14

North America

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This chapter should be cited as:

Field, C.B., L.D. Mortsch,, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running and M.J. Scott, 2007: North America. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 617-652.

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Executive summary

North America has experienced locally severe economic damage, plus substantial ecosystem, social and cultural disruption from recent weather-related extremes, including hurricanes, other severe storms, floods, droughts, heatwaves and wildfires (very high confidence).

Over the past several decades, economic damage from severe weather has increased dramatically, due largely to increased value of the infrastructure at risk. Annual costs to North America have now reached tens of billions of dollars in damaged property and economic productivity, as well as lives disrupted and lost. [14.2.3, 14.2.6, 14.2.7, 14.2.8]

The vulnerability of North America depends on the effectiveness and timing of adaptation and the distribution of coping capacity, which vary spatially and among sectors (very high confidence).

Although North America has considerable adaptive capacity, actual practices have not always protected people and property from adverse impacts of climate variability and extreme weather events. Especially vulnerable groups include indigenous peoples and those who are socially or economically disadvantaged. Traditions and institutions in North America have encouraged a decentralised response framework where adaptation tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems. 'Mainstreaming' climate change issues into decision making is a key prerequisite for sustainability. [14.2.6, 14.4, 14.5, 14.7]

Coastal communities and habitats will be increasingly stressed by climate change impacts interacting with development and pollution (very high confidence).

Sea level is rising along much of the coast, and the rate of change will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding and shoreline erosion. Storm impacts are likely to be more severe, especially along the Gulf and Atlantic coasts. Salt marshes, other coastal habitats, and dependent species are threatened by sea-level rise, fixed structures blocking landward migration, and changes in vegetation. Population growth and the rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change. Current adaptation is uneven and readiness for increased exposure is low. [14.2.3, 14.4.3, 14.5]

Climate change will constrain North America's over-allocated water resources, increasing competition among agricultural, municipal, industrial and ecological uses (very high confidence).

Rising temperatures will diminish snowpack and increase evaporation, affecting seasonal availability of water. Higher demand from economic development, agriculture and population growth will further limit surface and groundwater availability. In the Great Lakes and major river systems, lower levels are likely to exacerbate challenges relating to water quality, navigation, recreation, hydropower generation, water transfers and bi-national relationships. [14.2.1, 14.4.1, 14.4.6, Boxes 14.2 and 14.3]

Climate change impacts on infrastructure and human health and safety in urban centres will be compounded by ageing infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth and an ageing population (very high confidence).

While inertia in the political, economic, and cultural systems complicates near-term action, the long life and high value of North American capital stock make proactive adaptation important for avoiding costly retrofits in coming decades. [14.4.5, 14.4.6, 14.5, Box 14.3]

Without increased investments in countermeasures, hot temperatures and extreme weather are likely to cause increased adverse health impacts from heat-related mortality, pollution, storm-related fatalities and injuries, and infectious diseases (very high confidence).

Historically important countermeasures include early warning and surveillance systems, air conditioning, access to health care, public education, vector control, infrastructure standards and air quality management. Cities that currently experience heatwaves are expected to experience an increase in intensity and duration of these events by the end of the century, with potential for adverse health effects. The growing number of the elderly is most at risk. Water-borne diseases and degraded water quality are very likely to increase with more heavy precipitation. Warming and climate extremes are likely to increase respiratory illness, including exposure to pollen and ozone. Climate change is likely to increase risk and geographic spread of vector-borne infectious diseases, including Lyme disease and West Nile virus. [14.2.5, 14.2.6, 14.4.5, 14.4.6, 14.5]

Disturbances such as wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (very high confidence).

Although recent climate trends have increased vegetation growth, continuing increases in disturbances are likely to limit carbon storage, facilitate invasive species, and disrupt ecosystem services. Warmer summer temperatures are expected to extend the annual window of high fire ignition risk by 10-30%, and could result in increased area burned of 74-118% in Canada by 2100. Over the 21st century, pressure for species to shift north and to higher elevations will fundamentally rearrange North American ecosystems. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections will alter ecosystem structure, function and services. [14.2.4, 14.2.2, 14.4.2, Box 14.1]

14.1 Introduction

The United States (U.S.) and Canada will experience climate changes through direct effects of local changes (e.g., temperature, precipitation and extreme weather events), as well as through indirect effects, transmitted among regions by interconnected economies and migrations of humans and other species. Variations in wealth and geography, however, lead to an uneven distribution of likely impacts, vulnerabilities and capacities to adapt. This chapter reviews and synthesises the state of knowledge on direct and indirect impacts, vulnerability and adaptations for North America (comprising Canada and the U.S). Hawaii and other U.S. protectorates are discussed in Chapter 16 on Small Islands, and Mexico and Central America are treated in Chapter 13 on Latin America. Chapter 15, Polar Regions, covers high-latitude issues and peoples.

14.1.1 Key findings from the Third Assessment Report (TAR)

Key findings for the North America chapter of the Third Assessment Report (TAR) (Cohen et al., 2001) are:

Resources and ecosystems

- In western snowmelt-dominated watersheds, shifts in seasonal runoff, with more runoff in winter. Adaptation may not fully offset effects of reduced summer water availability.
- Changes in the abundance and spatial distribution of species important to commercial and recreational fisheries.
- Benefits from warming for food production in North America but with strong regional differences.
- Benefits from farm- and market-level adjustments in ameliorating impacts of climate change on agriculture.
- Increases in the area and productivity of forests, though carbon stocks could increase or decrease.
- Major role of disturbance for forest ecosystems. The forest-fire season is likely to lengthen, and the area subject to high fire danger is likely to increase significantly.
- Likely losses of cold-water ecosystems, high alpine areas, and coastal and inland wetlands.

Human settlements and health

- Less extreme winter cold in northern cities. Across North America, cities will experience more extreme heat and, in some locations, rising sea levels and risk of storm surge, water scarcity, and changes in timing, frequency, and severity of flooding.
- The need for changes in land-use planning and infrastructure design to avoid increased damages from heavy precipitation events.
- For communities that have the necessary resources, reduced vulnerability by adapting infrastructure.
- Increased deaths, injuries, infectious diseases, and stress-related disorders and other adverse effects associated with social disruption and migration from more frequent extreme weather.
- Increased frequency and severity of heatwaves leading to more illness and death, particularly among the young, elderly and frail. Respiratory disorders may be exacerbated by warming-induced deterioration in air quality.
- Expanded ranges of vector-borne and tick-borne diseases in North America but with modulation by public health measures and other factors.

Vulnerability and adaptation

- Increased weather-related losses in North America since the 1970s, with rising insured losses reflecting growing affluence and movement into vulnerable areas.
- Coverage, since the 1980s, by disaster relief and insurance programmes of a large fraction of flood and crop losses, possibly encouraging more human activity in at-risk areas.
- Responses by insurers to recent extreme events through limiting insurance availability, increasing prices and establishing new risk-spreading mechanisms. Improving building codes, land-use planning and disaster preparedness also reduce disaster losses.
- Awareness that developing adaptation responses requires a long, interdisciplinary dialogue between researchers and stakeholders, with substantial changes in institutions and infrastructure.
- Recognition that adaptation strategies generally address current challenges, rather than future impacts and opportunities.

14.1.2 Key differences from TAR

This assessment builds on the findings from the TAR and incorporates new results from the literature, including:

- Prospects for increased precipitation variability, increasing challenges of water management.
- The need to include groundwater and water-quality impacts in the assessment of water resources.
- The potential that multi-factor impacts may interact non-linearly, leading to tipping points.
- The potential importance of interactions among climate change impacts and with other kinds of local, regional and global changes.
- The potential for adaptation, but the unevenness of current adaptations.
- The challenge of linking adaptation strategies with future vulnerabilities.
- Availability of much more literature on all aspects of impacts, adaptation and vulnerability in North America.

14.2 Current sensitivity/vulnerability

Annual mean air temperature, on the whole, increased in North America for the period 1955 to 2005, with the greatest warming in Alaska and north-western Canada, substantial warming in the continental interior and modest warming in the south-eastern U.S. and eastern Canada (Figure 14.1). Spring and winter show the greatest changes in temperature (Karl et al., 1996; Hengeveld et al., 2005) and daily minimum (night-time) temperatures have warmed more than daily maximum (daytime) temperatures (Karl et al., 2005; Vincent and Mekis, 2006). The length of the vegetation growing season has increased an average of 2 days/decade since 1950 in Canada and the conterminous U.S., with most of the increase resulting from earlier spring warming (Bonsal et al., 2001; Easterling, 2002; Bonsal and Prowse, 2003; Feng and Hu, 2004). The warming signal in North America during the latter half of the 20th century reflects the combined influence of greenhouse gases, sulphate aerosols and natural external forcing (Karoly et al., 2003; Stott, 2003; Zwiers and Zhang, 2003).

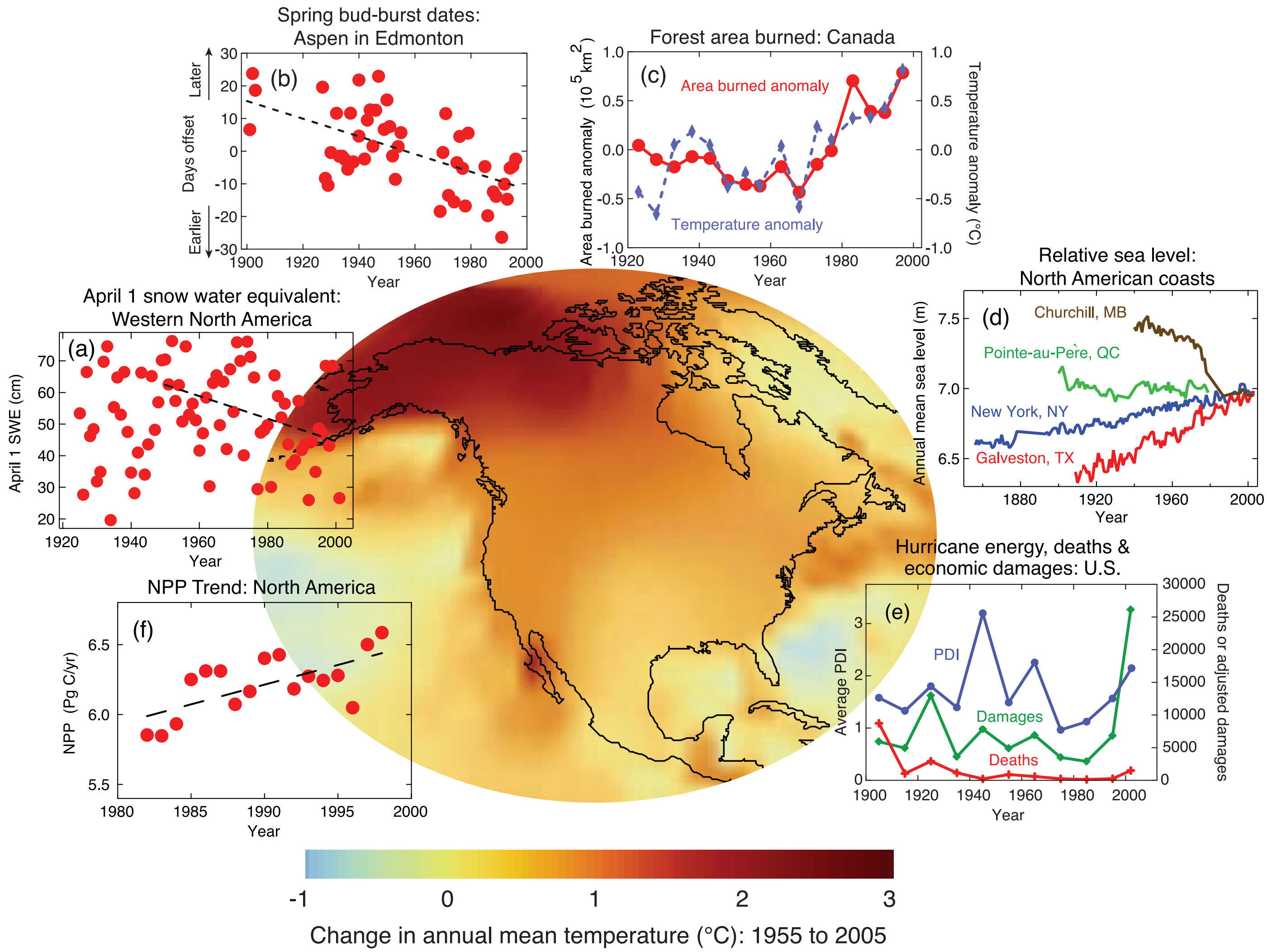

Figure 14.1. *Observed trends in some biophysical and socio-economic indicators. Background: change in annual mean temperature from 1955 to 2005 (based on the GISS2001 analysis for land from Hansen et al., 2001; and on the Hadley/Reyn_V2 analysis for sea surface from Reynolds et al., 2002). Insets: (a) trend in April 1 snow water equivalent (SWE) across western North America from 1925 to 2002, with a linear fit from 1950 to 2002 (data from Mote, 2003), (b) Spring bud-burst dates for trembling aspen in Edmonton since 1900 (data from Beaubien and Freeland, 2000), (c) anomaly in 5-year mean area burned annually in wildfires in Canada since 1930, plus observed mean summer air temperature anomaly, weighted for fire areas, relative to 1920 to 1999 (data from Gillett et al., 2004) (d) relative sea-level rise from 1850 to 2000 for Churchill, MB, Pointe-au-Père, QB, New York, NY, and Galveston, TX, (POL, 2006) (e) hurricane energy (power dissipation index (PDI) based on method of Emanuel, 2005), economic damages, million U.S. dollars (adjusted to constant 2005 US dollars and normalized accounting for changes in personal wealth and coastal population to 2004), and deaths from Atlantic hurricanes since 1900 (data from Pielke Jr. and Landsea, 1998 updated through 2005), and, (f) trend North American Net Primary Production (NPP) from 1981 to 1998 (data from Hicke et al., 2002).*

Annual precipitation has increased for most of North America with large increases in northern Canada, but with decreases in the south-west U.S., the Canadian Prairies and the eastern Arctic (see Working Group I Fourth Assessment (WGI AR4) Trenberth et al., 2007 Section 3.3.2.2, Figures 3.13 and 3.14) (Hengeveld et al., 2005; Shein, 2006). Heavy precipitation frequencies in the U.S. were at a minimum in the 1920s and 1930s, and increased to the 1990s (1895 to 2000) (Kunkel, 2003; Groisman et al., 2004). In Canada there is no consistent trend in extreme precipitation (Vincent and Mekis, 2006).

14.2.1 Freshwater resources

Streamflow in the eastern U.S. has increased 25% in the last 60 years (Groisman et al., 2004), but over the last century has decreased by about 2%/decade in the central Rocky Mountain region (Rood et al., 2005). Since 1950, stream discharge in both the Colorado and Columbia river basins has decreased, at the same time annual evapotranspiration (ET) from the conterminous U.S. increased by 55 mm (Walter et al., 2004). In regions with winter snow, warming has shifted the magnitude and timing of hydrologic events (Mote et al., 2005; Regonda et al., 2005; Stewart et al., 2005). The fraction of annual precipitation falling as rain (rather than snow) increased at 74% of the weather stations studied in the western mountains of the U.S. from 1949 to 2004 (Knowles et al., 2006). In Canada, warming from 1900 to 2003 led to a decrease in total precipitation as snowfall in the west and Prairies (Vincent and Mekis, 2006). Spring and summer snow cover has decreased in the U.S. west (Groisman et al., 2004). April 1 snow water equivalent (SWE) has declined 15 to 30% since 1950 in the western mountains of North America, particularly at lower elevations and primarily due to warming rather than changes in precipitation (Figure 14.1a) (see Mote et al., 2003; Mote et al., 2005; Lemke et al., 2007: Section 4.2.2.2.1). Whitfield and Cannon (2000) and Zhang et al. (2001) reported earlier spring runoff across Canada. Summer (May to August) flows of the Athabasca River have declined 20% since 1958 (Schindler and Donahue, 2006). Streamflow peaks in the snowmelt-dominated western mountains of the U.S. occurred 1 to 4 weeks earlier in 2002 than in 1948 (Stewart et al., 2005). Break up of river and lake ice across North America has advanced by 0.2 to 12.9 days over the last 100 years (Magnuson et al., 2000).

Vulnerability to extended drought is increasing across North America as population growth and economic development create more demands from agricultural, municipal and industrial uses, resulting in frequent over-allocation of water resources (Alberta Environment, 2002; Morehouse et al., 2002; Postel and Richter, 2003; Pulwarty et al., 2005). Although drought has been more frequent and intense in the western part of the U.S. and Canada, the east is not immune from droughts and attendant reductions in water supply, changes in water quality and ecosystem function, and challenges in allocation (Dupigny-Giroux, 2001; Bonsal et al., 2004; Wheaton et al., 2005).

14.2.2 Ecosystems

Three clear, observable connections between climate and terrestrial ecosystems are the seasonal timing of life-cycle events or phenology, responses of plant growth or primary production, and biogeographic distribution. Direct impacts on organisms interact with indirect effects of ecological mechanisms (competition, herbivory[1], disease), and disturbance (wildfire, hurricanes, human activities).

Phenology, productivity and biogeography

Global daily satellite data, available since 1981, indicate earlier onset of spring 'greenness' by 10-14 days over 19 years, particularly across temperate latitudes of the Northern Hemisphere (Myneni et al., 2001; Lucht et al., 2002). Field studies confirm these satellite observations. Many species are expanding leaves or flowering earlier (e.g., earlier flowering in lilac - 1.8 days/decade, 1959 to 1993, 800 sites across North America (Schwartz and Reiter, 2000), honeysuckle - 3.8 days/decade, western U.S. (Cayan et al., 2001), and leaf expansion in apple and grape - 2 days/decade, 72 sites in north-eastern U.S. (Wolfe et al., 2005), trembling aspen - 2.6 days/decade since 1900, Edmonton (Beaubien and Freeland, 2000)) (Figure 14.1b). The timing of autumn leaf fall, which is controlled by a combination of temperature, photoperiod and water deficits, shows weaker trends (Badeck et al., 2004).

Net primary production (NPP) in the continental U.S. increased nearly 10% from 1982 to 1998 (Figure 14.1f) (Boisvenue and Running, 2006), with the largest increases in croplands and grasslands of the Central Plains due to improved water balance (Lobell et al., 2002; Nemani et al., 2002; Hicke and Lobell, 2004).

North American forests can be influenced indirectly by climate through effects on disturbance, especially from wildfire, storms, insects and diseases. The area burned in wildfires has increased dramatically over the last three decades (see Box 14.1).

Wildlife population and community dynamics

North American animals are responding to climate change, with effects on phenology, migration, reproduction, dormancy and geographic range (Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003; Parmesan and Galbraith, 2004; Root et al., 2005). Warmer springs have led to earlier nesting for 28 migrating bird species on the east coast of the U.S. (Butler, 2003) and to earlier egg laying for Mexican jays (Brown et al., 1999) and tree swallows (Dunn and Winkler, 1999). In northern Canada, red squirrels are breeding 18 days earlier than 10 years ago (Reale et al., 2003). Several frog species now initiate breeding calls 10 to 13 days earlier than a century ago (Gibbs and Breisch, 2001). In lowland California, 70% of 23 butterfly species advanced the date of first spring flights by an average 24 days over 31 years (Forister and Shapiro, 2003). Reduced water depth, related to recent warming, in Oregon lakes has increased exposure of toad eggs to UV-B, leading to increased mortality from a fungal parasite (Kiesecker et al., 2001; Pounds, 2001).

Many North American species have shifted their ranges, typically to the north or to higher elevations (Parmesan and Yohe, 2003). Edith's checkerspot butterfly has become locally extinct in the southern, low-elevation portion of its western North American range but has extended its range 90 km north and 120 m higher in elevation (Parmesan, 1996; Crozier, 2003; Parmesan and Galbraith, 2004). Red foxes have expanded northward in northern Canada, leading to retreat of competitively subordinate arctic foxes (Hersteinsson and Macdonald, 1992).

14.2.3 Coastal regions

The North American coast is long and diverse with a wide range of trends in relative sea level (Figure 14.1d) (Shaw et al., 1998; Dyke and Peltier, 2000; Zervas, 2001). Relative sea level (see glossary) is rising in many areas, yet coastal residents are often unaware of the trends and their impacts on coastal retreat and flooding (O'Reilly et al., 2005). In the Great Lakes, both extremely high and extremely low water levels have been damaging and disruptive (Moulton and Cuthbert, 2000). Demand for waterfront property and building land continues to grow, increasing the value of property at risk (Heinz Center, 2000; Forbes et al., 2002b; Small and Nichols, 2003).

[1] The consumption of plants by animals.

Box 14.1. Accelerating wildfire and ecosystem disturbance dynamics

Since 1980, an average of 22,000 km^2/yr has burned in U.S. wildfires, almost twice the 1920 to 1980 average of 13,000 km^2/yr (Schoennagel et al., 2004). The forested area burned in the western U.S. from 1987 to 2003 is 6.7 times the area burned from 1970 to 1986 (Westerling et al., 2006). In Canada, burned area has exceeded 60,000 km^2/yr three times since 1990, twice the long-term average (Stocks et al., 2002). Wildfire-burned area in the North American boreal region increased from 6,500 km^2/yr in the 1960s to 29,700 km^2/yr in the 1990s (Kasischke and Turetsky, 2006). Human vulnerability to wildfires has also increased, with a rising population in the wildland-urban interface.

A warming climate encourages wildfires through a longer summer period that dries fuels, promoting easier ignition and faster spread (Running, 2006). Westerling et al. (2006) found that in the last three decades the wildfire season in the western U.S. has increased by 78 days, and burn durations of fires >1000 ha in area have increased from 7.5 to 37.1 days, in response to a spring-summer warming of 0.87°C. Earlier spring snowmelt has led to longer growing seasons and drought, especially at higher elevations, where the increase in wildfire activity has been greatest (Westerling et al., 2006). In Canada, warmer May to August temperatures of 0.8°C since 1970 are highly correlated with area burned (Figure 14.1c) (Gillett et al., 2004). In the south-western U.S., fire activity is correlated with El Niño-Southern Oscillation (ENSO) positive phases (Kitzberger et al., 2001; McKenzie et al., 2004), and higher Palmer Drought Severity Indices.

Insects and diseases are a natural part of ecosystems. In forests, periodic insect epidemics kill trees over large regions, providing dead, desiccated fuels for large wildfires. These epidemics are related to aspects of insect life cycles that are climate sensitive (Williams and Liebhold, 2002). Many northern insects have a two-year life cycle, and warmer winter temperatures allow a larger fraction of overwintering larvae to survive. Recently, spruce budworm in Alaska has completed its life cycle in one year, rather than the previous two (Volney and Fleming, 2000). Mountain pine beetle has expanded its range in British Columbia into areas previously too cold (Carroll et al., 2003). Insect outbreaks often have complex causes. Susceptibility of the trees to insects is increased when multi-year droughts degrade the trees' ability to generate defensive chemicals (Logan et al., 2003). Recent dieback of aspen stands in Alberta was caused by light snowpacks and drought in the 1980s, triggering defoliation by tent caterpillars, followed by wood-boring insects and fungal pathogens (Hogg et al., 2002).

Many coastal areas in North America are potentially exposed to storm-surge flooding (Titus and Richman, 2001; Titus, 2005). Some major urban centres on large deltas are below sea level (e.g., New Orleans on the Mississippi; Richmond and Delta on the Fraser), placing large populations at risk. Breaching of New Orleans floodwalls following Hurricane Katrina in 2005 (see Chapter 6, Section 6.4.1.2 and Box 6.4) and storm-wave breaching of a dike in Delta, British Columbia, in 2006 demonstrate the vulnerability. Under El Niño conditions, high water levels combined with changes in winter storms along the Pacific coast have produced severe coastal flooding and storm impacts (Komar et al., 2000; Walker and Barrie, 2006). At San Francisco, 140 years of tide-gauge data suggest an increase in severe winter storms since 1950 (Bromirski et al., 2003) and some studies have detected accelerated coastal erosion (Bernatchez and Dubois, 2004). Some Alaskan villages are threatened and require protection or relocation at projected costs up to US$54 million (Parson et al., 2001a). Recent severe tropical and extra-tropical storms demonstrate that North American urban centres with assumed high adaptive capacity remain vulnerable to extreme events. Recent winters with less ice in the Great Lakes and Gulf of St. Lawrence have increased coastal exposure to damage from winter storms. Winter ice provides seasonal shore protection, but can also damage shorefront homes and infrastructure (Forbes et al., 2002a).

Impacts on coastal communities and ecosystems can be more severe when major storms occur in short succession, limiting the opportunity to rebuild natural resilience (Forbes et al., 2004). Adaptation to coastal hazards under the present climate is often inadequate, and readiness for increased exposure is poor (Clark et al., 1998; Leatherman, 2001; West et al., 2001). Extreme events can add to other stresses on ecological integrity (Scavia et al., 2002; Burkett et al., 2005), including shoreline development and nitrogen eutrophication[2] (Bertness et al., 2002). Already, more than 50% of the original salt marsh habitat in the U.S. has been lost (Kennish, 2001). Impacts from sea-level rise can be amplified by 'coastal squeeze' (see Glossary) and submergence where landward migration is impeded and vertical growth is slower than sea-level rise (see Section 14.4.3) (Kennish, 2001; Scavia et al., 2002; Chmura and Hung, 2004).

14.2.4 Agriculture, forestry and fisheries

Agriculture

Over the last century, yields of major commodity crops in the U.S. have increased consistently, typically at rates of 1 to 2%/yr (Troyer, 2004), but there are significant variations across regions and between years. These yield trends are a result of cumulative changes in multiple factors, including technology, fertiliser use,

[2] Eutrophication is a process whereby water bodies, such as lakes, estuaries, or slow-moving streams receive excess nutrients that stimulate excessive plant growth (e.g., algal blooms and nuisance plants weeds).

seed stocks, and management techniques, plus any changes due to climate; the specific impact from any one factor may be positive or negative. In the Midwestern U.S. from 1970 to 2000, corn yield increased 58% and soybean yields increased 20%, with annual weather fluctuations resulting in year-to-year variability (Hicke and Lobell, 2004). Heavy rainfalls reduced the value of the U.S. corn crop by an average of US$3 billion/yr between 1951 and 1998 (Rosenzweig et al., 2002). In the Corn and Wheat Belt of the U.S., yields of corn and soybeans from 1982 to 1998 were negatively impacted by warm temperatures, decreasing 17% for each 1°C of warm-temperature anomaly (Lobell and Asner, 2003). In California, warmer nights have enhanced the production of high-quality wine grapes (Nemani et al., 2001), but additional warming may not result in similar increases. For twelve major crops in California, climate fluctuations over the last 20 years have not had large effects on yield, though they have been a positive factor for oranges and walnuts and a negative for avocados and cotton (Lobell et al., 2006).

North American agriculture has been exposed to many severe weather events during the past decade. More variable weather, coupled with out-migration from rural areas and economic stresses, has increased the vulnerability of the agricultural sector overall, raising concerns about its future capacity to cope with a more variable climate (Senate of Canada, 2003; Wheaton et al., 2005). North American agriculture is, however, dynamic. Adaptation to multiple stresses and opportunities, including changes in markets and weather, is a normal process for the sector. Crop and enterprise diversification, as well as soil and water conservation, are often used to reduce weather-related risks (Wall and Smit, 2005). Recent adaptations by the agricultural sector in North America, including improved water conservation and conservation tillage, are not typically undertaken as single discrete actions, but evolve as a set of decisions that can span several years in a dynamic and changing environment (Smit and Skinner, 2002) that includes changes in public policy (Goodwin, 2003). While there have been attempts to realistically model the dynamics of adaptation to climate change (Easterling et al., 2003), understanding of agriculture's current sensitivity to climate variability and its capacity to cope with climate change remains limited (Tol, 2002).

Forestry

Forest growth appears to be slowly accelerating (at a rate of less than 1%/decade) in regions where tree growth has historically been limited by low temperatures and short growing seasons (Caspersen et al., 2000; McKenzie et al., 2001; Joos et al., 2002; Boisvenue and Running, 2006). In black spruce at the forest-tundra transition in eastern Canada, height growth has been increasing since the 1970s (Gamache and Payette, 2004). Growth is slowing, however, in areas subject to drought. Radial growth of white spruce on dry south-facing slopes in Alaska has decreased over the last 90 years, due to increased drought stress (Barber et al., 2000). In semi-arid forests of the south-western U.S., growth rates have decreased since 1895, correlated with drought linked to warming temperatures (McKenzie et al., 2001). Relationships between tree-ring growth in sub-alpine forests and climate in the Pacific Northwest from 1895 to 1991 had complex topographic influences (Peterson and Peterson, 2001; Peterson et al., 2002). On high elevation north-facing slopes, growth of sub-alpine fir and mountain hemlock was negatively correlated with spring snowpack depth and positively correlated with summer temperatures, indicating growing-season temperature limitations. On lower elevation sites, however, growth was negatively correlated with summer temperature, suggesting water limitations. In Colorado, aspen have advanced into the more cold-tolerant spruce-fir forests over the past 100 years (Elliott and Baker, 2004). The northern range limit of lodgepole pine is advancing into the zone previously dominated by the more cold-tolerant black spruce in the Yukon (Johnstone and Chapin, 2003). A combination of warmer temperatures and insect infestations has resulted in economically significant losses of the forest resource base to spruce bark beetle in both Alaska and the Yukon (ACIA, 2004).

Freshwater fisheries

Most commercial freshwater fishing in North America occurs in rural or remote areas, with indigenous peoples often taking a major role. Recreational inland fisheries are also significant and increasing (DFO-MPO, 2002; DOI, 2002). Ecological sustainability of fish and fisheries productivity is closely tied to temperature and water supply (flows and lake levels). Climate change and variability increasingly have direct and indirect impacts, both of which interact with other pressures on freshwater fisheries, including human development (Schindler, 2001; Chu et al., 2003; Reed and Czech, 2005; Rose, 2005), habitat loss and alteration (including water pollution), biotic homogenisation due to invasions and introductions (Rahel, 2002), and over-exploitation (Post et al., 2002; Cooke and Cowx, 2004). Cold- and cool-water fisheries, especially Salmonids, have been declining as warmer/drier conditions reduce their habitat. The sea-run[3] salmon stocks are in steep decline throughout much of North America (Gallagher and Wood, 2003). Evidence for impacts of recent climate change is rapidly accumulating. Pacific salmon have been appearing in Arctic rivers (Babaluk et al., 2000). Salmonid species have been affected by warming in U.S. streams (O'Neal, 2002). Lake charr in an Ontario lake suffered recruitment[4] failure due to El Niño-linked warm temperatures (Gunn, 2002). Lake Ontario year-class productivity is strongly linked to temperature, with a shift in the 1990s toward warm-water species (Casselman, 2002). Walleye yield in lakes depends on the amount of cool, turbid habitat (Lester et al., 2004). Recent contraction in habitat for walleye in the Bay of Quinte, Lake Ontario was due in part to warming and lower water levels (Chu et al., 2005). Success of adult spawning and survival of the fry (new-borne) of brook trout is closely linked to cold groundwater seeps, which provide preferred temperature refuges for lake-dwelling populations (Borwick et al., 2006). Rates of fish-egg development and mortality increase with temperature rise within species-specific tolerance ranges (Kamler, 2002).

[3] Sea-run: having the habit of ascending a river from the sea, especially to spawn.
[4] Recruitment: the number of new juvenile fish reaching a size large enough to be caught by commercial fishing methods.

14.2.5 Human health

Many human diseases are sensitive to weather, from cardiovascular and respiratory illnesses due to heatwaves or air pollution, to altered transmission of infectious diseases. Synergistic effects of other activities can exacerbate weather exposures (e.g., via the urban heat island effect), requiring cross-sector risk assessment to determine site-specific vulnerability (Patz et al., 2005).

The incidence of infectious diseases transmitted by air varies seasonally and annually, due partly to climate variations. In the early 1990s, California experienced an epidemic of Valley Fever that followed five years of drought (Kolivras and Comrie, 2003). Water-borne disease outbreaks from all causes in the U.S. are distinctly seasonal, clustered in key watersheds, and associated with heavy precipitation (in the U.S. Curriero et al., 2001) or extreme precipitation and warmer temperatures (in Canada, Thomas et al., 2006). Heavy runoff after severe rainfall can also contaminate recreational waters and increase the risk of human illness (Schuster et al., 2005) through higher bacterial counts. This association is strongest at beaches closest to rivers (Dwight et al., 2002).

Food-borne diseases show some relationship with historical temperature trends. In Alberta, ambient temperature is strongly but non-linearly associated with the occurrence of three enteric pathogens, *Salmonella, E. coli* and *Campylobacter* (Fleury et al., 2006).

Many zoonotic diseases[5] are sensitive to climate fluctuations (Charron, 2002). The strain of West Nile virus (WNV) that emerged for the first time in North America during the record hot July 1999 requires warmer temperatures than other strains. The greatest WNV transmissions during the epidemic summers of 2002 to 2004 in the U.S. were linked to above-average temperatures (Reisen et al., 2006). Laboratory studies of virus replication in WNV's main *Culex* mosquito vector show high levels of virus at warmer temperatures (Dohm and Turell, 2001; Dohm et al., 2002). Bird migratory pathways and WNV's recent advance westward across the U.S. and Canada are key factors in WNV and must be considered in future assessments of the role of temperature in WNV dynamics. A virus closely related to WNV, Saint Louis encephalitis, tends to appear during hot, dry La Niña years, when conditions facilitate transmission by reducing the extrinsic incubation period[6] (Cayan et al., 2003).

Lyme disease is a prevalent tick-borne disease in North America for which there is new evidence of an association with temperature (Ogden et al., 2004) and precipitation (McCabe and Bunnell, 2004). In the field, temperature and vapour pressure contribute to maintaining populations of the tick *Ixodes scapularis* which, in the U.S., is the micro-organism's secondary host. A monthly average minimum temperature above -7ºC is required for tick survival (Brownstein et al., 2003).

Exposure to both extreme hot and cold weather is associated with increased morbidity and mortality, compared to an intermediate 'comfortable' temperature range (Curriero et al., 2002). Across 12 U.S. cities, hot temperatures have been associated with increased hospital admissions for cardiovascular disease (Schwartz et al., 2004a). Emergency hospital admissions have been directly related to extreme heat in Toronto (Dolney and Sheridan, 2006). Heat-response plans and heat early warning systems (EWS) can save lives (Ebi et al., 2004). After the 1995 heatwave, the city of Milwaukee initiated an 'extreme heat conditions plan' that almost halved heat-related morbidity and mortality (Weisskopf et al., 2002). Currently, over two dozen cities worldwide have warning systems focused on monitoring for dangerous air masses (Sheridan and Kalkstein, 2004).

14.2.6 Human settlements

Economic base of resource-dependent communities

Among the most climate-sensitive North American communities are those of indigenous populations dependent on one or a few natural resources. About 1.2 million (60%) of the U.S. tribal members live on or near reservations, and many pursue lifestyles with a mix of traditional subsistence activities and wage labour (Houser et al., 2001). Many reservation economies and budgets of indigenous governments depend heavily on agriculture, forest products and tourism (NAST, 2001). A 1993 hantavirus outbreak related indirectly to heavy rainfall led to a significant reduction in tourist visits to the American South-west (NAST, 2001). Many indigenous communities in northern Canada and Alaska are already experiencing constraints on lifestyles and economic activity from less reliable sea and lake ice (for travelling, hunting, fishing and whaling), loss of forest resources from insect damage, stress on caribou, and more exposed coastal infrastructure from diminishing sea ice (NAST, 2001; CCME, 2003; ACIA, 2005). Many rural settlements in North America, particularly those dependent on a narrow resource base, such as fishing or forestry, have been seriously affected by recent declines in the resource base, caused by a number of factors (CDLI, 1996). However, not all communities have suffered, as some Alaskan fishing communities have benefited from rising regional abundance of selected salmon stocks since the mid-1970s (Eggers, 2006).

Infrastructure and extreme events

About 80% of North Americans live in urban areas (Census Bureau, 2000; Statistics Canada, 2001b). North American cities, while diverse in size, function, climate and other factors, are largely shielded from the natural environment by technical systems. The devastating effects of hurricanes Ivan in 2004 and Katrina, Rita and Wilma in 2005, however, illustrate the vulnerability of North American infrastructure and urban systems that were either not designed or not maintained to adequate safety margins. When protective systems fail, impacts can be widespread and multi-dimensional (see Chapter 7, Boxes 7.2 and 7.4). Disproportionate impacts of Hurricane Katrina on the poor, infirm, elderly, and other dependent populations were amplified by inadequate public sector development and/or

[5] Zoonotic diseases: diseases caused by infectious agents that can be transmitted between (or are shared by) animals and humans.

[6] Extrinsic incubation period: the interval between the acquisition of an infectious agent by a vector and the vector's ability to transmit the agent to other hosts.

execution of evacuation and emergency services plans (Select Bipartisan Committee, 2006).

Costs of weather-related natural disasters in North America rose at the end of the 20th century, mainly as a result of the increasing value of infrastructure at risk (Changnon, 2003, 2005). Key factors in the increase in exposure include rising wealth, demographic shifts to coastal areas, urbanisation in storm-prone areas, and ageing infrastructure, combined with substandard structures and inadequate building codes (Easterling et al., 2000; Balling and Cerveny, 2003; Changnon, 2003, 2005). Trends in the number and intensity of extreme events in North America are variable, with many (e.g., hail events, tornadoes, severe windstorms, winter storms) holding steady or even decreasing (Kunkel et al., 1999; McCabe et al., 2001; Balling and Cerveny, 2003; Changnon, 2003; Trenberth et al., 2007: Section 3.8.4.2).

North America very likely will continue to suffer serious losses of life and property simply due to growth in property values and numbers of people at risk (very high confidence) (Pielke Jr., 2005; Pielke et al., 2005). Of the US$19 trillion value of all insured residential and commercial property in the U.S. states exposed to North Atlantic hurricanes, US$7.2 trillion (41%) is located in coastal counties. This economic value includes 79% of the property in Florida, 63% of the property in New York, and 61% of the property in Connecticut (AIR, 2002). Cumulative decadal hurricane intensity in the U.S. has risen in the last 25 years, following a peak in the mid 20th century and a later decline (Figure 14.1e). North American mortality (deaths and death rates) from hurricanes, tornadoes, floods and lightning have generally declined since the beginning of the 20th century, due largely to improved warning systems (Goklany, 2006). Mortality was dominated by three storms where the warning/evacuation system did not lead to timely evacuation: Galveston in 1900, Okeechobee in 1926, and Katrina in 2005.

Flood hazards are not limited to the coastal zone. River basins with a history of major floods (e.g., the Sacramento (Miller, 2003), the Fraser (Lemmen and Warren, 2004), the Red River (Simonovic and Li, 2004) and the upper Mississippi (Allen et al., 2003)) illustrate the sensitivity of riverine flooding to extreme events and highlight the critical importance of infrastructure design standards, land-use planning and weather/flood forecasts.

14.2.7 Tourism and recreation

The U.S. and Canada rank among the top ten nations for international tourism receipts (US$112 billion and US$16 billion, respectively) with domestic tourism and outdoor recreation markets that are several times larger (World Tourism Organization, 2002; Southwick Associates, 2006). Climate variability affects many segments of this growing economic sector. For example, wildfires in Colorado (2002) and British Columbia (2003) caused tens of millions of dollars in tourism losses by reducing visitation and destroying infrastructure (Associated Press, 2002; Butler, 2002; BC Stats, 2003). Similar economic losses were caused by drought-affected water levels in rivers and reservoirs in the western U.S. and parts of the Great Lakes (Fisheries and Oceans Canada, 2000; Kesmodel, 2002; Allen, 2003). The ten-day closure and clean-up following Hurricane Georges (September 1998) resulted in tourism revenue losses of approximately US$32 million in the Florida Keys (EPA, 1999). While the North American tourism industry acknowledges the important influence of climate, its impacts have not been analysed comprehensively (Scott et al., 2006).

14.2.8 Energy, industry and transportation

North American industry, energy supply and transportation networks are sensitive to weather extremes that exceed their safety margins. Costs of these impacts can be high. For example, power outages in the U.S. cost the economy US$30 billion to 130 billion annually (EPRI, 2003; LaCommare and Eto, 2004). The hurricanes crossing Florida in the summer of 2004 resulted in direct system restoration costs of US$1.4 billion to the four Florida public utilities involved (EEI, 2005). From 1994 to 2004, fourteen U.S. utilities experienced 81 other major storms, which cost an average of US$49 million/storm, with the highest single storm impact of US$890 million (EEI, 2005).

Although it was not triggered specifically by the concurrent hot weather, the 2003 summer outage in north-eastern U.S. and south-eastern Canada illustrates costs to North American society that result from large-scale power interruptions during periods of high demand. Over 50 million people were without power, resulting in US$180 million in insured losses and up to US$10 billion in total losses (Fletcher, 2004). Business interruptions were particularly significant, with costs of over US$250,000/hr incurred by the top quartile of recently surveyed companies (RM, 2003).

The impacts of Hurricanes Katrina, Rita and Wilma in 2005 and Ivan in 2004 demonstrated that the Gulf of Mexico offshore oil and natural gas platforms and pipelines, petroleum refineries, and supporting infrastructure can be seriously harmed by major hurricanes, which can produce national-level impacts, and require recovery times stretching to months or longer (Business Week, 2005; EEA, 2005; EIA, 2005a; Levitan and Associates Inc., 2005; RMS, 2005b; Swiss Re, 2005b, c, d, e).

Hydropower production is known to be sensitive to total runoff, to its timing, and to reservoir levels. For example, during the 1990s, Great Lakes levels fell as a result of a lengthy drought, and in 1999 hydropower production was down significantly both at Niagara and Sault St. Marie (CCME, 2003).

14.3 Assumptions about future trends

14.3.1 Climate

Recent climate model simulations (Ruosteenoja et al., 2003) indicate that by the 2010 to 2039 time slice, year-round temperatures across North America will be outside the range of present-day natural variability, based on 1000 year Atmosphere-Ocean General Circulation Model (AOGCM) simulations with either the CGCM2 or HadCM3 climate models. For most combinations of model, scenario, season and region, warming in the 2010 to 2039 time slice will be in the range of 1 to 3ºC.

Late in the century, projected annual warming is likely to be 2 to 3°C across the western, southern, and eastern continental edges, but more than 5ºC at high latitudes (Christensen et al., 2007: Section 11.5.3.1). The projected warming is greatest in winter at high latitudes and greatest in the summer in the south-west U.S. Warm extremes across North America are projected to become both more frequent and longer (Christensen et al., 2007: Section 11.5.3.3).

Annual-mean precipitation is projected to decrease in the south-west of the U.S. but increase over the rest of the continent (Christensen et al., 2007: Section 11.5.3.2). Increases in precipitation in Canada are projected to be in the range of +20% for the annual mean and +30% for the winter. Some studies project widespread increases in extreme precipitation (Christensen et al., 2007: Section 11.5.3.3), with greater risks of not only flooding from intense precipitation, but also droughts from greater temporal variability in precipitation. In general, projected changes in precipitation extremes are larger than changes in mean precipitation (Meehl et al., 2007: Section 10.3.6.1)

Future trends in hurricane frequency and intensity remain very uncertain. Experiments with climate models with sufficient resolution to depict some aspects of individual hurricanes tend to project some increases in both peak wind speeds and precipitation intensities (Meehl et al., 2007: Section 10.3.6.3). The pattern is clearer for extra-tropical storms, which are likely to become more intense, but perhaps less frequent, leading to increased extreme wave heights in the mid-latitudes (Meehl et al., 2007: Section 10.3.6.4).

El Niño events are associated with increased precipitation and severe storms in some regions, such as the south-east U.S., and higher precipitation in the Great Basin of the western U.S., but warmer temperatures and decreased precipitation in other areas such as the Pacific Northwest, western Canada, and parts of Alaska (Ropelewski and Halpert, 1986; Shabbar et al., 1997). Recent analyses indicate no consistent future trends in El Niño amplitude or frequency (Meehl et al., 2007: Section 10.3.5.4).

14.3.2 Social, economic, and institutional context

Canada and the U.S. have developed economies with per capita gross domestic product (GDP) in 2005 of US$31,572 and US$37,371, respectively (UNECE, 2005a,b). Future population growth is likely to be dominated by immigration (Campbell, 1996). Interests of indigenous peoples are important in both Canada and the U.S., especially in relation to questions of land management. With ageing populations, the costs of health care are likely to climb over several decades (Burleton, 2002).

Major parts of the economies of Canada and the U.S. are directly sensitive to climate, including the massive agricultural (2005 value US$316 billion) (Economic Research Service, 2006; Statistics Canada, 2006), transportation (2004 value US$510 billion) (Bureau of Transportation Statistics, 2006; Industry Canada, 2006) and tourism sectors (see Section 14.2.4, 14.2.7 and 14.2.8). Although many activities have limited direct sensitivity to climate (Nordhaus, 2006), the potential realm of climate-sensitive activities expands with increasing evidence that storms, floods, or droughts increase in frequency or intensity with climate change (Christensen et al., 2007: Section 11.5.3.3 and Meehl et al., 2007: Sections 10.3.6.1 and 10.3.6.2).

The economies of Canada and the U.S. have large private and public sectors, with strong emphasis on free market mechanisms and the philosophy of private ownership. If strong trends toward globalisation in the last several decades continue through the 21st century, it is likely that the means of production, markets, and ownership will be predominantly international, with policies and governance increasingly designed for the international marketplace (Stiglitz, 2002).

14.4 Key future impacts and vulnerabilities

14.4.1 Freshwater resources

Freshwater resources will be affected by climate change across Canada and the U.S., but the nature of the vulnerabilities varies from region to region (NAST, 2001; Environment Canada, 2004; Lemmen and Warren, 2004). In certain regions including the Colorado River, Columbia River and Ogallala Aquifer, surface and/or groundwater resources are intensively used for often competing agricultural, municipal, industrial and ecological needs, increasing potential vulnerability to future changes in timing and availability of water (see Box 14.2).

Surface water

Simulated annual water yield in basins varies by region, General Circulation Model (GCM) or Regional Climate Model (RCM) scenario (Stonefelt et al., 2000; Fontaine et al., 2001; Stone et al., 2001; Rosenberg et al., 2003; Jha et al., 2004; Shushama et al., 2006), and the resolution of the climate model (Stone et al., 2003). Higher evaporation related to warming tends to offset the effects of more precipitation, while magnifying the effects of less precipitation (Stonefelt et al., 2000; Fontaine et al., 2001).

Warming, and changes in the form, timing and amount of precipitation, will very likely lead to earlier melting and significant reductions in snowpack in the western mountains by the middle of the 21st century (high confidence) (Loukas et al., 2002; Leung and Qian, 2003; Miller et al., 2003; Mote et al., 2003; Hayhoe et al., 2004). In projections for mountain snowmelt-dominated watersheds, snowmelt runoff advances, winter and early spring flows increase (raising flooding potential), and summer flows decrease substantially (Kim et al., 2002; Loukas et al., 2002; Snyder et al., 2002; Leung and Qian, 2003; Miller et al., 2003; Mote et al., 2003; Christensen et al., 2004; Merritt et al., 2005). Over-allocated water systems of the western U.S. and Canada, such as the Columbia River, that rely on capturing snowmelt runoff, will be especially vulnerable (see Box 14.2).

Lower water levels in the Great Lakes are likely to influence many sectors, with multi-dimensional, interacting impacts (Figure 14.2) (high confidence). Many, but not all, assessments project lower net basin supplies and water levels for the Great Lakes – St. Lawrence Basin (Mortsch et al., 2000; Quinn and Lofgren, 2000; Lofgren et al., 2002; Croley, 2003). In addition

Box 14.2. Climate change adds challenges to managing the Columbia River system

Current management of water in the Columbia River basin involves balancing complex, often competing, demands for hydropower, navigation, flood control, irrigation, municipal uses, and maintenance of several populations of threatened and endangered species (e.g., salmon). Current and projected needs for these uses over-commit existing supplies. Water management in the basin operates in a complex institutional setting, involving two sovereign nations (Columbia River Treaty, ratified in 1964), aboriginal populations with defined treaty rights ('Boldt decision' in U.S. *vs.* Washington in 1974), and numerous federal, state, provincial and local government agencies (Miles et al., 2000; Hamlet, 2003). Pollution (mainly non-point source) is an important issue in many tributaries. The first-in-time first-in-right provisions of western water law in the U.S. portion of the basin complicate management and reduce water available to junior water users (Gray, 1999; Scott et al., 2004). Complexities extend to different jurisdictional responsibilities when flows are high and when they are low, or when protected species are in tributaries, the main stem or ocean (Miles et al., 2000; Mote et al., 2003).

With climate change, projected annual Columbia River flow changes relatively little, but seasonal flows shift markedly toward larger winter and spring flows and smaller summer and autumn flows (Hamlet and Lettenmaier, 1999; Mote et al., 1999). These changes in flows will likely coincide with increased water demand, principally from regional growth but also induced by climate change. Loss of water availability in summer would exacerbate conflicts, already apparent in low-flow years, over water (Miles et al. 2000). Climate change is also projected to impact urban water supplies within the basin. For example, a 2°C warming projected for the 2040s would increase demand for water in Portland, Oregon by 5.7 million m^3/yr with an additional demand of 20.8 million m^3/yr due to population growth, while decreasing supply by 4.9 million m^3/yr (Mote et al., 2003). Long-lead climate forecasts are increasingly considered in the management of the river but in a limited way (Hamlet et al., 2002; Lettenmaier and Hamlet, 2003; Gamble et al., 2004; Payne et al., 2004). Each of 43 sub-basins of the system has its own sub-basin management plan for fish and wildlife, none of which comprehensively addresses reduced summertime flows under climate change (ISRP/ISAB, 2004).

The challenges of managing water in the Columbia River basin will likely expand with climate change due to changes in snowpack and seasonal flows (Miles et al., 2000; Parson et al., 2001b; Cohen et al., 2003). The ability of managers to meet operating goals (reliability) will likely drop substantially under climate change (as projected by the HadCM2 and ECHAM4/OPYC3 AOGCMs under the IPCC IS92a emissions scenario for the 2020s and 2090s) (Hamlet and Lettenmaier, 1999). Reliability losses are projected to reach 25% by the end of the 21st century (Mote et al., 1999) and interact with operational rule requirements. For example, 'fish-first' rules would reduce firm power reliability by 10% under present climate and 17% in years during the warm phase of the Pacific Decadal Oscillation. Adaptive measures have the potential to moderate the impact of the decrease in April snowpack, but lead to 10 to 20% losses of firm hydropower and lower than current summer flows for fish (Payne et al., 2004). Integration of climate change adaptation into regional planning processes is in the early stages of development (Cohen et al., 2006).

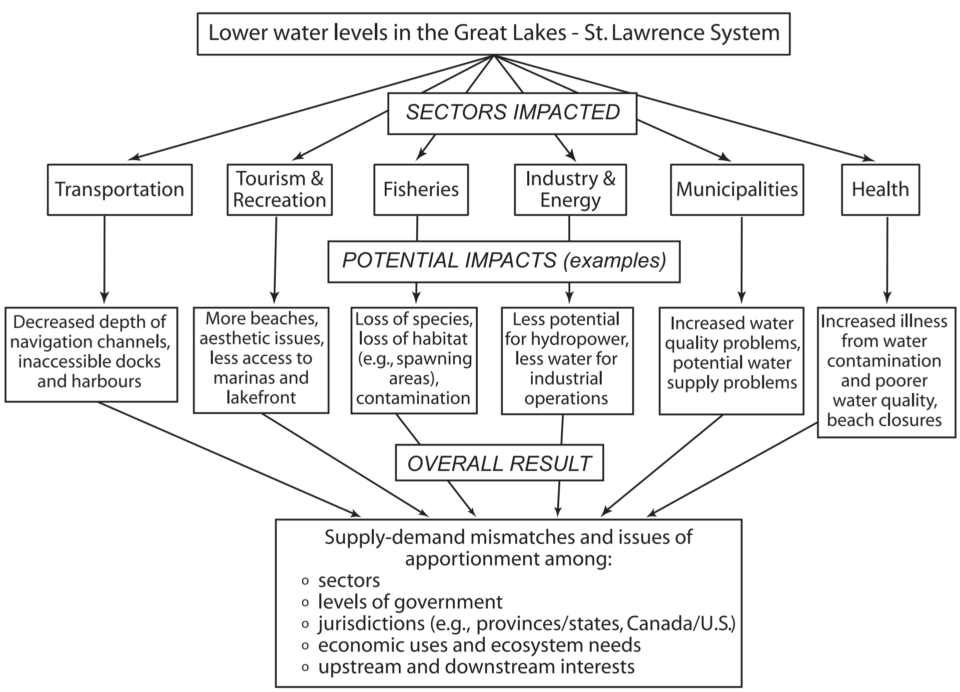

Figure 14.2. *Interconnected impacts of lower water levels in the Great Lakes - St Lawrence system (modified from Lemmen and Warren, 2004).*

to differences due to climate scenarios, uncertainties include atmosphere-lake interactions (Wetherald and Manabe, 2002; Kutzbach et al., 2005). Adapting infrastructure and dredging to cope with altered water levels would entail a range of costs (Changnon, 1993; Schwartz et al., 2004b). Adaptations sufficient to maintain commercial navigation on the St. Lawrence River could range from minimal adjustments to costly, extensive structural changes (St. Lawrence River-Lake Ontario Plan of Study Team, 1999; D'Arcy et al., 2005). There have been controversies in the Great Lakes region over diversions of water, particularly at Chicago, to address water quality, navigation, water demand and drought mitigation outside the region. Climate change will exacerbate these issues and create new challenges for bi-national co-operation (very high confidence) (Changnon and Glantz, 1996; Koshida et al., 2005).

Groundwater

With climate change, availability of groundwater is likely to be influenced by withdrawals (reflecting development, demand and availability of other sources) and recharge (determined by temperature, timing and amount of precipitation, and surface water interactions) (medium confidence) (Rivera et al., 2004). Simulated annual groundwater base flows and aquifer levels respond to temperature, precipitation and pumping – decreasing in scenarios that are drier or have higher pumping and increasing in a wetter scenario. In some cases there are base flow shifts - increasing in winter and decreasing in spring and early summer (Kirshen, 2002; Croley and Luukkonen, 2003; Piggott et al., 2003). For aquifers in alluvial valleys of south-central British Columbia, temperature and precipitation scenarios have less impact on groundwater recharge and levels than do projected changes in river stage[7] (Allen et al., 2004a,b).

Heavily utilised groundwater-based systems in the southwest U.S. are likely to experience additional stress from climate change that leads to decreased recharge (high confidence). Simulations of the Edwards aquifer in Texas under average recharge project lower or ceased flows from springs, water shortages, and considerable negative environmental impacts (Loáiciga, 2000; Loáiciga et al., 2000). Regional welfare losses associated with projected flow reductions (10 to 24%) range from US$2.2 million to 6.8 million/yr, with decreased net agricultural income as a consequence of water allocation shifting to municipal and industrial uses (Chen et al., 2001). In the Ogallala aquifer region, projected natural groundwater recharge decreases more than 20% in all simulations with warming of 2.5°C or greater (based on outputs from the GISS, UKTR and BMRC AOGCMs, with three atmospheric concentrations of CO_2: 365, 560 and 750 ppm) (Rosenberg et al., 1999).

Water quality

Simulated future surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries throughout North America consistently increase from 2 to 7°C (based on 2×CO_2 and IS92a scenarios) (Fang and Stefan, 1999; Hostetler and Small, 1999; Nicholls, 1999; Stefan and Fang, 1999; Lehman, 2002; Gooseff et al., 2005), with summer surface temperatures exceeding 30°C in Midwestern and southern lakes and reservoirs (Hostetler and Small, 1999). Warming is likely to extend and intensify summer thermal stratification, contributing to oxygen depletion. A shorter ice-cover period in shallow northern lakes could reduce winter fish kills caused by low oxygen (Fang and Stefan, 1999; Stefan and Fang, 1999; Lehman, 2002). Higher stream temperatures affect fish access, survival and spawning (e.g., west coast salmon) (Morrison et al., 2002).

Climate change is likely to make it more difficult to achieve existing water quality goals (high confidence). For the Midwest, simulated low flows used to develop pollutant discharge limits (Total Maximum Daily Loads) decrease over 60% with a 25% decrease in mean precipitation, reaching up to 100% with the incorporation of irrigation demands (Eheart et al., 1999). Restoration of beneficial uses (e.g., to address habitat loss, eutrophication, beach closures) under the Great Lakes Water Quality agreement will likely be vulnerable to declines in water levels, warmer water temperatures, and more intense precipitation (Mortsch et al., 2003). Based on simulations, phosphorus remediation targets for the Bay of Quinte (Lake Ontario) and surrounding watershed could be compromised as 3 to 4°C warmer water temperatures contribute to 77 to 98% increases in summer phosphorus concentrations in the bay (Nicholls, 1999), and as changes in precipitation, streamflow and erosion lead to increases in average phosphorus concentrations in streams of 25 to 35% (Walker, 2001). Decreases in snow cover and more winter rain on bare soil are likely to lengthen the erosion season and enhance erosion, increasing the potential for water quality impacts in agricultural areas (Atkinson et al., 1999; Walker, 2001; Soil and Water Conservation Society, 2003). Soil management practices (e.g., crop residue, no-till) in the Cornbelt may not provide sufficient erosion protection against future intense precipitation and associated runoff (Hatfield and Pruger, 2004; Nearing et al., 2004).

14.4.2 Ecosystems

Several simulations (Cox et al., 2000; Berthelot et al., 2002; Fung et al., 2005) indicate that, over the 21st century, warming will lengthen growing seasons, sustaining forest carbon sinks in North America despite some decreased sink strength resulting from greater water limitations in western forests and higher respiration in the tropics (medium confidence). Impacts on ecosystem structure and function may be amplified by changes in extreme meteorological events and increased disturbance frequencies. Ecosystem disturbances, caused either by humans or by natural events, accelerate both loss of native species and invasion of exotics (Sala et al., 2000).

Primary production

At high latitudes, several models simulate increased NPP as a result of expansion of forests into the tundra and longer growing seasons (Berthelot et al., 2002). In the mid-latitudes, simulated changes in NPP are variable, depending on whether there is sufficient enhancement of precipitation to offset

[7] River stage: water height relative to a set point.

increased evapotranspiration in a warmer climate (Bachelet et al., 2001; Berthelot et al., 2002; Gerber et al., 2004; Woodward and Lomas, 2004). Bachelet et al. (2001) project the areal extent of drought-limited ecosystems to increase by 11%/ºC warming in the continental U.S. By the end of the 21st century, ecosystems in the north-east and south-east U.S. will likely become carbon sources, while the western U.S. remains a carbon sink (Bachelet et al., 2004).

Overall forest growth in North America will likely increase modestly (10-20%) as a result of extended growing seasons and elevated CO_2 over the next century (Morgan et al., 2001), but with important spatial and temporal variations (medium confidence). Growth of white spruce in Québec will be enhanced by a 1ºC temperature increase but depressed with a 4ºC increase (Andalo et al., 2005). A 2ºC temperature increase in the Olympic Mountains (U.S.) would cause dominant tree species to shift upward in elevation by 300 to 600m, causing temperate species to replace sub-alpine species over 300 to 500 years (Zolbrod and Peterson, 1999). For widespread species such as lodgepole pine, a 3ºC temperature increase would increase growth in the northern part of its range, decrease growth in the middle, and decimate southern forests (Rehfeldt et al., 2001).

Population and community dynamics

For many amphibians, whose production of eggs and migration to breeding ponds is intimately tied to temperature and moisture, mismatches between breeding phenology and pond drying can lead to reproductive failure (Beebee, 1995). Differential responses among species in arrival or persistence in ponds will likely lead to changes in community composition and nutrient flow in ponds (Wilbur, 1997). Changes in plant species composition in response to climate change can facilitate other disturbances, including fire (Smith et al., 2000) and biological invasion (Zavaleta and Hulvey, 2004). Bioclimate modelling based on output from five GCMs suggests that, over the next century, vertebrate and tree species richness will decrease in most parts of the conterminous U.S., even though long-term trends (over millennia) ultimately favour increased richness in some taxa and locations (Currie, 2001). Based on relationships between habitat area and biodiversity, 15 to 37% of plant and animal species in a global sample are likely to be 'committed to extinction' by 2050, although actual extinctions will be strongly influenced by human forces and could take centuries (Thomas et al., 2004).

14.4.3 Coastal regions

Added stress from rapid coastal development, including an additional 25 million people in the coastal U.S. over the next 25 years, will reduce the effectiveness of natural protective features, leading to impaired resilience. As property values and investment continue to rise, coastal vulnerability tends to increase on a broad scale (Pielke Jr. and Landsea, 1999; Heinz Center, 2000), with a sensitivity that depends on the commitment to and flexibility of adaptation measures. Disproportionate impacts due to socio-economic status are likely to be exacerbated by rising sea levels and storm severity (Wu et al., 2002; Kleinosky et al., 2006).

Sea-level rise has accelerated in eastern North America since the late 19th century (Donnelly et al., 2004) and further acceleration is expected (high confidence). For The IPCC Special Report on Emissions Scenarios (SRES, Nakićenović and Swart, 2000) scenario A1B, global mean sea level is projected to rise by 0.35 ± 0.12 m from the 1980 to 1999 period to the 2090 to 2099 period (Meehl et al., 2007: Section 10.6.5). Spatial variability of sea-level rise has become better defined since the TAR (Church et al., 2004) and the ensemble mean for A1B shows values close to the global mean along most North American coasts, with slightly higher rates in eastern Canada and western Alaska, and stronger positive anomalies in the Arctic (Meehl et al., 2007: Figure 10.32). Vertical land motion will decrease (uplift) or increase (subsidence) the relative sea-level rise at any site (Douglas and Peltier, 2002).

Superimposed on accelerated sea-level rise, the present storm and wave climatology and storm-surge frequency distributions lead to forecasts of more severe coastal flooding and erosion hazards. The water-level probability distribution is shifted upward, giving higher potential flood levels and more frequent flooding at levels rarely experienced today (very high confidence) (Zhang et al., 2000; Forbes et al., 2004). If coastal systems, including sediment supply, remain otherwise unchanged, higher sea levels are likely to be correlated with accelerated coastal erosion (Hansom, 2001; Cowell et al., 2003).

Up to 21% of the remaining coastal wetlands in the U.S. mid-Atlantic region are potentially at risk of inundation between 2000 and 2100 (IS92a emissions scenario) (Najjar et al., 2000). Rates of coastal wetland loss, in Chesapeake Bay and elsewhere (Kennish, 2002), will increase with accelerated sea-level rise, in part due to 'coastal squeeze' (high confidence). Salt-marsh biodiversity is likely to be diminished in north-eastern marshes through expansion of cordgrass (*Spartina alterniflora*) at the expense of high-marsh species (Donnelly and Bertness, 2001). Many salt marshes in less developed areas have some potential to keep pace with sea-level rise (to some limit) through vertical accretion (Morris et al., 2002; Chmura et al., 2003; Chmura and Hung, 2004). Where rapid subsidence increases rates of relative sea-level rise, however, as in the Mississippi Delta, even heavy sediment loads cannot compensate for inundation losses (Rybczyk and Cahoon, 2002).

Potentially more intense storms and possible changes in El Niño (Meehl et al., 2007: Sections 10.3.5.4 and 10.3.6.3) are likely to result in more coastal instability (medium confidence) (see Section 14.3.1) (Scavia et al., 2002; Forbes et al., 2004; Emanuel, 2005). Damage costs from coastal storm events (storm surge, waves, wind, ice encroachment) and other factors (such as freeze-thaw) have increased substantially in recent decades (Zhang et al., 2000; Bernatchez and Dubois, 2004) and are expected to continue rising (high confidence). Higher sea levels in combination with storm surges will cause widespread problems for transportation along the Gulf and Atlantic coasts (Titus, 2002). More winters with reduced sea ice in the Gulf of St. Lawrence, resulting in more open water during the winter storm season, will lead to an increase in the average number of storm-wave events per year, further accelerating coastal erosion (medium confidence) (Forbes et al., 2004).

14.4.4 Agriculture, forestry and fisheries

Agriculture

Research since the TAR supports the conclusion that moderate climate change will likely increase yields of North American rain-fed agriculture, but with smaller increases and more spatial variability than in earlier estimates (high confidence) (Reilly, 2002). Most studies project likely climate-related yield increases of 5 to 20% over the first decades of the century, with the overall positive effects of climate persisting through much or all of the 21st century. This pattern emerges from recent assessments for corn, rice, sorghum, soybean, wheat, common forages, cotton and some fruits (Adams et al., 2003; Polsky et al., 2003; Rosenberg et al., 2003; Tsvetsinskaya et al., 2003; Antle et al., 2004; Thomson et al., 2005b), including irrigated grains (Thomson et al., 2005b). Increased climate sensitivity is anticipated in the south-eastern U.S. and in the U.S. Cornbelt (Carbone et al., 2003), but not in the Great Plains (Mearns et al., 2003). Crops that are currently near climate thresholds (e.g., wine grapes in California) are likely to suffer decreases in yields, quality, or both, with even modest warming (medium confidence) (Hayhoe et al., 2004; White et al., 2006).

Recent integrated assessment model studies explored the interacting impacts of climate and economic factors on agriculture, water resources and biome boundaries in the conterminous U.S. (Edmonds and Rosenberg, 2005; Izaurralde et al., 2005; Rosenberg and Edmonds, 2005; Sands and Edmonds, 2005; Smith et al., 2005; Thomson et al., 2005a,b,c,d), concluding that scenarios with decreased precipitation create important challenges, restricting the availability of water for irrigation and at the same time increasing water demand for irrigated agriculture and urban and ecological uses.

The critical importance of specific agro-climatic events (e.g., last frost) introduces uncertainty in future projections (Mearns et al., 2003), as does continued debate about the CO_2 sensitivity of crop growth (Long et al., 2005). Climate change is expected to improve the climate for fruit production in the Great Lakes region and eastern Canada but with risks of early season frost and damaging winter thaws (Bélanger et al., 2002; Winkler et al., 2002). For U.S. soybean yield, adjusting the planting date can reduce the negative effects of late season heat stress and can more than compensate for direct effects of climate change (Southworth et al., 2002).

Vulnerability of North American agriculture to climatic change is multi-dimensional and is determined by interactions among pre-existing conditions, indirect stresses stemming from climate change (e.g., changes in pest competition, water availability), and the sector's capacity to cope with multiple, interacting factors, including economic competition from other regions as well as advances in crop cultivars and farm management (Parson et al., 2003). Water access is the major factor limiting agriculture in south-east Arizona, but farmers in the region perceive that technologies and adaptations such as crop insurance have recently decreased vulnerability (Vasquez-Leon et al., 2002). Areas with marginal financial and resource endowments (e.g., the U.S. northern plains) are especially vulnerable to climate change (Antle et al., 2004). Unsustainable land-use practices will tend to increase the vulnerability of agriculture in the U.S. Great Plains to climate change (Polsky and Easterling, 2001).

Forestry

Across North America, impacts of climate change on commercial forestry potential are likely to be sensitive to changes in disturbances (Dale et al., 2001) from insects (Gan, 2004), diseases (Woods et al., 2005) and wildfires (high confidence) (see Box 14.1). Warmer summer temperatures are projected to extend the annual window of high fire ignition risk by 10-30%, and could result in increased area burned of 74-118% in Canada by 2100 (Brown et al., 2004; Flannigan et al., 2004). In the absence of dramatic increases in disturbance, effects of climate change on the potential for commercial harvest in one study for the 2040s ranged from mixed for a low emissions scenario (the EPPA LLH emissions scenario) to positive for a high emissions scenario (the EPPA HHL emissions scenario) (Perez-Garcia et al., 2002). Scenarios with increased harvests tend to lead to lower prices and, as a consequence, reduced harvests, especially in Canada (Perez-Garcia et al., 2002; Sohngen and Sedjo, 2005). The tendency for North American producers to suffer losses increases if climate change is accompanied by increased disturbance, with simulated losses averaging US$1 billion to 2 billion/yr over the 21st century (Sohngen and Sedjo, 2005). Increased tropospheric ozone could cause further decreases in tree growth (Karnosky et al., 2005). Risks of losses from Southern pine beetle likely depend on the seasonality of warming, with winter and spring warming leading to the greatest damage (Gan, 2004).

Warmer winters with more sporadic freezing and thawing are likely to increase erosion and landslides on forest roads, and reduce access for winter harvesting (Spittlehouse and Stewart, 2003).

Freshwater fisheries

Cold-water fisheries will likely be negatively affected by climate change; warm-water fisheries will generally gain; and the results for cool-water fisheries will be mixed, with gains in the northern and losses in the southern portions of ranges (high confidence) (Stefan et al., 2001; Rahel, 2002; Shuter et al., 2002; Mohseni et al., 2003; Fang et al., 2004). Salmonids, which prefer cold, clear water, are likely to experience the most negative impacts (Gallagher and Wood, 2003). Arctic freshwaters will likely be most affected, as they will experience the greatest warming (Wrona et al., 2005). Many warm-water and cool-water species will shift their ranges northward or to higher altitudes (Clark et al., 2001; Mohseni et al., 2003). In the continental U.S., cold-water species will likely disappear from all but the deeper lakes, cool-water species will be lost mainly from shallow lakes, and warm-water species will thrive except in the far south, where temperatures in shallow lakes will exceed survival thresholds (see Section 14.4.1) (Stefan et al., 2001). Species already listed as threatened will face increased risk of extinction (Chu et al., 2005), with pressures from climate exacerbated by the expansion of predatory species like smallmouth bass (Jackson and Mandrak, 2002). In Lake Erie, larval recruitment of river-spawning walleye will depend on temperature and flow changes, but lake-spawning stocks will likely decline due to the effects of warming and lower lake levels (Jones et al., 2006). Thermal habitat suitable for yellow perch will expand, while that for lake trout will contract (Jansen and Hesslein, 2004). While temperature increases may favour warm-water fishes like smallmouth bass, changes in water supply and flow regimes seem likely to have negative effects (Peterson and Kwak, 1999).

14.4.5 Human health

Risks from climate change to human health will be strongly modulated by changes in health care infrastructure, technology, and accessibility as well as ageing of the population, and patterns of immigration and/or emigration (UNPD, 2005). Across North America, the population over the age of 65 will increase slowly to 2010, and then grow dramatically as the Baby Boomers join the ranks of the elderly – the segment of the population most at risk of dying in heatwaves.

Heatwaves and health

Severe heatwaves, characterised by stagnant, warm air masses and consecutive nights with high minimum temperatures, will intensify in magnitude and duration over the portions of the U.S. and Canada where they already occur (high confidence) (Cheng et al., 2005). Late in the century, Chicago is projected to experience 25% more frequent heatwaves annually (using the PCM AOGCM with a business-as-usual emissions scenario, for the period 2080 to 2099) (Meehl and Tebaldi, 2004), and the projected number of heatwave days in Los Angeles increases from 12 to 44-95 (based on PCM and HadCM3 for the A1FI and B1 scenarios, for the 2070 to 2099 period) (Hayhoe et al., 2004).

Air pollution

Surface ozone concentration may increase with a warmer climate. Ozone damages lung tissue, causing particular problems for people with asthma and other lung diseases. Even modest exposure to ozone may encourage the development of asthma in children (McConnell et al., 2002; Gent et al., 2003). Ozone and non-volatile secondary particulate matter generally increase at higher temperatures, due to increased gas-phase reaction rates (Aw and Kleeman, 2002). Many species of trees emit volatile organic compounds (VOC) such as isoprene, a precursor of ozone (Lerdau and Keller, 1998), at rates that increase rapidly with temperature (Guenther, 2002).

For the 2050s, daily average ozone levels are projected to increase by 3.7 ppb across the eastern U.S. (based on the GISS/MM5 AOGCM and the SRES A2 emissions scenario), with the cities most polluted today experiencing the greatest increase in ozone pollution (Hogrefe et al., 2004). One-hour maximum ozone follows a similar pattern, with the number of summer days exceeding the 8-hour regulatory U.S. standard projected to increase by 68% (Bell et al., 2007). Assuming constant population and dose-response characteristics, ozone-related deaths from climate change increase by approximately 4.5% from the 1990s to the 2050s (Knowlton et al., 2004; Bell et al., 2007). The large potential population exposed to outdoor air pollution translates this small relative risk into a substantial attributable health risk.

Pollen

Pollen, another air contaminant, is likely to increase with elevated temperature and atmospheric CO_2 concentrations. A doubling of the atmospheric CO_2 concentration stimulated ragweed-pollen production by over 50% (Wayne et al., 2002). Ragweed grew faster, flowered earlier and produced significantly greater above-ground biomass and pollen at urban than at rural locations (Ziska et al., 2003).

Lyme disease

The northern boundary of tick-borne Lyme disease is limited by cold temperature effects on the tick, *Ixodes scapularis*. The northern range limit for this tick could shift north by 200 km by the 2020s, and 1000 km by the 2080s (based on projections from the CGCM2 and HadCM3 AOGCMs under the SRES A2 emissions scenario) (Ogden et al., 2006).

14.4.6 Human settlements

Economic base

The economies of resource-dependent communities and indigenous communities in North America are particularly sensitive to climate change, with likely winners and losers controlled by impacts on important local resources (see Sections 14.4.1, 14.4.4 and 14.4.7). Residents of northern Canada and Alaska are likely to experience the most disruptive impacts of climate change, including shifts in the range or abundance of wild species crucial to the livelihoods and well-being of indigenous peoples (high confidence) (see Chapter 15 Sections 15.4.2.4 and 15.5) (Houser et al., 2001; NAST, 2001; Parson et al., 2001a; ACIA, 2005).

Infrastructure, climate trends and extreme events

Many of the impacts of climate change on infrastructure in North America depend on future changes in variability of precipitation and extreme events, which are likely to increase but with substantial uncertainty (Meehl et al., 2007: Section 10.5.1; Christensen et al., 2007: Section 11.5.3). Infrastructure in Alaska and northern Canada is known to be vulnerable to warming. Among the most sensitive areas are those affected by coastal erosion and thawing of ice-rich permafrost (see Chapter 15 Section 15.7.1) (NAST, 2001; Arctic Research Commission, 2003; ACIA, 2005). Building, designing, and maintaining foundations, pipelines and road and railway embankments will become more expensive due to permafrost thaw (ACIA, 2005). Examples where infrastructure is projected to be at 'moderate to high hazard' in the mid-21st century include Shishmaref, Nome and Barrow in Alaska, Tuktoyaktuk in the Northwest Territories, the Dalton Highway in Alaska, the Dempster Highway in the Yukon, airfields in the Hudson Bay region, and the Alaska Railroad (based on the ECHAM1-A, GFDL89 and UKTR climate models) (Nelson et al., 2002; Instanes et al., 2005).

Since the TAR, a few studies have projected increasing vulnerability of infrastructure to extreme weather related to climate warming unless adaptation is effective (high confidence). Examples include the New York Metropolitan Region (Rosenzweig and Solecki, 2001) (see Box 14.3), the mid-Atlantic Region (Fisher, 2000; Barron, 2001; Wu et al.,

Box 14.3. North American cities integrate impacts across multiple scales and sectors

Impacts of climate change in the metropolitan regions of North America will be similar in many respects. Los Angeles, New York and Vancouver are used to illustrate some of the affected sectors, including infrastructure, energy and water supply. Adaptation will need to be multi-decadal and multi-dimensional, and is already beginning (see Section 14.5).

Infrastructure

Since most large North American cities are on tidewater, rivers or both, effects of climate change will likely include sea-level rise (SLR) and/or riverine flooding. The largest impacts are expected when SLR, heavy river flows, high tides and storms coincide (California Regional Assessment Group, 2002). In New York, flooding from the combination of SLR and storm surge could be several metres deep (Gornitz and Couch, 2001; Gornitz et al., 2001). By the 2090s under a strong warming scenario (the CGCM climate model with the CCGG emissions scenario), today's 100-year flood level could have a return period of 3 to 4 years, and today's 500-year flood could be a 1-in-50-year event, putting much of the region's infrastructure at increased risk (Jacob et al., 2001; Major and Goldberg, 2001).

Energy supply and demand

Climate change will likely lead to substantial increases in electricity demand for summer cooling in most North American cities (see Section 14.4.8). This creates a number of conflicts, both locally and at a distance. In southern California, additional summer electricity demand will intensify inherent conflicts between state-wide hydropower and flood-control objectives (California Regional Assessment Group, 2002). Operating the Columbia River dams that supply 90% of Vancouver's power would be complicated by lower flows and environmental requirements (see Box 14.2). In New York, supplying summer electricity demand could increase air pollutant levels (e.g., ozone) (Hill and Goldberg, 2001; Kinney et al., 2001; Knowlton et al., 2004) and health impacts could be further exacerbated by climate change interacting with urban heat island effects (Rosenzweig et al., 2005). Unreliable electric power, as in minority neighbourhoods during the New York heatwave of 1999, can amplify concerns about health and environmental justice (Wilgoren and Roane, 1999).

Water supply systems

North American city water supply systems often draw water from considerable distances, so climate impacts need not be local to affect cities. By the 2020s, 41% of the supply to southern California is likely to be vulnerable to warming from loss of Sierra Nevada and Colorado River basin snowpack (see Section 14.4.1). Similarly, less mountain snowpack and summer runoff could require that Vancouver undertakes additional conservation and water restrictions, expands reservoirs, and develops additional water sources (Schertzer et al., 2004). The New York area will likely experience greater water supply variability (Solecki and Rosenzweig, 2007). The New York system can likely accommodate this, but the region's smaller systems may be vulnerable, leading to a need for enhanced regional water distribution protocols (Hansler and Major, 1999).

Adaptation

Many cities in North America have initiated 'no regrets' actions based on historical experience. In the Los Angeles area, incentive and information programmes of local water districts encourage water conservation (MWD, 2005). A population increase of over 35% (nearly one million people) since 1970 has increased water use in Los Angeles by only 7% (California Regional Assessment Group, 2002). New York has reduced total water consumption by 27% and per capita consumption by 34% since the early 1980s (City of New York, 2005). Vancouver's 'CitiesPLUS' 100-year plan will upgrade the drainage system by connecting natural areas and waterways, developing locally resilient, smaller systems, and upgrading key sections of pipe during routine maintenance (Denault et al., 2002).

2002; Rygel et al., 2006) and the urban transportation network of the Boston metropolitan area (Suarez et al., 2005). For Boston, projections of a gradual increase (0.31%/yr) in the probability of the 100-year storm surge, as well as sea-level rise of 3 mm/yr, leads to urban riverine and coastal flooding (based on the CGCM1 climate model), but the projected economic damages do not justify the cost of adapting the transportation infrastructure to climate change.

Less reliable supplies of water are likely to create challenges for managing urban water systems as well as for industries that depend on large volumes of water (see Sections 14.2.1, 14.4.1). U.S. water managers anticipate local, regional or state-wide water shortages during the next ten years (GAO, 2003). Threats to reliable supply are complicated by the high population growth rates in western states where many water resources are at or approaching full utilisation (GAO, 2003) (see Section 14.4.1). Potential increases in heavy precipitation, with expanding impervious surfaces, could increase urban flood risks and create additional design challenges and costs for stormwater management (Kije Sipi Ltd., 2001).

14.4.7 Tourism and recreation

Although coastal zones are among the most important recreation resources in North America, the vulnerability of key tourism areas to sea-level rise has not been comprehensively assessed. The cost to protect Florida beaches from a 0.5 m rise in sea level, with sand replenishment, was estimated at US$1.7 billion to 8.8 billion (EPA, 1999).

Nature-based tourism is a major market segment, with over 900 million visitor-days in national/provincial/state parks in 2001. Visits to Canada's national parks system are projected to increase by 9 to 25% (2050s) and 10 to 40% (2080s) as a result of a lengthened warm-weather tourism season (based on the PCM GCM and the SRES B2 emissions scenario, and the CCSR GCM with A1) (Jones and Scott, 2006). This would have economic benefits for park agencies and nearby communities, but could exacerbate visitor-related ecological pressures in some parks. Climate-induced environmental changes (e.g., loss of glaciers, altered biodiversity, fire- or insect-impacted forests) would also affect park tourism, although uncertainty is higher regarding the regional specifics and magnitude of these impacts (Richardson and Loomis, 2004; Scott et al., 2007a).

Early studies of the impact of climate change on the ski industry did not account for snowmaking, which substantially lowers the vulnerability of ski areas in eastern North America for modest (B2 emissions scenario) but not severe (A1) warming (based on 5 GCMs for the 2050s) (Scott et al., 2003; Scott et al., 2007b). Without snowmaking, the ski season in western North America will likely shorten substantially, with projected losses of 3 to 6 weeks (by the 2050s) and 7 to 15 weeks (2080s) in the Sierra Nevada of California (based on PCM and HadCM3 GCMs for the B1 and A1FI scenarios), and 7 to 10 weeks at lower elevations and 2 to 14 weeks at higher elevations at Banff, Alberta (based on the PCM GCM with the B2 emissions scenario, and the CCSR GCM with A1, for the 2050s) (Hayhoe et al., 2004; Scott and Jones, 2005). With advanced snowmaking, the ski season in Banff shortens at low but not at high altitudes. The North American snowmobiling industry (valued at US$27 billion) (ISMA, 2006) is more vulnerable to climate change because it relies on natural snowfall. By the 2050s, a reliable snowmobile season disappears from most regions of eastern North America that currently have developed trail networks (based on the CGCM1 and HadCM3 GCMs with IS92a emissions, the PCM GCM with B2 emissions and the CCSR GCM with A1 emissions) (Scott, 2006; Scott and Jones, 2006).

14.4.8 Energy, industry and transportation

Energy demand

Recent North American studies generally confirm earlier work showing a small net change (increase or decrease, depending on methods, scenarios and location) in the net demand for energy in buildings but a significant increase in demand for electricity for space cooling, with further increases caused by additional market penetration of air conditioning (high confidence) (Sailor and Muñoz, 1997; Mendelsohn and Schlesinger, 1999; Morrison and Mendelsohn, 1999; Mendelsohn, 2001; Sailor, 2001; Sailor and Pavlova, 2003; Scott et al., 2005; Hadley et al., 2006). Ruth and Amato (2002) projected a 6.6% decline in annual heating fuel consumption for Massachusetts in 2020 (linked to an 8.7% decrease in heating degree-days) and a 1.9% increase in summer electricity consumption (12% increase in annual cooling degree-days). In Québec, net energy demand for heating and air conditioning across all sectors could fall by 9.4% of 2001 levels by 2100 (based on the CGCM1 GCM and the IS92a emissions scenario), with residential heating falling by 10 to 15% and air conditioning increasing two- to four-fold. Peak electricity demand is likely to decline in the winter peaking system of Quebec, while summer peak demand is likely to increase 7 to 17% in the New York metropolitan region (Ouranos, 2004).

Energy supply

Since the TAR, there have been regional but not national-level assessments of the effects of climate change on future hydropower resources in North America. For a 2 to 3°C warming in the Columbia River Basin and British Columbia Hydro service areas, the hydroelectric supply under worst-case water conditions for winter peak demand will likely increase (high confidence). However, generating power in summer will likely conflict with summer instream flow targets and salmon restoration goals established under the Endangered Species Act (Payne et al., 2004). This conclusion is supported by accumulating evidence of a changing hydrologic regime in the western U.S. and Canada (see Sections 14.2.1, 14.4.1, Box 14.2). Similarly, Colorado River hydropower yields will likely decrease significantly (medium confidence) (Christensen et al., 2004), as will Great Lakes hydropower (Moulton and Cuthbert, 2000; Lofgren et al., 2002; Mirza, 2004). James Bay hydropower will likely increase (Mercier, 1998; Filion, 2000). Lower Great Lake water levels could lead to large economic losses (Canadian $437 million to 660 million/yr), with increased water levels leading to small gains (Canadian $28 million to 42 million/yr) (Buttle et al., 2004; Ouranos, 2004). Northern Québec hydropower production would likely benefit from greater precipitation and more open-water conditions, but hydro plants in southern Québec would likely be affected by lower water levels. Consequences of changes in seasonal distribution of flows and in the timing of ice formation are uncertain (Ouranos, 2004).

Wind and solar resources are about as likely as not to increase (medium confidence). The viability of wind resources depends on both wind speed and reliability. Studies to date project wind resources that are unchanged by climate change (based on the HadGCM2 CGSa4 experiment) or reduced by 0 to 40% (based on CGCM1 and the SRES A1 scenario, and HadCM2 and RegCM2 and a 1%/yr CO_2 increase) (Segal et al., 2001; Breslow and Sailor, 2002). Future changes in cloudiness could slightly increase the potential for solar energy in North America south of 60°N (using many models, the A1B scenario and for 2080 to 2099 *vs*. 1980 to 1999) (Meehl et al., 2007: Figure 10.10). However, Pan et al. (2004) projected the opposite: that increased cloudiness will likely decrease the potential output of photovoltaics by 0 to 20% (based on HadCM2 and RegCM2 and a 1%/yr CO_2 increase for the 2040s).

Bioenergy potential is climate-sensitive through direct impacts on crop growth and availability of irrigation water. Bioenergy crops are projected to compete successfully for agricultural acreage at a price of US$33/Mg, or about US$1.83/10^9 joules (Walsh et al., 2003). Warming and precipitation increases are expected to allow the bioenergy crop switchgrass to compete effectively with traditional crops in the central U.S. (based on RegCM2 and a 2×CO_2 scenario) (Brown et al., 2000).

Construction

As projected in the TAR, the construction season in Canada and the northern U.S. will likely lengthen with warming (see Section 14.3.1 and Christensen et al., 2007 Section 11.5.3). In permafrost areas in Canada and Alaska, increasing depth of the 'active layer' or loss of permafrost can lead to substantial decreases in soil strength (ACIA, 2004). In areas currently underlain by permafrost, construction methods are likely to require changes (Cole et al., 1998), potentially increasing construction and maintenance costs (high confidence) (see Chapter 15 Section 15.7.1) (ACIA, 2005).

Transportation

Warmer or less snowy winters will likely reduce delays, improve ground and air transportation reliability, and decrease the need for winter road maintenance (Pisano et al., 2002). More intense winter storms could, however, increase risks for traveller safety (Andrey and Mills, 2003) and require increased snow removal. Continuation of the declining fog trend in at least some parts of North America (Muraca et al., 2001; Hanesiak and Wang, 2005) should benefit transport. Improvements in technology and information systems will likely modulate vulnerability to climate change (Andrey and Mills, 2004).

Negative impacts of climate change on transportation will very likely result from coastal and riverine flooding and landslides (Burkett, 2002). Although offset to some degree by fewer ice threats to navigation, reduced water depth in the Great Lakes would lead to the need for 'light loading' and, hence, adverse economic impacts (see Section 14.4.1) (du Vair et al., 2002; Quinn, 2002; Millerd, 2005). Adaptive measures, such as deepening channels for navigation, would need to address both institutional and environmental challenges (Lemmen and Warren, 2004).

Warming will likely adversely affect infrastructure for surface transport at high northern latitudes (Nelson et al., 2002). Permafrost degradation reduces surface load-bearing capacity and potentially triggers landslides (Smith and Levasseur, 2002; Beaulac and Doré, 2005). While the season for transport by barge is likely to be extended, the season for ice roads will likely be compressed (Lonergan et al., 1993; Lemmen and Warren, 2004; Welch, 2006). Other types of roads are likely to incur costly improvements in design and construction (Stiger, 2001; McBeath, 2003; Greening, 2004) (see Chapter 15 Section 15.7.1).

An increase in the frequency, intensity or duration of heat spells could cause railroad track to buckle or kink (Rosetti, 2002), and affect roads through softening and traffic-related rutting (Zimmerman, 2002). Some problems associated with warming can be ameliorated with altered road design, construction and management, including changes in the asphalt mix and the timing of spring load restrictions (Clayton et al., 2005; Mills et al., 2006).

14.4.9 Interacting impacts

Impacts of climate change on North America will not occur in isolation, but in the context of technological, economic (Nakićenović and Swart, 2000; Edmonds, 2004), social (Lebel, 2004; Reid et al., 2005) and ecological changes (Sala et al., 2000). In addition, challenges from climate change will not appear as isolated effects on a single sector, region, or group. They will occur in concert, creating the possibility of a suite of local, as well as long-distance, interactions, involving both impacts of climate change and other societal and ecosystem trends (NAST, 2001; Reid et al., 2005). In some cases, these interactions may reduce impacts or decrease vulnerability, but in others they may amplify impacts or increase vulnerability.

Effects of climate change on ecosystems do not occur in isolation. They co-occur with numerous other factors, including effects of land-use change (Foley et al., 2005), air pollution (Karnosky et al., 2005), wildfires (see Box 14.1), changing biodiversity (Chapin et al., 2000) and competition with invasives (Mooney et al., 2005). The strong dependence of ecosystem function on moisture balance (Baldocchi and Valentini, 2004), coupled with the greater uncertainty about future precipitation than about future temperature (Christensen et al., 2007: Section 11.5.3), further expands the range of possible futures for North American ecosystems.

People also experience climate change in a context that is strongly conditioned by changes in other sectors and their adaptive capacity. Interactions with changes in material wealth (Ikeme, 2003), the vitality of local communities (Hutton, 2001; Wall et al., 2005), the integrity of key infrastructure (Jacob et al., 2001), the status of emergency facilities and preparedness and planning (Murphy et al. 2005), the sophistication of the public health system (Kinney et al., 2001), and exposure to conflict (Barnett, 2003), all have the potential to either exacerbate or ameliorate vulnerability to climate change. Among the unexpected consequences of the population displacement caused by Hurricane Katrina in 2005 is the strikingly poorer health of storm evacuees, many of whom lost jobs, health insurance, and stable relationships with medical professionals (Columbia University Mailman School of Public Health, 2006).

Little of the literature reviewed in this chapter addresses interactions among sectors that are all impacted by climate change, especially in the context of other changes in economic activity, land use, human population, and changing personal and political priorities. Similarly, knowledge of the indirect impacts on North America of climate change in other geographical regions is very limited.

14.5 Adaptation: practices, options and constraints

The U.S. and Canada are developed economies with extensive infrastructure and mature institutions, with important regional and socio-economic variations (NAST, 2000; Lemmen and Warren, 2004). These capabilities have led to adaptation and coping strategies across a wide range of historic conditions, with both successes and failures. Most studies on adaptive strategies consider implementation based on past experiences (Paavola and Adger, 2002). Examples of adaptation based on future projections are rare (Smit and Wall, 2003; Devon, 2005). Expanding beyond reactive adaptation to proactive, anticipatory adaptive strategies presents many challenges. Progress toward meeting these challenges is just beginning in North America.

14.5.1 Practices and options

Canada and the U.S. emphasise market-based economies. Governments often play a role implementing large-scale adaptive measures, and in providing information and incentives to support development of adaptive capacity by private decision makers (UNDP, 2001; Michel-Kerjan, 2006). In practice, this means that individuals, businesses and community leaders act on perceived self interest, based on their knowledge of adaptive options. Despite many examples of adaptive practices in North America, under-investment in adaptation is evident in the recent rapid increase in property damage due to climate extremes (Burton and Lim, 2005; Epstein and Mills, 2005) and illustrates the current adaptation deficit.

Adaptation by individuals and private businesses

Research on adaptive behaviour for coping with projected climate change is minimal, though several studies address adaptations to historic variation in the weather. About 70% of businesses face some weather risk. The impact of weather on businesses in the U.S. is an estimated US$200 billion/yr (Lettre, 2000). Climate change may also create business opportunities. For example, spending on storm-worthiness and construction of disaster-resilient homes (Koppe et al., 2004; Kovacs, 2005b; Kunreuther, 2006) increased substantially after the 2004 and 2005 Atlantic hurricanes, as did the use of catastrophe bonds (CERES, 2004; Byers et al., 2005; Dlugolecki, 2005; Guy Carpenter, 2006).

Businesses in Canada and the U.S. are investing in climate-relevant adaptations, though few of these appear to be based on projections of future climate change. For example:

- Insurance companies are introducing incentives for homeowners and businesses that invest in loss prevention strategies (Kim, 2004; Kovacs, 2005b).
- Insurance companies are investing in research to prevent future hazard damage to insured property, and to adjust pricing models (Munich Re., 2004; Mills and Lecomte, 2006).
- Ski resort operators are investing in lifts to reach higher altitudes and in snow-making equipment (Elsasser et al., 2003; Census Bureau, 2004; Scott, 2005; Jones and Scott, 2006; Scott et al., 2007a).
- With highly detailed information on weather conditions, farmers are adjusting crop and variety selection, irrigation strategies and pesticide application (Smit and Wall, 2003).
- The forest resources sector is investing in improved varieties, forest protection, forest regeneration, silvicultural management and forest operations (Loehle et al., 2002; Spittlehouse and Stewart, 2003).

Adaptation by governments and communities

Many North American adaptations to climate-related risks are implemented at the community level. These include efforts to minimise damage from heatwaves, droughts, floods, wildfires or tornados. These actions may entail land-use planning, building code enforcement, community education and investments in critical infrastructure (Burton et al., 2002; Multihazard Mitigation Council, 2005).

Flooding and drought present recurring challenges for many North American communities (Duguid, 2002). When the City of Peterborough, Canada, experienced two 100-year flood events within three years, it responded by flushing the drainage systems and replacing the trunk sewer systems to meet more extreme 5-year flood criteria (Hunt, 2005). Recent droughts in six major U.S. cities, including New York and Los Angeles, led to adaptive measures involving investments in water conservation systems and new water supply-distribution facilities (Changnon and Changnon, 2000). To cope with a 15% increase in heavy precipitation, Burlington and Ottawa, Ontario, employed both structural and non-structural measures, including directing downspouts to lawns to encourage infiltration and increasing depression and street detention storage (Waters et al., 2003).

Some large cities (e.g., New Orleans) and important infrastructure (e.g., the only highway and rail link between Nova Scotia and the rest of Canada) are located on or behind dykes that will provide progressively less protection unless raised on an ongoing basis. Some potential damages may be averted through redesigning structures, raising the grade, or relocating (Titus, 2002). Following the 1996 Saguenay flood and 1998 ice storm, the province of Québec modified the Civil Protection Act and now requires municipalities to develop comprehensive emergency management plans that include adaptation strategies (McBean and Henstra, 2003). More communities are expected to re-examine their hazard management systems following the catastrophic damage in New Orleans from Hurricane Katrina (Kunreuther et al., 2006).

Rapid development and population growth are occurring in many coastal areas that are sensitive to storm impacts (Moser, 2005). While past extreme events have motivated some aggressive adaptation measures (e.g., in Galveston, Texas) (Bixel and Turner, 2000), the passage of time, new residents, and high demand for waterfront property are pushing coastal development into vulnerable areas.

Climate change will likely increase risks of wildfire (see Box 14.1). FireWise and FireSmart are programmes promoting wildfire safety in the U.S. and Canada, respectively (FireSmart, 2005; FireWise, 2005). Individual homeowners and businesses can participate, but the greatest reduction in risk will occur in communities that take a comprehensive approach, managing forests with controlled burns and thinning, promoting or enforcing appropriate roofing materials, and maintaining defensible space around each building (McGee et al., 2000).

Public institutions are responsible for adapting their own legislation, programmes and practices to appropriately anticipate climate changes. The recent Québec provincial plan, for example, integrates climate change science into public policy. Public institutions can also use incentives to encourage or to overcome disincentives to investment by private decision makers (Moser, 2006). Options, including tax assistance, loan guarantees and grants, can improve resilience to extremes and reduce government costs for disaster management (Moser, 2005). The U.S. National Flood Insurance Program is changing its policy to reduce the risk of multiple flood claims, which cost the programme more than US$200 million/yr (Howard, 2000). Households with two flood-related claims are now required to elevate their structure 2.5 cm above the 100-year flood level, or relocate. To complement this, a 5-year, US$1 billion programme to update and digitise flood maps was initiated in 2003 (FEMA, 2006). However, delays in implementing appropriate zoning can encourage accelerated, maladapted development in coastal communities and flood plains.

14.5.2 Mainstreaming adaptation

One of the greatest challenges in adapting North America to climate change is that individuals often resist and delay change (Bacal, 2000). Good decisions about adapting to climate change depend on relevant experience (Slovic, 2000), socio-economic factors (Conference Board of Canada, 2006), and political and institutional considerations (Yarnal et al., 2006; Dow et al., 2007). Adaptation is a complex concept (Smit et al., 2000; Dolan and Walker, 2006), that includes wealth and several other dimensions.

Experience and knowledge

The behaviour of people and systems in North America largely reflects historic climate experience (Schipper et al., 2003), which has been institutionalised through building codes, flood management infrastructure, water systems and a variety of other programmes. Canadian and U.S. citizens have invested in buildings, infrastructure, water and flood management systems designed for acceptable performance under historical conditions (Bruce, 1999; Co-operative Programme on Water and Climate, 2005; UMA Engineering, 2005; Dow et al., 2007). Decisions by community water managers (Rayner et al., 2005; Dow et al., 2007) and set-back regulations in coastal areas (Moser, 2005) also account for historic experience but rarely incorporate information about climate change or sea-level rise. In general, decision makers lack the tools and perspectives to integrate future climate, particularly events that exceed historic norms (UNDP, 2001).

Examples of adaptive behaviour influenced exclusively or predominantly by projections of climate change are largely absent from the literature, but some early steps toward planned adaptation have been taken by the engineering community, insurance companies, water managers, public health officials, forest managers and hydroelectric producers. Some initiatives integrate consideration of climate change into the environmental impact assessment process. Philadelphia, Toronto and a few other communities have introduced warning programmes to manage the health threat of heatwaves (Kalkstein, 2002). The introduction of Toronto's heat/health warning programme was influenced by both climate projections and fatalities from past heatwaves (Koppe et al., 2004; Ligeti, 2006).

Weather extremes can reveal a community's vulnerability or resilience (RMS, 2005a) and provide insights into potential adaptive responses to future events. Since the 1998 ice storm, Canada's two most populous provinces, Ontario and Québec, have strengthened emergency preparedness and response capacity. Included are comprehensive hazard-reduction measures and loss-prevention strategies to reduce vulnerability to extreme events. These strategies may include both public information programmes and long-term strategies to invest in safety infrastructure (McBean and Henstra, 2003). Adaptive behaviour is typically greater in the communities that recently experienced a natural disaster (Murphy et al., 2005). But the near absence of any personal preparedness following the 2003 blackout in eastern North America demonstrated that adaptive actions do not always follow significant emergencies (Murphy, 2004).

Socio-economic factors

Wealthier societies tend to have greater access to technology, information, developed infrastructure, and stable institutions (Easterling et al., 2004), which build capacity for individual and collective action to adapt to climate change. But average economic status is not a sufficient determinant of adaptive capacity (Moss et al., 2001). The poor and marginalised in Canada and the U.S. have historically been most at risk from weather shocks (Turner et al., 2003), with vulnerability directly related to income inequality (Yohe and Tol, 2002). Differences in individual capacity to cope with extreme weather were evident in New Orleans during and after Hurricane Katrina (Kunreuther et al., 2006), when the large majority of those requiring evacuation assistance were either poor or in groups with limited mobility, including elderly, hospitalised and disabled citizens (Murphy et al., 2005; Kumagi et al., 2006; Tierney, 2006).

Political and institutional capacity for autonomous adaptation

Public officials in Canada and the U.S. typically provide early and extensive assistance in emergencies. Nevertheless, emergency response systems in the U.S. and Canada are based on the philosophy that households and businesses should be capable of addressing their own basic needs for up to 72 hours after a disaster (Kovacs and Kunreuther, 2001). The residents' vulnerability depends on their own resources, plus those provided by public service organisations, private firms and others (Fischhoff, 2006). When a household is overwhelmed by an extreme event, household members often rely on friends, family and other social networks for physical and emotional support (Cutter et al., 2000; Enarson, 2002; Murphy, 2004). When a North American community responds to weather extremes, non-governmental organisations often coordinate support for community-based efforts (National Voluntary Organizations Active in Disaster, 2006).

An active dialogue among stakeholders and political institutions has the potential to clarify the opportunities for adaptation to changing climate. However, public discussion about adaptation is at an early stage in the U.S. and Canada (Natural Resources Canada, 2000), largely because national governments have focused public discussion on mitigation, with less attention to adaptation (Moser, 2005). Some public funds have been directed to research on impacts and adaptation, and both countries have undertaken national assessments with a synthesis of the adaptation literature, but neither country has a formal adaptation strategy (Conference Board of Canada, 2006). Integrating perspectives on climate change into legislation and regulations has the potential to promote or constrain adaptive behaviour (Natural Resources Canada, 2000). North American examples of public policies that influence adaptive behaviour include water allocation law in the western U.S. (Scheraga, 2001), farm subsidies (Goklany, 2007), public flood insurance in the U.S. (Crichton, 2003), guidance on preservation of wetlands and emergency management.

14.5.3 Constraints and opportunities

Social and cultural barriers

High adaptive capacity, as in most of North America, should be an asset for coping with or benefiting from climate change. Capacity, however, does not ensure positive action or any action at all. Societal values, perceptions and levels of cognition shape adaptive behaviour (Schneider, 2004). In North America, information about climate change is usually not 'mainstreamed' or explicitly considered (Dougherty and Osaman Elasha, 2004) in the overall decision-making process (Slovic, 2000; Leiss, 2001). This can lead to actions that are maladapted, for example, development near floodplains or coastal areas known to be vulnerable to climate change. Water managers are unlikely to use climate forecasts, even when they recognise the vulnerability, unless the forecast information can fit directly into their everyday management decisions (Dow et al., 2007).

Informational and technological barriers

Uncertainty about the local impacts of climate change is a barrier to action (NRC, 2004). Incomplete knowledge of disaster safety options (Murphy, 2004; Murphy et al., 2005) further constrains adaptive behaviour. Climate change information must be available in a form that fits the needs of decision-makers. For example, insurance companies use climate models with outputs specifically designed to support decisions related to the risk of insolvency, pricing and deductibles, regulatory and rating agency considerations, and reinsurance (Swiss Re, 2005a). Some electrical utilities have begun to integrate climate model output into planning and management of hydropower production (Ouranos, 2004).

A major challenge is the need for efficient technology and knowledge transfer. In general, questions about responsibility for funding research, involving stakeholders, and linking communities, government and markets have not been answered (Ouranos, 2004). Another constraint is resistance to new technologies (e.g., genetically modified crops), so that some promising adaptations in the agricultural, water resource management and forestry sectors are unlikely to be realised (Goklany, 2000, 2001).

Financial and market barriers

In the U.S., recent spending on adaptation to extremes has been a sound investment, contributing to reduced fatalities, injuries and significant economic benefits. The Multihazard Mitigation Council (2005) found that US$3.5 billion in spending between 1993 and 2003 on programmes to reduce future damages from flooding, severe wind and earthquakes contributed US$14 billion in societal benefits. The greatest savings were in flood (5-fold) and wind (4-fold) damage reduction. Adaptation also benefited government as each dollar of spending resulted in US$3.65 in savings or increased tax revenue. This is consistent with earlier case studies; the Canadian $65 million invested in 1968 to create the Manitoba Floodway has prevented several billion dollars in flood damage (Duguid, 2002).

Economic issues are frequently the dominant factors influencing adaptive decisions. This includes community response to coastal erosion (Moser, 2000), investments to enhance water resource systems (Report of the Water Strategy Expert Panel, 2005), protective retrofits to residences (Simmons et al., 2002; Kunreuther, 2006), and changes in insurance practices (Kovacs, 2005a). The cost and availability of economic resources clearly influence choices (WHO, 2003), as does the private versus public identity of the beneficiaries (Moser, 2000).

Sometimes, financial barriers interact with the slow turnover of existing infrastructure (Figure 14.3). Extensive property damage in Florida during Hurricane Andrew in 1992 led to significant revisions to the building code. If all properties in southern Florida met this updated code in 1992, then property damage from Hurricane Andrew would have been lower by nearly 45% (AIR, 2002). Florida will, however, still experience extensive damage from hurricanes through damage to the large number of older homes and businesses. Other financial barriers come from the challenge property owners face in recovering the costs of protecting themselves. Hidden adaptations tend to be undervalued, relative to obvious ones. For example, homes with storm shutters sell for more than homes without this visible adaptation, while less visible retrofits, such as tie-down straps to hold the roof in high winds, add less to the resale value of the home, relative to their cost (Simmons et al., 2002).

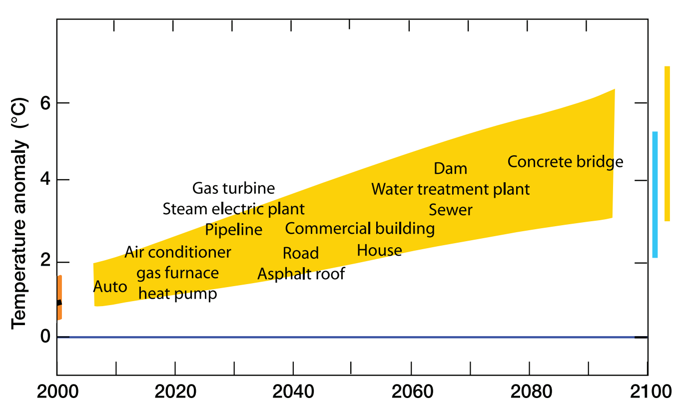

Figure 14.3. *Typical infrastructure lifetimes in North America (data from Lewis, 1987; Bettigole, 1990; EIA, 1999, 2001; Statistics Canada, 2001a; BEA, 2003), in relation to projected North American warming for 2000 to 2100 (relative to 1901-1950) for the A1B scenario, from the IPCC AR4 Multi-Model Dataset (yellow envelope). Measured and modelled anomalies for 2000 are shown with black and orange bars, respectively. Projected warming for 2091 to 2100 for the B1, A1B and A2 scenarios are indicated by the blue, yellow and red bars, respectively at the right (data from Christensen et al., 2007: Box 11.1 Figure 1).*

14.6 Case studies

Many of the topics discussed in this chapter have important dimensions, including interactions with other sectors, regions and processes, that make them difficult to assess from the perspective of a single sector. This chapter develops multi-sector case studies on three topics of special importance to North America – forest disturbances (see Box 14.1), water resources (using the Columbia River as an example) (see Box 14.2) and coastal cities (see Box 14.3).

14.7 Conclusions: implications for sustainable development

Climate change creates a broad range of difficult challenges that influence the attainment of sustainability goals. Several of the most difficult emerge from the long time-scale over which the changes occur (see Section 14.3) and the possible need for action well before the magnitude (and certainty) of the impacts is clear (see Section 14.5). Other difficult problems arise from the intrinsic global scale of climate change (EIA, 2005b). Because the drivers of climate change are truly global, even dedicated action at the regional scale has limited prospects for ameliorating regional-scale impacts. These two sets of challenges, those related to time-scale and those related to the global nature of climate change, are not in the classes that have traditionally yielded to the free-market mechanisms and political decision making that historically characterise Canada and the U.S. (see Section 14.5). Yet, the magnitude of the climate change challenge calls for proactive adaptation and technological and social innovation, areas where Canada and the U.S. have abundant capacity. An important key to success will be developing the capacity to incorporate climate change information into adaptation in the context of other important technological, social, economic and ecological trends.

The preceding sections describe current knowledge concerning the recent climate experience of North America, the impacts of the changes that have already occurred, and the potential for future changes. They also describe historical experience with and future prospects for dealing with climate impacts. The key points are:

- North America has experienced substantial social, cultural, economic and ecological disruption from recent climate-related extremes, especially storms, heatwaves and wildfires [14.2].
- Continuing infrastructure development, especially in vulnerable zones, will likely lead to continuing increases in economic damage from extreme weather [14.2.6, 14.4.6].
- The vulnerability of North America depends on the effectiveness of adaptation and the distribution of coping capacity, both of which are currently uneven and have not always protected vulnerable groups from adverse impacts of climate variability and extreme weather events [14.5].
- A key prerequisite for sustainability is 'mainstreaming' climate issues into decision making [14.5].
- Climate change will exacerbate stresses on diverse sectors in North America, including, but not limited to, urban centres, coastal communities, human health, water resources and managed and unmanaged ecosystems [14.4].
- Indigenous peoples of North America and those who are socially and economically disadvantaged are disproportionately vulnerable to climate change [14.2.6, 14.4.6].

14.8 Key uncertainties and research priorities

The major limits in understanding of climate change impacts on North America, and on the ability of its people, economies and ecosystems to adapt to these changes, can be grouped into seven areas.

- Projections of climate changes still have important uncertainties; especially on a regional scale (Christensen et al., 2007: Section 11.5.3). For North America, the greater uncertainty about future precipitation than about future temperature substantially expands the uncertainty of a broad range of impacts on ecosystems (see Section 14.4.2), hydrology and water resources (see Sections 14.4.1, 14.4.7), and on industries (see Sections 14.4.6, 14.4.7).
- North American people, economies and ecosystems tend to be much more sensitive to extremes than to average conditions [14.2]. Incomplete understanding of the relationship between changes in the average climate and extremes (Meehl et al., 2007: Section 10.3.6; Christensen et al., 2007: Section 11.5.3.3) limits our ability to connect future conditions with future impacts and the options for adaptation. There is a need for improved understanding of the relationship between changes in average climate and those extreme events with the greatest potential impact on North America, including hurricanes, other severe storms, heatwaves, floods, and prolonged droughts.
- For most impacts of climate change, we have at least some tools for estimating gradual change (see Section 14.4), but we have few tools for assessing the conditions that lead to tipping points, where a system changes or deteriorates rapidly, perhaps without further forcing.
- Most of the past research has addressed impacts on a single sector (e.g., health, transportation, unmanaged ecosystems). Few studies address the interacting responses of diverse sectors impacted by climate change, making it very difficult to evaluate the extent to which multi-sector responses limit options or push situations toward tipping points (see Section 14.4.9).
- Very little past research addresses impacts of climate change in a context of other trends with the potential to exacerbate impacts of climate change or to limit the range of response options (see Section 14.4.9) (but see Reid et al., 2005 for an important exception). A few North American examples of trends likely to complicate the development of strategies for dealing with climate change include continuing development in coastal areas (see Section 14.2.3), increasing demand on

freshwater resources (see Section 14.4.1), the accumulation of fuel in forest ecosystems susceptible to wildfire (see Box 14.1), and continued introductions of invasive species with the potential to disrupt agriculture and ecosystem processes (see Section 14.2.2, 14.2.4). In the sectors that are the subject of the most intense human management (e.g., health, agriculture, settlements, industry), it is possible that changes in technology or organisation could exacerbate or ameliorate impacts of climate change (see Section 14.4.9).

- Indirect impacts of climate change are poorly understood. In a world of ever-increasing globalisation, the future of North American people, economies and ecosystems is connected to the rest of the world through a dense network of cultural exchanges, trade, mixing of ecosystems, human migration and, regrettably, conflict (see Section 14.3). In this interconnected world, it is possible that profoundly important impacts of climate change on North America will be indirect consequences of climate change impacts on other regions, especially where people, economies or ecosystems are unusually vulnerable.
- Examples of North American adaptations to climate-related impacts are abundant, but understanding of the options for proactive adaptation to conditions outside the range of historical experience is limited (see Section 14.5).

All of these areas potentially interact, with impacts that are unevenly distributed among regions, industries, and communities. Progress in research and management is occurring in all these areas. Yet stakeholders and decision makers need information immediately, placing a high priority on strategies for providing useful decision support in the context of current knowledge, conditioned by an appreciation of the limits of that knowledge.

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