26 North America

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Executive Summary

Overview

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

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

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

Sector-Specific Climate Risks and Adaptation Opportunities

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

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

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

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

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

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

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

Adaptation Responses

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

26.1. Introduction

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

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

Findings from the Fourth Assessment Report

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

Observed Impacts and Processes Associated with Vulnerability

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

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

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

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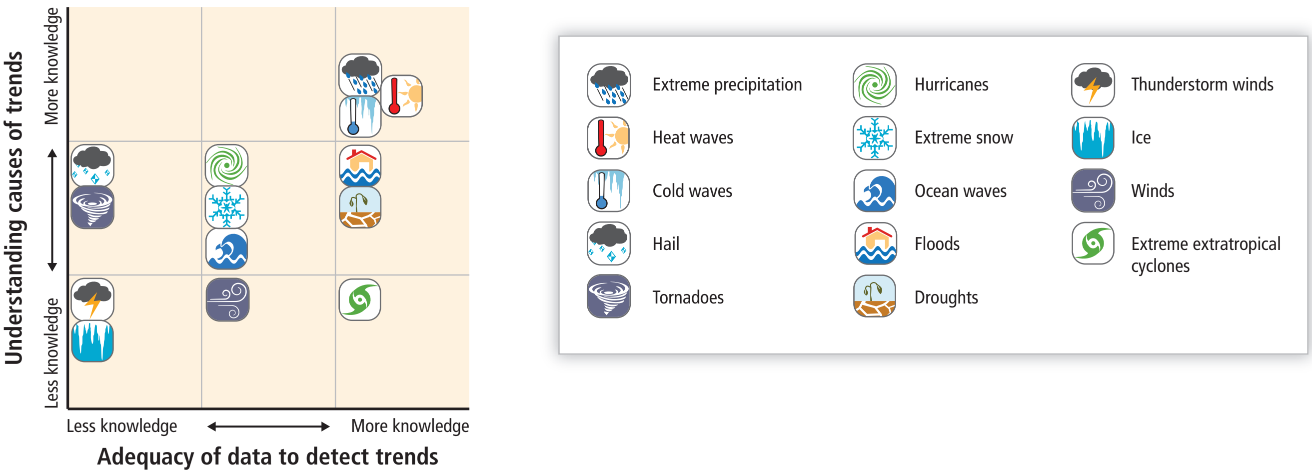
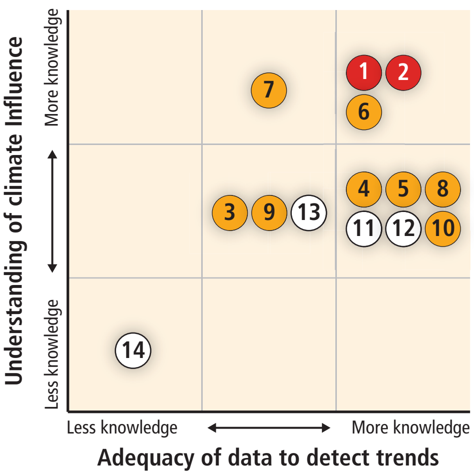
capacity and of institutional support and shows that these factors, which greatly enhance adaptive potential, are currently lacking in some regions (Section 26.5.3).

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

(a) Degree of understanding of causes of changes in climatic extreme events in the USA



(b) Degree of understanding of the climate influence in key impacts in North America



Trend detected and attributed

1. Earlier peak flow of snowmelt runoff in snow-dominated streams and rivers in western North America (Section 26.3.1)
2. Declines in the amount of water stored in spring snowpack in snow-dominated areas of western North America (Section 26.3.1)

Trend detected but not attributed

3. Northward and upward shifts in species' distributions in multiple taxa of terrestrial species, although not all taxa and regions (Section 26.4.1),
4. Increases in coastal flooding (Section 26.8.1)
5. Increases in wildfire activity, including fire season length and area burned by wildfires in the western USA and boreal Canada (Box 26-2)
6. Storm-related disaster losses in the USA (most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk; Sections 26.7.6.1, 26.8.1)
7. Increases in bark beetle infestation levels in pine tree species in western North America (Section 26.4.2.1)
8. Yield increases due in part to increasing temperatures in Canada and higher precipitation in the USA; yield variances attributed to climate variability in Ontario and Quebec; yield losses attributed to climate-related extremes across North America (Section 26.5.1)
9. Increases in tree mortality rates in old-growth forests in the western USA and western Canada from 1960 to 2007 (Section 26.4.2.1)
10. Changes in flooding in some urban areas due to extreme rainfall (Sections 26.3.1, 26.8.2.1)

Trend not detected

11. Changes in storm-related mortality in the USA (Section 26.6.1.2)
12. Changes in heat-related mortality in the USA (Section 26.6.1.2)
13. Increase in water supply shortages due to drought (Sections 26.3, 26.8.1)
14. Changes in cold-related mortality (Section 26.6.1.2)

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

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

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

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

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

26.2.1. Demographic and Socioeconomic Trends

26.2.1.1. Current Trends

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

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

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

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

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

Continued next page →

Box 26-1 (continued)

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

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

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

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

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

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

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

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

26.2.1.2. Future Trends

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

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

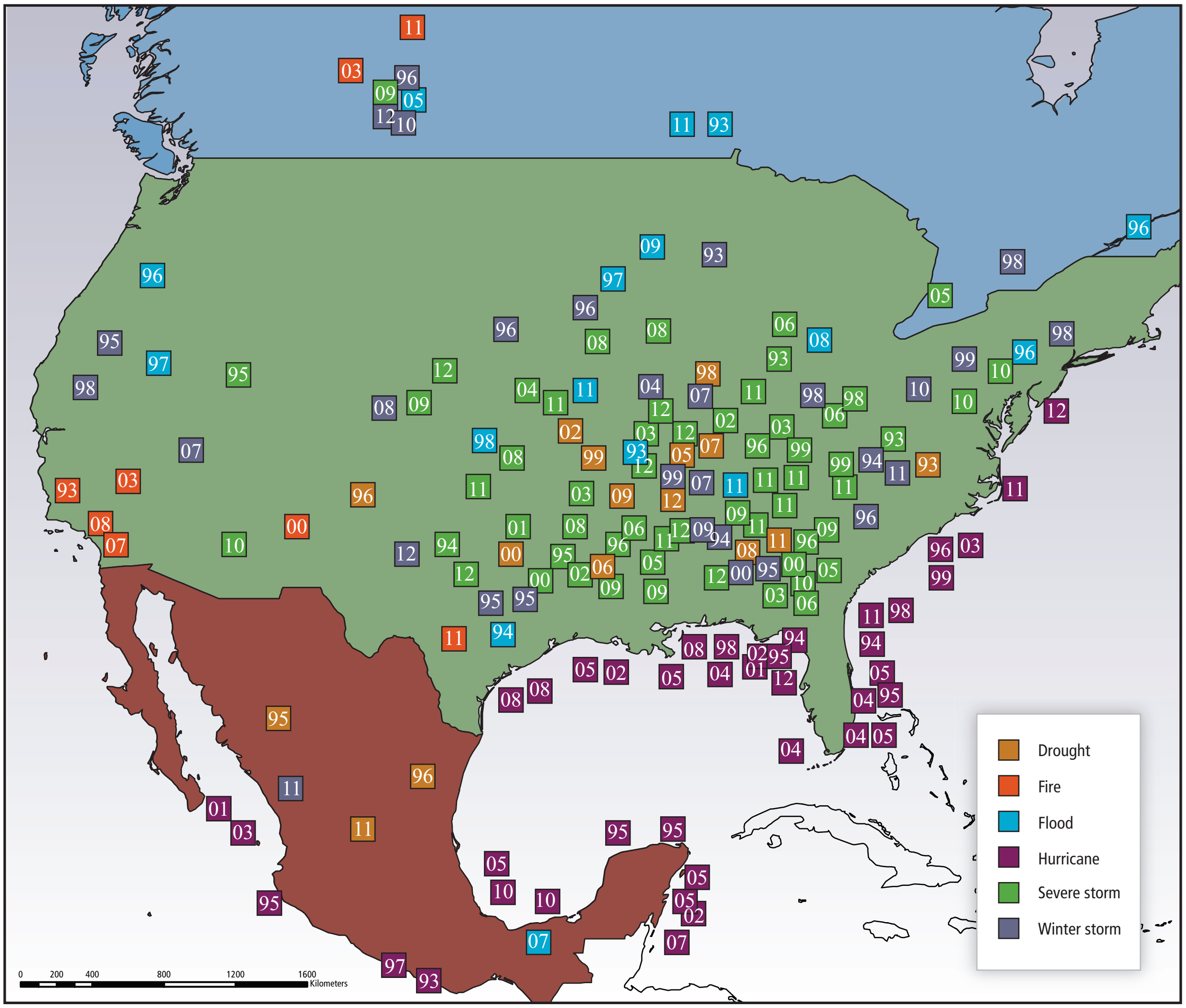
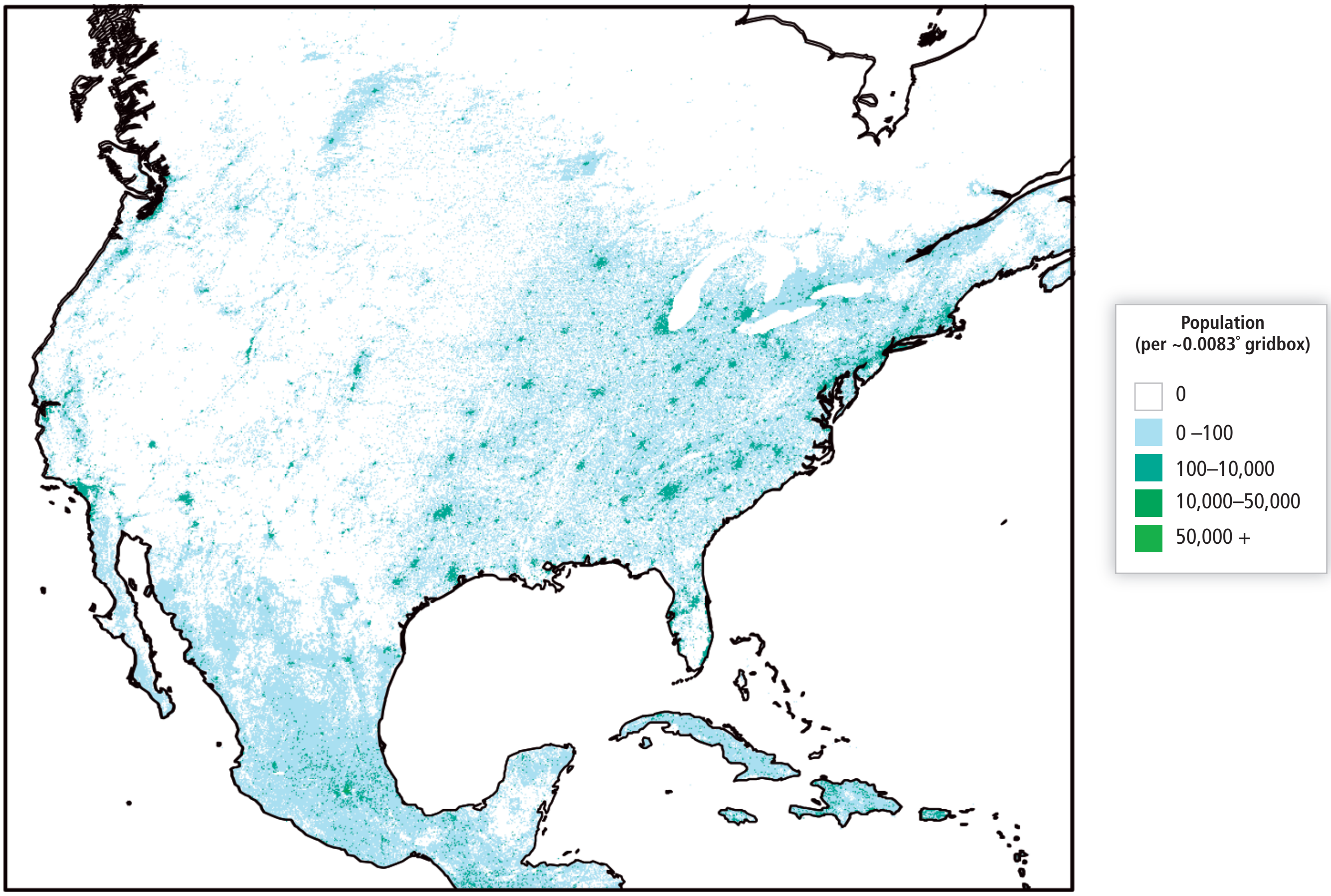


Figure 26-2 | Extreme events illustrating vulnerabilities for Mexico, the USA, and Canada. This figure offers a graphic illustration of location of extreme events and relevant vulnerability trends. The observed extreme events have not been attributed to anthropogenic climate change, yet they are climate-sensitive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

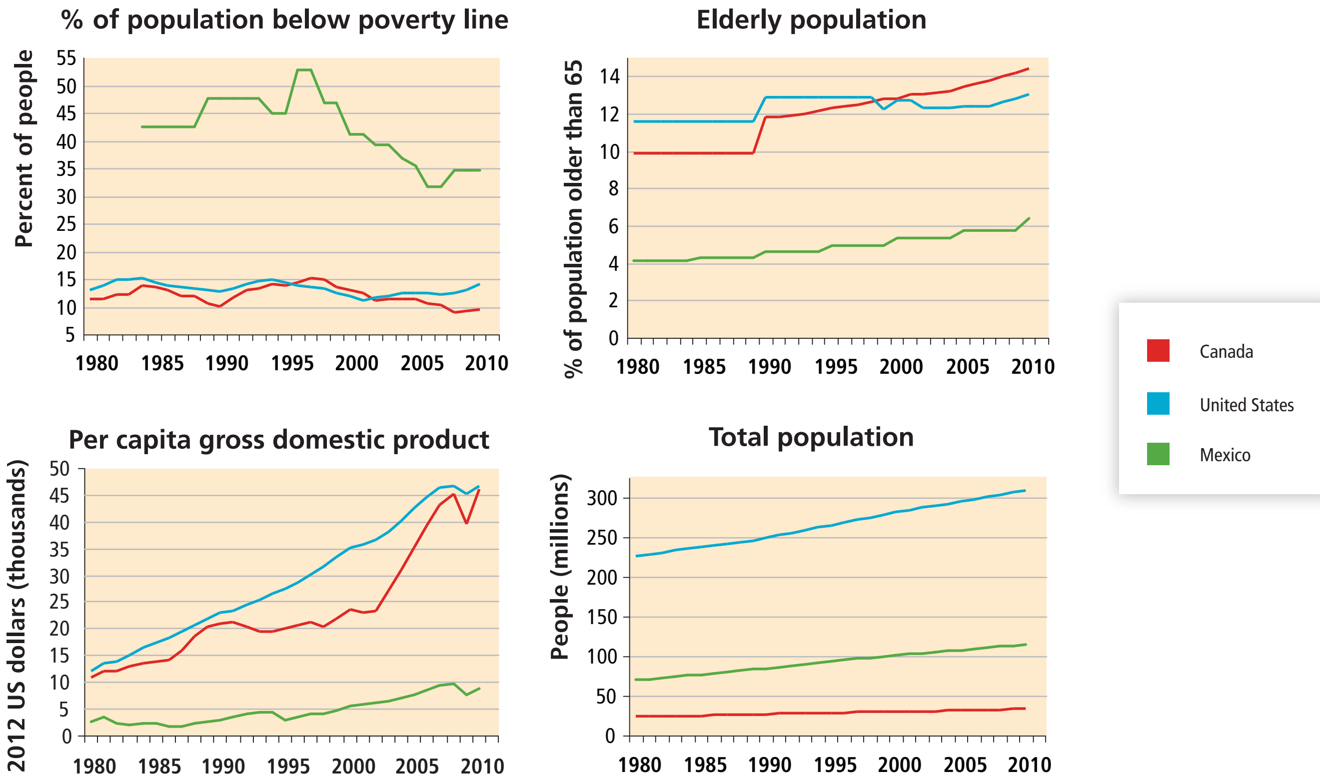
Continued next page →

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

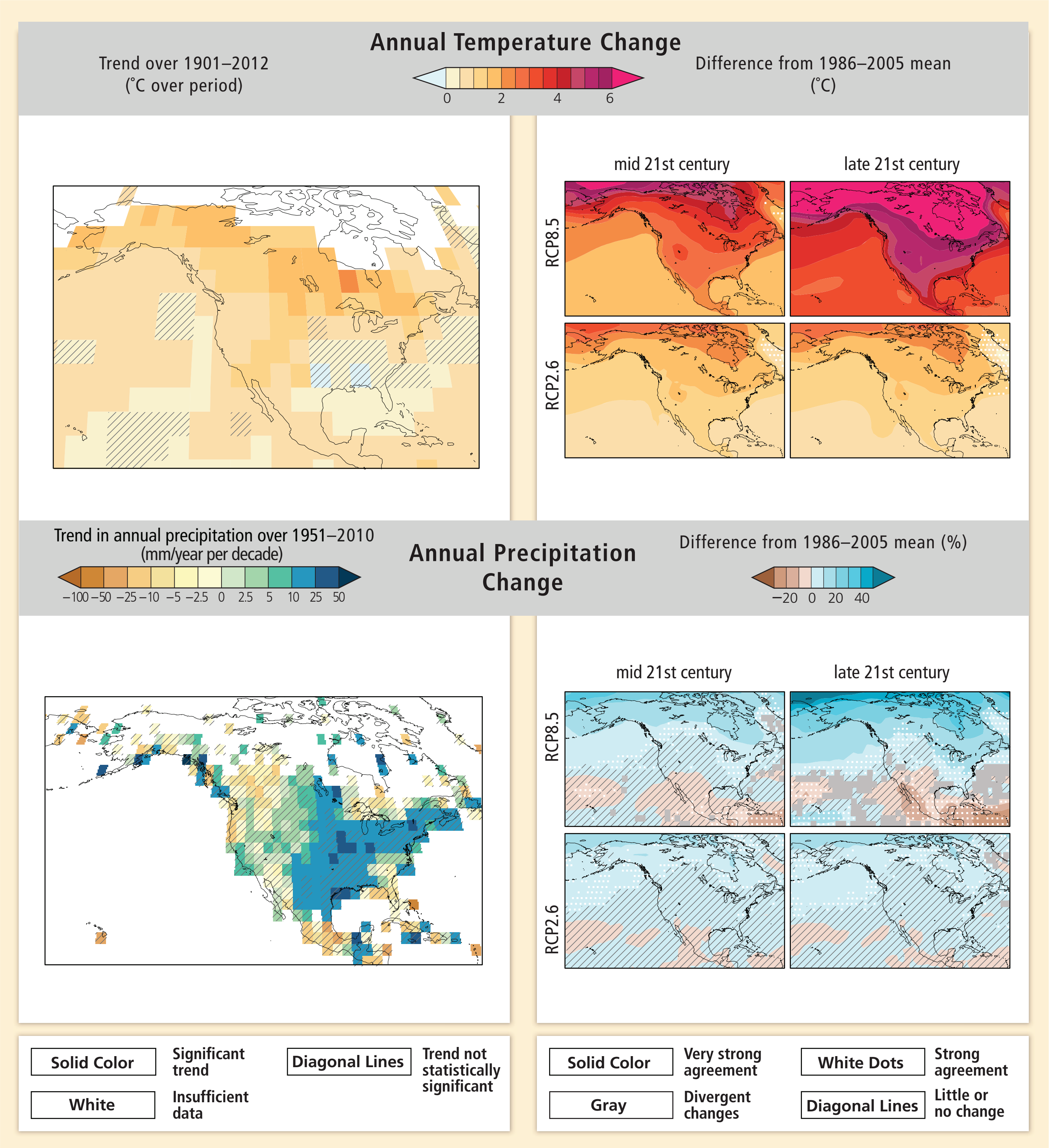


Figure 26-3 | Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Map of observed annual average temperature change from 1901–2012, derived from a linear trend. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Map of observed annual precipitation change 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

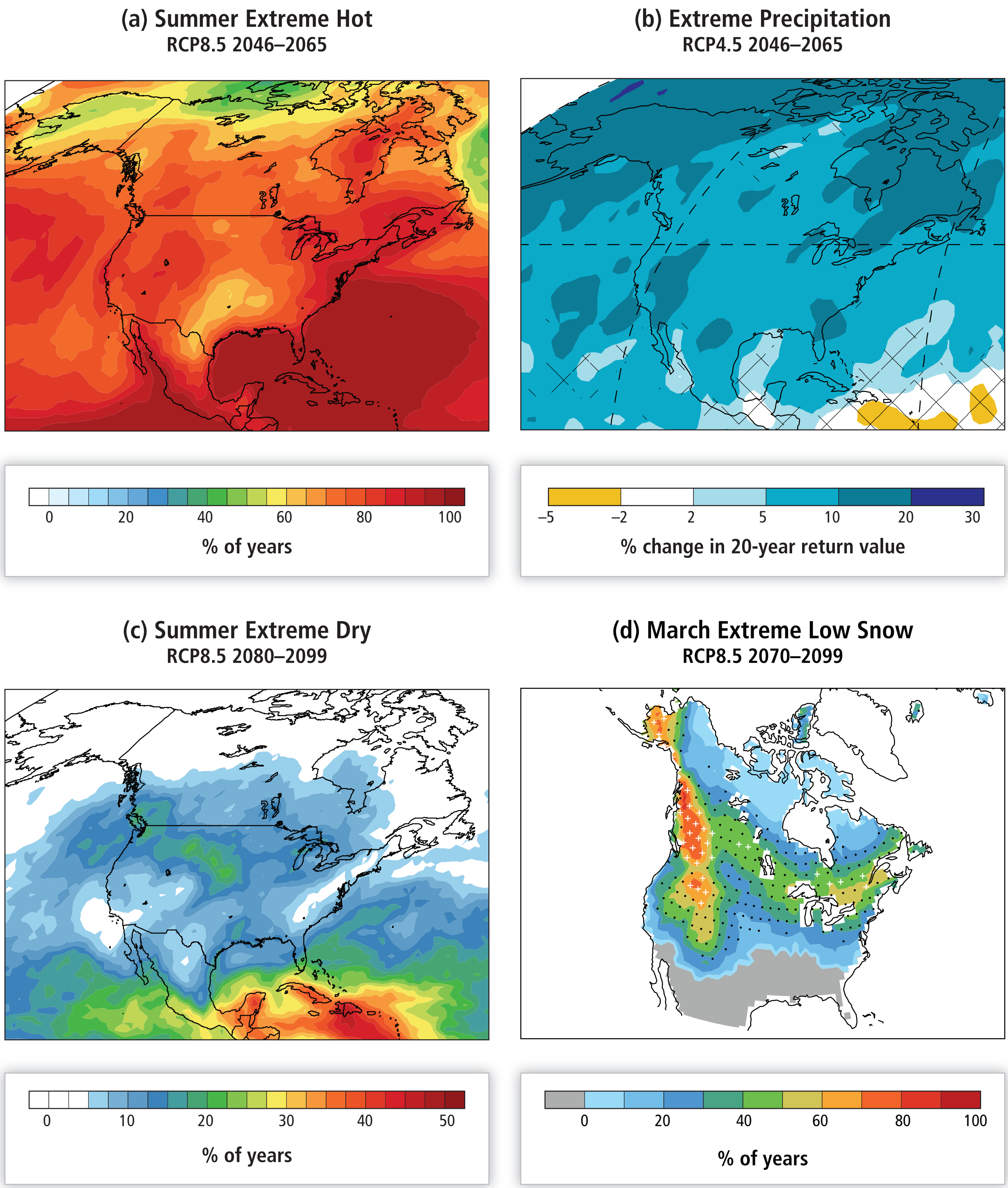


Figure 26-4 | Projected changes in extremes in North America. (a) The percentage of years in the 2046–2065 period of Representative Concentration Pathway 8.5 in which the summer temperature is greater than the respective maximum summer temperature of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 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).

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

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

26.3. Water Resources and Management

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

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

26.3.1. Observed Impacts of Climate Change on Water Resources

26.3.1.1. Droughts and Floods

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

26.3.1.2. Mean Annual Streamflow

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

26.3.1.3. Snowmelt

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

26.3.2. Projected Climate Change Impacts and Risks

26.3.2.1. Water Supply

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

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

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

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

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

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

26.3.2.2. Water Quality

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

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

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

26.3.2.3. Flooding

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

26.3.2.4 Instream Uses

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

26.3.3. Adaptation

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

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

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

26.4. Ecosystems and Biodiversity

26.4.1. Overview

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

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

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

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

26.4.2. Tree Mortality and Forest Infestation

26.4.2.1. Observed Impacts

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

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

26.4.2.2. Projected Impacts and Risks

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

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

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

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

26.4.3. Coastal Ecosystems

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

26.4.3.1. Observed Climate Impacts and Vulnerabilities

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

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

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

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

26.4.3.2. Projected Impacts and Risks

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

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

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

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

26.4.4. Ecosystems Adaptation, and Mitigation

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

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

Box 26-2 | Wildfires

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

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Box 26-2 (continued)

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

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

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

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

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

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

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

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

26.5. Agriculture and Food Security

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

26

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).

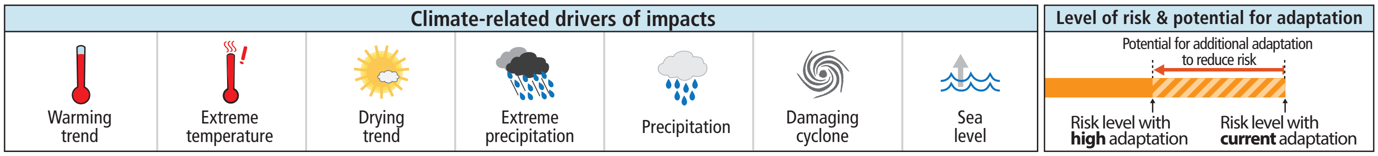
26.10. Key Risks, Uncertainties, Knowledge Gaps, and Research Needs

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	Very low — Medium — Very high
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	Very low — Medium — Very high
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	Very low — Medium — Very high

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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