantic Oceans (Hawaii Ocean Time-series (HOT) and Bermuda Atlantic Time-series Study (BATS)) showed increases in nutrient and chlorophyll levels and primary production over the same period, suggesting that other processes (e.g., ENSO, PDO, North Atlantic Oscillation (NAO), winds, eddies, advection) can counteract broad-scale trends at local scales (Box CC-PP). The continued warming of the surface layers of the Ocean will *very likely* further enhance stratification and potentially limit the nutrient supply to the euphotic zone in some areas. The response of upwelling to global warming is *likely* to vary between regions and represents a complex interplay between local and global variables and processes (Box CC-UW).

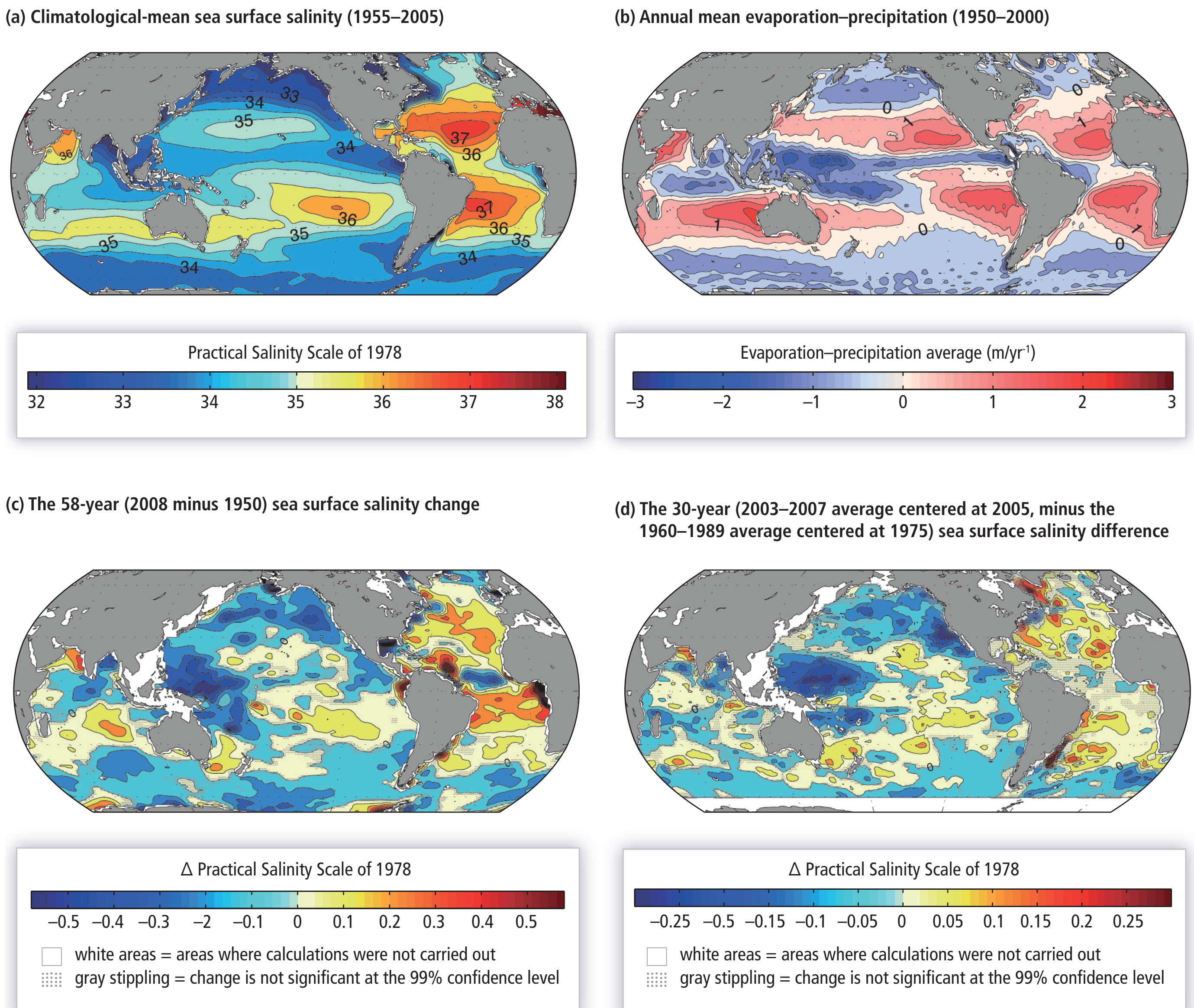

Figure 30-6 | (a) The 1955–2005 climatological-mean sea surface salinity (Antonov et al., 2010) color contoured at 0.5 Practical Salinity Scale 1978 (PSS78) intervals (black lines). (b) Annual mean evaporation-precipitation averaged over the period 1950–2000 (National Centers for Environmental Prediction (NCEP)) color contoured at 0.5 m yr–1 intervals (black lines). (c) The 58-year (2008 minus 1950) sea surface salinity change derived from the linear trend (PSS78), with seasonal and El Niño-Southern Oscillation (ENSO) signals removed (Durack and Wijffels, 2010) color contoured at 0.116 PSS78 intervals (black lines). (d) The 30-year (2003–2007 average centered at 2005, minus the 1960–1989 average centered at 1975) sea surface salinity difference (PSS78) (Hosoda et al., 2009) color contoured at 0.06 PSS78 intervals (black lines). Contour intervals in (c) and (d) are chosen so that the trends can be easily compared, given the different time intervals in the two analyzes. White areas in (c) and (d) are marginal seas where the calculations are not carried out. Regions where the change is not significant at the 99% confidence level are stippled in gray. Figure originally presented as WGI AR5 Figure 3.4. All salinity values quoted in the chapter are expressed on the Practical Salinity Scale 1978 (PSS78) (Lewis and Fofonoff, 1979).

30.3.2. Chemical Changes

30.3.2.1. Surface Salinity

The global water cycle is dominated by evaporation and precipitation occurring over ocean regions, with surface ocean salinity varying with temperature, solar radiation, cloud cover, and ocean circulation (Deser et al., 2004). Changes in salinity influence stratification of water masses and circulation. Ocean salinity varies regionally (Figure 30-6a) and is a function of the balance between evaporation and precipitation (Durack and Wijffels, 2010; WGI AR5 Section 3.3). Evaporation-dominated regions (Figure 30-6b) such as the STG and Atlantic and Western Indian Oceans (WGI AR5 Section 3.3.3) have elevated salinity, while areas of high precipitation such as the North Pacific, northeastern Indian Ocean, Southeast Asia, and the eastern Pacific have relatively low salinities (WGI AR5 Section 3.3.3; Figure 30-6a). It is *likely* that large-scale trends in salinity have also occurred in the Ocean interior, deriving from changes to salinity at the surface and subsequent subduction (WGI AR5 Section 3.3).

Salinity trends are consistent with the amplification of the global hydrological cycle (Durack et al., 2012; Pierce et al., 2012), a consequence of a warmer atmosphere *very likely* producing the observed trend in greater precipitation, evaporation, atmospheric moisture (Figure 30-6b), and extreme events (WGI AR5 Sections 2.6.2.1, 3.3.4; IPCC, 2012). Spatial patterns in salinity and evaporation-precipitation are correlated, providing indirect evidence that these processes have been enhanced since the 1950s (WGI AR5 Sections 3.3.2-4; WGI AR5 Figures 3.4, 3.5, 3.20d; WGI AR5 FAQ 3.3). These trends in salinity are *very likely* to have a discernible contribution from anthropogenic climate change (WGI AR5 Section 10.4.2). The combined changes in surface salinity and temperature are consistent with changes expected due to anthropogenic forcing of the climate system and are inconsistent with the effects of natural climate variability, either internal to the climate system (e.g., ENSO, PDO; Figure 30-6c,d) or external to it (e.g., solar forcing or volcanic eruptions; Pierce et al., 2012). There is *high confidence* between climate models that the observed trends in ocean salinity will continue as average global temperature increases (Durack and Wijffels, 2010; Terray et al., 2012). Ramifications of these changes are largely unknown but are of interest given the role of ocean salinity and temperature in fundamental processes such as the AMOC.

30.3.2.2. Ocean Acidification

The Ocean has absorbed approximately 30% of atmospheric CO_2 from human activities, resulting in decreased ocean pH and carbonate ion concentrations, and increased bicarbonate ion concentrations (Box CC-OA; WGI AR5 Box 3.2; WGI AR5 Figure SM30-2). The chemical response to increased CO_2 dissolving into the Ocean from the atmosphere is known with *very high confidence* (WGI AR5 Section 6.4.4). Factors such as temperature, biological processes, and sea ice (WGI AR5 Section 6.4) play significant roles in determining the saturation state of seawater for polymorphs (i.e., different crystalline forms) of calcium carbonate. Consequently, pH and the solubility of aragonite and calcite are naturally lower at high latitudes and in upwelling areas (e.g., California Current EBUE), where organisms and ecosystems may be relatively more exposed to ocean acidification as a result (Feely et al., 2012; Gruber et al., 2012; Figures 30-7a,b, SM30-2). Aragonite and calcite concentrations vary with depth, with under-saturation occurring at deeper depths in the Atlantic (calcite: 3500 to 4500 m, aragonite: 400 to 3000 m) as opposed to the Pacific and Indian Oceans (calcite: 100 to 3000 m, aragonite: 100 to 1200 m; Feely et al., 2004, 2009; Orr et al., 2005; Figure 30-8).

Surface ocean pH has decreased by approximately 0.1 pH units since the beginning of the Industrial Revolution (*high confidence*) (Figure 30-7a; WGI AR5 Section 3.8.2; WGI AR5 Box 3.2), with pH decreasing at the rate of –0.0013 and 0.0024 pH units yr^{-1} (WGI AR5 Section 3.8.2; WGI AR5 Table 3.2). The presence of anthropogenic CO_2 diminishes with

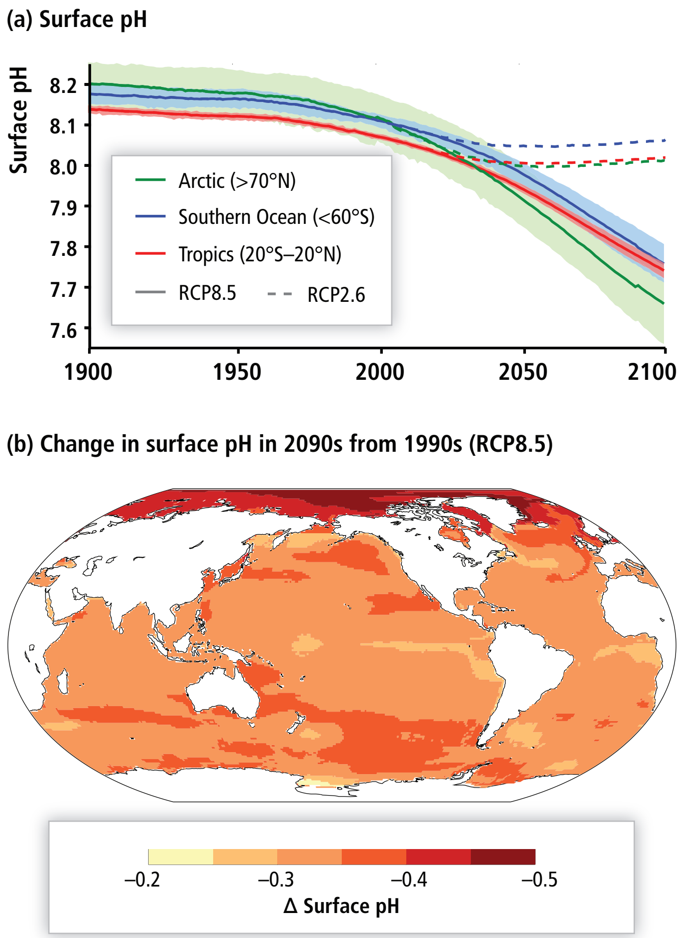

Figure 30-7 | Projected ocean acidification from 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System models under RCP8.5 (other Representative Concentration Pathway (RCP) scenarios have also been run with the CMIP5 Models): (a) Time series of surface pH shown as the mean (solid line) and range of models (shaded area), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue). (b) Maps of the median model's change in surface pH from 1990s. Panel (a) also includes mean model results from RCP2.6 (dashed lines). Over most of the Ocean, gridded data products of carbonate system variables are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following (Orr et al., 2005). Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), the results are shown without bias correction. The bias correction reduces the range of model projections by up to a factor of four; for example, in panel (a) compare the large range of model projections for the Arctic (without bias correction) to the smaller range in the Southern Ocean (with bias correction). Figure originally presented in WGI AR5 Figure 6.28.

depth. The saturation horizons of both polymorphs of calcium carbonate, however, are shoaling rapidly (1 to 2 m yr^{-1}, and up to 5 m yr^{-1} in regions such as the California Current (Orr et al., 2005; Feely et al., 2012). Further increases in atmospheric CO_2 are *virtually certain* to further acidify the Ocean and change its carbonate chemistry (Figures SM30-2, 30-7, 30-8). Doubling atmospheric CO_2 (~RCP4.5; Rogelj et al., 2012) will decrease ocean pH by another 0.1 unit and decrease carbonate ion concentrations by approximately 100 µmol kg^{-1} in tropical oceans (Figure 30-8a) from the present-day average of 250 µmol kg^{-1} (*high confidence*). Projected changes for the open Ocean by 2100 (Figures 30-7, 30-8) range from a pH change of –0.14 unit with RCP2.6 (421 ppm CO_2, +1°C, 22% reduction of carbonate ion concentration) to a pH change of –0.43 unit with RCP8.5

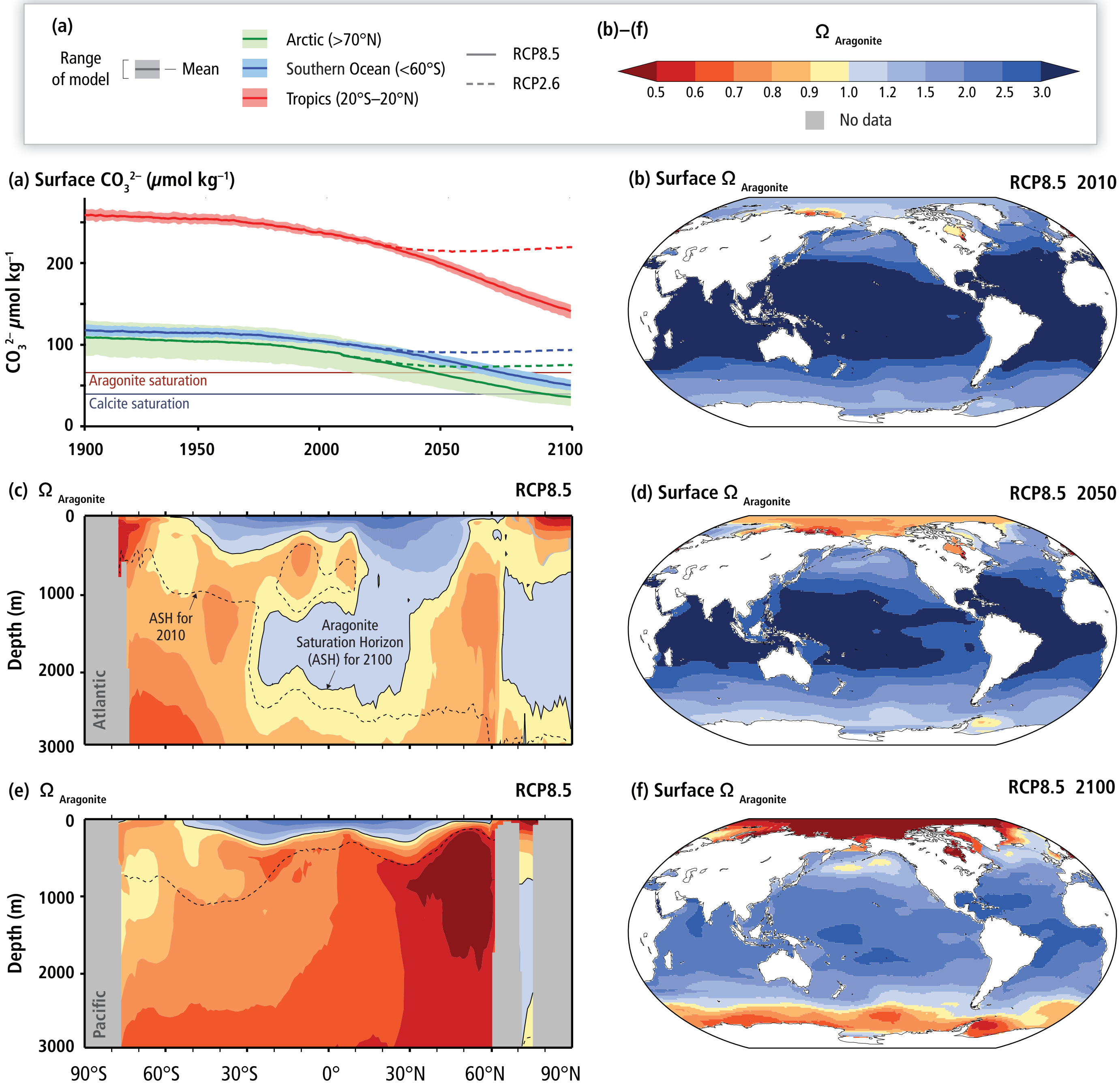

Figure 30-8 | Projected aragonite saturation state ($\Omega_{Aragonite}$) from 11 Coupled Model Intercomparison Project Phase 5 (CMIP5) Earth System Models under Representative Concentration Pathway 8.5 (RCP8.5) scenario. (a) Time series of surface carbonate ion (CO_3^{2-}) concentration shown as the mean (solid line) and range of models (shaded area), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue); maps of the median model's surface $\Omega_{Aragonite}$ in (b) 2010, (d) 2050, and (f) 2100; and zonal mean sections (latitude vs. depth) of $\Omega_{Aragonite}$ in 2100 over (c) the Atlantic Ocean and (e) the Pacific Ocean, while the ASH (Aragonite Saturation Horizon) is shown for 2010 (dotted line) and 2100 (solid line). Panel (a) also includes mean model results from RCP2.6 (dashed lines). As for Figure 30-7, gridded data products of carbonate system variables (Key et al., 2004) are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following Orr et al. (2005). Where gridded data products are unavailable (Arctic Ocean, all marginal seas, and the Ocean near Indonesia), results are shown without bias correction. Figure originally presented in WGI AR5 Figure 6.29.

(936 ppm CO_2, +3.7°C, 56% reduction of carbonate ion concentration). The saturation horizons will also become significantly shallower in all oceans (with the aragonite saturation horizon between 0 and 1500 m in the Atlantic Ocean and 0 and 600 m (poles vs. equator) in the Pacific Ocean; Sabine et al., 2004; Orr et al., 2005; WGI AR5 Section 6.4.4; WGI AR5 Figure 6.28). Trends toward under-saturation of aragonite and calcite will also partly depend on ocean temperature, with surface polar waters expected to become seasonally under-saturated with respect to aragonite and calcite within a couple of decades (Figure 30-8c,d,e,f; Box CC-OA; McNeil and Matear, 2008).

Overall, observations from a wide range of laboratory, mesocosm, and field studies reveal that marine macro-organisms and ocean processes are sensitive to the levels of ocean acidification projected under elevated atmospheric CO_2 (*high confidence*; Box CC-OA, Section 6.3.2; Munday et al., 2009; Kroeker et al., 2013). Ecosystems that are characterized by high rates of calcium carbonate deposition (e.g., coral reefs, calcareous plankton communities) are sensitive to decreases in the saturation states of aragonite and calcite (*high confidence*). These changes are *very likely* to have broad consequences such as the loss of three-dimensional coral reef frameworks (Hoegh-Guldberg et al., 2007; Manzello et al., 2008; Fabricius et al., 2011; Andersson and Gledhill, 2013; Dove et al., 2013) and restructuring of food webs at relatively small (~50 ppm) additional increases in atmospheric CO_2. Projected shoaling of the aragonite and calcite saturation horizons are *likely* to impact deep water (100 to 2000 m) communities of scleractinian corals and other benthic organisms as atmospheric CO_2 increases (Orr et al., 2005; Guinotte et al., 2006; WGI AR5 Section 6.4.4), although studies from the Mediterranean and seamounts off southwest Australia report that some deep water corals may be less sensitive (Thresher et al., 2011; Maier et al., 2013). Organisms are also sensitive to changes in pH with respect to physiological processes such as respiration and neural function (Section 6.3.2). Owing to the relatively short history, yet growing effort, to understand the implications of rapid changes in pH and ocean carbonate chemistry, there are a growing number of organisms and processes reported to be sensitive. The impact of ocean acidification on marine organisms and ecosystems continues to raise serious scientific concern, especially given that the current rate of ocean acidification (at least 10 to 100 times faster than the recent glacial transitions (Caldeira and Wickett, 2003; Hoegh-Guldberg et al., 2007)) is unprecedented within the last 65 Ma (*high confidence*; Ridgwell and Schmidt, 2010) and possibly 300 Ma of Earth history (*medium confidence*; Hönisch et al., 2012; Section 6.1.2).

30.3.2.3. Oxygen Concentration

Dissolved O_2 is a major determinant of the distribution and abundance of marine organisms (Section 6.3.3). Oxygen concentrations vary across ocean basins and are lower in the eastern Pacific and Atlantic basins, and northern Indian Ocean (Figure 30-9b; Section 6.1.1.3). In contrast, some of the highest concentrations of O_2 are associated with cooler high-latitude waters (Figure 30-9b). There is *high agreement* among analyses providing *medium confidence* that O_2 concentrations have decreased in the upper layers of the Ocean since the 1960s, particularly in the equatorial Pacific and Atlantic Oceans (WGI AR5 Section 3.8.3; WGI AR5 Figure 3.20). A formal fingerprint analysis undertaken by Andrews et al. (2013) concluded that recent decreases in oceanic O_2 are due to external influences (*very likely*). Conversely, O_2 has increased in the North and South Pacific, North Atlantic, and Indian Oceans, and is consistent with greater mixing and ventilation due to strengthening wind systems (WGI AR5 Section 3.8.3). The reduction in O_2 concentration in some areas of the Ocean is consistent with that expected from higher ocean temperatures and a reduction in mixing (increasing stratification) (WGI AR5 Section 3.8.3). Analysis of ocean O_2 trends over time (Helm et al., 2011b) reveals that the decline in O_2 solubility with increased temperature is responsible for no more than 15% of the observed change. The remaining 85%, consequently, is associated with increased deep-sea microbial respiration and reduced O_2 supply due to increased ocean stratification (WGI AR5 Section 6.1.1.3). In coastal areas, eutrophication can lead to increased transport of organic carbon into adjacent ocean habitats where microbial metabolism is stimulated, resulting in a rapid drawdown of O_2 (Weeks et al., 2002; Rabalais et al., 2009; Bakun et al., 2010).

The development of hypoxic conditions (defined as O_2 concentrations below ~60 μmol kg^{-1}) over recent decades has been documented across

Frequently Asked Questions

FAQ 30.1 | Can we reverse the impacts of climate change on the ocean?

In less than 150 years, greenhouse gas (GHG) emissions have resulted in such major physical and chemical changes in our oceans that it will take thousands of years to reverse them. There are a number of reasons for this. Given its large mass and high heat capacity, the ability of the Ocean to absorb heat is 1000 times larger than that of the atmosphere. The Ocean has absorbed at least nine-tenths of the Earth's heat gain between 1971 and 2010. To reverse that heating, the warmer upper layers of the Ocean have to mix with the colder deeper layers. That mixing can take as much as 1000 years. This means it will take centuries to millennia for deep ocean temperatures to warm in response to today's surface conditions, and at least as long for ocean warming to reverse after atmospheric GHG concentrations decrease (*virtually certain*). But climate change-caused alteration of basic conditions in the Ocean is not just about temperature. The Ocean becomes more acidic as more carbon dioxide (CO_2) enters it and will take tens of thousands of years to reverse these profound changes to the carbonate chemistry of the ocean (*virtually certain*). These enormous physical and chemical changes are producing sweeping and profound changes in marine ecosystems. Large and abrupt changes to these ecosystems are unlikely to be reversible in the short to medium term (*high confidence*).

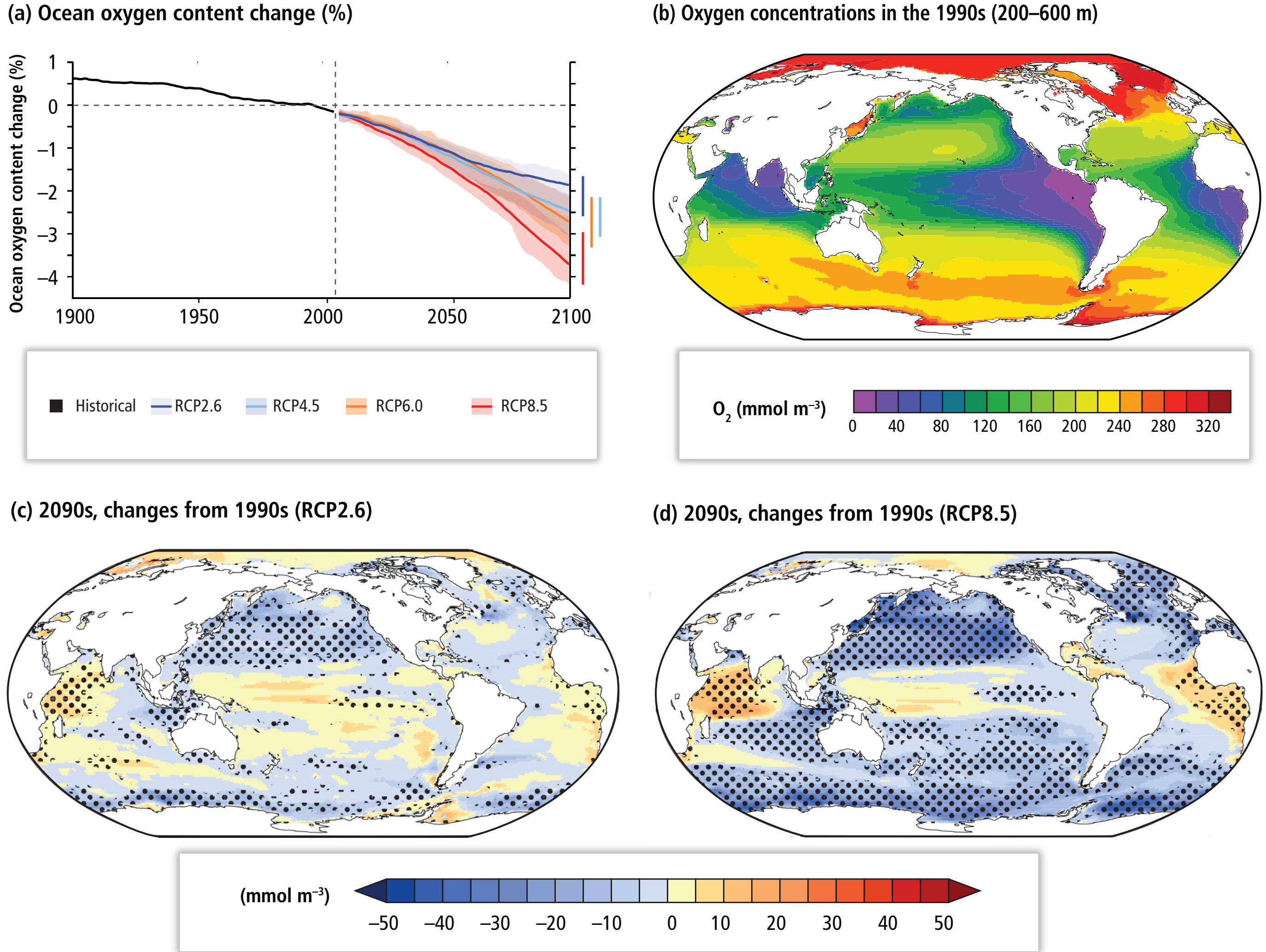

Figure 30-9 | (a) Simulated changes in dissolved O_2 (mean and model range as shading) relative to 1990s for Representative Concentration Pathway 2.6 (RCP2.6), RCP4.5, RCP6.0, and RCP8.5. (b) Multi-model mean dissolved O_2 (mmol m^{-3}) in the main thermocline (200 to 600 m depth average) for the 1990s, and changes in the 2090s relative to 1990s for RCP2.6 (c) and RCP8.5 (d). To indicate consistency in the sign of change, regions are stippled when at least 80% of models agree on the sign of the mean change. These diagnostics are detailed in Cocco et al. (2013) in a previous model intercomparison using the Special Report on Emission Scenarios (SRES)-A2 scenario and have been applied to Coupled Model Intercomparison Project Phase 5 (CMIP5) models here. Models used: Community Earth System Model 1–Biogeochemical (CESM1-BGC), Geophysical Fluid Dynamics Laboratory–Earth System Model 2G (GFDL-ESM2G), Geophysical Fluid Dynamics Laboratory–Earth System Model 2M (GFDL-ESM2M), Hadley Centre Global Environmental Model 2–Earth System (HadGEM2-ES), Institute Pierre Simon Laplace–Coupled Model 5A–Low Resolution (IPSL-CM5A-LR), Institute Pierre Simon Laplace–Coupled Model 5A–Medium Resolution (IPSL-CM5A-MR), Max Planck Institute–Earth System Model–Low Resolution (MPI-ESM-LR), Max Planck Institute–Earth System Model–Medium Resolution (MPI-ESM-MR), Norwegian Earth System Model 1 (Emissions capable) (NorESM1). Figure originally presented in WGI AR5 Figure 6.30.

a wide array of ocean sub-regions including some SES (e.g., Black and Baltic Seas), the Arabian Sea, and the California, Humboldt, and Benguela Current systems, where eruptions of hypoxic, sulfide-laden water have also occurred in some cases (Weeks et al., 2002). Localized, seasonal hypoxic "dead zones" have emerged in economically valuable coastal areas such as the Gulf of Mexico (Turner et al., 2008; Rabalais et al., 2010), the Baltic Sea (Conley et al., 2009), and the Black Sea (Kideys, 2002; Ukrainskii and Popov, 2009) in connection with nutrient fluxes from land. Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, the minimum O_2 threshold (less than 2 mg l^{-1} or ~60 µmol^{-1}) is found at 300 m depth and upwelling of increasingly hypoxic waters is well documented (Karstensen et al., 2008). Hypoxic waters in the northern Arabian Sea and Bay of Bengal are located close to continental shelf areas. Long-term measurements reveal that O_2 concentrations are declining in these waters, with *medium evidence* that economically significant mesopelagic fish populations are being threatened by a reduction in suitable habitat as respiratory stress increases (Koslow et al., 2011). It should be noted that hypoxia profiles based on a critical threshold of 60 µmol kg^{-1} can convey an overly simplistic message given that critical concentrations of O_2 in this regard are very much species, size, temperature, and life history stage specific. This variability in sensitivity is, however, a critical determinant for any attempt to understand how ecosystems will respond to changing future O_2 levels (Section 6.3.3).

There is *high agreement* among modeling studies that O_2 concentrations will continue to decrease in most parts of the Ocean due to the effect of temperature on O_2 solubility, microbial respiration rates, ocean ventilation, and ocean stratification (Figure 30-9c,d; WGI AR5 Table 6.14; Andrews et al., 2013), with implications for nutrient and carbon cycling, ocean productivity, marine habitats, and ecosystem structure (Section 6.3.5). The outcomes of these global changes are *very likely* to be influenced by regional differences in variables such as wind stress, coastal processes, and the supply of organic matter.

30.4. Global Patterns in the Response of Marine Organisms to Climate Change and Ocean Acidification

Given the close relationship between organisms and ecosystems with the physical and chemical elements of the environment, changes are expected in the distribution and abundance of marine organisms in response to ocean warming and acidification (Section 6.3; Boxes CC-MB, CC-OA). Our understanding of the relationship between ocean warming and acidification reveals that relatively small changes in temperature and other variables can result in often large biological responses that range from simple linear trends to more complex non-linear outcomes. There has been an increase in studies that focus on the influence and consequences of climate change for marine ecosystems since AR4 (Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013), representing an opportunity to examine, and potentially attribute, detected changes within the Ocean to climate change.

Evidence of global and regional responses of marine organisms to recent climate change has been shown through assessments of multiple studies focused on single species, populations, and ecosystems (Tasker, 2008; Thackeray et al., 2010; Przeslawski et al., 2012; Poloczanska et al., 2013). The most comprehensive assessment, in terms of geographic spread and number of observed responses, is that of Poloczanska et al. (2013). This study reveals a coherent pattern in observed responses of ocean life to recent climate change across regions and taxonomic groups, with 81% of responses by organisms and ecosystems being consistent with expected changes to recent climate change (*high confidence*; Box CC-MB). On average, spring events in the Ocean have advanced by 4.4 ± 0.7 days per decade (mean ± SE) and the leading edges of species' distributions have extended (generally poleward) by 72.0 ± 0.35 km per decade. Values were calculated from data series ranging from the 1920s to 2010, although all series included data after 1990. The fastest range shifts generally occurred in regions of high thermal velocity (the speed and direction at which isotherms move (Burrows et al., 2011; Section 30.3.1.1)). Subsequently, Pinsky et al. (2013), using a database of 360 fish and invertebrate species and species groups from coastal waters around North America, showed differences in the speed and directions that species shift can be explained by differences in local climate velocities (Box CC-MB).

30.5. Regional Impacts, Risks, and Vulnerabilities: Present and Future

This section explores the impacts, risks, and vulnerabilities of climate change for the seven sub-regions within the Ocean. There is considerable variability from region to region, especially in the extent and interaction of climate change and non-climate change stressors. Although the latter may complicate attribution attempts in many sub-regions, interactions between the two groups of stressors may also represent opportunities to reduce the overall effects on marine organisms and processes of the environmental changes being driven by climate change (including ocean acidification) (Crain et al., 2008; Griffith et al., 2012).

30.5.1. High-Latitude Spring Bloom Systems

High-Latitude Spring Bloom Systems (HLSBSs) stretch from 35°N to the edge of the winter sea ice (and from 35°S to the polar front) and provide 36% of world's fish catch (Figure 30-1b). Although much of the North Pacific is iron limited (Martin and Fitzwater, 1988) and lacks a classical spring bloom (McAllister et al., 1960), strong seasonal variability of primary productivity is pronounced at all high latitudes because of seasonally varying photoperiod and water column stability (Racault et al., 2012). Efficient transfer of marine primary and secondary production to higher trophic levels, including commercial fish species, is influenced by the magnitude as well as the spatial and temporal synchrony between successive trophic production peaks (Hjort, 1914; Cushing, 1990; Beaugrand et al., 2003; Beaugrand and Reid, 2003).

Frequently Asked Questions

FAQ 30.2 | Does slower warming in the Ocean mean less impact on plants and animals?

The greater thermal inertia of the Ocean means that temperature anomalies and extremes are lower than those seen on land. This does not necessarily mean that impacts of ocean warming are less for the ocean than for land. A large body of evidence reveals that small amounts of warming in the Ocean can have large effects on ocean ecosystems. For example, relatively small increases in sea temperature (as little as 1°C to 2°C) can cause mass coral bleaching and mortality across hundreds of square kilometers of coral reef (*high confidence*). Other analyses have revealed that increased temperatures are spreading rapidly across the world's oceans (measured as the movement of bands of equal water temperature or isotherms). This rate of warming presents challenges to organisms and ecosystems as they try to migrate to cooler regions as the Ocean continues to warm. Rapid environmental change also poses steep challenges to evolutionary processes, especially where relatively long-lived organisms such as corals and fish are concerned (*high confidence*).

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The average temperature of the surface waters of the North Atlantic HLSBS has warmed by 0.07°C per decade, resulting in an increase in sea temperature of 0.44°C between 1950 and 2009 (*likely*) (*p*-value = 0.15; Table 30-1). Over the same period, both winter and summer temperatures have increased significantly (0.05°C per decade and 0.12°C per decade respectively, p-value ≤ 0.05). Since the 1970s, the Atlantic Ocean has warmed more than any other ocean basin (0.3°C per decade; Figure 30-2a; WGI AR5 Section 3.2.2), with greatest warming rates over European continental shelf areas such as the southern North Sea, the Gulf Stream front, the sub-polar gyres, and the Labrador Sea (MacKenzie and Schiedek, 2007a,b; Levitus et al., 2009; Lee et al., 2011; González-Taboada and Anadón, 2012). Basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming and the current warm phase of the Atlantic Multi-decadal Oscillation (AMO) (Wang and Dong, 2010; WGI AR5 Section 14.7.6).

The North Atlantic is one of the most intensively fished ocean sub-regions. The major areas for harvesting marine living resources span the eastern North American, European, and Icelandic shelves (Livingston and Tjelmeland, 2000). In addition, the deep regions of the Nordic Seas and the Irminger Sea contain large populations of pelagic fish such as herring, blue whiting, and mackerel and mesopelagic fish such as pearlsides and redfish. The region covers a wide latitudinal range from 35°N to 80°N and, hence, a large span in thermal habitats. This is reflected in the latitudinal gradient from subtropical/temperate species along the southern fringe to boreal/arctic species along the northern fringe.

Climate change is *virtually certain* to drive major changes to the northern fringes of the Atlantic HLSBS by 2100. For the Barents Sea region, which borders the HLSBS and Arctic regions, modeling projections from 1995 to 2060 (SRES B2 scenario) gave an increase in phytoplankton production of 8%, an increase in Atlantic zooplankton production of 20%, and a decrease of Arctic zooplankton production of 50% (Ellingsen et al., 2008). These changes result in a total increase in zooplankton production in the HLSBS section of the Barents Sea and a decrease in the Arctic section. Together with poleward shifts of fish species, a substantial increase in fish biomass and catch is also *very likely* at the northern fringes of the HLSBS (Cheung et al., 2011). However, for some species such as capelin, which feeds in summer at the ice edge and spawns in spring at the southern Atlantic Norwegian/Murman coast of the Barents Sea, the continuous temperature increase is *very likely* to cause discontinuous changes in conditions. The limited migration potential for this small pelagic fish is also *likely* to drive an eastward shift in spawning areas to new spawning grounds along the Novaja Semlja coast (Huse and Ellingsen, 2008).

Observations of fish and other species moving to higher latitudes (Beare et al., 2005; Perry et al., 2005; Collie et al., 2008; Lucey and Nye, 2010) within the North Atlantic HLSBS are consistent with results of modeling exercises (Stenevik and Sundby, 2007; Cheung et al., 2011). Examples from the Barents (Section 28.2.2.1), Nordic, and North Seas (Box 6-1; Section 23.4.6) show how warming from the early 1980s influenced North Atlantic ecosystems, where substantial biological impacts such as large-scale modification of the phenology, abundance, and distribution of plankton assemblages and reorganization of fish assemblages have been observed (Beaugrand et al., 2002; Edwards, 2004; Edwards and Richardson, 2004; Tasker, 2008; Nye et al., 2009; Head and Pepin, 2010; Simpson et al., 2011). The ranges of some cold-water zooplankton assemblages in the northeast Atlantic have contracted towards the Arctic since 1958, and have been replaced by warm-water zooplankton assemblages (specifically copepods) (*high confidence*), which moved up to 1000 km northward (Beaugrand et al., 2002; Beaugrand, 2009). Although changes to surface circulation may have played a role (Reid et al., 2001), the primary driver of the shift was shown to be regional warming (Beaugrand et al., 2002; Beaugrand, 2004). Reorganization of zooplankton communities and an observed decline in mean size has implications for energy transfer to higher trophic levels including commercial fish stocks (Beaugrand et al., 2003; Kirby and Beaugrand, 2009; Lindley et al., 2010; Section 23.4.6). Warm-water species of fish have increased in abundance on both sides of the North Atlantic (*medium confidence*; Beare et al., 2005; Collie et al., 2008; Genner et al., 2010; Hermant et al., 2010; Lucey and Nye, 2010; Simpson et al., 2011). The diversity of zooplankton and fish has increased as more diverse warm-water assemblages extend northward in response to changing environmental conditions (*high confidence*; Kane, 2007; Hiddink and ter Hofstede, 2008; Beaugrand, 2009; Mountain and Kane, 2010; ter Hofstede et al., 2010; Box 6-1; Section 23.4.6).

The past decade has been the warmest decade ever recorded in the Barents Sea, resulting in large populations of krill shrimp and pelagic and demersal fish stocks linked to the Atlantic and boreal ecosystem of the Barents Sea (*high confidence*; Johannesen et al., 2012; Section 28.2.2.1). Recruitment to boreal fish stocks such as cod, haddock, and herring has increased (Eriksen et al., 2012). The relatively warm Atlantic waters have advanced northward and eastward (Årthun et al., 2012) and sea ice has retreated along with the Arctic water masses. As a result, boreal euphausiids, which are mainly confined to Atlantic water, have increased in biomass and distribution (Dalpadado et al., 2012), enhancing growth of young cod *Gadus morhua* (boreal) as well as the more Arctic (arcto-boreal) capelin (*Mallotus villosus*). The abundance of amphipods of more Arctic origin has decreased, resulting in poorer feeding conditions for polar zooplankton predators such as polar cod (*Boreogadus saida*). Blue whiting (*Micromesistius poutassou*), which spawns west of the British Isles and feeds on zooplankton in the Norwegian Sea during the summer, extended their summer feeding distribution into the Barents Sea during the recent warm period.

The Norwegian Sea is one of the two core regions for the herbivore copepod *Calanus finmarchicus*, an important prey species for pelagic fish and early life stages of all fish around the rim of this high-latitude sea including the North Sea and the Barents Sea (Sundby, 2000). *C. finmarchicus* is the main food item for some of the world's largest fish stocks such as the Norwegian spring-spawning herring (*Clupea harengus*), blue whiting (*M. poutassou*), and northeast Atlantic mackerel (*Scomber scombrus*). These stocks have increased considerably during the recent warming that started in the early 1980s (Huse et al., 2012). The individual size of herring has also increased, enabling longer feeding migrations to utilize boreal zooplankton occurring closer to distant Arctic water masses. Mackerel (*Scomber scombrus*) has advanced northward and westward into Icelandic waters (Astthorsson et al., 2012) and was even observed in East Greenland water in summer 2013 (Nøttestad et al., 2013). Since 2004, the sum of spawning stock biomass of the three pelagic fish species (herring, blue whiting, and mackerel) leveled out at around 16 million tonnes.

Observed changes in the phenology of plankton groups in the North Sea over the past 50 years are driven by climate forcing, in particular regional warming (*high confidence*; Edwards and Richardson, 2004; Wiltshire and Manly, 2004; Wiltshire et al., 2008; Lindley et al., 2010; Lindley and Kirby, 2010; Schluter et al., 2010), although responses are species-specific with substantial variation within functional groups (Edwards and Richardson, 2004; Box 6-1). For example, the peak maximum abundance of the copepod *C. finmarchicus* advanced by 10 days from the 1960s to the 2000s, but its warm-water equivalent, *C. helgolandicus*, did not advance (Bonnet et al., 2005). In the North Sea, bottom temperatures in winter have warmed by 1.6°C (1980–2004; Dulvy et al., 2008). The whole demersal fish community shifted deeper by 3.6 m per decade over the period 1980–2004, although mean latitude of the whole community did not show net displacement (Dulvy et al., 2008). Within the community, cool-water specialists generally shifted northward while abundant warm-water species shifted southward, reflecting winter warming of the southern North Sea. The cold winter temperatures of the shallow regions of the southern North Sea have acted to exclude species with warm-water affinities. Trawl survey data from the rapidly warming southern North Sea suggests waves of immigration by southern species such as red mullet (*Mullus surmuletus*), anchovy (*Engraulis encrasicholus*), and sardines (*Sardina pilchardus*), linked to increasing population sizes and warming temperatures (Beare et al., 2004, 2005).

In the northeast Atlantic, range expansions and contractions linked to changing climate have also been observed in benthic crustaceans, bivalves, gastropods, and polychaetes (*medium confidence*; Mieszkowska et al., 2007; Beukema et al., 2009; Berke et al., 2010). For example, the southern range limit of the common intertidal barnacle, *Semibalanus balanoides*, contracted northward along European coastlines at a rate of 15 to 50 km per decade since 1872, and its retreat is attributed to reproductive failure as winter temperatures warm (Southward et al., 2005; Wethey and Woodin, 2008). *Chthamalus montagui*, its warm-water competitor, increased in abundance to occupy the niche vacated by *S. balanoides* (*high confidence*; Southward et al., 1995; Poloczanska et al., 2008).

Many of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing, that span periods of cooling and warming over the past century, are from the northeast Atlantic (Toresen and Østvedt, 2000; Southward et al., 2005; Sundby and Nakken, 2008; Edwards et al., 2010; Poloczanska et al., 2013). Meta-analysis of 288 long-term data sets (spanning up to 90 years) of zooplankton, benthic invertebrates, fish, and seabirds from the OSPAR Commission Maritime Area in the North-east Atlantic showed widespread changes in distribution, abundance, and seasonality that were consistent (77%) with expectations from enhanced greenhouse warming (Tasker, 2008). The study brought together evidence of changes in ocean climate and ecological responses across a range of species that encompassed both exploited and unexploited species from a variety of information types including peer-reviewed reports from International Council for the Exploration of the Sea (ICES) Working Groups. In particular, observations indicated poleward shifts in zooplankton communities, increasing abundance of fish species in the northern part of their ranges and decreases in southern parts, and the expansion of benthic species into more northerly or less coastal areas (*high confidence*).

The major portion of the literature on the influence of climate change on the North Atlantic region covers time spans that are longer than for most other sub-regions of the Ocean. Even here, however, the bulk of the literature is limited to the last 30 to 50 years. The few publications covering the first half of the 20th century represent an important longer term perspective on the influence of climate change (Toresen and Østvedt, 2000; Drinkwater, 2006; Sundby and Nakken, 2008; Bañón, 2009; Astthorsson et al., 2012). For example, distinct changes in fauna were associated with a pronounced warming period over 1920–1940 (Wood and Overland, 2010), when fish and other fauna shifted northward (Iversen, 1934; Southward et al., 2005; Drinkwater, 2006; Hátún et al., 2009). The major lesson from these reports is that a rapid large-scale temperature increase occurred in the high-latitude North Atlantic between the 1920s and 1940s, with basin-scale consequences for marine ecosystems that are comparable to warming and observed impacts over the last 30 years. The former event was of great concern within the scientific community, particularly during the late 1940s and early 1950s (Iversen, 1934; Tåning, 1949, 1953; Southward, 1980). However, with the subsequent long-term cooling in the 1970s, discussion around climate responses was discontinued (Southward, 1980). The centennial-long perspective indicates that multi-decadal variability has played a major role in changes observed over the past 30 years. The 150-year instrumental record shows distinct warm phases of the AMO during approximately 1930–1965 and from 1995, and cool phases between approximately 1900–1930 and 1960–1995 (WGI AR5 Section 14.7.6). However, it is *virtually certain* that the enhanced warming in recent decades cannot be explained without external forcing (WGI AR5 Section 10.3.1.1.3). Understanding the changes in inter-decadal variability over the next century is particularly important. The current warm phase of the AMO is *likely* to terminate in the next few decades, leading to a cooling influence in the North Atlantic and potentially offsetting some of the effects of global warming (WGI AR5 Sections 11.3.2.4.1, 14.7.6). Over the transition period, the climate of the North Atlantic is *likely* to change more rapidly than during previous transitions since 1900.

30.5.1.1.2. North Pacific

Sub-decadal variability in the North Pacific HLSBS is dominated by ENSO (Trenberth, 1990; WGI AR5 Section 14.4). Unlike the North Atlantic HLSBS, the North Pacific HLSBS does not show any significant trends in temperature over time, *very likely* as a consequence of climate variability influences on long-term warming patterns (1950–2009; Table 30-1). Decadal and longer periods of variability in the North Pacific are reflected in the principal mode, the Pacific Decadal Oscillation (PDO; WGI AR5 Section 14.7.3), with periodicities in SST of both 15 to 25 years and 50 to 70 years (Minobe, 1997; Mantua and Hare, 2002). Further modes of climate variability include the North Pacific Gyre Oscillation (NPGO; Di Lorenzo et al., 2008; Chhak et al., 2009). The PDO exhibits SST anomalies of one sign along the eastern boundary and the opposite sign in western and central Pacific. The PDO has been reported to have

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an anthropogenic component (Bonfils and Santer, 2011) but confidence in this is *very low* (*limited evidence*, *low agreement*; WGI AR5 Section 10.3.3). The interplay of the phases of these modes of variability has strong influence on high-latitude Pacific ecosystems (*very high confidence*). In the space of 3 years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) (McKinnell et al., 2010; McKinnell and Dagg, 2010). This rapid change was accompanied by large changes in primary productivity, zooplankton communities, and fish and seabird populations (McKinnell et al., 2010; McKinnell and Dagg, 2010; Batten and Walne, 2011; Bi et al., 2011; Keister et al., 2011).

Climate transitions among phases of variability tend to be characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter (Hunt et al., 2002; Peterson and Schwing, 2003; Litzow and Ciannelli, 2007; Litzow et al., 2008; Alheit, 2009). Periods of broad-scale environmental change were observed across high-latitude ecosystems in the North Pacific HLSBS (eastern Bering Sea and Gulf of Alaska) during 1976–1978, 1987–1989, and 1998–1999. These periods were associated with regime shifts in foraging fish that occurred in 1979–1982, 1988–1992, and 1998–2001. The changes indicate how basin-scale variability such as the PDO can manifest across distinct ecosystems (Overland et al., 2008; Link et al., 2009a,b). Phenological shifts observed in the zooplankton communities of the North Pacific were *very likely* in response to decadal climate variability, with distinct changes noted after the climate shifts of the 1970s and 1990s (Mackas et al., 1998; Peterson and Schwing, 2003; Chiba et al., 2006). Modeling evidence suggests a weak shift in PDO toward more occurrences of the negative phase but the credibility of projections remains uncertain (WGI AR5 Section 14.7.3). It is *about as likely as not* that the PDO will change its form or behavior in the future (WGI AR5 Section 14.7.3).

The Kuroshio-Oyashio Extension (KOE) in the northwest Pacific displays pronounced decadal-scale variability (Yatsu et al., 2008; Sugisaki et al., 2010). "Warm periods" in the mid-1970s and late 1980s were accompanied by dramatic changes in pelagic ecosystems and sardine and anchovy stocks (Chiba et al., 2008; Yatsu et al., 2008). Observations and climate model simulations indicate that global warming is *likely* to further alter the dynamics of the Kuroshio Current and the KOE over the coming century (McPhaden and Zhang, 2002; Sakamoto et al., 2005; Wu et al., 2012; Zhang et al., 2014). Alteration of the KOE will alter the timing, magnitude, and structure of spring blooms in the western Pacific and have implications for pelagic fish recruitment, production, and biogeochemical cycles (Ito et al., 2004; Hashioka et al., 2009; Yatsu et al., 2013).

Commercial catches of salmon species in the North Pacific HLSBS follow decadal fluctuations in climate (Hare and Mantua, 2000; Mantua and Hare, 2002). Catches peaked in the warm periods of the 1930s–1940s and 1990s–2000s, with 2009 yielding the highest catch to date, and warming trends are *about as likely as not* to have contributed to recent peaks in some sub-regions (Morita et al., 2006; Irvine and Fukuwaka, 2011). Poleward range shifts of some large pelagic fish in the western North Pacific, such as yellowtail *Seriola quinqueradiata* and Spanish mackerel *Scomberomorus niphonius*, were attributed, in part, to regional warming (*high confidence*) and these two species are projected to shift 39 to 71 km poleward from the 2000s to 2030s under SRES A1B (Tian et al., 2012; Jung et al., 2014). Anticipating ecological responses to future anthropogenic climate change also requires evaluation of the role of changes to climate beyond warming per se. For example, declining sea level pressure in the North Pacific is *likely* influenced by anthropogenic forcing (Gillett et al., 2003; Gillett and Stott, 2009; WGI AR5 Section 10.3.3.4) and sea level pressure in turn is related to atmospheric climate parameters (e.g., turbulent mixing via wind stress) that regulate commercially significant fish populations (Wilderbuer et al., 2002).

The northern fringe of the Bering Sea is among the most productive of marine sub-regions and includes the world's largest single-species fishery, walleye pollock (*Theragra chalcogramma*; Hunt et al., 2010). This region underwent major changes in recent decades as a result of climate variability, climate change, and fishing impacts (Litzow et al., 2008; Mueter and Litzow, 2008; Jin et al., 2009; Hunt et al., 2010; Section 28.2.2.1). Seasonal sea ice cover declined since the 1990s (to 2006), although there is no linear trend between 1953 and 2006, and the initiation of spring ice retreat over the southeastern Bering Sea shelf started to occur earlier (Wang et al., 2007a). Concurrent with the retreat of the "cold pool," an area of reduced water temperature (<2°C) on the northern Bering Sea shelf that is formed as a consequence of sea ice and is maintained over summer (Hunt et al., 2010), bottom trawl surveys of fish and invertebrates show a significant community-wide northward distribution shift and a colonization of the former cold pool areas by sub-Arctic fauna (*high confidence*; Wang et al., 2006a; Mueter and Litzow, 2008).

Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, waters low in dissolved O_2 (Oxygen Minimum Zone (OMZ)) are found at 300 m depth (Karstensen et al., 2008). Sporadic upwelling of these low-O_2 waters along the continental shelf is well documented, where biological respiration can further reduce dissolved O_2 levels and result in hypoxic or anoxic conditions that lead to mortality of coastal fishes and invertebrates (Grantham et al., 2004; Chan et al., 2008). The magnitude and severity of seasonal hypoxic conditions in shallow-shelf waters of the eastern North Pacific HLSBS increased in recent decades (Bograd et al., 2008; Chan et al., 2008). In addition, minimum pH values in the water column usually occur near the depths of the OMZ (WGI AR5 Box 3.2). A shoaling of the aragonite saturation horizon has *likely* resulted in low-aragonite conditions within the density layers being upwelled on the shelf of the west coast of the USA, increasing the risk of seasonally upwelled water being relatively acidified (Feely et al., 2008) with observed impacts on Pacific oyster (*Crassostrea gigas*) hatcheries (Barton et al., 2012). In the time period 1991–2006, reductions in pH in the North Pacific between 800 and ~100 m were attributed in approximately equal measure to anthropogenic and natural variations (Byrne et al., 2010; WGI AR5 Section 3.8.2; WGI AR5 Figure 3.19).

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the Southern Hemisphere are much less pronounced and are of smaller magnitude than those at Northern Hemisphere high latitudes (Yoder et al., 1993). The Southern Hemisphere HLSBS is broadly bounded by the subtropical front and the sub-Antarctic front. Associated with the subtropical front is intense biological activity of bloom-forming coccolithophores (phytoplankton) (Brown and Yoder, 1994). The calcifying plankton assemblages play a key role in carbon cycles in the region and the transport of carbon to deep ocean sediments. The coccolithophore, *Emiliania huxleyi*, extended its range south of 60° in the southwest Pacific (141°E to 145°E) over the 2 decades since 1983 (Cubillos et al., 2007). Although the drivers for this range extension are not clear, it was proposed that the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

Large regions of the sub-Antarctic surface waters are *likely* to become undersaturated with respect to aragonite during winter by 2030, which will impact calcifying plankton and Southern Ocean ecosystems (McNeil and Matear, 2008; Bednaršek et al., 2012; Section 28.2.2.2). Shell weights of the modern foraminifer, *Globigerina bulloides*, in the sediments of the sub-Antarctic region of the HLSBS south of Australia were observed to be 30 to 35% lower than those from sediment cores representing preindustrial periods, consistent with a recent decline in pH (Moy et al., 2009). Examination of the pteropod, *Limacina helicina antarctica*, captured from polar waters further south shows severe levels of shell dissolution consistent with the shoaling of the aragonite saturation horizon and indicates that the impact of ocean acidification is already occurring (Bednaršek et al., 2012).

While the South Pacific HLSBS has not shown warming overall, both the warmest and coolest months show a slight, but significant, increase over time (both 0.05°C per decade from 1950 to 2009, p-value ≤ 0.05; Table 30-1), although some areas within this sub-region have warmed. For example, the western Tasman Sea has shown enhanced warming since 1900 as compared to average global trends (*high confidence*). This has been driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific STG and intensification of the southward-flowing East Australian Current (EAC; Cai, 2006; Hill et al., 2008; Wu et al., 2012; WGI AR5 Section 3.6.2). Model simulations suggest both stratospheric ozone depletion and greenhouse forcing contribute to the observed trend in wind stress (Cai and Cowan, 2007). Coinciding with this warming and intensified EAC is the observation that a number of benthic invertebrates, fish, and zooplankton are now found further south than they were in the mid-20th century (Ling, 2008; Pitt et al., 2010; Last et al., 2011). Warming facilitated the establishment of the grazing urchin, *Centrostephanus rodgersii*, in eastern Tasmania during the late 1970s (*high confidence*), which has resulted in deleterious effects on macroalgal beds (Ling, 2008; Ling et al., 2008, 2009; Banks et al., 2010).

30.5.1.2. Key Risks and Vulnerabilities

Projected changes to the temperature of surface waters match those of the past 50 years, with average sea temperatures in the HLSBS regions projected to increase by 0.35°C to 1.17°C in the near term (2010–2039) and by 1.70°C to 4.84°C over the long term (2010–2099) under the "business as usual" (BAU) RCP8.5 scenario (Table SM30-4). Under the lower case scenario considered here (RCP2.6), projected rates of regional warming are much lower (0.12°C to 0.79°C) in the near term, with slight cooling for some regions in the long term (–0.16°C to 1.46°C). Risks to HLSBS from warming of surface waters include changes to primary production and carbon cycling, and the reorganization of ecosystems in response to warmer and more acidified oceans. Both primary production and the timing of the spring bloom in HLSBS are very sensitive to environmental change. Latitudinal shifts in the distribution of phyto- and zooplankton communities will alter seasonality, community composition, and bloom dynamics (Beaugrand, 2009; Ito et al., 2010; Shoji et al., 2011). Alteration of the structure and composition of plankton communities can propagate through high-latitude food webs due to tight trophic linkages (Edwards and Richardson, 2004; Beaugrand et al., 2010; Beaugrand and Kirby, 2010). Mechanisms are complex, and tend to be non-linear, with impacts on ecosystems, fisheries, and biogeochemical cycles being hard to project with any certainty (Box CC-PP). A reorganization of commercial fish stocks, with attendant social and economic disruption, is a key risk of ongoing climate change in HLSBS sub-regions. AR4 reported that the productivity of some marine fisheries is *likely* to increase in the North Atlantic (WGII AR4 Sections 10.4.1, 12.4.7). A large number of publications since then has substantially extended documentation of these trends and has begun to elucidate the nuances in how marine ecosystems and organisms respond (Sumaila et al., 2011).

An additional risk exists for sub-polar areas from the loss of seasonal sea ice. Decreases in seasonal sea ice are *very likely* to lead to increases in the length of the growth season and the intensity of the light available to fuel phytoplankton growth and, hence, enhance primary production and attending modifications of ecosystem structure (Arrigo et al., 2008). In the long term, however, primary production may decrease due to the reduced supply of nutrients to the surface layers (Box CC-PP). The decline in Arctic sea ice will open ecological dispersal pathways, as well as new shipping routes (Section 30.6.2.3), between the North Atlantic and the North Pacific; large numbers of the Pacific diatom, *Neodenticula seminae*, were found in the North Atlantic in 1999 (Reid et al., 2007).

HLSBSs are also vulnerable to rapid changes in the carbonate chemistry of ocean waters. Ocean acidification will produce additional and large-scale challenges. There is *medium agreement* that calcifying organisms in these regions will be negatively affected by ocean acidification, with substantial impacts on higher trophic levels, although there is *limited evidence* at this point.

30.5.2. Equatorial Upwelling Systems

The largest upwelling systems are found in the equatorial regions of the eastern Pacific and Atlantic Oceans (Figure 30-1a). Equatorial Upwelling Systems (EUS) produce highly productive "cold tongues" that stretch westward across equatorial areas, which is different from other upwelling systems (e.g., EBUE; Section 30.5.5). The associated upwelling is a consequence of the Earth's rotation and easterly (westward) winds and currents, which drive water northward and southward at the northern and southern edges of these sub-regions. As result, cold, nutrient-rich, and high CO_2/low pH waters are transported from the deeper layers of the Ocean to the surface, driving high levels of primary productivity that support 4.7% of total global fisheries productivity (Table SM30-1; Figure 30-1b). Interannual modes of variability (e.g., ENSO; WGI AR5 Section 14.4) dominate EUS, particularly in the Pacific (Barber et al., 1994; McCarthy et al., 1996; Signorini et al., 1999; Le Borgne et al., 2002;

Christian and Murtugudde, 2003; Mestas-Nuñez and Miller, 2006; Pennington et al., 2006; Wang et al., 2006b). Upwelling of the Pacific EUS declines during El Niño events, when the trade winds weaken, or even reverse, and is strengthened during La Niña events. ENSO periodicity controls primary productivity and consequently has a strong influence over associated fisheries production (Mestas-Nuñez and Miller, 2006). The Intertropical Convergence Zone (ITCZ; WGI AR5 Section 14.3.1.1), an important determinant of regional ocean temperature, is located at the edges of the Indian and Pacific equatorial upwelling zone and influences a range of variables including productivity, fisheries, and precipitation. The EUS are also affected by inter-decadal variability (e.g., Inter-decadal Pacific Oscillation (IPO); Power et al., 1999; WGI AR5 Section 14.3).

30.5.2.1. Observed Changes and Potential Impacts

The average sea temperature associated with the EUS has increased significantly (p-value ≤ 0.05), by 0.43°C and 0.54°C from 1950 to 2009 in the Pacific and Atlantic EUS, respectively (Table 30-1). In the Pacific, regional variability in SST trends is driven by the temporal patterns in ENSO and the more frequent El Niño Modoki or Central Pacific El Niño events in recent decades (*high confidence*; Ashok et al., 2007; Yu and Kao, 2007; Lee and McPhaden, 2010; WGI AR5 Section 14.2.4.4). The faster warming of the Atlantic EUS is *likely* to be associated with a weakening of upwelling (Tokinaga and Xie, 2011). SLR in the eastern equatorial Pacific has been decreasing by up to –10 mm yr^{-1} since 1993 (Church et al., 2006; Figure 30-5).

Coral reefs in the EUS of the eastern Pacific (e.g., Galápagos and Cocos Islands) have relatively low species diversity and poorly developed carbonate reef frameworks, due to the low pH and aragonite saturation of upwelling waters (*high confidence*; Glynn, 2001; Manzello et al., 2008; Manzello, 2010). Prolonged periods of elevated temperature associated with El Niño have negatively affected corals, kelps, and associated organisms, and resulted in several possible local extinctions (*high confidence*; Glynn, 2011). Since 1985, coral reefs from west of South America to the Gilbert Islands of Kiribati have experienced the highest levels of thermal stress relative to other areas (Donner et al., 2010). In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific (Glynn, 1984; Baker et al., 2008). Subsequent canonical El Niño and Central Pacific El Niño events in 1997/1998, 2002/2003, 2004/2005, and 2009/2010 (WGI AR5 Section 14.4.2; WGI AR5 Figure 14.13) triggered mass coral bleaching by adding to the background increases in sea temperatures (*high confidence*; Donner et al., 2010; Obura and Mangubhai, 2011; Vargas-Ángel et al., 2011). In some locations, impacts of El Niño have also interacted with other anthropogenic changes, such as those arising from changes to fishing pressure (Edgar et al., 2010), further complicating the attribution of recent ecological changes to climate change.

30.5.2.2. Key Risks and Vulnerabilities

Climate models indicate that ENSO is *virtually certain* to continue to be a major driver of oceanic variability over the coming century, although not all models can accurately replicate its behavior (WGI AR5 Section 9.5.3). Superposition of a warming ocean on future ENSO activity (possibly modified in frequency and intensity) is *likely* to result in oceanic conditions that are different from those experienced during past El Niño and La Niña events (Power and Smith, 2007). Temperatures within EUS sub-regions are projected to continue to warm significantly (p-value ≤ 0.05). Under RCP8.5, SST of the Atlantic EUS is projected to increase by 0.81°C over 2010–2039 and 2.56°C over 2010–2099, with similar increases projected for the Pacific EUS (Table SM30-4). Differences between RCPs for the two EUS become clear beyond mid-century, with warming of SST over 2010–2099 being 0.43°C and 0.46°C under RCP2.6, and 3.01°C and 3.03°C under RCP8.5, for Pacific and Atlantic EUS respectively (Table SM30-4). These projected increases in sea temperature will increase heat stress and ultimately irreversibly degrade marine ecosystems such as coral reefs (*very likely*). Further increases in atmospheric CO_2 will cause additional decrease in pH and aragonite saturation of surface waters (adding to the low pH and aragonite saturation of upwelling conditions), with significant differences between emission trajectories by the middle of the century. These changes in ocean carbonate chemistry are *very likely* to negatively affect some

Frequently Asked Questions

FAQ 30.3 | How will marine primary productivity change with ocean warming and acidification?

Drifting microscopic plants known as phytoplankton are the dominant marine primary producers at the base of the marine food chain. Their photosynthetic activity is critically important to life in general. It provides oxygen, supports marine food webs, and influences global biogeochemical cycles. Changes in marine primary productivity in response to climate change remain the single biggest uncertainty in predicting the magnitude and direction of future changes in fisheries and marine ecosystems (*low confidence*). Changes have been reported to a range of different ocean systems (e.g., High-Latitude Spring Bloom Systems, Subtropical Gyre Systems, Equatorial Upwelling Systems, and Eastern Boundary Upwelling Ecosystems), some of which are consistent with changes in ocean temperature, mixing, and circulation. However, direct attribution of these changes to climate change is made difficult by long-term patterns of variability that influence productivity of different parts of the Ocean (e.g., Pacific Decadal Oscillation). Given the importance of this question for ocean ecosystems and fisheries, longer time series studies for understanding how these systems are changing as a result of climate change are a priority (*high agreement*).

marine calcifiers, although many of the species from this region are adapted to the low aragonite and calcite saturation states that result from equatorial upwelling, albeit with much lower rates of calcification (Manzello, 2010; Friedrich et al., 2012). A substantial risk exists with respect to the synergistic interactions between sea temperature and declining pH, especially as to how they influence a large number of key biological processes (Box CC-OA).

There is *low confidence* in the current understanding of how (or if) climate change will influence the behavior of ENSO and other long-term climate patterns (Collins et al., 2010; WGI AR5 Section 12.4.4.2). There is also low agreement between different CMIP5 General Circulation Models (GCMs) on how ocean warming will affect ENSO, with no significant change to ENSO amplitude in half of the models examined, and both increasing and decreasing activity in others (Guilyardi et al., 2012). These differences appear to be a consequence of the delicate balance within ENSO between dampening and amplifying feedbacks, and the different emphasis given to these processes within the different GCMs (Collins et al., 2010). Other studies have looked at the interaction between the STG and EUS, and warming of surface waters in the Pacific, with at least one study projecting the possible expansion of the STG at the expense of the EUS (Polovina et al., 2011). In the latter case, the area of equatorial upwelling within the North Pacific would decrease by 28%, and primary production and fish catch by 15%, by 2100. Many of the projected changes imply additional consequences for pelagic fisheries resulting from the migration of fish stocks deriving from changing distribution of particular sea temperatures (Lehodey et al., 2006, 2008, 2011; Cheung et al., 2010; Sumaila et al., 2011; Bell et al., 2013b). These projections suggest that fisheries within EUS will experience increased vulnerability as a result of climate change (*low confidence*).

30.5.3. Semi-Enclosed Seas

Semi-Enclosed Seas (SES) represent a subset of ocean sub-regions that are largely land locked and consequently heavily influenced by surrounding landscapes and local climates (Healy and Harada, 1991). In most cases, they support small but regionally significant fisheries (3.3% of global production; Table SM30-1; Figure 30-1b) and opportunities for other industries such as tourism. Five SES (all over 200,000 km^2 with single entrances <120 km wide) are considered here. This particular geography results in reduced circulation and exchange with ocean waters, and jurisdictions for these water bodies that are shared by two or more neighboring states. In many cases, the small volume and disconnected nature of SES (relative to coastal and oceanic environments) makes them highly vulnerable to both local and global stressors, especially with respect to the much reduced options for the migration of organisms as conditions change.

30.5.3.1. Observed Changes and Potential Impacts

30.5.3.1.1. Arabian Gulf

The Arabian Gulf (also referred to as the Persian Gulf), along with the Red Sea, is the world's warmest sea, with both extreme negative and positive temperature excursions (annual temperature range of 12°C to 35°C). Like other SES, the Arabian Gulf is particularly vulnerable to changing environmental conditions as a result of its landlocked nature. Trends in SST were not significant over the period 1950–2009 (Table 30-1), which is probably due to long-term variability, and a consequence of regional and abrupt changes that occurred in the late 1980s (Conversi et al., 2010). In keeping with this, recent (1985–2002) localized analyses (e.g., Kuwait Bay) show strong and significant warming trends (based in this case on Advanced Very High Resolution Radiometer (AVHRR) National Oceanic and Atmospheric Administration (NOAA) satellite data) of 0.6°C per decade (Al-Rashidi et al., 2009). There is *limited evidence* and *low agreement* as to how this variability influences marine ecosystems and human activities within the Arabian Gulf, although impacts on some ecosystem components (e.g., coral reefs) have been defined to some extent. The mass coral bleaching and mortality that occurred in 1996 and 1998 were a direct result of the sensitivity of reef-building corals to unusually elevated sea temperatures (*high confidence*; Riegl, 2002, 2003; Box CC-CR). These changes to coral reefs have resulted in a loss of fish species that feed on coral-associated invertebrates while herbivores and planktivorous fish abundances have increased (*medium confidence*; Riegl, 2002). Despite coral ecosystems in this sub-region being adapted to some of the highest temperatures in shallow seas on Earth, anthropogenic climate change is driving higher frequencies and intensities of mass coral bleaching and mortality (Riegl et al., 2011). Other biological changes (e.g., harmful algal blooms and fish kills; Heil et al., 2001) have been associated with the increasing sea temperatures of the Arabian Gulf, although attribution to increasing temperatures as opposed to other factors (e.g., water quality) is limited (Bauman et al., 2010).

30.5.3.1.2. Red Sea

Few studies have focused on attributing recent changes in Red Sea ecosystems to climate change (including ocean acidification). The Red Sea warmed by 0.74°C from 1982 to 2006 (Belkin, 2009), although trends in the average SST, however, are not significant from 1950 to 2009 (p-value > 0.05; Table 30-1) owing to a high degree of variability involved when longer periods were examined (supplementary material in Belkin, 2009). The temperature of the warmest month of the year, however, showed a significant increase over the 60-year period (0.05°C per decade; Table 30-1). Regional trends within the Red Sea may also differ, with at least one other study reporting higher rates of warming for the central Red Sea (1.46°C, relative to 1950–1997 NOAA Extended Reconstructed SST (ERSST) v3b climatology; Cantin et al., 2010).

Long-term monitoring of coral community structure and size over 20 years shows that average colony size of corals has declined (*high confidence*) and species' latitudinal limits may have changed (*medium confidence*). The decline in average colony size is ascribed to heat-mediated bleaching as well as increases in coral diseases and crown of thorns starfish (*Acanthaster* sp.) predation (Riegl et al., 2012). The patterns of this decline correlate well with the pattern of recent heating in the Red Sea (Raitsos et al., 2011), with the biggest changes being seen in the southern part of the Red Sea. Skeletal growth of the long-lived massive coral *Diploastrea heliopora* has declined significantly, *very likely* due to warming temperatures (*medium confidence*; p-value ≥ 0.05; Cantin et al., 2010).

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Cantin et al. (2010) proposed that the massive coral *Diploastrea helipora* will cease to grow in the central Red Sea by 2070 under SRES A1B and A2 (*medium confidence*), although this may not hold for other coral species. For example, an increase in linear extension of *Porites* corals, beginning in the 1980s, was recorded in the northern Red Sea (Heiss, 1996), where temperatures have increased by 0.74ºC from 1982 to 2006 (Belkin, 2009), suggesting that these corals were living in sub-optimal conditions (cooler waters). They may therefore benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline, as they are doing in other oceans. Riegl and Piller (2003) concluded that coral habitats at moderate depths in the Red Sea might provide important refugia from some aspects of climate change in the future (*limited evidence*). Silverman et al. (2007) quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate chemistry (pH, aragonite saturation). Their results demonstrate a strong negative effect of ocean acidification on ecosystem-scale calcification and decalcification, and show that small changes in carbonate dissolution could have large-scale implications for the long-term persistence of carbonate coral reef systems within the Red Sea (Silverman et al., 2007, 2009).

30.5.3.1.3. Black Sea

The temperature of the surface waters of the Black Sea increased by 0.96ºC from 1982 to 2006 (Belkin, 2009), which is consistent with other studies (*high confidence*; Buongiorno Nardelli et al., 2010; Bozkurt and Sen, 2011). As with other SES (i.e., Arabian Gulf and Baltic, Mediterranean, and Red Seas), longer data sets do not reveal a significant trend due to large-scale variability prior to 1982, which may be due to the influence of AMO, NAO, and other long-term sources of variability (Table 30-1; supplementary material in Belkin, 2009). Buongiorno Nardelli et al. (2010) observed that short-term SST variability (week-month) is strongly influenced by interactions with the overlying atmosphere, which itself is strongly influenced by the surrounding land temperatures. As with the Mediterranean and Red Seas, however, a significant upward trend in the temperature is recorded in the warmest month of the year over the period 1950–2009 (Table 30-1). Freshwater discharge from rivers draining into the Black Sea has remained more or less constant since the early 1960s (Ludwig et al., 2009). Increasing water temperature has steadily eliminated the Cold Intermediate Layer (CIL; temperatures below 8°C) throughout the Black Sea basin over 1991–2003 (*high confidence*; Oguz et al., 2003). Reduced water column mixing and upwelling during warmer winter periods has reduced the supply of nutrients to the upper layers of the Black Sea (Oguz et al., 2003) and expanded areas of low O_2 in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin (*high confidence*; Murray et al., 1989). These changes coincided with the collapse of fish stocks and the invasion by the ctenophore, *Mnemiopsis leidyi*, in the 1980s (Oguz et al., 2008), while inputs of nutrients such as phosphate from the Danube River has decreased strongly since 1992–1993 (Oguz and Velikova, 2010). Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s (Yunev et al., 2007; Oguz and Velikova, 2010). The Black Sea system is very dynamic and is strongly affected by non-climate stressors in addition to climate change, making attribution of detected trends to climate change difficult.

30.5.3.1.4. Baltic Sea

Temperatures in the highly dynamic Baltic Sea increased substantially since the early 1980s (Aleksandrov et al., 2009; Belkin, 2009), with increases of 1.35°C (1982–2006) being among the highest rate of change seen in any SES (Belkin, 2009). Increases of this magnitude are not seen in longer records throughout the Baltic Sea (1861–2001: MacKenzie et al., 2007; MacKenzie and Schiedek, 2007a,b; 1900–1998: Madsen and Højerslev, 2009). The salinity of the surface and near bottom waters of the Baltic Sea, for example, Gdansk Basin (Aleksandrov et al., 2009) and central Baltic (Fonselius and Valderrama, 2003; Möllmann et al., 2003), decreased from 1975 to 2000, due to changing rainfall and river runoff, and a reduction in the pulses of seawater (vital for oxygenation and related chemical changes) from the North Sea through its opening via the Kattegat (*high confidence*; Samuelsson, 1996; Conley et al., 2009; Hänninen and Vuorinen, 2011). There is a strong vertical zonation within the Baltic Sea in terms of the availability of O_2. The shallow sub-regions of the Baltic are relatively well oxygenated. However, O_2 levels are low in the deeper basins, producing conditions in which organisms and ecosystems are exposed to prolonged hypoxia.

The annual biomass of phytoplankton has declined almost threefold in the Baltic Transition Zone (Kattegat, Belt Sea) and Western Baltic Sea since 1979 (Henriksen, 2009), reputedly due to changing nitrogen loads in the Danish Straits (*medium confidence*) in addition to increasing sea temperature (*very likely*; Madsen and Højerslev, 2009). Reduced phytoplankton production may have decreased the productivity of fisheries in the western Baltic Sea and the Transition Zone (*low* to *medium confidence*; Chassot et al., 2007). Decreasing salinity in the Baltic deep basins may also affect zooplankton reproduction, especially that of the copepod *Pseudocalanus acuspes*, contributing to density-dependent decrease in growth of the commercially important herring and sprat stocks (*high confidence*; Möllmann et al., 2003, 2005; Casini et al., 2011). The strong relationship between phytoplankton and fish production, and increasing sea temperature, decreasing salinity, and other environmental factors, suggests that major changes in fisheries production will occur as sea temperatures increase and the hydrological cycle in the Baltic region changes (*high confidence*; MacKenzie et al., 2012). A combination of climate change-induced oceanographic changes (i.e., decreased salinity and increased temperatures), eutrophication, and overfishing have resulted in major changes in trophic structure in the deep basins of the Baltic Sea (Möllmann et al., 2009). This had important implications for cod, a commercially important top predator (*medium confidence*; Lindegren et al., 2010).

30.5.3.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and Central Europe. SST within the Mediterranean increased by 0.43°C from 1957 to 2008 (supplementary material in Belkin, 2009), although analysis of data from 1950 to 2009 detected only a significant trend in summer temperature (0.11°C per decade, p-value ≤ 0.05; Table 30-1) due to large fluctuations in SST prior to the 1980s. Surface temperatures increased in the Mediterranean Sea consistent with significant increases in SST at a number of monitoring sites (*robust evidence*, *high agreement*; e.g., Coma et al., 2009; Conversi et al., 2010; Calvo et al., 2011). It is *likely* that temperatures, along with salinity, have also increased at depth (400 m or more) in the western Mediterranean Sea over the past 30 to 40 years which, when analyzed in the context of heat budget and water flux of the Mediterranean, is consistent with anthropogenic greenhouse warming (Bethoux et al., 1990; Rixen et al., 2005; Vargas-Yáñez et al., 2010). Large-scale variability such as the AMO and NAO can obscure or accentuate the overall warming trend (Marullo et al., 2011; WGI AR5 Sections 14.5.1, 14.7.6). Relatively warm episodes in the 1870s, 1930–1970s, and since the mid-1990s, for example, exhibit an influence of the AMO (Kerr, 2000; Moron, 2003). Reported temperature anomalies in the Mediterranean, often locally manifesting themselves as periods of low wind, increased water column stratification, and a deepening thermocline, are associated with positive phases of the NAO index (Molinero et al., 2005; Lejeusne et al., 2010).

Sea levels have increased rapidly in some areas over recent decades and are also strongly influenced by NAO phases. The rate has been approximately 3.4 mm yr^{-1} (1990–2009) in the northwest Mediterranean (*high confidence*; Calvo et al., 2011). These influences are reduced when measurements are pooled over longer time scales, resulting in a lower rate of SLR (Massuti et al., 2008). If the positive phase of the NAO is more frequent in the future (Terray et al., 2004; Kuzmina et al., 2005; WGI AR5 Section 14.4.2), then future SLR may be slightly suppressed as a result of atmospheric influences (*medium confidence*; Jordà et al., 2012). As temperatures have increased, the Mediterranean has become more saline (+0.035 to 0.040 psu from 1950 to 2000; Rixen et al., 2005) with the length of the thermal stratification period persisting twice as long in 2006 as it did in 1974 (Coma et al., 2009).

Conditions within the Mediterranean Sea changed abruptly and synchronously with similar changes across the North, Baltic, and Black Seas in the late 1980s (Conversi et al., 2010), which possibly explains the lack of trend in SES SST when examined from 1950 to 2009 (Table 30-1). These changes in physical conditions (increased temperature, higher sea level pressure, positive NAO index) also coincided with step changes in the diversity and abundance of zooplankton, decreases in stock abundance of anchovies and the frequency of "red tides," and increases in mucilage outbreaks (Conversi et al., 2010). Mucilage outbreaks are strongly associated with warmer and more stratified water columns (*high confidence*), and lead to a greater abundance and diversity of marine microbes and potentially disease-causing organisms (*likely*; Danovaro et al., 2009). Increasing temperatures are also driving the northward spread of warm-water species (*medium confidence*) such as the sardine *Sardinella aurita* (Sabatés et al., 2006; Tsikliras, 2008), and have contributed to the spread of the invading Atlantic coral *Oculina patagonia* (Serrano et al., 2013). The recent spread of warm-water species that have invaded through the Straits of Gibraltar and the Suez Canal into cooler northern areas is leading to the "tropicalization" of Mediterranean fauna (*high confidence*; Bianchi, 2007; Ben Rais Lasram and Mouillot, 2008; CIESM, 2008; Galil, 2008, 2011). Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin (Raitsos et al., 2010; Section 23.6.5).

In addition to general warming patterns, periods of extreme temperatures have had large-scale and negative consequences for Mediterranean marine ecosystems. Unprecedented mass mortality events, which affected at least 25 prominent invertebrate species, occurred during the summers of 1999, 2003, and 2006 across hundreds of kilometers of coastline in the northwest Mediterranean Sea (*very high confidence*; Cerrano et al., 2000; Garrabou et al., 2009; Calvo et al., 2011; Crisci et al., 2011). Events coincided with either short periods (2 to 5 days: 2003, 2006) of high sea temperatures (27°C) or longer periods (30 to 40 days) of modestly high temperatures (24°C: 1999; Bensoussan et al., 2010; Crisci et al., 2011). Impacts on marine organisms have been reported in response to the extreme conditions during these events (e.g., gorgonian coral mortality; Coma et al., 2009), shoot mortality, and anomalous flowering of seagrasses (*high confidence*; Diaz-Almela et al., 2007; Marbà and Duarte, 2010). The frequency and intensity of these types of heat stress events are expected to increase as sea temperatures increase (*high confidence*).

Longer-term data series (over several decades) of changes in relative acidity of the Mediterranean Sea are scarce (Calvo et al., 2011; The MerMex Group, 2011). Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05 to 0.14 pH units since the preindustrial period (*medium confidence*; Luchetta et al., 2010; Touratier and Goyet, 2011). Anthropogenic CO_2 has penetrated the entire Mediterranean water column, with the western basin being more contaminated than the eastern basin (Touratier and Goyet, 2011). Studies that have explored the consequences of ocean acidification for the biology and ecology of the Mediterranean Sea are rare (Martin and Gattuso, 2009; Rodolfo-Metalpa et al., 2010; Movilla et al., 2012), although insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia in Italy, where biodiversity decreases with decreasing pH toward the vents, with a notable decline in calcifiers (Hall-Spencer et al., 2008). Transplants of corals, molluscs, and bryozoans along the acidification gradients around seeps reveal a low level of vulnerability to CO_2 levels expected over the next 100 years (*low confidence*; Rodolfo-Metalpa et al., 2010, 2011). However, periods of high temperature can increase vulnerability to ocean acidification, thereby increasing the long-term risk posed to Mediterranean organisms and ecosystems as temperatures warm. Significantly, some organisms such as seagrasses and some macroalgae appeared to benefit from local ocean acidification (Hall-Spencer et al., 2008).

30.5.3.2. Key Risks and Vulnerabilities

SES are highly vulnerable to changes in global temperature on account of their small volume and landlocked nature. Consequently, SES will respond faster than most other parts of the Ocean (*high confidence*). Risks to ecosystems within SES are *likely* to increase as water columns become further stratified under increased warming, promoting hypoxia at depth and reducing nutrient supply to the upper water column (*medium evidence*, *high agreement*). The impact of rising temperatures on SES is exacerbated by their vulnerability to other human influences such as over-exploitation, pollution, and enhanced runoff from modified coastlines. Due to a mixture of global and local human stressors, key fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years (*medium confidence*). A major risk exists for SES from projected increases in the frequency of temperature extremes that drive mass mortality events, increasing water column stabilization leading to reduced mixing, and changes to the distribution and abundance of marine organisms. The vulnerability of marine ecosystems, fisheries, and human communities associated with the SES will continue to increase as global temperatures increase.

Sea temperatures are *very likely* to increase in the five SES under moderate (RCP6.0) to high (RCP8.5) future scenarios. Under BAU (RCP8.5; Table SM30-3), sea temperatures in the SES are projected to increase by 0.93°C to 1.24°C over 2010–2039 (Table SM30-4). Increases of 3.45°C to 4.37°C are projected over 2010–2099, with the greatest increases projected for the surface waters of the Baltic Sea (4.37°C) and Arabian Gulf (4.26°C), and lower yet substantial amounts of warming in the Red Sea (3.45°C) (Table SM30-4). The heat content added to these small ocean regions is *very likely* to increase stratification, which will reduce the nutrient supply to the upper layers of the water column, reducing primary productivity and driving major changes to the structure and productivity of fisheries. Reduced mixing and ventilation, along with increased microbial metabolism, will *very likely* increase hypoxia and expand the number and extent of "dead zones." Changing rainfall intensity (Section 23.3; WGI AR5 Section 12.4.5) can exert a strong influence on the physical and chemical conditions within SES, and in some cases will combine with other climatic changes to transform these areas. These changes are likely to increase the risk of reduced bottom-water O_2 levels to Baltic and Black Sea ecosystems (due to reduced solubility, increased stratification, and microbial respiration), which is *very likely* to affect fisheries. These changes will increase the frequency and intensity of impacts arising from heat stress, based on responses to temperature extremes seen over the past 30 years, such as the mass mortality of benthic organisms that occurred in the Mediterranean Sea during the summers of 1999, 2003, and 2006, and the Arabian Gulf in 1996 and 1998. Extreme temperature events such as heat waves are projected to increase (*high confidence*; Section 23.2; IPCC, 2012). Projections similar to those outlined in Section 30.5.4.2 can be applied to the coral reefs of the Arabian Gulf and the Red Sea, where temperatures are *very likely* to increase above established thresholds for mass coral bleaching and mortality (*very high confidence*; Figure 30-10).

30.5.4. Coastal Boundary Systems

The Coastal Boundary Systems (CBS) are highly productive regions, comprising 10.6% of primary production and 28.0% of global fisheries production (Table SM30-1; Figure 30-1b). The CBS include the marginal seas of the northwest Pacific, Indian, and Atlantic Oceans, encompassing the Bohai/Yellow Sea, East China Sea, South China Sea, and Southeast Asian Seas (e.g., the Timor, Arafura, and Sulu Seas, and the northern coast of Australia) in the Pacific; the Arabian Sea, Somali Current system, East Africa coast, Mozambique Channel, and Madagascar in the Indian Ocean; and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean). Some CBS are dominated by powerful currents such as the Kuroshio (Pacific), or are strongly influenced by monsoons (e.g., Asian-Australian and African monsoons).

30.5.4.1. Observed Changes and Potential Impacts

Many ecosystems within the CBS are strongly affected by the local activities of often-dense coastal human populations. Activities such as the overexploitation of fisheries, unsustainable coastal development, and pollution have resulted in the widespread degradation of CBS ecosystems (Burke et al., 2002, 2011). These influences have combined with steadily increasing ocean temperature and acidification to drive major changes to a range of important ecosystems over the past 50 years. Understanding the interactions between climate change and non-climate change drivers is a central part of the detection and attribution process within the CBS.

Overall, the CBS warmed by 0.14°C to 0.80°C from 1950 to 2009 (Table 30-1), although changes within the Gulf of Mexico/Caribbean Sea sub-region were not significant (p-value > 0.05) over this period. Key sub-regions within the CBS such as the Coral Triangle and Western Indian Ocean warmed by 0.79°C and 0.60°C, respectively, from 1950 to 2009 (Table 30-1). Rates of SLR vary from decreasing sea levels (–5 to –10 mm yr^{-1}) to low (2 to 3 mm yr^{-1}, Caribbean) to very high (10 mm yr^{-1}, Southeast Asia; Figure 30-5) rates of increase. Ocean acidification also varies from region to region (Figure SM30-2), and is influenced by oceanographic and coastal processes, which often have a large human component.

30.5.4.1.1. Bohai/Yellow Sea/East China Sea

The Bohai Sea, Yellow Sea, and the East China Sea (ECS) are shallow marginal seas along the edge of the northwest Pacific that are strongly influenced by the Kuroshio Current (Matsuno et al., 2009), the East Asian Monsoon (EAM), and major rivers such as the Yellow (Huang He) and Yangtze (Changjiang) Rivers. Upwelling of the Kuroshio sub-surface waters provides abundant nutrients that support high levels of primary productivity (Wong et al., 2000, 2001). The ecosystems of the ECS are heavily affected by human activities (e.g., overfishing and pollution), which tend to compound the influence and consequences of climate change.

SST within the ECS has increased rapidly since the early 1980s (*high confidence*; Lin et al., 2005; Jung, 2008; Cai et al., 2011; Tian et al., 2012). The largest increases in SST have occurred in the ECS in winter (1.96°C, 1955–2005) and in the Yellow Sea in summer (1.10°C, 1971–2006; Cai et al., 2011). These changes in SST are closely linked to a weakening of the EAM (e.g., Cai et al., 2006, 2011; Tang et al., 2009) and increasing warmth of the Kuroshio Current (Qi et al., 2010; Zhang et al., 2011; Wu et al., 2012). At the same time, dissolved O_2 has decreased (Lin et al., 2005; Jung, 2008; Qi et al., 2010), with an associated increase in the extent of the hypoxic areas in coastal areas of the Yellow Sea/ECS (Jung, 2008; Tang, 2009; Ning et al., 2011).

Primary productivity, biomass yields, and fish capture rates have experienced large changes within the ECS over the past decades (*limited evidence*, *medium agreement*; *low confidence*; Tang et al., 2003; Lin et al., 2005; Tang, 2009). Fluctuations in herring abundance appear to closely track SST shifts within the Yellow Sea (Tang, 2009). For plankton and fish species, the proportions of warm-water species relative to warm-temperate species in the Changjiang River Estuary (extending to the southern Taiwan Strait) have changed over past decades (Zhang et al., 2005; Ma et al., 2009; Lin and Yang, 2011). Northward shifts in catch distribution for some pelagic fish species in Korean waters were driven, in part, by warming SST (*medium confidence*; Jung et al., 2014). The frequency of harmful algal blooms and blooms of the giant jellyfish *Nemopilema nomurai* in the offshore area of the ECS have increased and have been associated with ocean warming and other factors such as eutrophication (Ye and Huang, 2003; Tang, 2009; Cai and Tan, 2010). Although attribution of these changes to anthropogenic climate change is complicated by the increasing influence of non-climate-related human activities, many of these changes are consistent with those expected as SST increases.

30.5.4.1.2. South China Sea

The South China Sea (SCS) is surrounded by continental areas and includes large numbers of islands, and is connected to the Pacific, ECS, and Sulu Sea by straits such as the Luzon and Taiwan Strait. The region is greatly influenced by cyclones/typhoons, and by the Pearl, Red, and Mekong Rivers. The region has a distinct seasonal circulation and is greatly influenced by the southwest monsoon (in summer), the Kuroshio Current, and northeast monsoon (in winter). The SCS includes significant commercial fisheries areas and includes coral reefs, mangroves, and seagrass beds.

The surface waters of the SCS have been warming steadily from 1945 to 1999 with the annual mean SST in the central SCS increasing by 0.92°C (1950–2006; Cai et al., 2009), a rate similar to that observed for the entire Indo-Pacific/Southeast Asian CBS from 1950 to 2009 (0.80°C; Table 30-1). Significant freshening in the SCS intermediate layer since the 1960s has been observed (Liu et al., 2007). The temperature change of the upper layers of the SCS has made a significant contribution to sea level variation, which is heterogeneous in space and time (Li et al., 2002; Cheng and Qi, 2007; Liu et al., 2007).

Identifying the extent to which climate change is influencing the SCS is difficult due to confounding non-climate change factors and their interactions (e.g., local human pollution, over-exploitation together with "natural" climate variability such as EAM, ENSO, and PDO). Changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries, and the size of demersal trawl catches in the northern SCS observed over the period 1976–2004 (*limited evidence*, *medium agreement*; Ning et al., 2009). Coral reefs and mangroves are degrading rapidly as a result of both climate change and non-climate change-related factors (*very likely*; Box CC-CR; Chen et al., 2009; China-SNAP, 2011; Zhao et al., 2012). Mass coral bleaching and mortality of coral reefs within the SCS were triggered by elevated temperatures in 1998 and 2007 (Yu et al., 2006; Li et al., 2011). Conversely, warming enabled the establishment of a high-latitude, non-carbonate, coral community in Daya Bay in northern SCS, although this community has recently degraded as a result of increasing anthropogenic stresses (Chen et al., 2009; Qiu et al., 2010).

30.5.4.1.3. Southeast Asian Seas

The Southeast Asian Seas (SAS) include an archipelago of diverse islands that interact with the westward flow of the North Equatorial Current and the Indonesian Throughflow (Figure 30-1a). A large part of this region is referred to as the "Coral Triangle" (Veron et al., 2009). The world's most biologically diverse marine area, it includes parts of Malaysia, Indonesia, the Philippines, Timor Leste, the Solomon Islands, and Papua New Guinea. SST increased significantly from 1985 to 2006 (Peñaflor et al., 2009; McLeod et al., 2010), although with considerable spatial variation. Trends examined over longer periods (1950–2009) show significant warming (+0.80°C, p-value ≤ 0.05; Table 30-1). The sea level is rising by up to 10 mm yr^{-1} in much of this region (Church et al., 2004, 2006; Green et al., 2010). Like other tropical areas in the world, coral reefs within SAS have experienced periods of elevated temperature, which has driven several mass coral bleaching and mortality events since the early 1980s (*high confidence*; Hoegh-Guldberg et al., 2009; McLeod et al., 2010; Figure 30-10a). The most recent occurred during warm conditions in 2010 (Krishnan et al., 2011). These changes are the result of increasing ocean temperatures and are *very likely* to be a consequence of anthropogenic climate change (*high confidence*; Box CC-CR; WGI AR5 Section 10.4.1). Although calcification rates of some key organisms (e.g., reef-building corals; Tanzil et al., 2009) have slowed over the past 2 decades, it is not possible to conclude that the changes are due to ocean acidification. While a large part of the decline in coral reefs has been due to increasing local stresses (principally destructive fishing, declining water quality, and over-exploitation of key reef species), projected increases in SST represent a major challenge for these valuable ecosystems (*high agreement*; Burke et al., 2002; Burke and Maidens, 2004).

30.5.4.1.4. Arabian Sea and Somali Current

The Arabian Sea and Somali Current are relatively productive ocean areas, being strongly influenced by upwelling and the monsoonal system. Wind-generated upwelling enhances primary production in the western Arabian Sea (Prakash and Ramesh, 2007). Several key fisheries within this region are under escalating pressure from both fishing and climate change. SST increased by 0.18°C and 0.26°C in the Arabian Sea and Somali Current, respectively, from 1982 to 2006 (HadSST2; Rayner et al., 2003; Belkin, 2009), which is consistent with the overall warming of the Western Indian Ocean portion of the CBS from 1950 to 2009 (0.60°C; Table 30-1). Salinity of surface waters in the Arabian Sea increased by 0.5 to 1.0% over the past 60 years (Figure 30-6c), due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf. As in other tropical sub-regions, increasing sea temperatures have increased the frequency of mass coral bleaching and mortality within this region (Wilkinson and Hodgson, 1999; Goreau et al., 2000; Wilkinson, 2004).

The aragonite saturation horizon in both the Arabian Sea and Bay of Bengal is now 100 to 200 m shallower than in preindustrial times as a result of ocean acidification (*medium confidence*; Feely et al., 2004). Shoaling of the aragonite saturation horizon is *likely* to affect a range of organisms and processes, such as the depth distribution of pteropods (zooplankton) in the western Arabian Sea (*medium confidence*; Hitchcock et al., 2002; Mohan et al., 2006). More than 50% of the area of OMZs in the world's oceans occur in the Arabian Sea and Bay of Bengal and long-term measurements reveal that O_2 concentrations are declining in this region (*high confidence*; Helly and Levin, 2004; Karstensen et al., 2008; Stramma et al., 2010; Section 30.3.2.3). The information regarding the consequences of climate change within this region is undeveloped and suggests that important physical, chemical, and biological responses to climate change need to be the focus of further investigation.

30.5.4.1.5. East Africa coast and Madagascar

The Western Indian Ocean strongly influences the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagos (Comoros, Mauritius, and the Seychelles). Sea temperatures in the Western Indian Ocean have increased by 0.60°C over 1950–2009 (*high confidence*; *p*-value ≤ 0.05; Table 30-1), increasing the frequency of positive thermal anomalies that have triggered mass coral bleaching and mortality events across the region over the past 2 decades (*high confidence*; Baker et al., 2008; Nakamura et al., 2011; Box CC-HS). Trends in changes in SST and surface salinity vary with location along the East African coastline, with faster rates at higher latitudes (Figure 30-2). Periods of heat stress over the past 20 years have triggered mass coral bleaching and mortality on coral reef ecosystems within this region (McClanahan et al., 2007, 2009a,b,c; Ateweberhan and McClanahan, 2010; Ateweberhan et al., 2011). Steadily increasing sea temperatures have also produced anomalous growth rates in long-lived corals such as *Porites* (*high confidence*; McClanahan et al., 2009b). Differences in the susceptibility of reef-building corals to stress from rising sea temperatures has also resulted in changes to the composition of coral (*high confidence*; *p*-value ≤ 0.05; McClanahan et al., 2007) and benthic fish communities (*high confidence*; *p*-value ≤ 0.05; Graham et al., 2008; Pratchett et al., 2011a). These changes are *very likely* to alter species composition and potentially the productivity of coastal fisheries (*robust evidence*, *high agreement*; *high confidence*; Jury et al., 2010), although there may be a significant lag between the loss of coral communities and the subsequent changes in the abundance and community structure of fish populations (*p*-value ≤ 0.05; Graham et al., 2007). Some of these potential changes can be adverted or reduced by interventions such as the establishment of marine protected areas and changes to fishing management (McClanahan et al., 2008; Cinner et al., 2009; Jury et al., 2010; MacNeil et al., 2010).

30.5.4.1.6. Gulf of Mexico and Caribbean Sea

The Gulf of Mexico and Caribbean Sea form a semi-contained maritime province within the Western Atlantic. These areas are dominated by a range of activities including mineral extraction, fishing, and tourism, which provide employment and opportunity for almost 75 million people who live in coastal areas of the USA, Mexico, and a range of other Caribbean nations (Adams et al., 2004). The Gulf of Mexico and Caribbean Sea have warmed by 0.31°C and 0.50°C, respectively, from 1982 to 2006 (*very likely*; Belkin, 2009). Warming trends are not significant from 1950 to 2009 (Table 30-1), which may be partly due to spatial variability in warming patterns (Section 30.5.3.1). The Caribbean region has experienced a sustained decrease in aragonite saturation state from 1996 to 2006 (*very likely*; Gledhill et al., 2008). Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2 to 3 mm yr^{-1} from 1950 to 2000 (Church et al., 2004; Zervas, 2009).

Understanding influences of climate change on ocean ecosystems in this region is complicated by the confounding influence of growing human populations and activities. The recent expansion of the seasonal hypoxic zone, and the associated "dead zone," in the Gulf of Mexico has been attributed to nitrogen inputs driven by land management (Turner and Rabalais, 1994; Donner et al., 2004) and changes to river flows, wind patterns, and thermal stratification of Gulf waters (*high confidence*; Justić et al., 1996, 2007; Levin et al., 2009; Rabalais et al., 2009). The increases in coastal pollution and fishing have potentially interacted with climate change to exacerbate impacts on marine ecosystems within this region (Sections 5.3.4, 29.3). These changes have often been abrupt and non-linear (Taylor et al., 2012).

A combination of local and global disturbances has driven a large-scale loss of reef-building corals across the Caribbean Sea since the late 1970s (*high confidence*; Hughes, 1994; Gardner et al., 2003). Record thermal stress in 2005 triggered the largest mass coral bleaching and mortality event on record for the region, damaging coral reefs across hundreds of square kilometers in the eastern Caribbean Sea (*high confidence*; Donner et al., 2007; Eakin et al., 2010). Although conditions in 2010 were milder than in 2005, elevated temperatures still occurred in some parts of the Caribbean (Smith et al., 2013). Increasing temperatures in the Caribbean have also been implicated in the spread of marine diseases (Harvell et al., 1999, 2002, 2004) and some introduced species (*likely*; Firth et al., 2011). As in other sub-regions, pelagic fish species are sensitive to changes in sea temperature and modify their distribution and abundance accordingly (Muhling et al., 2011). Fish and invertebrate assemblages in the Gulf of Mexico have shifted deeper in response to SST warming over 1970s–2011 (*medium confidence*; Pinsky et al., 2013).

Coral ecosystems in the Caribbean Sea are at risk from ocean acidification (*very likely*; Albright et al., 2010; Albright and Langdon, 2011), although impacts have yet to be observed under field conditions. Ocean acidification may also be altering patterns of fish recruitment to coral reefs, although direct evidence for how this has affected Caribbean species is lacking (*low confidence*; Dixson et al., 2008, 2010; Munday et al., 2009).

30.5.4.2. Key Risks and Vulnerabilities

Worldwide, 850 million people live within 100 km of tropical coastal ecosystems such as coral reefs and mangroves deriving multiple benefits including food, coastal protection, cultural services, and income from industries such as fishing and tourism (Burke et al., 2011). Marine ecosystems within the CBS are sensitive to increasing sea temperatures (Figure 30-10), although detection and attribution are complicated by the significant influence and interaction with non-climate change stressors (water quality, over-exploitation of fisheries, coastal degradation; Box CC-CR). Warming is likely to have changed the primary productivity of ocean waters, placing valuable ecosystems and fisheries within the ECS at risk (*low* to *medium confidence*). Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of the CBS. Given the consequences for coastal ecosystems and fisheries, these changes are *very likely* to increase the vulnerability of coastal communities throughout the CBS.

Sea temperatures are increasing within many parts of CBS ecosystems (1950–2009; Table 30-1), and will continue to do so over the next few decades and century. Sea temperatures are projected to change by

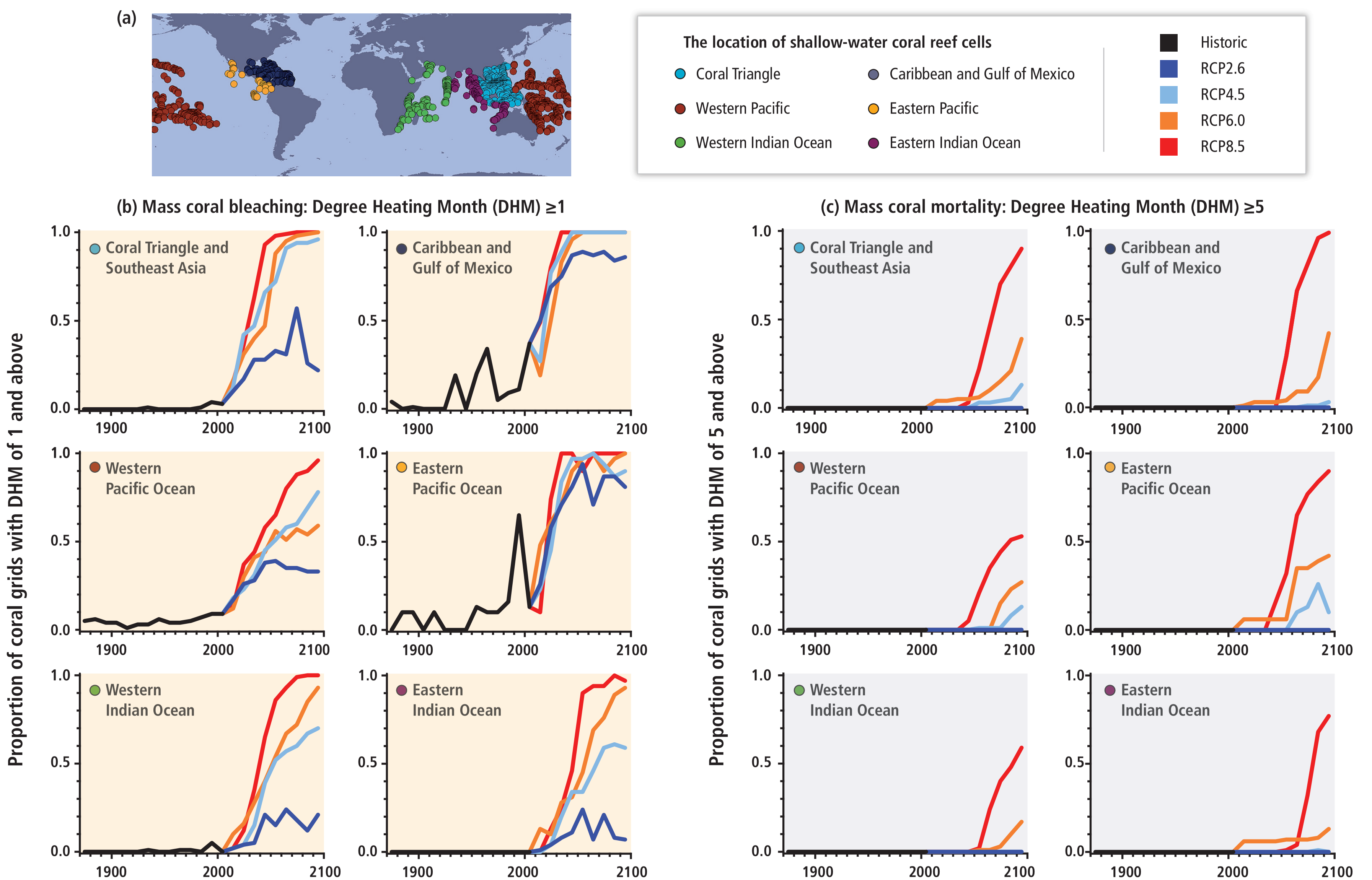

Figure 30-10 | Annual maximum proportions of reef pixels with Degree Heating Months (DHM, Donner et al., 2007) for each of the six coral regions (a, Figure 30-4b)—(b) DHM ≥1 (used for projecting the incidence of coral bleaching; Strong et al., 1997, 2011) and (c) DHM ≥5 (associated with bleaching followed by significant mortality; Eakin et al., 2010)—for the period 1870–2009 using the Hadley Centre Interpolated sea surface temperature 1.1 (HadISST1.1) data set. The black line on each graph is the maximum annual area value for each decade over the period 1870–2009. This value is continued through 2010–2099 using Coupled Model Intercomparison Project Phase 5 (CMIP5) data and splits into the four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, and 8.5). DHM were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHM, the annual percentage of grid cells with DHM ≥1 and DHM ≥5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010–2099 are the average of these maximum proportion values for each RCP. Monthly sea surface temperature anomalies were derived using a 1985–2000 maximum monthly mean climatology derived in the calculations for Figure 30-4. This was done separately for HadISST1.1, the CMIP5 models, and each of the four RCPs, at each grid cell for every region. DHMs were then derived by adding up the monthly anomalies using a 4-month rolling sum. Figure SM30-3 presents past and future sea temperatures for the six major coral reef provinces under historic, un-forced, RCP4.5 and RCP8.5 scenarios.

0.34°C to 0.50°C over the near term (2010–2039) and by 0.23°C to 0.74°C over the long term (2010–2099) under the lowest RCP scenario (RCP2.6). Under BAU (RCP8.5), CBS sea temperatures are projected to increase by 0.62°C to 0.85°C over the near term and 2.44°C to 3.32°C over the long term (Table SM30-4). Given the large-scale impacts (e.g., mass coral bleaching and mortality events) that have occurred in response to much smaller changes in the past over CBS regions (0.14°C to 0.80°C from 1950–2009; Table 30-1), the projected changes of 2.44°C to 3.32°C over 2010–2099 are *very likely* to have large-scale and negative consequences for the structure and function of many CBS ecosystems (*virtually certain*), especially given the observed sensitivity of coral reefs to relatively small increases in temperature over the past 3 decades (Hoegh-Guldberg, 1999; Eakin et al., 2010; Lough, 2012).

It is *very likely* that coral-dominated reef ecosystems within the CBS (and elsewhere) will continue to decline and will consequently provide significantly less ecosystem goods and services for coastal communities if sea temperatures increase by more than 1°C above current temperatures (Box CC-CR; Figure 30-10). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle sub-regions (Strong et al., 1997, 2011; Hoegh-Guldberg, 1999), with the exposure to higher temperatures that are projected under medium (RCP4.5) to high (RCP8.5) scenarios, reveals that both coral reef-rich regions are *virtually certain* to experience levels of thermal stress (DHM ≥ 1) that cause coral bleaching every 1 to 2 years by the mid- to late part of this century (*robust evidence*, *high agreement*; *very high confidence*; Figures 30-4b,c, 30-10, 30-12, SM30-3; van Hooidonk et al., 2013). The frequency of mass mortality events (DHM ≥ 5; Figure 30-10a,b,c) also increases toward a situation whereevents that occur every 1 to 2 years by the mid- to late part of this century under low to high climate change scenarios (*robust evidence*, *high agreement*; *very high confidence*; Hoegh-Guldberg, 1999; Donner et al., 2005; Frieler et al., 2012). Mass mortality events that affect coral reefs will result in changes to community composition in the near term (2010–2039; Berumen and Pratchett, 2006; Adjeroud et al., 2009) and a continuing downward trend in coral cover in the longer term (Gardner et al., 2003; Bruno and Selig, 2007; Baker et al., 2008).

It is *virtually certain* that composition of coral reef fish populations (Graham et al., 2007; Pratchett et al., 2008, 2011a,b) will change. The productivity of many fisheries will decrease (*limited evidence*, *medium agreement*) as waters warm, acidify, and stratify, and as crucial habitat, such as coral reefs, degrade (*low confidence*). These changes are *very likely* to increase the vulnerability of millions of people who live in coastal communities and depend directly on fisheries and other goods and services provided by ecosystems such as coral reefs (Hoegh-Guldberg et al., 2009; McLeod et al., 2010).

30.5.5. Eastern Boundary Upwelling Ecosystems

The Eastern Boundary Upwelling Ecosystems (EBUE) include the California, Peru/Humboldt, Canary/northwest Africa, and Benguela Currents. They are highly productive sub-regions with rates of primary productivity that may exceed 1000 g C m^{-2} yr^{-1}. Although these provinces comprise less than 2% of the Ocean area, they contribute nearly 7% of marine primary production (Figure 30-1b) and more than 20% of the world's marine capture fisheries (Pauly and Christensen, 1995). Catches in the EBUE are dominated by planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous benthic fish such as hake. Nutrient input from upwelling of cooler waters stimulates primary production that is transferred to mid and upper trophic levels, resulting in substantial fish, seabird, and marine mammal populations. As a result, the EBUE are considered "hotspots" of productivity and biodiversity (Block et al., 2011). The high level of productivity is a result of large-scale atmospheric pressure gradients and wind systems that advect surface waters offshore, leading to the upwelling of cold, nutrient-rich waters from depth (Box CC-UP; Chavez and Messie, 2009; Chavez et al., 2011). Upwelling waters are typically low in pH and high in CO_2, and are likely to continue to enhance changes in pH and CO_2 resulting from rising atmospheric CO_2 (Feely et al., 2008; Gruber, 2011).

30.5.5.1. Observed Changes and Potential Impacts

There are extensive studies of the coupled climate-ecosystem dynamics of individual EBUE (e.g., California Current). Decadal variability poses challenges to the detection and attribution of changes within the EBUE to anthropogenic climate change, although there are a number of long-term studies that have been able to provide insight into the patterns of change and their causes. Like other ocean sub-regions, EBUE are projected to warm under climate change, with increased stratification and intensified winds as westerly winds shift poleward (*likely*). However, cooling has also been predicted for some EBUE, resulting from the intensification of wind-driven upwelling (Bakun, 1990). The California and Canary Currents have warmed by 0.73°C and 0.53°C (*very likely*; *p*-value ≤ 0.05, 1950–2009; Table 30-1), respectively, while no significant trend was detected in the sea surface temperatures of the Benguela (*p*-value = 0.44) and Humboldt Currents (*p*-value = 0.21) from 1950 to 2009 (Table 30-1). These trends match shorter-term trends for various EBUE using Pathfinder version 5 data (Demarcq, 2009). These differences are *likely* to be the result of differences in the influence of long-term variability and the specific responses of coastal wind systems to warming, although an analysis of wind data over the same period did not pick up clear trends (*low confidence*, with respect to long-term wind trends; Demarcq, 2009; Barton et al., 2013).

How climate change will influence ocean upwelling is central to resolving ecosystem and fishery responses within each EBUE. There is considerable debate, however, as to whether or not climate change will drive an intensification of upwelling (e.g., Bakun et al., 2010; Narayan et al., 2010; Barton et al., 2013) in all regions. This debate is outlined in Box CC-UP. EBUE are also areas of naturally low pH and high CO_2 concentrations due to upwelling, and consequently may be vulnerable to ocean acidification and its synergistic impacts (Barton et al., 2012). A full understanding of the consequences of ocean acidification for marine organisms and ecosystems is discussed elsewhere (Boxes CC-OA, CC-UP; Sections 6.2, 6.3.2; Kroeker et al., 2013; WGI AR5 Section 6.4).

30.5.5.1.1. Canary Current

Part of the North Atlantic STG, the Canary Current extends from northern Morocco southwestward to the North Atlantic Equatorial Current. It is linked with the Portugal Current (which is sometimes considered part of the Canary Current) upstream. The coastal upwelling system, however, is limited to a narrow belt along the Saharan west coast to the coast of Guinea, with the most intense upwelling occurring centrally, along the coasts of Mauritania (15°N to 20°N) and Morocco (21°N to 26°N). Total fish catches, comprising mainly coastal pelagic sardines, sardinellas, anchovies, and mackerel, have fluctuated around 2 million tonnes yr^{-1} since the 1970s (www.seaaroundus.org/lme/27.aspx). Contrasting with the other EBUE, fishing productivity is modest, probably partly due to the legacy of uncontrolled fishing in the 1960s (Arístegui et al., 2009).

Most observations suggest that the Canary Current has warmed since the early 1980s (Arístegui et al., 2009; Belkin, 2009; Demarcq, 2009; Barton et al., 2013), with analysis of HadISST1.1 data from 1950 to 2009 indicating warming of 0.53°C from 1950–2009 (p-value ≤ 0.05; Table 30-1). Gómez-Gesteira et al. (2008) suggest a 20 and 45% decrease in the strength of upwelling in winter and summer, respectively, from 1967 to 2006, consistent with a decrease in wind strength and direction over the past 60 years. More recently, Barton et al. (2013) show no clear increasing or decreasing trend in wind strength over the past 60 years, and a lack of agreement among wind trends and variability from different wind products (e.g., Pacific Fisheries Environmental Laboratory (PFEL), International Comprehensive Ocean-Atmosphere Data Set (ICOADS), Wave- and Anemometer-based Sea Surface Wind (WASWind)). Barton et al. (2013) present no evidence for changes in upwelling intensity, with the exception of upwelling off northwest Spain, where winds are becoming slightly less favorable. Alteration of wind direction and strength influences upwelling and hence nutrient concentrations; however, nutrient levels can also change in response to other variables such as the supply of iron-laden dust from the Sahara (Alonso-Pérez et al., 2011). There is *medium evidence* and *medium agreement* that primary production in the Canary Current has decreased over the past 2 decades (Arístegui et al., 2009; Demarcq, 2009), in contrast to the nearby upwelling region off northwest Spain where no significant trend was observed (Bode et al., 2011). Satellite chlorophyll records (Sea-viewing Wide Field-of-view Sensor (SeaWiFS), Moderate Resolution Imaging Spectrometer (MODIS)) are relatively short, making it difficult to distinguish the influence of warming oceans from longer term patterns of variability (Arístegui et al., 2009; Henson et al., 2010). Changing temperature has resulted in changes to important fisheries species. For example, Mauritanian waters have become more suitable as feeding and spawning areas for some fisheries species (e.g., *Sardinella aurita*) as temperatures increased (Zeeberg et al., 2008). Clear attribution of these changes depends on the linkage between the Azores High and global temperature, and on longer records for both physical and biological systems, as pointed out for data sets in general (Arístegui et al., 2009; Henson et al., 2010).

30.5.5.1.2. Benguela Current

The Benguela Current originates from the eastward-flowing, cold South Atlantic Current, flows northward along the southwest coast of Africa, and is bounded north and south by the warm-water Angola and Agulhas Currents, respectively. Upwelling is strongest and most persistent toward the center of the system in the Lüderitz-Orange River upwelling cell (Hutchings et al., 2009). Fish catch reached a peak in the late 1970s of 2.8 million tonnes yr^{-1} (www.seaaroundus.org/lme/29/1.aspx), before declines in the northern Benguela, due to overfishing and inter-decadal environmental variability, resulted in a reduced catch of around 1 million tonnes yr^{-1} (present) (Cury and Shannon, 2004; Heymans et al., 2004; Hutchings et al., 2009). Offshore commercial fisheries currently comprise sardine, anchovy, horse mackerel, and hake, while the inshore artisanal and recreational fisheries comprise a variety of fish species mostly caught by hook and line.

Most research on the Benguela Current has focused on fisheries and oceanography, with little emphasis on climate change. As with the other EBUE, strong interannual and inter-decadal variability in physical oceanography make the detection and attribution of biophysical trends to climate change difficult. Nevertheless, the physical conditions of the Benguela Current are highly sensitive to climate variability over a range of scales, especially to atmospheric teleconnections that alter local wind stress (Hutchings et al., 2009; Leduc et al., 2010; Richter et al., 2010; Rouault et al., 2010). Consequently, there is *medium agreement*, despite *limited evidence* (Demarcq, 2009), that upwelling intensity and associated variables (e.g., temperature, nutrient, and O_2 concentrations) from the Benguela system will change as a result of climate change (Box CC-UP).

The temperature of the surface waters of the Benguela Current did not increase from 1950 to 2009 (p-value $> +0.05$; Table 30-1), although shorter records show an decrease in the south-central Benguela Current (0.35°C to 0.55°C per decade; Rouault et al., 2010) or an increase for the whole Benguela region (0.24°C; Belkin, 2009). These differences between short versus long records indicate the substantial influence of long-term variability on the Benguela system (Belkin, 2009). Information on other potential consequences of climate change within the Benguela system is sparse. SLR is similar to the global mean, although it has not been measured rigorously within the Benguela (Brundrit, 1995; Veitch, 2007). Although upwelling water in the northern and southern portions of the Benguela Current exhibits elevated and suppressed partial pressure of CO_2, respectively (Santana-Casiano et al., 2009), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, although periodic hypoxic events in the Benguela system are largely driven by natural advective processes, these may be exacerbated by future climate change (Monteiro et al., 2008; Bakun et al., 2010).

Despite its apparent sensitivity to environmental variability, there is *limited evidence* of ecological changes in the Benguela Current EBUE due to climate change (Poloczanska et al., 2013). For example, pelagic fish (Roy et al., 2007), benthic crustaceans (Cockcroft et al., 2008), and seabirds (Crawford et al., 2008) have demonstrated general eastward range shifts around the Cape of Good Hope. Although these may be associated with increased upwelling along the South African south coast, specific studies that attribute these changes to anthropogenic climate change are lacking. Trawl surveys of demersal fish and cephalopod species showed consistently predictable "hotspots" of species richness over a 20- to 30-year study period (the earliest surveys since 1984 off South Africa) that were associated with greater depths and cooler bottom waters (Kirkman et al., 2013). However, major changes in the structure and function of the demersal community have been shown in some parts of the Benguela Current EBUE in response to environmental change, for example, due predominantly to fishing pressure in the 1960s and environmental forcing in the early 2000s in the southern Benguela (Howard et al., 2007); therefore, changes driven by climate change may eventually affect the persistence of these biodiversity hotspots (Kirkman et al., 2013).

30.5.5.1.3. California Current

The California Current spans approximately 23° of latitude from central Baja California, Mexico, to central British Columbia, Canada, linking the North Pacific Current (West Wind Drift) with the North Equatorial and Kuroshio Currents to form the North Pacific Gyre. High productivity driven by advective transport and upwelling (Hickey, 1979; Chelton et al., 1982; Checkley and Barth, 2009; Auad et al., 2011) supports well-studied ecosystems and fisheries. Fish catches have been approximately 0.6 million tonnes yr^{-1} since 1950 (www.seaaroundus.org/lme/3.aspx), which makes it the lowest catch of the four EBUE. The ecosystem supports the foraging and reproductive activities of 2 to 6 million seabirds from around 100 species (Tyler et al., 1993). Marine mammals are diverse and relatively abundant, including recovering populations of humpback whales, among other species (Barlow et al., 2008).

The average temperature of the California Current warmed by 0.73°C from 1950 to 2009 (*p*-value ≤ 0.05; Table 30-1) and by 0.14°C to 0.80°C from 1985 to 2007 (Demarcq, 2009). Like other EBUE, the California Current is characterized by large-scale interannual and inter-decadal climate-ecosystem variability (McGowan et al., 1998; Hare and Mantua, 2000; Chavez et al., 2003; Checkley and Barth, 2009). During an El Niño, coastally trapped Kelvin waves from the tropics deepen the thermocline, thereby severely reducing upwelling and increasing ocean temperatures from California to Washington (Peterson and Schwing, 2003; King et al., 2011). Atmospheric teleconnections to the tropical Pacific alter wind stress and coastal upwelling. Therefore, the ENSO is intimately linked with Bakun's (1990) upwelling intensification hypothesis (Box CC-UP). Inter-decadal variability in the California Current stems from variability in the Pacific-North America pattern (Overland et al., 2010), which is influenced by the PDO (Mantua et al., 1997; Peterson and Schwing, 2003) and the NPGO (Di Lorenzo et al., 2008). The major effects of the PDO and NPGO appear north of 39°N (Di Lorenzo et al., 2008; Menge et al., 2009).

There is *robust evidence* and *medium agreement* that the California Current has experienced a decrease in the number of upwelling events (23 to 40%), but an increase in duration of individual events, resulting in an increase of the overall magnitude of upwelling events from 1967 to 2010 (*high confidence*; Demarcq, 2009; Iles et al., 2012). This is consistent with changes expected under climate change yet remains complicated by the influence of decadal-scale variability (*low confidence*; Iles et al., 2012). Oxygen concentrations have also undergone large and consistent decreases from 1984 to 2006 throughout the California Current, with the largest relative decreases occurring below the thermocline (21% at 300 m). The hypoxic boundary layer (<60 µmol kg^{-1}) has also shoaled by up to 90 m in some regions (Bograd et al., 2008). These changes are consistent with the increased input of organic carbon into deeper layers from enhanced upwelling and productivity, which stimulates microbial activity and results in the drawdown of O_2 (*likely*, Bakun et al., 2010; but see also McClatchie et al., 2010; Koslow et al., 2011; WGI AR5 Section 3.8.3). These changes are *likely* to have reduced the available habitat for key benthic communities as well as fish and other mobile species (Stramma et al., 2010). Increasing microbial activity will also increase the partial pressure of CO_2, decreasing the pH and carbonate concentration of seawater. Together with the shoaling of the saturation horizon, these changes have increased the incidence of low O_2 and low pH water flowing onto the continental shelf (*high confidence*; 40 to 120 m; Feely et al., 2008), causing problems for industries such as the shellfish aquaculture industry (Barton et al., 2012).

30.5.5.1.4. Humboldt Current

The Humboldt Current is the largest of the four EBUE, covering an area larger than the other three combined. It comprises the eastern edge of the South Pacific Gyre, linking the northern part of the Antarctic Circumpolar Current with the Pacific South Equatorial Current. Although the primary productivity per unit area is modest compared to that of the other EBUE, the total Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since the 1960s) of 8 million tonnes yr^{-1} (www.seaaroundus.org/lme/13/1.aspx), although decadal-scale variations range from 2.5 to 13 million tonnes yr^{-1}. While anchovies currently contribute 80% of the total catch, they alternate with sardines on a multi-decadal scale, with their dynamics mediated by the approach and retreat of subtropical waters to and from the coast (Alheit and Bakun, 2010). This variability does not appear to be changing due to anthropogenic climate change. Thus, from the late 1970s to the early 1990s, sardines were more important (Chavez et al., 2003). The other major commercial fish species are jack mackerel among the pelagic fish and hake among the demersal fish.

The Humboldt Current EBUE did not show an overall warming trend in SST over the last 60 years (*p*-value > 0.05; Table 30-1), which is consistent with other data sets (1982–2006, HadISST1.1: Belkin, 2009; 1985–2007, Pathfinder: Demarcq, 2009). Wind speed has increased in the central portions of the Humboldt Current, although wind has decreased in its southern and northern sections (Demarcq, 2009). The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity exerting opposing drivers on upwelling and which, if they intensify, would decrease temperatures (*limited evidence*, *medium agreement*). Similar to the Canary Current EBUE, however, there was a significant increase in the temperatures of the warmest month of the year over the period 1950–2009 (*p*-value ≤ 0.05; Table 30-1).

Primary production is suppressed during warm El Niño events and amplified during cooler La Niña phases, these changes then propagate through to higher trophic levels (Chavez et al., 2003; Tam et al., 2008; Taylor et al., 2008). However, in addition to trophic changes, there is also a direct thermal impact on organisms, which varies depending on the thermal adaptation window for each species (*high confidence*). A 37-year zooplankton time series for the coast of Peru showed no persistent trend in abundance and diversity (Ayón et al., 2004), although observed shifts coincided with the shifts in the regional SST. As for other EBUE, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least two studies (Mendelssohn and Schwing, 2002; Gutiérrez et al.,

2011) provide additional evidence that the northern Humboldt Current has cooled (due to upwelling intensification) since the 1950s, a trend matched by increasing primary production. This is not entirely consistent with the lack of significant change over the period 1950–2009 (p-value > 0.05; Table 30-1). Nevertheless, these relationships are *likely* to be complex in their origin, especially in their sensitivity to the long-term changes associated with ENSO and PDO, and the fact that areas within the Humboldt Current EBUE may be showing different behaviors.

30.5.5.2. Key Risks and Vulnerabilities

EBUE are vulnerable to changes that influence the intensity of currents, upwelling, and mixing (and hence changes in SST, wind strength and direction), as well as O_2 content, carbonate chemistry, nutrient content, and the supply of organic carbon to deep offshore locations (*robust evidence*, *high agreement*; *high confidence*). The extent to which any particular EBUE is vulnerable to these factors depends on location (Figure 3 from Gruber, 2011) and other factors such as alternative sources of nutrient input and fishing pressure (Bakun et al., 2010). This complex interplay between regional and global drivers means that our understanding of how factors such as upwelling within the EBUE will respond to further climate change is uncertain (Box CC-UP; Rykaczewski and Dunne, 2010).

In the GCM ensembles examined (Table SM30-3), modest rates of warming (0.22°C to 0.93°C) occur within the four EBUEs in the near term. Over 2010–2099, however, EBUE SSTs warm by 0.07°C to 1.02°C under RCP2.6, and 2.52°C to 3.51°C under RCP8.5 (Table SM30-4). These high temperatures have the potential to increase stratification of the water column and substantially reduce overall mixing in some areas. In contrast, the potential strengthening of coastal wind systems would intensify upwelling and stimulate primary productivity through the increased injection of nutrients into the photic zone of the EBUE (Box CC-UP). Garreaud and Falvey (2009) explored how wind stress along the South American coast would change by 2100 under SRES B2 and A2 scenarios. Using an ensemble of 15 GCMs, southerly wind systems upwelling increased along the subtropical coast of South America, extending and strengthening conditions for upwelling.

Changes in the intensity of upwelling within the EBUE will drive fundamental changes to the abundance, distribution, and viability of resident organisms, although an understanding of their nature and direction is limited. In some cases, large-scale decreases in primary productivity and dependent fisheries are projected to occur for EBUE ecosystems (Blanchard et al., 2012), while other projections question the strong connection between primary productivity and fisheries production (Arístegui et al., 2009). Increased upwelling intensity also has potential disadvantages. Elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed, where it is *virtually certain* to increase microbial respiration and hence increase low O_2 stress (Weeks et al., 2002; Bakun et al., 2010). Increased wind stress may also increase turbulence, breaking up food concentrations (affecting trophic transfer), or causing excessive offshore advection, which could remove plankton from shelf habitats. The central issue for the EBUE is therefore whether or not upwelling will intensify and, if so, whether the negative consequences (e.g., reduced O_2 and elevated CO_2) associated with upwelling intensification will outweigh potential benefits from increased primary production and fisheries catch.

30.5.6. Subtropical Gyres

Subtropical gyres (STG) dominate the Pacific, Atlantic, and Indian Oceans (Figure 30-1a), and consist of large stable water masses that circulate clockwise (Northern Hemisphere) and anticlockwise (Southern Hemisphere) due to the Coriolis Effect. The oligotrophic areas at the core of the STG represent one of the largest habitats on Earth, contributing 21.2% of ocean primary productivity and 8.3% of the

Frequently Asked Questions

FAQ 30.4 | Will climate change increase the number of "dead zones" in the oceans?

Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms. Dead zones are persistent hypoxic conditions where the water doesn't have enough dissolved oxygen to support oxygen-dependent marine species. These areas exist all over the world and are expanding, with impacts on coastal ecosystems and fisheries (*high confidence*). Dead zones are caused by several factors, particularly eutrophication where too many nutrients run off coastal cities and agricultural areas into rivers that carry these materials out to sea. This stimulates primary production, leading to a greater supply of organic carbon, which can sink into the deeper layers of the ocean. As microbial activity is stimulated, there is a sharp reduction in dissolved oxygen levels and an increased risk of dead zones (*high confidence*). Climate change can influence the distribution of dead zones by increasing water temperature and hence microbial activity, as well as reducing mixing (i.e., increasing layering or stratification) of the Ocean, thereby reducing mixing of oxygen-rich surface layers into the deeper parts of the Ocean. In other areas, increased upwelling can lead to stimulated productivity, which can also lead to more organic carbon entering the deep ocean, where it is consumed, decreasing oxygen levels (*medium confidence*). Managing local factors such as the input of nutrients into coastal regions can play an important role in reducing the rate at which dead zones are spreading across the world's oceans (*high agreement*).

global fish catch (Figure 30-1b; Table SM30-1). A number of small island nations are found within this region. While many of the observed changes within these nations have been described in previous chapters (e.g., Sections 5.3-4, 29.3-5), region-wide issues and consequences are discussed here due to the strong linkages between ocean and coastal issues.

30.5.6.1. Observed Changes and Potential Impacts

The central portions of the STG are oligotrophic (Figure SM30-1). Temperatures within the STG of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL), and South Atlantic (SATL) have increased at rates of 0.020°C, 0.024°C, 0.032°C, 0.025°C, and 0.027°C yr^{-1} from 1998 to 2010, respectively (Signorini and McClain, 2012). This is consistent with increases observed from 1950 to 2009 (0.25°C to 0.67°C; Table 30-1). However, differences among studies done over differing time periods emphasize the importance of long-term patterns of variability. Salinity has decreased across the North and South Pacific STG (Figure 30-6c; WGI AR5 Section 3.3.3.1), consistent with warmer sea temperatures and an intensification of the hydrological cycle (Boyer, 2005).

The North and South Pacific STG have expanded since 1993 (*high confidence*), with these changes *likely* being the consequence of a combination of wind forcing and long-term variability (Parrish et al., 2000; WGI AR5 Section 3.6.3). Chlorophyll levels, as determined by remote-sensing of ocean color (Box CC-UP), have decreased in the NPAC, IOCE, and NATL by 9, 12, and 11%, respectively (p-value ≤ 0.5; Signorini and McClain, 2012) over and above the inherent seasonal and interannual variability from 1998 to 2010 (Vantrepotte and Mélin, 2011). Chlorophyll levels did not change in the remaining two gyres (SPAC and SATL, and confirmed for SPAC by Lee and McPhaden (2010) and Lee et al. (2010)). Furthermore, over the period 1998–2007, median cell diameter of key phytoplankton species exhibited statistically significant linear declines of about 2% in the North and South Pacific, and 4% in the North Atlantic Ocean (Polovina and Woodworth, 2012). Changes in chlorophyll and primary productivity in these sub-regions have been noted before (McClain et al., 2004; Gregg et al., 2005; Polovina et al., 2008) and are influenced by seasonal and longer-term sources of variability (e.g., ENSO, PDO; Section 6.3.4; Figure 6-9). These changes represent a significant expansion of the world's most unproductive waters, although caution must be exercised given the limitations of satellite detection methods (Box CC-PP) and the shortness of records relative to longer-term patterns of climate variability. There is *high confidence* that changes that reduce the vertical transport of nutrients into the euphotic zone (e.g., decreased wind speed, increasing surface temperatures, and stratification) will reduce the rate of primary productivity and hence fisheries.

30.5.6.1.1. Pacific Ocean Subtropical Gyres

Pacific climate is heavily influenced by the position of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation (WGI AR5 Section 14.3.1). These features are also strongly influenced by interannual to inter-decadal climate patterns of variability including ENSO and PDO. The current understanding of how ENSO and PDO will change as average global temperatures increase is not clear (*low confidence*; Collins et al., 2010; WGI AR5 Section 12.4.4.2). The position of both the ITCZ and SPCZ vary seasonally and with ENSO (Lough et al., 2011), with a northward migration during the Northern Hemisphere summer and a southward migration during the Southern Hemisphere summer. These changes, along with the West Pacific Monsoon, determine the timing and extent of the wet and dry seasons in SPAC and NPAC sub-regions (Ganachaud et al., 2011). Tropical cyclones are prominent in the Pacific (particularly the western Pacific), and CBS sub-regions between 10° and 30° north and south of the equator, although the associated storm systems may occasionally reach higher latitudes. Spatial patterns of cyclones vary with ENSO, spreading out from the Coral Sea to the Marquesas Islands during El Niño and contracting back to the Coral Sea, New Caledonia, and Vanuatu during La Niña (Lough et al., 2011). Historically, there have been almost twice as many land-falling tropical cyclones in La Niña as opposed to El Niño years off the east coast of Australia, with a declining trend in the number of severe tropical cyclones from 0.45 per year in the early 1870s to 0.17 per year in recent times (Callaghan and Power, 2011).

The Pacific Ocean underwent an abrupt shift to warmer sea temperatures in the mid-1970s as a result of both natural (e.g., IPO) and climate forcing (*high confidence*; Meehl et al., 2009). This change coincided with changes to total rainfall, rain days, and dry spells across the Pacific, with the direction of change depending on the location relative to the SPCZ. Countries such as the Cook Islands, Tonga, Samoa and American Samoa, and Fiji tend to experience drought conditions as the SPCZ (with cooler sea temperatures) moves toward the northeast during El Niño (*high confidence*). The opposite is true during La Niña conditions. The consequences of changing rainfall on the countries of the Pacific STG are discussed in greater detail elsewhere (Sections 5.4, 29.3; Table 29-1). Although these changes are due to different phases of long-term variability in the Pacific, they illustrate the ramifications and sensitivity of the Pacific to changes in climate change.

Elevated sea temperatures within the Pacific Ocean have increased the frequency of widespread mass coral bleaching and mortality since the early 1980s (*very high confidence*; Hoegh-Guldberg and Salvat, 1995; Hoegh-Guldberg, 1999; Mumby et al., 2001; Baker et al., 2008; Donner et al., 2010). There are few, if any, scientific records of mass coral bleaching and mortality prior to this period (*high confidence*; Hoegh-Guldberg, 1999). Rates of decline in coral cover on coastal coral reef ecosystems range between 0.5 and 2.0% per year depending on the location within the Indo-Pacific region (*high confidence*; Bruno and Selig, 2007; Hughes et al., 2011; Sweatman et al., 2011; De'ath et al., 2012). The reasons for this decline are complex and involve non-climate change-related factors (e.g., coastal pollution and overfishing) as well as global warming and possibly acidification. A recent comprehensive analysis of the ecological consequences of coral bleaching and mortality concluded that "bleaching episodes have resulted in catastrophic loss of coral reefs in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics" (*high confidence*; Baker et al., 2008, p. 435). Increasing sea levels have also caused changes in seagrass and mangrove systems. Gilman et al. (2007) found a reduction in mangrove area with SLR, with the observed mean landward recession of three mangrove areas over 4 decades being 25, 64, and 72 mm yr^{-1}, 12 to 37 times faster than the observed rate of SLR. Significant interactions exist between climate change and coastal development, where migration shoreward depends on the extent to which coastlines have been modified or barriers to successful migration have been established.

Changes in sea temperature also lead to changes in the distribution of key pelagic fisheries such as skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), big-eye tuna (*T. obesus*), and South Pacific albacore tuna (*T. alalunga*), which make up the majority of key fisheries in the Pacific Ocean. Changes in distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate the close association of pelagic fish stocks and water temperature. The shift in habitat for top predators in the northeast Pacific was examined by Hazen et al. (2012), who used tracking data from 23 marine species and associated environmental variables to predict changes of up to 35% in core habitat for these species within the North Pacific. Potential habitats are predicted to contract for the blue whale, salmon shark, loggerhead turtle, and blue and mako sharks, while potential habitats for the sooty shearwater; black -footed albatross; leatherback turtle; white shark; elephant seal; and albacore, bluefin and yellowfin tuna are predicted to expand (Hazen et al., 2012). However, expansion of OMZs in the Pacific STG is predicted to compress habitat (depth) for hypoxia-intolerant species such as tuna (Stramma et al., 2010, 2012).

Reduction of ocean productivity of the STG (Sarmiento et al., 2004; Signorini and McClain, 2012) reduces the flow of energy to higher trophic levels such as those of pelagic fish (Le Borgne et al., 2011). The distribution and abundance of fisheries stocks such as tuna are also sensitive to changes in sea temperature, and hence long-term variability such as ENSO and PDO. The redistribution of tuna in the western central equatorial region has been related to the position of the oceanic convergence zones, where the warm pool meets the cooler tongue of the Pacific. These changes have been reliably reproduced by population models that use temperature as a driver of the distribution and abundance of tuna (Lehodey et al., 1997, 2006). Projections of big-eye tuna (*T. obesus*) distributions under SRES A2 show an improvement in spawning and feeding habitats by 2100 in the eastern tropical Pacific and declines in the western tropical Pacific, leading to an eastern displacement of tuna stocks (Lehodey et al., 2008, 2010b).

30.5.6.1.2. Indian Ocean Subtropical Gyre

Like the Pacific Ocean, the Indian Ocean plays a crucial role in global weather patterns, with teleconnections throughout Africa, Australasia, Asia, and the Americas (e.g., Clark et al., 2000; Manhique et al., 2011; Meehl and Arblaster, 2011; Nakamura et al., 2011). Increasing sea level, temperature, storm distribution and intensity, and changing seawater chemistry all influence the broad range of physical, chemical, and biological aspects of the Indian Ocean. Coral reef ecosystems in the Indian Ocean gyre system were heavily affected by record positive sea temperature anomalies seen in the Southern Hemisphere between February to April 1998 (*robust evidence*, *high agreement*; *high confidence*; Ateweberhan et al., 2011). Coral cover across the Western Indian Ocean declined by an average of 37.7% after the 1998 heat stress event (Ateweberhan et al., 2011). Responses to the anomalously warm conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases in coral cover directly after the 1998 event (from 40 to 53% coral cover in 1977–1997 to 7% in 1999–2000; *high confidence*; Ateweberhan et al., 2011). Coral reefs lining the islands of southern India and Sri Lanka experienced similar decreases in coral cover (45%, 1977–1997 to 12%, 1999–2000). Corals in the southwestern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, Réunion, and Rodrigues) showed less impact (44%, 1977–1997 to 40%, 1999–2000). Recovery from these increases in mortality has been variable, with sites such as those around the central Indian Ocean islands exhibiting fairly slow recovery (13% by 2001–2005) while those around southern India and Sri Lanka are showing much higher rates (achieving a mean coral cover of 37% by 2001–2005; Ateweberhan et al., 2011). These changes to the population size of key reef-building species will drive major changes in the abundance and composition of fish populations in coastal areas, and affect other ecosystem services that are important for underpinning tourism and coastal protection (*medium confidence*; Box CC-CR).

Fisheries that exploit tuna and other large pelagic species are very valuable to many small island states within the Indian Ocean. As with Pacific fisheries, the distribution and abundance of large pelagic fish in the Indian Ocean is greatly influenced by sea temperature. The anomalously high sea temperatures of 1997–1998 (leading to a deepening of the mixed layer in the west and a shoaling in the east) coincided with anomalously low primary production in the Western Indian Ocean and a major shift in tuna stocks (*high confidence*; Menard et al., 2007; Robinson et al., 2010). Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which was unprecedented for the tuna fishery (*high confidence*). As a result of these changes, many countries throughout the Indian Ocean lost significant tuna-related revenue (Robinson et al., 2010). In 2007, tuna fishing revenue was again reduced by strong surface warming and deepening of the mixed layer, and associated with a modest reduction in primary productivity in the west. These trends highlight the overall vulnerability of tuna fishing countries in the Indian Ocean to climate variability, a situation similar to that in the other major oceans of the world.

30.5.6.1.3. Atlantic Ocean Subtropical Gyres

SST has increased within the two STG of the Atlantic Ocean over the last 2 decades (Belkin, 2009; Signorini and McClain, 2012). Over longer periods of time (1950–2009), trends in average temperature are not significant for the North Atlantic STG (p-value > 0.05) while they remain so for the South Atlantic STG (*very likely*; 0.08°C per decade, p-value ≤ 0.05; Table 30-1). In both cases, however, temperatures in the coolest and warmest months increased significantly (Table 30-1). The difference between these studies (i.e., over 10 to 30 years vs. 60 years) emphasizes the importance of long-term patterns of variability in the North Atlantic region. Variability in SST at a period of about 60 to 80 years is associated with the Atlantic Multi-decadal Oscillation (AMO; Trenberth and Shea, 2006). Sea surface temperatures influence hurricane activity (*very likely*) with recent record SST associated with record hurricane activity in 2005 in the Atlantic (Trenberth and Shea, 2006) and mass coral bleaching and mortality in the eastern Caribbean (*high confidence*; Eakin et al., 2010). In the former case, analysis concluded that 0.1°C of the SST anomaly was attributable to the state of the AMO while 0.45°C was due to ocean warming as a result of anthropogenic influences (Trenberth and Shea, 2006).

These changes have influenced the distribution of key fishery species as well the ecology of coral reefs in Bermuda (Wilkinson and Hodgson, 1999; Baker et al., 2008) and in the eastern Caribbean (Eakin et al., 2010). Small island nations such as Bermuda depend on coral reefs for fisheries and tourism and are vulnerable to further increases in sea temperature that cause mass coral bleaching and mortality (*high confidence*; Box CC-CR; Figure 30-10). As with the other STG, phytoplankton communities and pelagic fish stocks are sensitive to temperature changes that have occurred over the past several decades. Observation of these changes has enabled development of models that have a high degree of accuracy in projecting the distribution and abundance of these elements within the Atlantic region in general (Cheung et al., 2011).

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30.5.6.2. Key Risks and Vulnerabilities

SSTs of the vast STGs of the Atlantic, Pacific, and Indian Oceans are increasing, which is *very likely* to increase stratification of the water column. In turn, this is *likely* to reduce surface concentrations of nutrients and, consequently, primary productivity (*medium confidence*; Box CC-PP). Warming is projected to continue (Table SM30-4), with substantial increases in the vulnerability and risk associated with systems that have been observed to change so far (*high confidence*; Figure 30-12). Under RCP2.6, the temperatures of the STG are projected to increase by 0.17°C to 0.56°C in the near term (over 2010–2039) and between –0.03°C to 0.90°C in the long term (over 2010–2099) (Table SM30-4). Under RCP8.5, however, surface temperatures of the world's STG are projected to be 0.45°C to 0.91°C warmer in the near term and 1.90°C to 3.44°C warmer in the long term (Table SM30-4). These changes in temperature are *very likely* to increase water column stability, reduce the depth of the mixed layer, and influence key parameters such as nutrient availability and O_2 concentrations. It is not clear as to how longer-term sources of variability such as ENSO and PDO will change (WGI AR5 Sections 14.4, 14.7.6) and ultimately influence these trends.

The world's most oligotrophic ocean sub-regions are *likely* to continue to expand over coming decades, with consequences for ecosystem services such as gas exchange, fisheries, and carbon sequestration. Polovina et al. (2011) explored this question for the North Pacific using a climate model that included a coupled ocean biogeochemical component to investigate potential changes under an SRES A2 scenario (~RCP6.0 to RCP8.5; see also Figure 1.5 from Rogelj et al., 2012). Model projections indicated the STG expanding by approximately 30% by 2100, driven by the northward drift of the mid-latitude westerlies and enhanced stratification of the water column. The expansion of the STG occurred at the expense of the equatorial upwelling and other regions within the North Pacific. In the North Pacific STG, the total primary production is projected to decrease by 10 to 20% and large fish catch by 19 to 29% by 2100 under SRES A2 (Howell et al., 2013; Woodworth-Jefcoats et al., 2013). However, our understanding of how large-scale eddy systems will change in a warming world is incomplete, as are the implications for primary productivity of these large and important systems (Boxes CC-PP, CC-UP).

Understanding how storm frequency and intensity will change represents a key question for many countries and territories within the various STG. Projections of increasing sea temperature are *likely* to change the behavior of tropical cyclones. At the same time, the maximum wind speed and rainfall associated with cyclones is *likely* to increase, although future trends in cyclones and severe storms are *very likely* to vary from region to region (WGI AR5 Section 14.6). Patterns such as "temporal clustering" can have a strong influence on the impact of tropical cyclones on ecosystems such as coral reefs (Mumby et al., 2011), although how these patterns will change within all STG is uncertain at this point. However, an intensifying hydrological cycle is expected to increase precipitation in many areas (*high confidence*; WGI AR5 Sections 2.5, 14.2), although longer droughts are also expected in other STG (*medium confidence*). Changes in the hydrological cycle impact coastal ecosystems, increasing damage through coastal flooding and physical damage from storm waves (Mumby et al., 2011). Improving our understanding of how weather systems associated with features such as the SPCZ (WGI AR5 Section 14.3.1) will vary is critical to climate change adaptation of a large number of nations associated with the STG. Developing an understanding of how ocean temperature, climate systems such as the SPCZ and ITCZ, and climate change and variability (e.g., ENSO, PDO) interact will be essential in this regard. For example, variability in the latitude of the SPCZ is projected to increase, possibly leading to more extreme events in Pacific Island countries (Cai et al., 2012).

The consequences of projected sea temperatures on the frequency of coral bleaching and mortality within key sub-regions of the STG are outlined in Box CC-CR and Figures 30-10 and SM30-3. As with other sub-regions (particularly CBS, STG, and SES) dominated by coral reefs, mass coral bleaching and mortality becomes an annual risk under all scenarios, with mass mortality events beginning to occur every 1 to 2 years by 2100 (*virtually certain*; Box CC-CR; Figures 30-10, SM30-3). Coral-dominated reef ecosystems (areas with more than 30% coral cover) are *very likely* to disappear under these circumstances by the mid part of this century (van Hooidonk et al., 2013). The loss of substantial coral communities has implications for the three-dimensional structure of coral reefs (Box CC-CR) and the role of the latter as habitat for organisms such as fish (Hoegh-Guldberg, 2011; Hoegh-Guldberg et al., 2011a; Pratchett et al., 2011a; Bell et al., 2013b).

The consequences of increasing sea temperature can be exacerbated by increasing ocean acidification, with potential implications for reef calcification (*medium confidence*; Kleypas et al., 1999; Hoegh-Guldberg et al., 2007; Doney et al., 2009), reef metabolism and community calcification (Dove et al., 2013), and other key ecological processes (Pörtner et al., 2001, 2007; Munday et al., 2009). Ocean pH within the STG will continue to decrease as atmospheric CO_2 increases, bringing pH within the STG to 7.9 and 7.7 at atmospheric concentrations of 450 ppm and 800 ppm, respectively (Figure SM30-2a; Box CC-OA). Aragonite saturation states will decrease to around 1.6 (800 ppm) and 3.3 (450 ppm; Figure SM30-2b). Decreasing carbonate ion concentrations and saturation states pose serious risks to other marine calcifiers such as encrusting coralline algae, coccolithophores (phytoplankton), and a range of benthic invertebrates (Doney et al., 2009; Feely et al., 2009).

Increasing sea temperatures and sea level are also *likely* to influence other coastal ecosystems (e.g., mangroves, seagrass meadows) in the Pacific, although significant gaps and uncertainties exist (Section 29.3.1.2; Waycott et al., 2007, 2011). Many of the negative consequences for coral reefs, mangroves, and seagrass meadows are *likely* to have negative consequences for dependent coastal fisheries (through habitat destruction) and tourism industries (*medium confidence*; Bell et al., 2011a, 2013a; Pratchett et al., 2011a,b).

Populations of key large pelagic fish are projected to move many hundreds of kilometers east of where they are today in the Pacific STG (*high confidence*; Lehodey et al., 2008, 2010a, 2011, 2013), with implications for income, industry, and food security across multiple Pacific Island nations (*high confidence*; Cheung et al., 2010; McIlgorm et al., 2010; Bell et al., 2011b, 2013a; Section 7.4.2; Tables 29-2, 29-4). These predictions of species range displacements, contractions, and expansions in response to anticipated changes in the Ocean (Box CC-MB) present both a challenge and an opportunity for the development of large-scale management strategies to preserve these valuable species. Our understanding of the consequences of reduced O_2 for pelagic fish populations is not clear, although there is *high agreement* on the potential physiological outcomes (Section 6.3.3). Those species that are intolerant to hypoxia, such as skipjack and yellowfin tuna (Lehodey et al., 2011), will have their depth range compressed in the Pacific STG, which will increase their vulnerability to fisheries and reduce overall fisheries habitat and productivity (*medium confidence*; Stramma et al., 2010, 2011). Despite the importance of these potential changes, our understanding of the full range of consequences is *limited* at this point.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the Deep Sea (DS) are challenging because of difficulty of access and scarcity of long-term, comprehensive observations (Smith, Jr. et al., 2009). The size of this habitat is also vast, covering well over 54% of the Earth's surface and stretching from the top of the mid-oceanic ridges to the bottom of deep ocean trenches (Smith, Jr. et al., 2009). The fossil record in marine sediments reveals that the DS has undergone large changes in response to climate change in the past (Knoll and Fischer, 2011). The paleo-skeletal record shows that it is the rate, not just the magnitude, of climate change (temperature, O_2, and CO_2) that is critical to marine life in DS. The current rate of change in key parameters *very likely* exceeds that of other major events in Earth history. Two primary time scales are of interest. The first is the slow rate (century-scale) of ocean circulation and mixing, and consequently the slow rate at which DS ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at the surface of the Ocean, which represents a critical food supply to DS animals (Smith, Jr. and Kaufmann, 1999; Smith, Jr. et al., 2009). It can also represent a potential risk in some circumstances where the flux of organic carbon into the deep ocean, coupled with increased sea temperatures, can lead to anoxic areas (dead zones) as metabolism is increased and O_2 decreased (Chan et al., 2008; Stramma et al., 2010).

30.5.7.1. Observed Changes and Potential Impacts

The greatest rate of change of temperature is occurring in the upper 700 m of the Ocean (*very high confidence*; WGI AR5 Section 3.2), although smaller yet significant changes are occurring at depth. The DS environment is typically cold (~–0.5°C to 3°C; Smith et al., 2008), although abyssal temperatures in the SES can be higher (e.g., Mediterranean DS ~12°C; Danovaro et al., 2010). In the latter case, DS organisms can thrive in these environments as well, illustrating the variety of temperature conditions that differing species of abyssal life have adapted to. Individual species, however, are typically constrained within a narrow thermal and O_2-demand window of tolerance (Pörtner, 2010) and therefore it is *likely* that shifts in the distribution of DS species and regional extinctions will occur. Warming over multiple decades has been observed below 700 m (Levitus et al., 2005, 2009), with warming being minimal at mid-range depths (2000 to 3000 m), and increasing toward the sea floor in some sub-regions (e.g., Southern Ocean; WGI AR5 Chapter 3). For the deep Atlantic Ocean, the mean age of deep waters (mean time since last exposure to the atmosphere) is approximately 250 years; the oldest deep waters of the Pacific Ocean are >1000 years old. The patterns of ocean circulation are clearly revealed by the penetration of tracers and the signal of CO_2 released from burning fossil fuel penetrating into the abyss (Sabine et al., 2004). It will take many centuries for full equilibration of deep ocean waters and their ecosystems with recent planetary warming and CO_2 levels (Wunsch and Heimbach, 2008).

Temperature accounts for approximately 86% of the variance in the export of organic matter to the DS (*medium confidence*; Laws et al., 2000). Consequently, upper ocean warming will reduce the export of organic matter to the DS (*medium confidence*), potentially changing the distribution and abundance of DS organisms and associated food webs, and ecosystem processes (Smith, Jr. and Kaufmann, 1999). Most organic matter entering the DS is recycled by microbial systems at relatively shallow depths (Buesseler et al., 2007), and at rates that are temperature dependent. Upper ocean warming will increase the rate of sub-surface decomposition of organic matter (*high confidence*), thus intensifying the intermediate depth OMZs (Stramma et al., 2008, 2010) and reducing food supply to the abyssal ocean.

Particulate organic carbon is exported from the surface to deeper layers of the Ocean (>500 m) with an efficiency of between 20 and 50% (Buesseler et al., 2007), much of it being recycled by microbes before it reaches 1000 m (Smith, Jr. et al., 2009). The export of organic carbon is dependent on surface net primary productivity, which is *likely* to vary (Box CC-PP), influencing the supply of food to DS (Laws et al., 2000; Smith et al., 2008). Warming of intermediate waters will also increase respiration at mid-water depths, reducing the flux of organic carbon. Our understanding of other components of DS ecosystems is also relatively poor. For example, there is *limited evidence* and *limited agreement* as to how ocean warming and acidification are *likely* to affect ecosystems such as those associated with hydrothermal vents (Van Dover, 2012).

Oxygen concentrations are decreasing in the DS (Stramma et al., 2008; Helm et al., 2011a). Although the largest signals occur at intermediate water depths < 1000 m (Nakanowatari et al., 2007; Whitney et al., 2007; Falkowski et al., 2011), some waters >1000 m depth are also experiencing a decline (Jenkins, 2008). The quantity of dissolved O_2

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throughout the Ocean will be reduced with warming due to direct effects on solubility (*high confidence*), with these effects being widely distributed (Shaffer et al., 2009). It is also *virtually certain* that metabolic rates of all animals and microbial respiration rates will increase with temperature (Brown et al., 2004). Thus, increased microbial activity and reduced O_2 solubility at higher temperatures will have additive consequences for the decline of O_2 (*high confidence*) even in the DS. The DS waters are relatively well oxygenated owing to the higher solubility of O_2 in colder waters and the low supply rate of organic matter to great depths. The availability of oxygen to marine animals is governed by a combination of concentration, temperature, pressure, and related properties such as diffusivity. Analysis by Hofmann et al. (2013) reveals that the supply potential of oxygen to marine animals in cold deep waters is similar to that at much shallower depths (*very high confidence*).

Anthropogenic CO_2 has penetrated to at least 1000 m in all three ocean basins (particularly the Atlantic; Doney et al., 2009). Further declines of calcite and aragonite in already under-saturated DS water will presumably decrease biological carbonate structure formation and increase dissolution, as has happened many times in Earth's past (*high confidence*; Zeebe and Ridgwell, 2011). Some cold-water corals (reported down to 3500 m) already exist in waters under-saturated with respect to aragonite (Lundsten et al., 2009). Although initial investigations suggested that ocean acidification (reduced by 0.15 and 0.30 pH units) would result in a reduction in the calcification rate of deep water corals (30 and 56%, respectively), accumulating evidence shows that ocean acidification may have far less impact than previously anticipated on the calcification of some deep water corals (*limited evidence*, *medium agreement*; *low confidence*) although it may reduce important habitats given that dead unprotected coral mounds are *likely* to dissolve in under-saturated waters (Thresher et al., 2011; Form and Riebesell, 2012; Maier et al., 2013).

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to DS communities through increasing temperature, decreasing O_2 and pH, and changing carbonate chemistry (*high confidence*; Keeling et al., 2010). Risks associated with the DS have implications for the Ocean and planet given the high degree of inherent dependency and connectivity. The resulting changes to the flow of organic carbon to some parts of the DS (e.g., STG) are *very likely* to affect DS ecosystems (*medium confidence*; Smith et al., 2008). As with the Ocean generally, there is a need to fill in the substantial gaps that exist in our knowledge and understanding of the world's largest habitat and its responses to rapid anthropogenic climate change.

30.5.8. Detection and Attribution of Climate Change Impacts with Confidence Levels

The analysis in this chapter and elsewhere in AR5 has identified a wide range of physical, chemical, and ecological components that have changed over the last century (Box CC-MB). Figure 30-11 summarizes a number of examples from the Ocean as a region together with the degree of confidence in both the detection and attribution steps. For ocean warming and acidification, confidence is *very high* that changes are being detected and that they are due to changes to the atmospheric GHG content. There is considerable confidence in both the detection (*very high confidence*) and attribution (*high confidence*) of mass coral bleaching and mortality, given the well-developed understanding of environmental processes and physiological responses driving these events (Box CC-CR; Section 6.3.1). For other changes, confidence is lower, either because detection of changes has been difficult, or monitoring programs are not long established (e.g., field evidence of declining calcification), or because detection has been possible but models are in conflict (e.g., wind-driven upwelling). The detection and attribution of recent changes is discussed in further detail in Sections 18.3.3-4.

30.6. Sectoral Impacts, Adaptation, and Mitigation Responses

Human welfare is highly dependent on ecosystem services provided by the Ocean. Many of these services are provided by coastal and shelf areas, and are consequently addressed in other chapters (e.g., Sections 5.4.3, 7.3.2.4, 22.3.2.3). Oceans contribute provisioning (e.g., food, raw materials; see Section 30.6.2.1), regulating (e.g., gas exchange, nutrient recycling, carbon storage, climate regulation, water flux), supporting (e.g., habitat, genetic diversity), and cultural (e.g., recreational, religious) services (MEA, 2005; Tallis et al., 2013). The accumulating evidence indicating that fundamental ecosystem services within the Ocean are shifting rapidly should be of major concern, especially with respect to the ability of regulating and supporting ecosystem services to underpin current and future human population demands (Rockström et al., 2009; Ruckelshaus et al., 2013). Discussion here is restricted to environmental, economic, and social sectors that have direct relevance to the Ocean—namely natural ecosystems, fisheries and aquaculture, tourism, shipping, oil and gas, human health, maritime security, and renewable energy. The influences of climate change on Ocean sectors will be mediated through simultaneous changes in multiple environmental and ecological variables (see Figure 30-12), and the extent to which changes can be adapted to and/or risks mitigated (Table 30-3). Both short- and longer-term adaptation is necessary to address impacts arising from warming, even under the lowest stabilization scenarios assessed.

Sectoral approaches dominate resource use and management in the Ocean (e.g., shipping tends to be treated in isolation from fishing within an area), yet cumulative and interactive effects of individual stressors are known to be ubiquitous and substantial (Crain et al., 2008). Climate change consistently emerges as a dominant stressor in regional- to global-scale assessments, although land-based pollution, commercial fishing, invasive species, coastal habitat modification, and commercial activities such as shipping all rank high in many places around the world (e.g., Sections 5.3.4, 30.5.3-4; Halpern et al., 2009, 2010). Such cumulative effects pose challenges to managing for the full suite of stressors to marine systems, but also present opportunities where mitigating a few key stressors can potentially improve overall ecosystem condition (e.g., Halpern et al., 2010; Kelly et al., 2011). The latter has often been seen as a potential strategy for reducing negative consequences of climate impacts on marine ecosystems by boosting ecosystem resilience, thus buying time while the core issue of reducing GHG emissions is tackled (West et al., 2009).

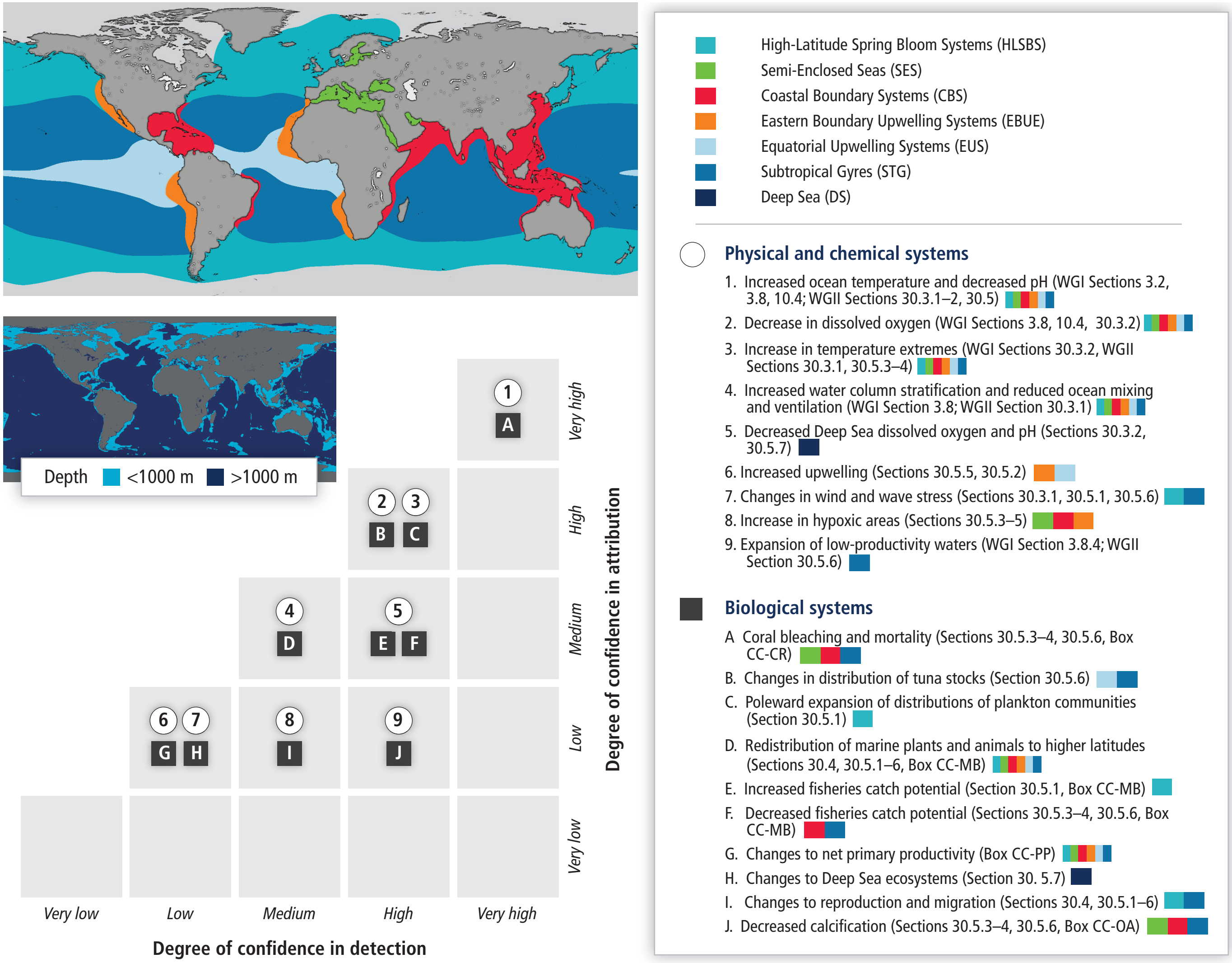


Figure 30-11 | Expert assessment of degree of confidence in detection and attribution of physical and chemical changes (white circles) and ecological changes (dark gray squares) across sub-regions, as designated in Figure 30-1a, and processes in the Ocean (based on evidence explored throughout Chapter 30 and elsewhere in AR5). Further explanation of this figure is given in Sections 18.3.3-4 and 18.6.

30.6.1. Natural Ecosystems

Adaptation in natural ecosystems may occur autonomously, such as tracking shifts in species' composition and distributions (Poloczanska et al., 2013), or engineered by human intervention, such as assisted dispersal (Section 4.4.2.4; Hoegh-Guldberg et al., 2008). Currently, adaptation strategies for marine ecosystems include reducing additional stressors (e.g., maintaining water quality, adapting fisheries management) and maintaining resilience ecosystems (e.g., Marine Protected Areas), and are moving toward whole-of-ecosystem management approaches. Coral reefs, for example, will recover faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained (*medium confidence*; Hughes et al., 2003), indicating that reducing overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of GHGs to stabilize global temperature and ocean chemistry.

Approaches such as providing a formal valuation of ecological services from the Ocean have potential to facilitate adaptation by underpinning more effective governance, regulation, and ocean policy while at the same time potentially improving management of these often vulnerable services through the development of market mechanisms and incentives (Beaudoin and Pendleton, 2012). Supporting, regulating, and cultural ecosystem services tend to transcend the immediate demands placed on provisioning services and are difficult to value in formal economic terms owing to their complexity, problems such as double counting, and the value of non-market goods and services arising from marine ecosystems generally (Fu et al., 2011; Beaudoin and Pendleton, 2012).

"Blue Carbon" is defined as the organic carbon sequestered by marine ecosystems such as phytoplankton, mangrove, seagrass, and salt marsh ecosystems (Laffoley and Grimsditch, 2009; Nellemann et al., 2009). In this respect, Blue Carbon will provide opportunities for both adaptation to, and mitigation of, climate change if key uncertainties in inventories, methodologies, and policies for measuring, valuing, and implementing Blue Carbon strategies are resolved (McLeod et al., 2011). Sediment surface levels in vegetated coastal habitats can rise several meters over thousands of years, building carbon-rich deposits (Brevik and Homburg,

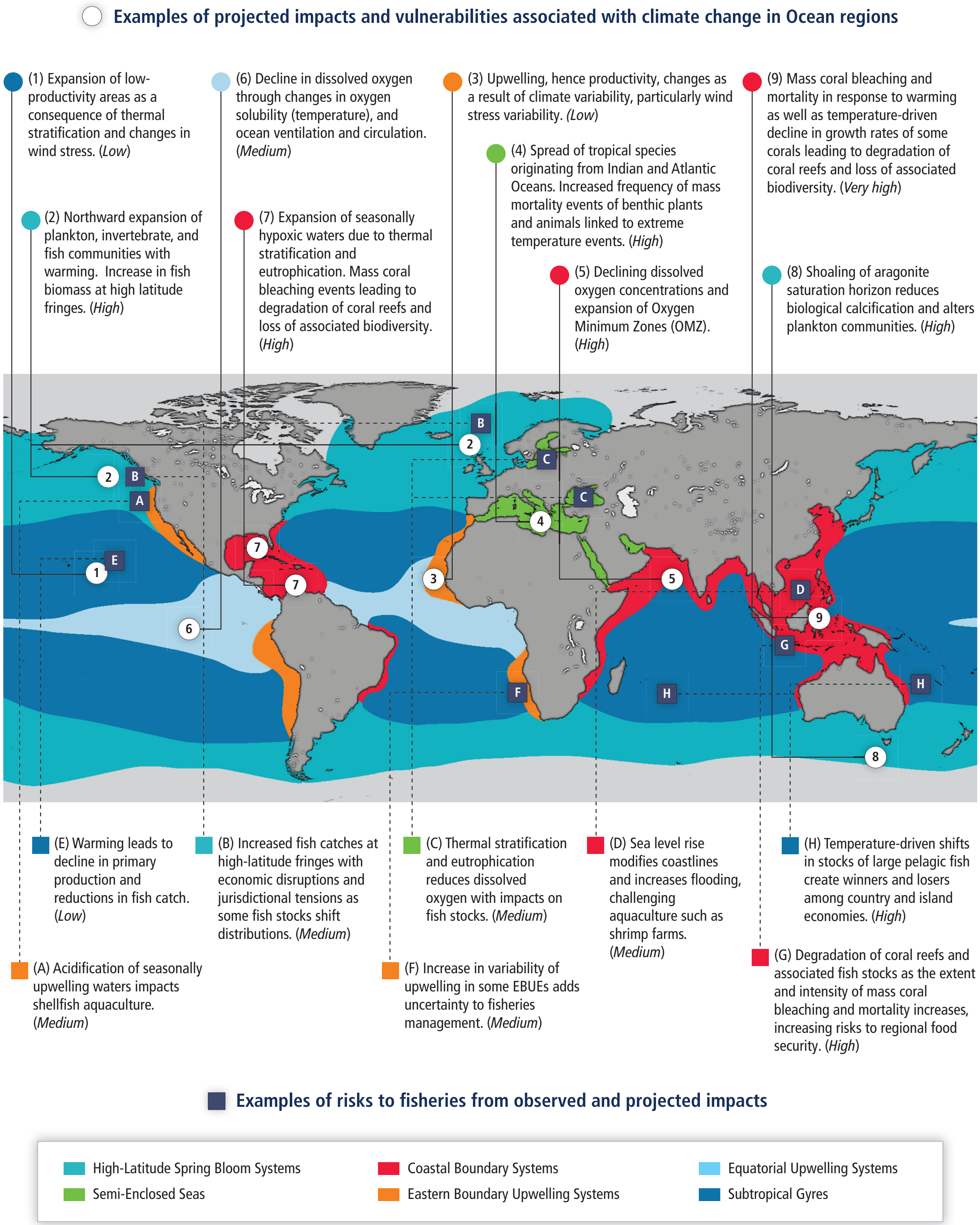


Figure 30-12 | Top: Examples of projected impacts and vulnerabilities associated with climate change in Ocean sub-regions. Bottom: Examples of risks to fisheries from observed and projected impacts across Ocean sub-regions. Words in parentheses indicate level of confidence. Details of sub-regions are given in Table 30-1a and Section 30.1.1.

2004; Lo Iacono et al., 2008). The degradation of coastal habitats not only liberates much of the carbon associated with vegetation loss, but can also release and oxidize buried organic carbon through erosion of cleared coastlines (*high confidence*; Duarte et al., 2005). Combining data on global area, land use conversion rates, and near-surface carbon stocks for marshes, mangroves, and seagrass meadows, Pendleton et al. (2012) revealed that the CO_2 emissions arising from destruction of these three ecosystems was equivalent to 3 to 19% of the emissions generated by deforestation globally, with economic damages estimated to be US$6 to US$42 billion annually. Similarly, Luisetti et al. (2013) estimate the carbon stock of seagrass and salt marshes in Europe, representing less than 4% of global carbon stocks in coastal vegetation, was valued at US$180 million, at EU Allowance price of €8/tCO_2 in June 2012. A reversal of EU Environmental Protection Directives could result in economic losses of US$1 billion by 2060. Blue Carbon strategies can also be justified in light of the numerous ecosystem services these ecosystems provide, such as protection against coastal erosion and storm damage, and provision of habitats for fisheries species (Section 5.5.7).

30.6.2. Economic Sectors

30.6.2.1. Fisheries and Aquaculture

The Ocean provided 64% of the production supplied by world fisheries (capture and aquaculture) in 2010, amounting to 148.5 million tonnes of fish and shellfish (FAO, 2012). This production, valued at US$217.5 billion, supplied, on average, 18.6 kg of protein-rich food per person to an estimated population of 6.9 billion (FAO, 2012). Marine capture fisheries supplied 77.4 million tonnes with highest production from the northwest Pacific (27%), west-central Pacific (15%), northeast Atlantic (11%), and southeast Pacific (10%) (FAO, 2012). World aquaculture production (59.9 million tonnes in 2010) is dominated by freshwater fishes; nevertheless, marine aquaculture supplied 18.1 million tonnes (30%) (FAO, 2012).

Marine capture fisheries production increased from 16.8 million tonnes in 1950 to a peak of 86.4 million tonnes in 1996, then declined before stabilizing around 80 million tonnes (FAO, 2012). The stagnation of marine capture fisheries production is attributed to full exploitation of around 60% of the world's marine fisheries and overexploitation of 30% (estimates for 2009) (FAO, 2012). Major issues for industrial fisheries include illegal, unreported, and unregulated fishing; ineffective implementation of monitoring, control, and surveillance; and overcapacity in fishing fleets (World Bank and FAO, 2008; FAO, 2012). Such problems are being progressively addressed in several developed and developing countries (Hilborn, 2007; Pitcher et al., 2009; Worm et al., 2009), where investments have been made in stock assessment, strong management, and application of the FAO Code of Conduct for Responsible Fisheries and the FAO Ecosystem Approach to Fisheries Management.

The significance of marine capture fisheries is illustrated powerfully by the number of people engaged in marine small-scale fisheries (SSF) in developing countries. SSF account for around half of the fish harvested from the Ocean, and provide jobs for more than 47 million people—about 12.5 million fishers and another 34.5 million people engaged in post-harvest activities (Mills et al., 2011). SSF are often characterized by large numbers of politically weak fishers operating from decentralized localities, with poor governance and insufficient data to monitor catches effectively (Kurien and Willmann, 2009; Cochrane et al., 2011; Pomeroy and Andrew, 2011). For these SSF, management that aims to avoid further depletion of overfished stocks may be more appropriate in the short-term than management aimed at maximizing sustainable production. These aims are achieved through adaptive management by (1) introduction of harvest controls (e.g., size limits, closed seasons and areas, gear restrictions, and protection of spawning aggregations) to avoid irreversible damage to stocks in the face of uncertainty (Cochrane et al., 2011); (2) flexible modification of these controls through monitoring (Plagányi et al., 2013); and (3) investing in the social capital and institutions needed for communities and governments to manage SSF (Makino et al., 2009; Pomeroy and Andrew, 2011).

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries resulting in loss of coastal and oceanic habitat (Hazen et al., 2012; Stramma et al., 2012), the movement of species (Cheung et al., 2011), the spread and increase of disease and invading species (Ling, 2008; Raitsos et al., 2010; Chan et al., 2011), and changes in primary production (Chassot et al., 2010). There is *medium evidence* and *medium agreement* that these changes will change both the nature of fisheries and their ability to provide food and protein for hundreds of millions of people (Section 7.2.1.2). The risks to ecosystems and fisheries vary from region to region (Section 7.3.2.4). Dynamic bioclimatic envelope models under SRES A1B project potential increases in fisheries production at high latitudes, and potential decreases at lower latitudes by the mid-21st century (Cheung et al., 2010; Section 6.5). Overall, warming temperatures are projected to shift optimal environments for individual species polewards and redistribute production; however, changes will be region specific (Cheung et al., 2010; Merino et al., 2012).

Fisheries, in particular shellfish, are also vulnerable to declining pH and carbonate ion concentrations. As a result, the global production of shellfish fisheries is *likely* to decrease (Cooley and Doney, 2009; Pickering et al., 2011) with further ocean acidification (*medium confidence*; Sections 6.3.2, 6.3.5, 6.4.1.1; Box CC-OA). Impacts may be first observed in EBUE where upwelled water is already relatively low in O_2 and under-saturated with aragonite (Section 30.5.5). Seasonal upwelling of acidified waters onto the continental shelf in the California Current region has recently affected oyster hatcheries along the coast of Washington and Oregon (Barton et al., 2012; Section 30.5.5.1.1). Whether declining pH and aragonite saturation due to climate change played a role is unclear; however, future declines will increase the risk of such events occurring.

Most marine aquaculture species are sensitive to changing ocean temperature (Section 6.3.1.4; exposed through pens, cages, and racks placed directly in the sea, utilization of seawater in land-based tanks, collection of wild spat) and, for molluscs particularly, changes in carbonate chemistry (Turley and Boot, 2011; Barton et al., 2012; Section 6.3.2.4). Environmental changes can therefore impact farm profitability, depending on target species and farm location. For example, a 1°C rise in SST is projected to shift production of Norwegian salmonids further north but may increase production overall (Hermansen and Heen, 2012). Industries for non-food products, which can be important for regional livelihoods such as Black Pearl in Polynesia, are also affected by rising SST. Higher temperatures are known to affect the quality of pearl nacre, and can increase levels of disease in adult oysters (Pickering et al., 2011; Bell et al., 2013b). Aquaculture production is also vulnerable to extreme events such as storms and floods (e.g., Chang et al., 2013). Flooding and inundation by seawater may be a problem to shore facilities on low-lying coasts. For example, shrimp farming operations in the tropics will be challenged by rising sea levels, which will be exacerbated by mangrove encroachment and a reduced ability for thorough-drying of ponds between crops (Della Patrona et al., 2011).

The impacts of climate change on marine fish stocks are expected to affect the economics of fisheries and livelihoods in fishing nations through changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labor markets, and industry re-organization (Sumaila et al., 2011; Section 6.4.1). A study of the potential vulnerabilities of national economies to the effects of climate change on fisheries, in terms of exposure to warming, relative importance of fisheries to national economies and diets, and limited societal capacity to adapt, concluded that a number countries including Malawi, Guinea, Senegal, Uganda, Sierra Leone, Mozambique, Tanzania, Peru, Colombia, Venezuela, Mauritania, Morocco, Bangladesh, Cambodia, Pakistan, Yemen, and Ukraine are most vulnerable (Allison et al., 2009).

Aquaculture production is expanding rapidly (Bostock et al., 2010) and will play an important role in food production and livelihoods as the human demand for protein grows. This may also add pressure on capture fisheries (FAO, 2012; Merino et al., 2012). Two-thirds of farmed food fish production (marine and freshwater) is achieved with the use of feed derived from wild-harvested, small, pelagic fish and shellfish. Fluctuations in the availability and price of fishmeal and fish oil for feeds, as well as their availability, pose challenges for the growth of sustainable aquaculture production, particularly given uncertainties in changes in EBUE upwelling dynamics to climate change (Section 30.5.5). Technological advances and changes in management such as increasing feed efficiencies, using alternatives to fishmeal and fish oil, and farming of herbivorous finfish, coupled with economic and regulatory incentives, will reduce the vulnerability of aquaculture to the impacts of climate change on small, pelagic fish abundance (Naylor et al., 2009; Merino et al., 2010; FAO, 2012).

The challenges of optimizing the economic and social benefits of both industrial fisheries and SSF and aquaculture operations, which often already include strategies to adapt to climatic variability (Salinger et al., 2013), are now made more complex by climate change (Cochrane et al., 2009; Brander, 2010, 2013). Nevertheless, adaptation options include establishment of early warning systems to aid decision making, diversification of enterprises, and development of adaptable management systems (Chang et al., 2013). Vulnerability assessments that link oceanographic, biological, and socioeconomic systems can be applied to identify practical adaptations to assist enterprises, communities, and households to reduce the risks from climate change and capitalize on the opportunities (Pecl et al., 2009; Bell et al., 2013b; Norman-López et al., 2013). The diversity of these adaptation options, and the policies needed to support them, are illustrated by the examples in the following subsections.

30.6.2.1.1. Tropical fisheries based on large pelagic fish

Fisheries for skipjack, yellowfin, big-eye, and albacore tuna provide substantial economic and social benefits to the people of Small Island Developing States (SIDS). For example, tuna fishing license fees contribute substantially (up to 40%) to the government revenue of several Pacific Island nations (Gillett, 2009; Bell et al., 2013b). Tuna fishing and processing operations also contribute up to 25% of gross domestic product in some of these nations and employ more than 12,000 people (Gillett, 2009; Bell et al., 2013b). Considerable economic benefits are also derived from fisheries for top pelagic predators in the Indian and Atlantic Oceans (FAO, 2012; Bell et al., 2013a). Increasing sea temperatures and changing patterns of upwelling are projected to cause shifts in the distribution and abundance of pelagic top predator fish stocks (Sections 30.5.2, 30.5.5-6), with potential to create "winners" and "losers" among island economies as catches of the transboundary tuna stocks change among and within their exclusive economic zones (EEZs; Bell et al., 2013a,b).

A number of practical adaptation options and supporting policies have been identified to minimize the risks and maximize the opportunities associated with the projected changes in distribution of the abundant skipjack tuna in the tropical Pacific (Bell et al., 2011b, 2013a; Lehodey et al., 2011; Table 30-2). These adaptation and policy options include (1) full implementation of the regional "vessel day scheme," designed to distribute the economic benefits from the resource in the face of climatic variability, and other schemes to control fishing effort in subtropical areas; (2) strategies for diversifying the supply of fish for canneries in the west of the region as tuna move progressively east; (3) continued effective fisheries management of all tuna species; (4) energy efficiency programs to assist domestic fleets to cope with increasing fuel costs and the possible need to fish further from port; and (5) the eventual restructuring of regional fisheries management organizations to help coordinate management measures across the entire tropical Pacific. Efforts to ensure provision of operational-level catch and effort data from all industrial fishing operations will improve models for projecting redistribution of tuna stocks and quotas under climate change (Nicol et al., 2013; Salinger et al., 2013). Similar adaptation options and policy responses are expected to be relevant to the challenges faced by tuna fisheries in the tropical and subtropical Indian and Atlantic Oceans.

30.6.2.1.2. Small-scale fisheries

Small-scale fisheries (SSF) account for 56% of catch and 91% of people working in fisheries in developing countries (Mills et al., 2011). SSF are fisheries that tend to operate at family or community level, have low levels of capitalization, and make an important contribution to food security and livelihoods. They are often dependent on coastal ecosystems, such as coral reefs, that provide habitats for a wide range of harvested fish and invertebrate species. Despite their importance to many developing countries, such ecosystems are under serious pressure from human activities including deteriorating coastal water quality, sedimentation, ocean warming, overfishing, and acidification (Sections 7.2.1.2, 30.3, 30.5; Box CC-CR). These pressures are translating into a steady decline in live coral cover, which is *very likely* to continue over the coming decades, even where integrated coastal zone management is in place

Table 30-2 | Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socioeconomic benefits derived from pelagic and coastal fisheries and aquaculture, and to maximize the opportunities. These measures are classified as win–win (W–W) adaptations, which address other drivers of the sector in the short term and climate change in the long term, or lose–win (L–W) adaptations, where benefits do not exceed costs in the short term but accrue under longer term climate change (modified from Bell et al., 2013b). WCPFC = Western and Central Pacific Fisheries Commission.

	Adaptation options	Supporting policies
Economic development	• Full implementation of the vessel day scheme to control fishing effort by the Parties to the Nauru Agreement[a] (W–W) • Diversifying sources of fish for canneries in the region and maintaining trade agreements, e.g., an economic partnership agreement with the European Union (W–W) • Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change (W–W) • Energy efficiency programs to assist fleets to cope with oil price rises and minimize CO_2 emissions and reduce costs of fishing further afield as tuna distributions shift east (W–W) • Pan-Pacific tuna management through merger of the WCPFC and Inter-American Tropical Tuna Commission to coordinate management measures across the tropical Pacific (L–W)	• Strengthen national capacity to administer the vessel day scheme. • Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna. • Include implications of climate change in management objectives of the WCPFC. • Apply national management measures to address climate change effects for subregional concentrations of tuna in archipelagic waters beyond the mandate of WCPFC. • Require all industrial tuna vessels to provide operational-level catch and effort data to improve the models for redistribution of tuna stocks during climate change.
Food security	• Manage catchment vegetation to reduce transfer of sediments and nutrients to coasts to reduce damage to adjacent coastal coral reefs, mangroves, and seagrasses that support coastal fisheries (W–W). • Foster the care of coral reefs, mangroves, and seagrasses by preventing pollution, managing waste, and eliminating direct damage to these coastal fish habitats (W–W). • Provide for migration of fish habitats by prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help the plants colonize landward areas as sea level rises (L–W). • Sustain and diversify catches of demersal coastal fish to maintain the replenishment potential of all stocks (L–W). • Increase access to tuna caught by industrial fleets through storing and selling tuna and by-catch landed at major ports to provide inexpensive fish for rapidly growing urban populations (W–W). • Install fish aggregating devices close to the coast to improve access to fish for rural communities as human populations increase and demersal fish decline (W–W). • Develop coastal fisheries for small pelagic fish species, e.g., mackerel, anchovies, pilchards, sardines, and scads (W–W?). • Promote simple post-harvest methods, such as traditional smoking, salting, and drying, to extend the shelf life of fish when abundant catches are landed (W–W).	• Strengthen governance for sustainable use of coastal fish habitats by (1) building national capacity to understand the threats of climate change; (2) empowering communities to manage fish habitats; and (3) changing agriculture, forestry, and mining practices to prevent sedimentation and pollution. • Minimize barriers to landward migration of coastal habitats during development of strategies to assist other sectors to respond to climate change. • Apply "primary fisheries management" to stocks of coastal fish and shellfish to maintain their potential for replenishment. • Allocate the necessary quantities of tuna from total national catches to food security to increase access to fish for both urban and coastal populations. • Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security. • Include anchored inshore fish aggregating devices as part of national infrastructure for food security.
Livelihoods	• Relocate pearl farming operations to deeper water and to sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for good growth and survival of pearl oysters and formation of high-quality pearls (L–W). • Raise the walls and floor of shrimp ponds so that they drain adequately as sea level rises (L–W). • Identify which shrimp ponds may need to be rededicated to producing other commodities (L–W).	• Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be "climate-proofed" and relocated if necessary. • Strengthen environmental impact assessments for coastal aquaculture activities to include the additional risks posed by climate change. • Develop partnerships with regional technical agencies to provide support for development of sustainable aquaculture.

[a]The Parties to the Nauru Agreement are Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, and Tuvalu.

(Sections 30.5.4, 30.5.6). For example, coral losses around Pacific Islands are projected to be as high as 75% by 2050 (Hoegh-Guldberg et al., 2011a). Even under the most optimistic projections (a 50% loss of coral by 2050), changes to state of coral reefs (Box CC-CR; Figures 30-10, 30-12) are *very likely* to reduce the availability of associated fish and invertebrates that support many of the SSF in the tropics (*high confidence*). In the Pacific, the productivity of SSF on coral reefs has been projected to decrease by at least 20% by 2050 (Pratchett et al., 2011b), which is also *likely* to occur in other coral reef areas globally given the similar and growing stresses in these other regions (Table SM30-1; Section 30.5.4).

Adaptation options and policies for building the resilience of coral reef fisheries to climate change suggested for the tropical Pacific include (1) strengthening the management of catchment vegetation to improve water quality along coastlines; (2) reducing direct damage to coral reefs; (3) maintaining connectivity of coral reefs with mangrove and seagrass habitats; (4) sustaining and diversifying the catch of coral reef fish to maintain their replenishment potential; and (5) transferring fishing effort from coral reefs to skipjack and yellowfin tuna resources by installing anchored fish-aggregating devices (FAD) close to shore (Bell et al., 2011b; 2013a,b; Table 30-2). These adaptation options and policies represent a "no regrets" strategy in that they provide benefits for coral reef fisheries and fishers irrespective of climate change and ocean acidification.

30.6.2.1.3. Northern Hemisphere HLSBS fisheries

The high-latitude fisheries in the Northern Hemisphere span from around 30/35°N to 60°N in the North Pacific and 80°N in the North Atlantic, covering a wide range of thermal habitats supporting subtropical/temperate species to boreal/arctic species. The characteristics of these

HLSBS environments, as well as warming trends, are outlined in Section 30.5.1 and Table 30-1. In part, as a result of 30 years of increase in temperature (Belkin, 2009; Sherman et al., 2009), there has been an increase in the size of fish stocks associated with high-latitude fisheries in the Northern Hemisphere. This is particularly the case for the Norwegian spring-spawning herring, which has recovered from near-extinction as a result of overfishing and a cooler climate during the 1960s (Toresen and Østvedt, 2000). The major components of both pelagic and demersal high-latitude fish stocks are boreal species located north of 50°N. Climate change is projected to increase high-latitude plankton production and displace zooplankton and fish species poleward. As a combined result of these future changes, the abundance of fish (particularly boreal species) may increase in the northernmost part of the high-latitude region (Cheung et al., 2011), although increases will only be moderate in some areas.

The changes in distribution and migration of pelagic fish shows considerable spatial and temporal variability, which can increase tensions among fishing nations. In this regard, tension over the Atlantic mackerel fisheries has led to what many consider the first climate change-related conflict between fishing nations (Cheung et al., 2012; Section 30.6.5), and which has emphasized the importance of developing international collaboration and frameworks for decision making (Miller et al., 2013; Sections 15.4.3.3, 30.6.7). The Atlantic mackerel has over the recent decades been a shared stock between the EU and Norway. However, the recent advancement of the Atlantic mackerel into the Icelandic EEZ during summer has resulted in Icelandic fishers operating outside the agreement between the EU and Norway. Earlier records of mackerel from the first half of the 20th and second half of the 19th century show, however, that mackerel was present in Icelandic waters during the earlier warm periods (Astthorsson et al., 2012). In the Barents Sea, the northeast Arctic cod, *Gadus morhua*, reached record-high abundance in 2012 and also reached its northernmost-recorded distribution (82°N) (ICES, 2012). A further northward migration is impossible as this would be into the Deep Sea Polar Basin, beyond the habitat of shelf species. A further advancement eastwards to the Siberian shelf is, however, possible. The northeast Arctic cod stock is shared exclusively by Norway and Russia, and to date there has been a good agreement between those two nations on the management of the stock. These examples highlight the importance of international agreements and cooperation (Table 30-4).

The HLSBS fisheries constitute a large-scale high-tech industry, with large investments in highly mobile fishing vessels, equipment, and land-based industries with capacity for adapting fisheries management and industries for climate change (Frontiers Economics, Ltd., 2013). Knowledge of how climate fluctuations and change affect the growth, recruitment, and distribution of fish stocks is presently not incorporated into fisheries management strategies (Perry et al., 2010). These strategies are vital for fisheries that hope to cope with the challenges of a changing ocean environment, and are centrally important to any attempt to develop ecosystem-based management and sustainable fisheries under climate change. The large pelagic stocks, with their climate-dependent migration pattern, are shared among several nations. Developing equitable sharing of fish quotas through international treaties (Table 30-4) is a necessary adaptation for a sustainable fishery. Factors presently taken into account in determining the shares of quotas are the historical fishery, bilateral exchanges of quotas for various species, and the time that stocks are in the various EEZs.

30.6.2.2. Tourism

Tourism recreation represents one of the world's largest industries, accounting for 9% (>US$6 trillion) of global GDP and employing more than 255 million people. It is expected to grow by an average of 4% annually and reach 10% of global GDP within the next 10 years (WTTC, 2012). As with all tourism, that which is associated with the Ocean is heavily influenced by climate change, global economic and socio-political conditions, and their interactions (Scott et al., 2012b; Section 10.6.1). Climate change, through impacts on ecosystems (e.g., coral reef bleaching), can reduce the appeal of destinations, increase operating costs, and/or increase uncertainty in a highly sensitive business environment (Scott et al., 2012b).

Several facets of the influence of climate change on the Ocean directly impact tourism (Section 10.6). Tourism is susceptible to extreme events such as violent storms, long periods of drought, and/or extreme precipitation events (Sections 5.4.3.4, 10.6.1; IPCC, 2012). SLR, through its influence on coastal erosion and submergence, salinization of water supplies, and changes to storm surge, increases the vulnerability of coastal tourism infrastructure, tourist safety, and iconic ecosystems (*high confidence*; Sections 5.3.3.2, 5.4.3.4, 10.6; Table SPM.1; IPCC, 2012). For example, approximately 29% of resorts in the Caribbean are within 1 m of the high tide mark and 60% are at risk of beach erosion from rapid SLR (Scott et al., 2012a).

Increasing sea temperatures (Section 30.3.1.1) can change attractiveness of locations and the opportunities for tourism through their influence on the movement of organisms and the state of ecosystems such as coral reefs (Section 10.6.2; Box CC-CR; UNWTO and UNEP, 2008). Mass coral bleaching and mortality (triggered by elevated sea temperatures; *high confidence*) can decrease the appeal of destinations for diving-related tourism, although the level of awareness of tourists of impacts (e.g., <50% of tourists were concerned about coral bleaching during a major bleaching year, 1998) and expected economic impacts have been found to be uncertain (Scott et al., 2012b). Some studies, however, have noted reduced tourist satisfaction and identified "dead coral" as one of the reasons for disappointment at the end of the holiday (Westmacott et al., 2000). Tourists respond to changes in factors such as weather and opportunity by expressing different preferences. For example, preferred conditions and hence tourism are projected to shift toward higher latitudes with climate change, or from summer to cooler seasons (Amelung et al., 2007; Section 10.6.1).

Options for adaptation by the marine tourism sector include (1) identifying and responding to inundation risks with current infrastructure, and planning for projected SLR when building new tourism infrastructure (Section 5.5; Scott et al., 2012a); (2) promoting shoreline stability and natural barriers by preserving ecosystems such as mangroves, salt marshes, and coral reefs (Section 5.5; Scott et al., 2012b); (3) deploying forecasting and early-warning systems in order to anticipate challenges to tourism and natural ecosystems (Strong et al., 2011; IPCC, 2012); (4) preparation of risk management and disaster preparation plans in order to respond to extreme events; (5) reducing the effect of other stressors on ecosystems and building resilience in iconic tourism features such as coral reefs and mangroves; and (6) educating tourists to improve understanding of the negative consequences of climate change over those stemming from local stresses (Scott et al., 2012a,b). Adaptation plans for tourism industries need to address specific operators and regions. For example, some operators may have costly infrastructure at risk while others may have few assets but are dependent on the integrity of natural environments and ecosystems (Turton et al., 2010).

30.6.2.3. Shipping

International shipping accounts for more than 80% of world trade by volume (UNCTAD, 2009a,b) and approximately 3% of global CO_2 emissions from fuel combustion although CO_2 emissions are expected to increase two- to threefold by 2050 (Heitmann and Khalilian, 2010; WGIII AR5 Section 8.1). Changes in shipping routes (Borgerson, 2008) and variation in the transport network due to shifts in grain production and global markets, as well as new fuel and weather-monitoring technology, may alter these emission patterns (WGIII AR5 Sections 8.3, 8.5). Extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damaging infrastructure and introducing additional dangers to ships, crews, and the environment (UNCTAD, 2009a,b; Pinnegar et al., 2012; Section 10.4.4). These issues have been assessed by some countries which have raised concerns over the potential for costly delays and cancellation of services, and the implications for insurance premiums as storminess and other factors increase risks (Thornes et al., 2012).

Climate change may benefit maritime transport by reducing Arctic sea ice and consequently shorten travel distances between key ports (Borgerson, 2008), thus also decreasing total GHG emissions from ships (WGIII AR5 Section 8.5.1). Currently, the low level of reliability of this route limits its use (Schøyen and Bråthen, 2011), and the potential full operation of the Northwest Passage and Northern Sea Route would require a transit management regime, regulation (e.g., navigation, environmental, safety, and security issues), and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interest in the Arctic. Further discussion of issues around melting Arctic sea ice and the Northern Sea Route are given in Chapter 28 (Sections 28.2.6, 28.3.4).

30.6.2.4. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry face potential impacts from climate change on its ocean-based activities. More than 100 oil and gas platforms were destroyed in the Gulf of Mexico by the unusually strong Hurricanes Katrina and Rita in 2005. Other consequences for oil pipelines and production facilities ultimately reduced US refining capacity by 20% (IPCC, 2012). The increasing demand for oil and gas has pushed operations to waters 2000 m deep or more, far beyond continental shelves. The very large-scale moored developments required are exposed to greater hazards and higher risks, most of which are not well understood by existing climate/weather projections. Although there is a strong trend toward seafloor well completions with a complex of wells, manifolds, and pipes that are not exposed to surface forcing, these systems face different hazards from instability and scouring of the unconsolidated sediments by DS currents (Randolph et al., 2010). The influence of warming oceans on sea floor stability is widely debated due largely to uncertainties about the effects of methane and methane hydrates (Sultan et al., 2004; Archer et al., 2009; Geresi et al., 2009). Declining sea ice is also opening up the Arctic to further oil and gas extraction. Discussion of potential expansion of oil and mineral production in the Arctic is made in Chapter 28 (Sections 28.2.5-6, 28.3.4).

The principal threat to oil and gas extraction and infrastructure in maritime settings is the impact of extreme weather (Kessler et al., 2011), which is *likely* to increase given that future storm systems are expected to have greater energy (Emanuel, 2005; Trenberth and Shea, 2006; Knutson et al., 2010). Events such as Hurricane Katrina have illustrated challenges which will arise for this industry with projected increases in storm intensity (Cruz and Krausmann, 2008). In this regard, early warning systems and integrated planning offer some potential to reduce the effect of extreme events (IPCC, 2012).

30.6.3. Human Health

Major threats to public health due to climate change include diminished security of water and food supplies, extreme weather events, and changes in the distribution and severity of diseases, including those due to marine biotoxins (Costello et al., 2009; Sections 5.4.3.5, 6.4.2.3, 11.2). The predominantly negative impacts of disease for human communities are expected to be more serious in low-income areas such as Southeast Asia, southern and east Africa, and various sub-regions of South America (Patz et al., 2005), which also have under-resourced health systems (Costello et al., 2009). Many of the influences are directly or indirectly related to basin-scale changes in the Ocean (e.g., temperature, rainfall, plankton populations, SLR, and ocean circulation; McMichael et al., 2006). Climate change in the Ocean may influence the distribution of diseases such as cholera (Section 11.5.2.1), and the distribution and occurrence of HABs. The frequency of cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens are correlated with sea surface temperatures, multi-decadal fluctuations of ENSO, and plankton blooms, which may provide insight into how this disease may change with projected rates of ocean warming (Colwell, 1996; Pascual et al., 2000; Rodó et al., 2002; Patz et al., 2005; Myers and Patz, 2009; Baker-Austin et al., 2012). The incidence of diseases such as ciguatera also shows links to ENSO, with ciguatera becoming more prominent after periods of elevated sea temperature. This indicates that ciguatera may become more frequent in a warmer climate (Llewellyn, 2010), particularly given the higher prevalence of ciguatera in areas with degraded coral reefs (*low confidence*; Pratchett et al., 2011a).

30.6.4. Ocean-Based Mitigation

30.6.4.1. Deep Sea Carbon Sequestration

Carbon dioxide capture and storage into the deep sea and geologic structures are also discussed in WGIII AR5 Chapter 7 (Sections 7.5.5, 7.8.2, 7.12). The economic impact of deliberate CO_2 sequestration beneath the sea floor has previously been reviewed (IPCC, 2005). Active CO_2 sequestration from co-produced CO_2 into sub-sea geologic formations is being instigated in the North Sea and in the Santos Basin offshore from Brazil. These activities will increase as offshore oil and gas production increasingly exploits fields with high CO_2 in the source gas and oil. Significant risks from the injection of high levels of CO_2 into deep ocean waters have been identified for DS organisms and ecosystems although chronic effects have not yet been studied. These risks are similar to those discussed previously with respect to ocean acidification and could further exacerbate declining O_2 levels and changing trophic networks in deep water areas (Seibel and Walsh, 2001; Section 6.4.2.2).

There are significant issues within the decision frameworks regulating these activities. Dumping of any waste or other matter in the sea, including the seabed and its subsoil, is strictly prohibited under the 1996 London Protocol (LP) except for those few materials listed in Annex I. Annex 1 was amended in 2006 to permit storage of CO_2 under the seabed. "Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-Seabed Geological Formations" were adopted by the parties to the LP in 2007. The Guidelines take a precautionary approach to the process, requiring Contracting Parties under whose jurisdiction or control such activities are conducted to issue a permit for the disposal subject to stringent conditions being fulfilled (Rayfuse and Warner, 2012).

30.6.4.2. Offshore Renewable Energy

Renewable energy supply from the Ocean includes ocean energy and offshore wind turbines. The global technical potential for ocean and wind energy is not as high as solar energy although considerable potential still remains. Detailed discussion of the potential of renewable energy sources are given in WGIII AR5 Chapter 7 (Sections 7.4.2, 7.5.3, 7.8.2). There is an increasing trend in the renewable energy sector to offshore wind turbines (Section 10.2.2). At present, there is *high uncertainty* about how changes in wind intensity and patterns, and extreme events (from climate change), will impact the offshore wind energy sector. Given the design and engineering solutions available to combat climate change impacts (Tables 10-1, 10-7), it is *unlikely* that this sector will face insurmountable challenges from climate change.

30.6.5. Maritime Security and Related Operations

Climate change and its influence on the Ocean has become an area of increasing concern in terms of the maintenance of national security and the protection of citizens. These concerns have arisen as nation-states increasingly engage in operations ranging from humanitarian assistance in climate-related disasters to territorial issues exacerbated by changing coastlines, human communities, resource access, and new seaways (Kaye, 2012; Rahman, 2012; Section 12.6). In this regard, increasing sea levels along gently sloping coastlines can have the seemingly perverse outcome that the territorial limits to the maritime jurisdiction of the State might be open to question as the distance from national baselines to the outer limits of the EEZ increases beyond 200 nm over time (Schofield and Arsana, 2012).

Changes in coastal resources may also be coupled with decreasing food security to compound coastal poverty and lead, in some cases, to increased criminal activities such as piracy; IUU fishing; and human, arms, and drug trafficking (Kaye, 2012). While the linkages have not been clearly defined in all cases, it is possible that changes in the Ocean as result of climate change will increase pressure on resources aimed at maintaining maritime security and countering criminal activity, disaster relief operations, and freedom of navigation (Section 12.6.2). National maritime security capacity and infrastructure may also require rethinking as new challenges present themselves as a result of climate change and ocean acidification (Allen and Bergin, 2009; Rahman, 2012; Sections 12.6.1-2).

Opportunities may also arise from changes to international geography such as formation of new ice-free seaways through the Arctic, which may benefit some countries in terms of maintaining maritime security and access (Section 28.2.6). Conversely, such new features may also lead to increasing international tensions as States perceive new vulnerabilities from these changes to geography.

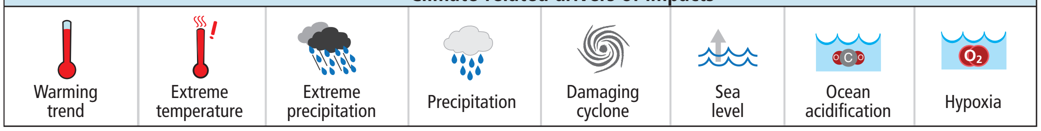
Like commercial shipping (Section 30.6.2.3), naval operations in many countries result in significant GHG emissions (e.g., the US Navy emits around 2% of the national GHG emissions; Mabus, 2010). As a result, there are a number of programs being implemented by navies around the world to try and reduce their carbon footprint and air pollution such as improving engine efficiency, reducing fouling of vessels, increasing the use of biofuels, and using nuclear technology for power generation, among other initiatives.

30.7. Synthesis and Conclusions

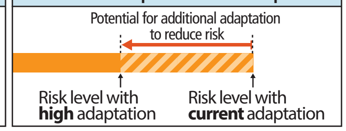
Evidence that human activities are fundamentally changing the Ocean is *virtually certain*. Sea temperatures have increased rapidly over the past 60 years at the same time as pH has declined, consistent with the expected influence of rising atmospheric concentrations of CO_2 and other GHGs (*very high confidence*). The rapid rate at which these fundamental physical and chemical parameters of the Ocean are changing is unprecedented within the last 65 Ma (*high confidence*) and possibly 300 Ma (*medium confidence*). As the heat content of the Ocean has increased, the Ocean has become more stratified (*very likely*), although there is considerable regional variability. In some cases, changing surface wind has influenced the extent of mixing and upwelling, although our understanding of where and why these differences occur regionally is uncertain. The changing structure and function of the Ocean has led to changes in parameters such as O_2, carbonate ion, and inorganic nutrient concentrations (*high confidence*). Not surprisingly, these fundamental changes have resulted in responses by key marine organisms, ecosystems, and ecological processes, with negative implications for hundreds of millions of people that depend on the ecosystem goods and services provided (*very likely*). Marine organisms are migrating at rapid rates toward higher latitudes, fisheries are transforming, and many organisms are shifting their reproductive and migratory activity in time and in concert with changes in temperature and other parameters. Ecosystems such as coral reefs are declining rapidly (*high confidence*). An extensive discussion of these changes is provided in previous sections and in other chapters of AR5.

Table 30-3 | Key risks to ocean and coastal issues from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer term era of climate options (here, for 2080–2100), for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each time frame, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Climate-related drivers of impacts



Level of risk & potential for adaptation



Risks to ecosystems and adaptation options

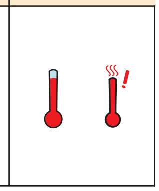
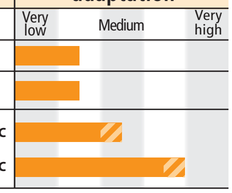
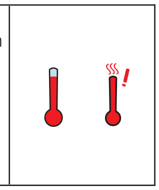
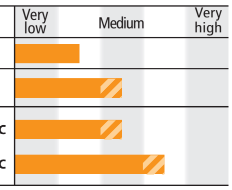
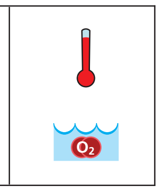
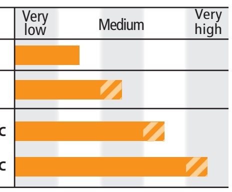
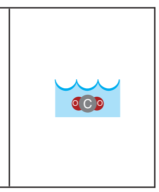
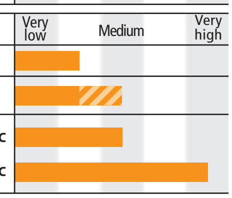
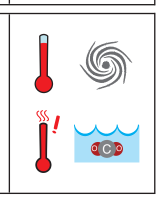
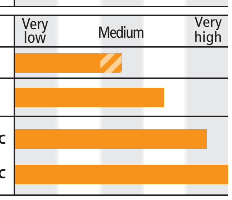
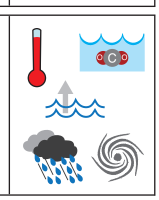
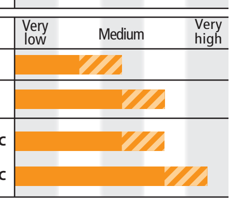
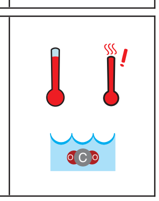
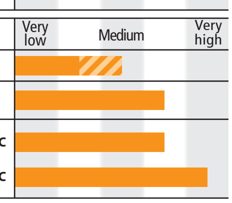
Key risk	Adaptation issues & prospects	Climatic drivers	Timeframe	Risk & potential for adaptation
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans. (*medium confidence*) [6.5.1, 6.3.4, Box CC-PP]	Adaptation options are limited to the translocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, or to the expansion of aquaculture.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Distributional shift in fish and invertebrate species, fall in fisheries catch potential at low latitudes, e.g., in EUS, CBS, and STG regions. (*high confidence*) [6.3.1, Box CC-MB]	Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their changes in distribution to maintain temperatures. Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well as deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication, the expansion of sustainable aquaculture and development of alternative livelihoods in some regions.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects. (*high confidence*) [6.3.3, 30.5.3.2, 30.5.4.1-2]	Human adaptation options involve the large-scale translocation of industrial fishing activities as a consequence of the hypoxia-induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running off of coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae. (*high confidence*) [5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA]	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely limited by the CO_2 concentrations and high temperatures reached; adaptation options shifting to exploit more resilient species or the protection of habitats with low natural CO_2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, exacerbated by ocean acidification, e.g., in CBS, SES, and STG regions. (*high confidence*) [5.4.2.4, 6.4.2, 30.3.1.1, 30.3.2.2, 30.5.2, 30.5.3, 30.5.4, 30.5.6, Box CC-CR]	Evidence of rapid evolution by corals is very limited or nonexistent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely given estimates that they need to move at the speed of 10 – 20 km yr^{-1} to keep up with the pace of climate change. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Coastal inundation and habitat loss due to sea level rise, extreme events, changes in precipitation, and reduced ecological resilience, e.g., in CBS and STG subregions. (*medium to high confidence*) [5.5.2, 5.5.4, 30.5.6.1.3, 30.6.2.2, Box CC-CR]	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing, physical destruction, and unsustainable aquaculture. Reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients. Increased mangrove, coral reef, and seagrass protection and restoration to protect numerous ecosystem goods and services such as coastal protection, tourist value, and fish habitat.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	
Marine biodiversity loss with high rate of climate change. (*medium confidence*) [6.3.1-3, 6.4.1.2-3, Table 30.4, Box CC-MB]	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from tourism and fishing.		Present Near term (2030 – 2040) Long term 2°C / 4°C (2080 – 2100)	

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Table 30-3 (continued)

Risks to fisheries				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Decreased production of global shellfish fisheries. (*high confidence*) [6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, Box CC-OA]	Effective shift to alternative livelihoods, changes in food consumption patterns, and adjustment of (global) markets.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Global redistribution and decrease of low-latitude fisheries yields are paralleled by a global trend to catches having smaller fishes. (*medium confidence*) [6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2]	Increasing coastal poverty at low latitudes as fisheries becomes smaller – partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrialized fishing efforts.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries. (*high confidence*) [6.3.1, 6.4.3, Table 30.4]	International fisheries agreements and instruments, such as the tuna commissions, may have limited success in establishing sustainable fisheries yields.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Variability of small pelagic fishes in EBUEs is becoming more extreme at interannual to multidecadal scales, making industry and management decisions more uncertain. (*medium confidence*) [6.3.2, 6.3.3, 30.5.2, 30.5.5, Box CC-UP]	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction. (*high confidence*) [6.4.1, 30.5.3-4, 30.5.6, Box CC-CR]	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high
Current spatial management units, especially the marine protected areas (MPAs), may fail in the future due to shifts in species distributions and community structure. (*high confidence*) [6.3.1, 6.4.2.1, 30.5.1, Box CC-MB]	Continuous revision and shifts of MPA borders, and of MPA goals and performance.		Present Near term (2030–2040) Long term (2080–2100) 2°C / 4°C	Very low – Medium – Very high

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30.7.1. Key Risks and Vulnerabilities

The rapid changes in the physical, chemical, and biological state of the Ocean pose a number of key risks and vulnerabilities for ecosystems, communities, and nations worldwide. Table 30-3 and Figure 30-12 summarize risks and vulnerabilities from climate change and ocean acidification, along with adaptation issues and prospects, and a summary of expert opinion on how these risks will change under further changes in environmental conditions.

Rising ocean temperatures are changing the distribution, abundance, and phenology of many marine species and ecosystems, and consequently represent a key risk to food resources, coastal livelihoods, and industries such as tourism and fishing, especially for HLSBS, CBS, STG, and EBUE (Sections 6.3.1, 6.3.4, 7.3.2.4, 30.5; Figure 30-12; Table 30-3; Box CC-MB). Key risks involve changes in the distribution and abundance of key fishery species (*high confidence*; Section 30.6.2.1; Figure 30-12 A,B,G,H) as well as the spread of disease and invading organisms, each of which has the potential to impact ecosystems as well as aquaculture and fishing (Sections 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.4, 7.4.2, 29.5.3-4; Table 30-3). Adaptation to these changes may be possible in the short-term through dynamic fisheries policy and management (i.e., relocation of fishing effort; Table 30-3), as well as monitoring and responding to potential invading species in coastal settings. The increasing frequency of thermal extremes (Box CC-HS) will also increase the risk that the thermal threshold of corals and other organisms is exceeded on a more frequent

Table 30-3 (continued)

Risks to humans and infrastructure (continued)				
Key risk	**Adaptation issues & prospects**	**Climatic drivers**	**Timeframe**	**Risk & potential for adaptation**
Reduced coastal socioeconomic security. (*high confidence*) [5.5.2, 5.5.4, 30.6.5, 30.7.1]	Human adaptation options involve (1) protection using coastal defences (e.g. seawalls where appropriate and economic) and soft measures (e.g., mangrove replanting and enhancing coral growth); (2) accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure; and (3) managed retreat as a last viable option. Vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high *
				**High confidence* in existence of adaptation measures, *Low confidence* in magnitude of risk reduction
Reduced livelihoods and increased poverty. (*medium confidence*) [6.4.1-2, 30.6.2, 30.6.5]	Human adaptation options involve the large-scale translocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other species of interest.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Impacts due to increased frequency of harmful algal blooms (*medium confidence*) [6.4.2.3]	Adaptation options include improved monitoring and early warning system, reduction of stresses favoring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*) [IPCC 2012, 30.6.5, 12.4-12.6, 29.3]	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people, and increase humanitarian crises.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*) [IPCC 2012, 30.6.5, 12.4-12.6, 29.3]	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		Present Near term (2030 – 2040) Long term (2080 – 2100) 2°C 4°C	Very low / Medium / Very high

CBS = Coastal Boundary Systems; EBUE = Eastern Boundary Upwehlling Ecosystems; EUS = Equatorial Upwelling Systems; HLSBS = High-Latitude Spring Bloom Systems; SES = Semi-Enclosed Seas; STG = Subtropical Gyres.

basis (especially in CBS, STG, SES, HLSBS, and EUS regions; Sections 6.2, 30.5; Box CC-CR). These changes pose a key risk to vulnerable ecosystems such as mangroves and coral reefs, with potential to have a series of serious impacts on fisheries, tourism, and coastal ecosystem services such as coastal protection (Sections 5.4.2.4, 6.3.2, 6.3.5, 6.4.1.3, 7.2.1.2, 29.3.1.2, 30.5; Table 30-3; Box CC-CR). Genetic adaptation of species to increasing levels of stress may not occur fast enough given fairly long generation times of organisms such as reef-building corals and many other invertebrates and fish (Table 30-3). In this case, risks may be reduced by addressing stresses not related to climate change (e.g., pollution, overfishing), although this strategy could have minimal impact if further increases in sea temperature occur (*high confidence*).

Loss of these important coastal ecosystems is associated with emerging risks associated with the collapse of some coastal fisheries along with livelihoods, food, and regional security (*medium confidence*). These changes are *likely* to be exacerbated by other key risks such as coastal inundation and habitat loss due to SLR, as well as intensified precipitation events (*high confidence*; Section 5.4; Box CC-CR). Adaptation options in this case include engineered coastal defenses, reestablishing coastal vegetation such as mangroves, protecting water supplies from salination, and developing strategies for coastal communities to withdraw to less vulnerable locations over time (Section 5.5).

The recent decline in O_2 concentrations has been ascribed to warming through the effect on ocean mixing and ventilation, as well as the solubility of O_2 and its consumption by marine microbes (Sections 6.1.1.3, 6.3.3, 30.3.2.3, 30.5.7). This represents a key risk to ocean ecosystems (*medium confidence*; Figure 30-12 5,6,C). These changes increase the vulnerability of marine communities, especially those below the euphotic zone, to hypoxia and ultimately lead to a restriction of suitable habitat (*high confidence*; Figure 30-12 5). In the more extreme case, often exacerbated by the contribution of organic carbon from land-based sources, "dead zones" may form. Decreasing oxygen, consequently, is *very likely* to increase the vulnerability of fisheries and aquaculture (*medium confidence*; Figure 30-12 C), and consequently puts livelihoods at risk, particularly in EBUE (e.g., California and Humboldt Current ecosystems; Section 30.5.5), SES (e.g., Baltic and Black Seas; Section 30.5.3), and CBS (e.g., Gulf of Mexico, northeast Indian Ocean; Sections 30.3.2.3, 30.5.4). It is *very likely* that the warming of surface waters has also increased the stratification of the upper ocean by about 4% between 0 and 200 m from 1971 to 2010 in all oceans north of about 40°S. In many cases, there is significant adaptation opportunity to reduce hypoxia locally by reducing the flow of organic carbon, hence microbial activity, within these coastal systems (Section 30.5.4). Relocating fishing effort, and modifying procedures associated with industries such as aquaculture, may offer some opportunity to adapt to these changes (*likely*). Declining O_2 concentrations are *likely* to have significant impacts on DS habitats, where organisms are relatively sensitive to environmental changes of this nature owing to the very constant conditions under which they have evolved (Section 30.5.7).

Ocean acidification has increased the vulnerability of ocean ecosystems by affecting key aspects of the physiology and ecology of marine organisms (particularly in CBS, STG, and SES; Section 6.3.2; Table 30-3; Box CC-OA). Decreasing pH and carbonate ion concentrations reduce the ability of marine organisms to produce shells and skeletons, and may interfere with a range of biological processes such as reproduction, gas exchange, metabolism, navigation ability, and neural function in a broad range of marine organisms that show minor to major influences of ocean acidification on their biology (Sections 6.3.2, 30.3.2.2; Box CC-OA). Natural variability in ocean pH can interact with ocean acidification to create damaging periods of extremes (i.e., high CO_2, low O_2 and pH), which can have a strong effect on coastal activities such as aquaculture (*medium confidence*; Section 6.2; Figure 30-12 A; Box CC-UP). There may be opportunity to adapt aquaculture to increasingly acidic conditions by monitoring natural variability and restricting water intake to periods of optimal conditions. Reducing other non-climate change or ocean acidification associated stresses also represents an opportunity to build greater ecological resilience against the impacts of changing ocean carbonate chemistry. Ocean acidification is also an emerging risk for DS habitats as CO_2 continues to penetrate the Ocean, although the impacts and adaptation options are poorly understood and explored. Ocean acidification has heightened importance for some groups of organisms and ecosystems (Box CC-OA). In ecosystems that are heavily dependent on the accumulation of calcium carbonate over time (e.g., coral reefs, *Halimeda* beds), increasing ocean acidification puts at risk ecosystems services that are critical for hundreds of thousands of marine species, plus people and industries, particularly within CBS, STG, and SES (*high confidence*). Further risks may emerge from the non-linear interaction of different factors (e.g., increasing ocean temperature may amplify effects of ocean acidification, and vice versa) and via the interaction of local stressors with climate change (e.g., interacting changes may lead to greater ecosystems disturbances than each impact on its own). There is an urgent need to understand these types of interactions and impacts, especially given the long time it will take to return ocean ecosystems to preindustrial pH and carbonate chemistry (i.e., tens of thousands of years (FAQ 30.1) should CO_2 emissions continue at the current rate).

It is *very likely* that surface warming has increased stratification of the upper ocean, contributing to the decrease in O_2 along with the temperature-related decreases in oxygen solubility (WGI AR5 Section 3.8.3). Changes to wind speed, wave height, and storm intensity influence the location and rate of mixing within the upper layers of the Ocean and hence the concentration of inorganic nutrients (e.g., in EBUE, EUS; Figure 30-12 1,3). These changes to ocean structure increase the risks and vulnerability of food webs within the Ocean. However, our understanding of how primary productivity is going to change in a warming and more acidified ocean is limited, as is our understanding of how upwelling will respond to changing surface wind as the world continues to warm (Boxes CC-PP, CC-UP). As already discussed, these types of changes can have implications for the supply of O_2 into the Ocean and the upward transport of inorganic nutrients to the euphotic zone. Although our understanding is limited, there is significant potential for regional increases in wind speed to result in greater rates of upwelling and the supply of inorganic nutrients to the photic zone. Although this may increase productivity of phytoplankton communities and associated fisheries, greater rates of upwelling can increase the risk of hypoxic conditions developing at depth as excess primary production sinks into the Ocean and stimulates microbial activity at depth (Sections 6.1.1.3, 30.3.2.3, 30.5.5; Table 30-3). Changes in storm intensity may increase the risk of damage to shipping and industrial infrastructure, which increases the risk of accidents and delays to the transport of products between countries, security operations, and the extraction of minerals from coastal and oceanic areas (Section 30.6.2; IPCC, 2012).

Frequently Asked Questions

FAQ 30.5 | How can we use non-climate factors to manage climate change impacts on the oceans?

The Ocean is exposed to a range of stresses that may or may not be related to climate change. Human activities can result in pollution, eutrophication (too many nutrients), habitat destruction, invasive species, destructive fishing, and over-exploitation of marine resources. Sometimes, these activities can increase the impacts of climate change, although they can, in a few circumstances, dampen the effects as well. Understanding how these factors interact with climate change and ocean acidification is important in its own right. However, reducing the impact of these non-climate factors may reduce the overall rate of change within ocean ecosystems. Building ecological resilience through ecosystem-based approaches to the management of the marine environment, for example, may pay dividends in terms of reducing and delaying the effects of climate change (*high confidence*).

The proliferation of key risks and vulnerabilities to the goods and services provided by ocean ecosystems as a result of ocean warming and acidification generate a number of key risks for the citizens of almost every nation. Risks to food security and livelihoods are expected to increase over time, aggravating poverty and inequity (Table 30-3). As these problems increase, regional security is likely to deteriorate as disputes over resources increase, along with increasing insecurity of food and nutrition (Sections 12.4-6, 29.3.3, 30.6.5; Table 30-3; IPCC, 2012).

30.7.2. Global Frameworks for Decision Making

Global frameworks for decision making are central to management of vulnerability and risk at the scale and complexity of the world's oceans. General frameworks and conventions for policy development and decision making within oceanic and coastal regions are important in terms of the management of stressors not directly due to ocean warming or acidification, but that may influence the outcome of these two factors. Tables 30-3 and 30-4 outline a further set of challenges arising from multiple interacting stressors, as well as potential risks and vulnerabilities, ramifications, and adaptation options. In the latter case, examples of potential global frameworks and initiatives for beginning and managing these adaptation options are described. These frameworks represent opportunities for global cooperation and the development of international, regional, and national policy responses to the challenges posed by the changing ocean (Kenchington and Warner, 2012; Tsamenyi and Hanich, 2012; Warner and Schofield, 2012).

The United Nations Convention on the Law of the Sea (UNCLOS) was a major outcome of the third UN Conference on the Law of the Sea (UNCLOS III). The European Union and 164 countries have joined in the

Table 30-4 | Ramifications, adaptation options, and frameworks for decision making for ocean regions. Symbols for primary drivers: IC = ice cover; NU = nutrient concentration; OA = ocean acidification; SLR = sea level rise; SS = storm strength; T = sea temperature (↑ = increased; ↓ = decreased; * = uncertain).

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key references and chapter sections
↑T, ↑OA	Spatial and temporal variation in primary productivity (*medium confidence* at global scales; Box CC-PP)	Reduced fisheries production impacts important sources of income to some countries while others may see increased productivity (e.g., as tuna stocks shift eastwards in the Pacific) (*medium confidence*).	Reduced national income, increased unemployment, plus increase in poverty. Potential increase in disputes over national ownership of key fishery resources (*likely*)	Increased international cooperation over key fisheries. Improved understanding of linkages between ocean productivity, recruitment, and fisheries stock levels. Implementation of the regional "vessel day scheme" provides social and economic incentives to fisheries and fishers for adaptation.	UNCLOS, PEMSEA, CTI, RFMO agreements, UNSFSA	Bell et al. (2011, 2013a); Tsamenyi and Hanich (2012); Sections 6.4.1, 6.5.3, 30.6.2.1, 30.7.2; Box CC-PP
↑T, ↑OA	Ecosystem regime shifts (e.g., coral to algal reefs; structural shifts in phytoplankton communities) (*medium confidence*)	Reduced fisheries production of coastal habitats and ecosystems such as coral reefs (*medium confidence*).	Decreased food and employment security and human migration away from coastal zone (*likely*)	Strengthen coastal zone management to reduce contributing stressors (e.g., coastal pollution, over-harvesting, and physical damage to coastal resources). Promote Blue Carbon[a] initiatives.	PEMSEA, CTI, PACC, MARPOL, UNHCR, CBD, International Organization for Migration, Global Environment Facility, International Labor Organization	Bell et al. (2013a); Sections 5.4.3, 6.3.1–2, 12.4, 29.3.1, 29.3.3, 30.5.2–4, 30.5.6, 30.6.1, 30.6.2.1; Box CC-CR
		Tourist appeal of coastal assets decreases as ecosystems change to less "desirable" state, reducing income to some countries (*low confidence*).	Increased levels of coastal poverty in some countries as tourist income decreases (*likely*)	As above, strengthen coastal zone management and reduce additional stressors on tourist sites; implement education programs and awareness among visitors. Diversify tourism activities.	CBD, PEMSEA, CTI, PACC, UNHCR, MARPOL	Kenchington and Warner (2012); Sections 5.5.4.1, 6.4.1–2, 10.6, 30.6.2.2
		Increased risk of some diseases (e.g., ciguatera, harmful algal blooms) as temperatures increase shift and ecosystems shift away from coral dominance (*low confidence*).	Increased disease and mortality; decreases in coastal food resources and fisheries income (*likely*)	Increase monitoring and education surrounding key risks (e.g., ciguatera); develop alternate fisheries and income for periods when disease incidence increases, and develop or update health response plans.	National policy strategies and regional cooperation needed	Llewellyn (2010); Sections 6.4.2.3, 10.6, 29.3.3.2, 29.5.3, 30.6.3
		Increased poverty and dislocation of coastal people (particularly in the tropics) as coastal resources such as fisheries degrade (*medium confidence*)	Increased population pressure on migration destinations (e.g., large regional cities), and reduced freedom to navigate in some areas (as criminal activity increases) (*likely*)	Develop alternative industries and income for affected coastal people. Strengthen coastal security both nationally and across regions. Increase cooperation over handling of criminal activities.	UNCLOS, PEMSEA, CTI, International Ship and Port Facility Security, IMO, Bali Process, Association of Southeast Asian Nations MLA Treaty and bilateral extradition and MLA agreements	Kaye (2012); Rahman (2012); Sections 12.4–6,29.3.3, 29.6.2, 30.6.5

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[a]Blue Carbon initiatives include conservation and restoration of mangroves, saltmarsh, and seagrass beds as carbon sinks (Section 30.6.1).

Notes: CBD = Convention on Biological Diversity; CTI = Coral Triangle Initiative; IHO = International Hydrographic Organization; IOM = International Organization of Migration; ISPS = International Ship and Port Facility Security; MARPOL = International Convention for the Prevention of Pollution From Ships; MLA = mutual legal assistance; PACC = Pacific Adaptation to Climate Change Project; PEMSEA = Partnerships in Environmental Management for the Seas of East Asia; RFMO = Regional Fisheries Management Organizations; UNCLOS = United Nations Convention on the Law of the Sea; UNHCR = United Nations High Commissioner for Refugees; UNSFSA = United Nations Straddling Fish Stocks Agreement.

Table 30-4 (continued)

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key references and chapter sections
↑T	Migration of organisms and ecosystems to higher latitudes (*high confidence*)	Reorganization of commercial fish stocks and ecological regime shifts (*medium to high confidence*)	Social and economic disruption (*very likely*)	Increase international cooperation and improve understanding of regime changes; implement early-detection monitoring of physical and biological variables and regional seasonal forecasting; include related uncertainties into fisheries management; provide social and economic incentives for industry.	UNCLOS, CBD, RFMO agreements, UNSFSA	Sections 7.4.2, 6.5, 30.5, 30.6.2.1; Box CC-MB
		Increase in abundance, growing season, and distributional extent of pests and fouling species (*medium confidence*)	Increased disease risk to aquaculture and fisheries. Income loss and increased operating and maintenance costs (*very likely*)	Increase environmental monitoring; promote technological advances to deal with pest and fouling organisms; increase vigilance and control related to biosecurity.	IMO, ballast water management, Anti- Fouling Convention	Sections 6.4.1.5, 7.3.2.4, 29.5.3–4, 30.6.2.1; Box CC-MB
		Threats to human health increase due to expansion of pathogen distribution to higher latitudes (*low confidence*)	Increased disease and mortality in some coastal communities (*likely*)	Reduce exposure through increased monitoring and education, adoption, or update of health response plans to outbreaks.	UNICEF, World Health Ogranization, IHOs, and national governments	Myers and Patz (2009); Sections 6.4.3, 10.8.2, 11.7, 29.3.3, 30.6.3; Box CC-MB
↑T, ↑NU, ↑OA*	Increased incidence of harmful algal blooms (*low confidence*)	Increased threats to ecosystems, fisheries, and human health (*medium confidence*)	Reduced supply of marine fish and shellfish and greater incidence of disease among some coastal communities (*likely*)	Provide early-detection monitoring and improve predictive models; provide education and adoption or update of health response plans.	CTI, PEMSEA, World Health Organization, MARPOL	Llewellyn (2010);, Sections 30.6.3, 11.7, 6.4.2.3
↑T	Increased precipitation as a result of intensified hydrological cycle in some coastal areas (*medium confidence*)	Increased freshwater, sediment, and nutrient flow into coastal areas; increase in number and severity of flood events (*medium to high confidence*)	Increasing damage to coastal reef systems with ecological regime shifts in many cases (*very likely*)	Improve management of catchment and coastal processes; expand riparian vegetation along creeks and rivers; improve agricultural retention of soils and nutrients.	CTI, PEMSEA, Secretariat of the Pacific Regional Environment Programme	Sections 3.4, 29.3.1, 30.5.4, 30.6.1
↑T	Changing weather patterns, storm frequency (*medium confidence*)	Increased risk of damage to infrastructure such as that involved in shipping and oil and gas exploration and extraction (*medium to low confidence*)	Increased damage and associated costs (*likely*)	Adjust infrastructure specifications, develop early-warning systems, and update emergency response plans to extreme events.	IMO	IPCC (2012); Sections 10.4.4, 29.3, 30.6.2.3–4
↑SLR, ↑SS	Increased wave exposure of coastal areas and increased sea level (*high confidence*)	Exposure of coastal infrastructure and communities to damage and inundation, increased coastal erosion (*high confidence*)	Increased costs to human towns and settlements, numbers of displaced people, and human migration (*very likely*)	Develop integrated coastal management that considers SLR in planning and decision making; increase understanding of the issues through education.	UNICEF, IHOs, and national governments	Warner (2012); Sections 5.5, 12.4.1, 29.5.1, 30.3.1.2, 30.6.5
		Inundation of coastal aquifers reduces water supplies and decreases coastal agricultural productivity (*high confidence*).	Reduced food and water security leads to increased coastal poverty, reduced food security, and migration (*very likely*).	Assist communities in finding alternatives for food and water, or assist in relocation of populations and agriculture from vulnerable areas.	UNICEF, IHOs, and national governments.	Warner (2012); Sections 5.4.3, 12.4.1, 29.3.2, 30.3.1.2
↑SLR	Risk of inundation and coastal erosion, especially in low-lying countries (*high confidence*)	UNCLOS-defined limits of maritime jurisdiction will contract as national baselines shift inland. Potential uncertainty increases in some areas with respect to the international boundaries to maritime jurisdiction (*high confidence*).	Lack of clarity increases, as do disputes over maritime limits and maritime jurisdiction. Some nations at risk of major losses to their territorial waters (*very likely*)	Seek resolution of "shifting national baselines" issue (retreat and redefinition, stabilization, or fixation of exclusive economic zones and other currently defined maritime jurisdiction limits).	UNCLOS	IPCC (2012); Schofield and Arsana (2012); Warner and Schofield (2012); Sections 5.5, 30.6.5
↑T, ↓IC	Loss of summer sea ice (*high confidence*)	Access to northern coasts of Canada, USA, and Russia increases security concerns (*high confidence*).	Potential for increased tension on different interpretations of access rights and boundaries (*likely to very likely*)	Seek early resolution of areas in dispute currently and in the future.	UNCLOS	Chapter 28
		New resources become available as ice retreats, increasing vulnerability of international borders in some cases (*medium confidence*).	Tensions over maritime claims and ownership of resources (*likely*)	Sort out international agreements.		

Convention. UNCLOS replaced earlier frameworks that were built around the "freedom of the seas" concept and that limited territorial rights to 3 nm off a coastline. UNCLOS provides a comprehensive framework for the legitimate use of the Ocean and its resources, including maritime zones, navigational rights, protection and preservation of the marine environment, fishing activities, marine scientific research, and mineral resource extraction from the seabed beyond national jurisdiction. The relationship between climate change and UNCLOS is not clear and depends on interpretation of key elements within the UNFCCC (United Nations Framework Convention for Climate Change) and Kyoto Protocol (Boyle, 2012). However, UNCLOS provides mechanisms to help structural adaptation in response to challenges posed by climate change. In a similar way, there is a wide range of other policy and legal frameworks that structure and enable responses to the outcomes of rapid anthropogenic climate change in the Ocean.

There are many existing international conventions and agreements that explicitly recognize climate change (Table 30-4). The UN Straddling Fish Stocks Agreement (UNSFSA) aims at enhancing international cooperation of fisheries resources, with an explicit understanding under Article 6 that management needs to take account "existing and predicted oceanic, environmental and socio-economic conditions" and to undertake "relevant research, including surveys of abundance, biomass surveys, hydro-acoustic surveys, research on environmental factors affecting stock abundance, and oceanographic and ecological studies" (UNSFSA, Annex 1, Article 3). International conventions such as these will become increasingly important as changes to the distribution and abundance of fisheries are modified by climate change and ocean acidification.

Global frameworks for decision making are increasingly important in the case of the Ocean, most of which falls outside national boundaries (Oude Elferink, 2012; Warner, 2012). Approximately 64% of the Ocean (40% of the Earth's surface) is outside EEZs and continental shelves of the world's nations (high seas and seabed beyond national jurisdiction). With rapidly increasing levels of exploitation, there are increasing calls for more effective decision frameworks aimed at regulating fishing and other activities (e.g., bio-prospecting) within these ocean "commons." These international frameworks will become increasingly valuable as nations respond to impacts on fisheries resources that stretch across national boundaries. One such example is the multilateral cooperation that was driven by President Yudhoyono of Indonesia in August 2007 and led to the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI), which involves region-wide (involving 6.8 million km^2 including 132,800 km of coastline) cooperation between the governments of Indonesia, Philippines, Malaysia, Papua New Guinea, the Solomon Islands, and Timor Leste on reversing the decline in coastal ecosystems such as coral reefs (Clifton, 2009; Hoegh-Guldberg et al., 2009; Veron et al., 2009). Partnerships, such as CTI, have the potential to provide key frameworks to address issues such as interaction between the over-exploitation of coastal fishing resources and the recovery of reefs from mass coral bleaching and mortality, and the implications of the movement of valuable fishery stocks beyond waters under national jurisdiction.

An initiative called the Global Partnership for Oceans set out to establish a global framework with which to share experience, resources, and expertise, as well as to engage governments, industry, civil, and public sector interests in both understanding and finding solutions to key issues such as overfishing, pollution, and habitat destruction (Hoegh-Guldberg et al., 2013). Similarly, the Areas Beyond National Jurisdiction (ABNJ, Global Environment Facility) Initiative has been established to promote the efficient, collaborative, and sustainable management of fisheries resources and biodiversity conservation across the Ocean.

Global partnerships are also essential for providing support to the many nations that often do not have the scientific or financial resources to solve the challenges that lie ahead (Busby, 2009; Mertz et al., 2009). In this regard, international networks and partnerships are particularly significant in terms of assisting nations in developing local adaptation solutions to their ocean resources. By sharing common experiences and strategies through global networks, nations have the chance to tap into a vast array of options with respect to responding to the negative consequences of climate change and ocean acidification on the world's ocean and coastal resources.

30.7.3. Emerging Issues, Data Gaps, and Research Needs

Although there has been an increase in the number of studies being undertaken to understand the physical, chemical, and biological changes within the Ocean in response to climate change and ocean acidification, the number of marine studies of ecological impacts and risks still lag behind terrestrial studies (Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013). Rectifying this gap should be a major international objective given the importance of the Ocean in terms of understanding and responding to future changes and consequences of ocean warming and acidification.

30.7.3.1. Changing Variability and Marine Impacts

Understanding the long-term variability of the Ocean is critically important in terms of the detection and attribution of changes to climate change (Sections 30.3, 30.5.8), but also in terms of the interaction between variability and anthropogenic climate change. Developing instrument systems that expand the spatial and temporal coverage of the Ocean and key processes will be critical to documenting and understanding its behavior under further increases in average global temperature and changes in the atmospheric concentration of CO_2. International collaborations such as the Argo network of oceanographic floats illustrate how international cooperation can rapidly improve our understanding of the physical behavior of the Ocean and will provide important insight into its long-term subsurface variability (Schofield et al., 2013).

30.7.3.2. Surface Wind, Storms, and Upwelling

Improving our understanding of the potential behavior of surface wind in a warming world is centrally important to our understanding of how upwelling will change in key regions (e.g., EUS, EBUE; Box CC-UP). Understanding these changes will provide important information for future fisheries management but will also illuminate the potential risks of intensified upwelling leading to hypoxia at depth and the potential expansion of "dead zones" (Sections 30.3.2, 30.5.2-4). Understanding surface wind in a warming climate will also yield important information on surface mixing as well as how surface wave height might also vary, improving our understanding of potential interactions in coastal areas between wind, waves, and SLR (Section 30.3.1). Given the importance of mixing and upwelling to the supply of inorganic nutrients to the surface layers of the ocean, understanding these important phenomena at the ocean-atmosphere interface will provide important insight into how ocean warming and acidification are likely to impact ecosystems, food webs, and ultimately important fisheries such as those found along the west coasts of Africa and the Americas.

30.7.3.3. Declining Oxygen Concentrations

The declining level of O_2 in the Ocean is an emerging issue of major importance (Section 30.3.2). Developing a better understanding of the role and temperature sensitivity of microbial systems in determining O_2 concentrations will enable a more coherent understanding of the changes and potential risks to marine ecosystems. Given the importance of microbial systems to the physical, chemical, and biological characteristics of the Ocean, it is extremely important that these systems receive greater focus, especially with regard to their response to ocean warming and acidification. This is particularly important for the DS (>1000 m), which is the most extensive habitat on the planet. In this respect, increasing our understanding of DS habitats and how they may be changing under the influence of climate change and ocean acidification is of great importance. Linkages between changes occurring in the surface layers and those associated with the DS are particularly important in light of our need to understand how rapidly changes are occurring and what the implications are for the metabolic activity and O_2 content of DS habitats.

30.7.3.4. Ocean Acidification

The rapid and largely unprecedented changes to ocean acidification represent an emerging issue given the central importance of pH and the concentration of ions such as carbonate in the biology of marine organisms (Box CC-OA). Despite the relatively short history of research on this issue, there are already a large number of laboratory and field studies that demonstrate a large range of effects across organisms, processes, and ecosystems. Key gaps (Gattuso et al., 2011) remain in our understanding of how ocean acidification will interact with other changes in the Ocean, and whether or not biological responses to ocean acidification are necessarily linear. The vulnerability of fishery species (e.g., molluscs) to ocean acidification represents an emerging issue, with a need for research to understand and develop strategies for fishery and aquaculture industries to minimize the impacts. Understanding of how carbonate structures such as coral reefs and *Halimeda* beds will respond to a rapidly acidifying ocean represents a key gap and research need, especially in understanding the rate at which consolidated carbonate structures and related habitats are likely to erode and dissolve. Interactions between ocean acidification, upwelling, and decreasing O_2 represent additional areas of concern and research. There is also a need to improve our understanding of the socioeconomic ramifications of ocean acidification (Turley and Boot, 2011; Hilmi et al., 2013).

30.7.3.5. Net Primary Productivity

Oceanic phytoplankton are responsible for approximately 50% of global net primary productivity. However, our understanding of how oceanic primary production is likely to change in a warmer and more acidified ocean is uncertain (Boxes CC-PP, CC-UP). Changes in net primary productivity will resonate through food webs and ultimately affect fisheries production. Given the central role that primary producers and their associated ecological processes play in ocean ecosystem functioning, the understanding of how net primary productivity is likely to vary at global and regional levels is improved (Sections 30.5.2, 30.5.5). At the same time, understanding how plankton communities will vary spatially and temporarily will be important in any attempt to understand how fish populations will fare in a warmer and more acidified ocean. The research challenge is to determine when and where net primary production is expected to change, coupled with research on adaptation strategies for coping with the changes to the global distribution of seafood procurement, management, and food security.

30.7.3.6. Movement of Marine Organisms and Ecosystems

Marine organisms are moving generally toward higher latitudes or deeper waters consistent with the expectation of a warming ocean. Our current understanding of which organisms and ecosystems are moving, ramifications for reorganization of ecosystems and communities, and the implications for nations is uncertain at best. Given the implications for fisheries, invasive species, and the spread of disease, it is imperative that our understanding of the movement of ecosystems is improved. Documentation of species' responses and a deeper understanding of the processes that lead to persistent range shifts, and a focus on the ecosystem, social, and economic implications of range shifts is an important research need.

30.7.3.7. Understanding Cumulative and Synergistic Impacts

Understanding cumulative and synergistic impacts is poorly developed for ocean systems. Much of our understanding has been built on experimental approaches that are focused on single stressors that respond gradually without interaction or impacts that accumulate over time (Table 30-3). Multifactorial experiments exploring the impact of combined variables (e.g., elevated temperature and acidification at the same time) will enable more realistic projections of the future to be established. Equally, developing a better understanding of how biological and ecological responses change in relation to key environmental variables should also be a goal of future research. In this regard, assumptions that responses are likely to be gradual and linear over time ultimately have little basis, yet are widespread within the scientific literature.

30.7.3.8. Reorganization of Ecosystems and Food Webs

The pervasive influence of ocean warming and acidification on the distribution, abundance, and function of organisms and processes has and will continue to drive the reorganization of ecosystems and food webs (*virtually certain*; Hoegh-Guldberg and Bruno, 2010; Poloczanska et al., 2013; Box CC-MB). One of the inevitable outcomes of differing tolerances and responses to climate change and ocean acidification is the development of novel assemblages of organisms in the near future. Such communities are likely to have no past or contemporary counterparts, and will consequently require new strategies for managing coastal areas and fisheries. Changes to a wide array of factors related or not related to climate change have the potential to drive extremely complex changes in community structure and, consequently, food web dynamics. Developing a greater capability for detecting and understanding these changes will be critical for future management of ocean and coastal resources.

30.7.3.9. Socio-ecological Resilience

Many communities depend on marine ecosystems for food and income yet our understanding of the consequences of environmental degradation is poor. For example, although there is *high confidence* that coral reefs will continue to deteriorate at current rates of climate change and ocean acidification (Gardner et al., 2003; Bruno and Selig, 2007; De'ath et al., 2012), there is relatively poor understanding of the implications for the hundreds of millions of people who depend on these important coastal ecosystems for food and livelihoods. Improving our understanding of how to reinforce socio-ecological resilience in communities affected by the deterioration of key coastal and oceanic ecosystems is central to developing effective adaptation responses to these growing challenges (Section 30.6, Tables 30-3, 30-4).

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