IPCC WGII Fourth Assessment Report – Draft for Government and Expert Review

Chapter 14 – North America

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Contents

Executive Summary

North America has already experienced substantial ecosystem, social, and cultural disruption from recent climate extremes (high confidence). Experience with recent hurricanes, wildfires, and other extreme events highlights the vulnerabilities within North America (high confidence) [14.2].

Economic damage from extreme weather will continue increasing, with direct and indirect consequences of climate change playing a growing role (high confidence)**.** Over the past five decades, economic damage from severe weather has increased dramatically due largely to an increase in the value of infrastructure at risk (very high confidence) [14.2]. Annual average costs to North America will continue to be billions of dollars in damaged property and economic productivity, as well as lives disrupted and lost (very high confidence). [14.2.6, 14.4.6]

The vulnerability of North America depends not only on temperature precipitation, water balance, storm intensity, sea level rise and other changes but also on the effectiveness and timing of adaptation and the distribution of coping capacity, which varies among sub-regions and sectors (high confidence) [14.4]. Inertia in the political, economic, and cultural systems, plus the long life of capital stock, requires near-term action to avoid costly retrofits in coming decades.

North America has considerable adaptive capacity, but this capacity has not always protected its populations from adverse impacts of climate variability and extreme weather events (very high confidence). Cultural traditions and institutions in North America have yielded a decentralized response framework where climate is not a central concern. North America has responded to climate experience, but the responses have often been reactive, unevenly distributed, or focused on coping with rather than preventing problems (high confidence). A key prerequisite for sustainability is mainstreaming climate issues into decision making [14.5, 14.7].

Climate change will exacerbate stresses on infrastructure and human well-being in urban centres (high confidence)**.** Climate impacts in urban areas will be compounded by urban heat islands, air pollution, aging infrastructure, maladapted urban form and building stock, water quality and supply challenges, and population growth, and a growing elderly population (high confidence) [14.4.6]. Early action can play an important role in increasing resilience (Box 14.5).

Coastal communities and habitats will be further stressed by climate change impacts interacting with development and pollution (high confidence) [14.4.3]. Sea level is rising along much of the coast, and the rate will increase in the future, exacerbating the impacts of progressive inundation, storm-surge flooding, and shoreline erosion (very high confidence) [14.2.3, 14.4.3]. Increased intensity and frequency of storms are likely to add to the severity of impacts (medium confidence). Salt marshes, other coastal habitats and dependent species are threatened by sea-level rise, fixed structures blocking landward migration, and changes in vegetation (high confidence). Population growth and rising value of infrastructure in coastal areas increases vulnerability to climate variability and future climate change (high confidence) [14.2.3, 14.4.3]. Adaptation to coastal hazards is often inadequate, due in part to ignoring the risks and conflicting objectives among decision-makers (high confidence) [14.2].

Warm temperatures and extreme weather already affect human health via heat-related mortality, pollution, storm-related fatalities and injuries, and infectious diseases (very high confidence) [14.2.5]. Heat wave deaths are very likely to increase (high confidence). Waterborne diseases and degraded water quality are very likely to increase with greater rainfall runoff (high confidence) [14.4.1]. Warming and climate extremes are likely to increase respiratory illness, including exposure to pollen (medium confidence). High temperatures and/or droughts are likely to increase risk of vector-borne infectious diseases (low confidence). Lyme disease-carrying tick populations will likely spread northwards (medium confidence). The magnitude of these climate-related health impacts also depends on local non-climatic factors, including accessibility of health care and early warning and response capabilities [14.2.5, 14.4.5].

Indigenous peoples of North America experience substantial impacts from climate-related events, including disruption of the ecological, economic, and cultural resource base (high confidence)**.** These communities will be among those most vulnerable to future climate change [14.2.6, 14.4.6].

Hardships from extreme events disproportionately affect those who are socially and economically disadvantaged (high confidence)**,** as shown by recent hurricanes. This pattern is likely to persist and, when coupled with climate change, reduce the overall well-being of the most vulnerable populations (medium confidence) [14.2.6, 14.4.6].

Climate change will constrain North America's already heavily managed water resources (high confidence)**.** Diminishing snowpack and glacier storage will affect timing and availability of water and intensify competition among uses (high confidence) [Box 14.2, 14.4]. Warming also adds additional stress on groundwater availability, compounding effects of higher demand from economic development and population growth (medium confidence) [14.4]. In the Great Lakes-St. Lawrence system, lower lake levels are likely to exacerbate issues of water quality, navigation, hydropower generation, water diversions, and binational cooperation (high confidence).

Impacts on agriculture from climate change and elevated CO_2 will be positive overall, but with important variation among sub-regions and sub-sectors (medium confidence). These will be strongly modulated by changes in technology, biotechnology, and water availability (high confidence). Adaptation is likely to be most challenging in regions that depend on irrigation, long-lived perennial crops, or crops with high cultural and tourism value (medium confidence) [14.4.4, 14.5.4].

Disturbances like wildfire and insect outbreaks are increasing and are likely to intensify in a warmer future with drier soils and longer growing seasons (high confidence) [14.4.2, Box 14.3]**.** Over the 21st century, the tendency for species and ecosystems to shift north and to higher elevations will fundamentally rearrange the map of North American ecosystems (medium confidence). Recent climate trends have increased ecosystem net primary production, and this trend is likely to continue for the next few decades (high confidence) [14.2.2]. Continuing increases in disturbances are likely to limit carbon storage, facilitate invasives, and amplify the potential for major changes in ecosystem services (medium confidence) [14.4.2].

Introduction

The United States (U.S.) and Canada will experience one set of climate changes through direct effects of local changes e.g., temperature, precipitation, and extreme weather events and other indirect impacts, telegraphed 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 synthesizes the state of knowledge on both direct and indirect impacts, vulnerability and adaptations for North America (comprised of Canada and the U.S as Mexico and Central America are treated in chapter 13 on Latin America). Chapter 15, on Polar Regions, covers high latitude issues and peoples in greater detail than this chapter. Structurally, this chapter is parallel to the other regional chapters in this volume.

14.1 Summary of knowledge assessed in the TAR

14.1.1 Key findings from TAR

Key findings for the North America Chapter of the TAR are summarized as a reference from which to elaborate new knowledge for this Chapter.

Resources and ecosystems

- In western snowmelt-dominated watersheds, shifts in seasonal runoff are likely, with more runoff occurring in winter. Adaptive measures may not fully offset effects of reduced summer water availability for water uses and ecosystems.
- The abundance and spatial distribution of species important to commercial and recreational fisheries may be affected by impacts on coastal and marine ecosystems.
- Warming generally benefits food production in North America but there will be strong regional effects with changes in comparative advantage.
- Economic studies have probably overestimated negative effects of climate change on agriculture as they have not accounted for farm- and market-level adjustments.
- The areal extent and productivity of forests are expected to increase, though carbon stocks could increase or decrease.
- Disturbance factors will have a range of effects on forest ecosystem structure. The forest fire season is likely to start earlier, and the area subject to high to extreme fire danger may increase significantly.
- Losses of coldwater ecosystems, high alpine areas, and coastal and inland wetlands are possible.

Human settlements and health

- Northern cities may contend with fewer periods of extreme winter cold. 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.
- Changes in the frequency/intensity/duration of heavy precipitation events may require changes in land-use planning and infrastructure design to avoid increased damages.
- Adapting infrastructure can reduce vulnerability but certain communities may not have the necessary resources.
- More frequent extreme events may increase deaths, injuries, infectious diseases, and stress-related disorders and other adverse health effects associated with social disruption and migration.
- Increased frequency and severity of heat waves may lead to more illness and death, particularly among the young, elderly, and frail. Respiratory disorders may be exacerbated by warming-induced deterioration in air quality.
- Vector-borne and tick-borne diseases may expand their ranges in North America but public health measures and other socioeconomic factors influence the existence or extent of such diseases.

Vulnerability and adaptation

- Weather-related losses have been increasing in North America since the 1970s; rising insured losses reflect growing affluence and continued movement of populations into vulnerable areas.
- Since the 1980s, Canadian government disaster relief programs have covered roughly 86% of flood losses. U.S. government crop and flood insurance programs may have encouraged more human activity in at-risk areas.
- Insurers have responded to recent extreme events by limiting insurance availability, increasing prices and establishing new risk-spreading mechanisms. Advancing building codes, land use planning and disaster preparedness also reduce disaster losses.
- Climate-related impacts are likely to require substantial changes in institutions and infrastructure. Developing adaptation responses requires a long process of interdisciplinary and intercultural dialogue between researchers and stakeholders.
- Emerging adaptation strategies generally address current challenges, but there are few cases of implementing adaptation to meet future impacts and opportunities.

14.1.2. Key differences from TAR

This assessment builds upon the findings from the TAR and incorporates new insights gained from reviewing the literature including recognition of:

- A tendency for models to project future warming with more droughts, leading to increasing severity of water resource shortages.
- Impacts on water resources now include impacts on groundwater and water quality, as well as surface water.
- The critical role of ecological disturbance (fire, insects, land management) at regional and continental scales as both a climate impact and a climate feedback.
- The role of multi-factor, interacting impacts which may lead to tipping points.
- The interactions among climate change impacts and other kinds of local, regional, and global changes.
- The role of adaptation and adaptive capacity, and its contribution to modulating impacts.
- The continuum between current vulnerabilities, adaptive capacity, and long-term adaptation.

14.2 Current sensitivity/vulnerability

Annual mean air temperature for Canada (south of 60°N) increased 0.9°C from 1900-1998 and in the conterminous U.S., the increase was 0.6°C/100 yrs from 1895-2002 (Fig. 14.1) (Zhang et al., 2000c; Groisman et al., 2004). Regional variation is strong, with accelerated warming in the Arctic (see Chapter 15). The most warming has occurred in spring and winter (Karl et al., 1996; Bonsal et al., 2001), and minimum daily temperatures have warmed more rapidly than maximum (Easterling et al., 1997; Zhang et al., 2000c; Bonsal et al., 2001). 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 from earlier spring warming (Bonsal et al., 2001; Easterling, 2002; Bonsal and Prowse, 2003; Feng and Hu, 2004). The largest increase was in the western U.S. The warming in North America during the latter half of the 20th century reflects the combined influence of greenhouse gases sulphate aerosols, and natural variation (Karoly *et al.*, 2003; Stott, 2003; Zwiers and Zhang, 2003).

Total annual precipitation increased 5-30% across most of southern Canada (1900-1998) (Zhang *et al.*, 2000c) and 7% in the U.S. (1895-2002) (Groisman *et al.*, 2004). Heavy precipitation frequencies in the U.S. were at a minimum in the 1920s and 1930s, and increased to the 1990s (1895-2000) (Groisman et al., 2004; Kunkel et al., 2004), a pattern not repeated in Canada (Zhang *et al.*, 2000b).

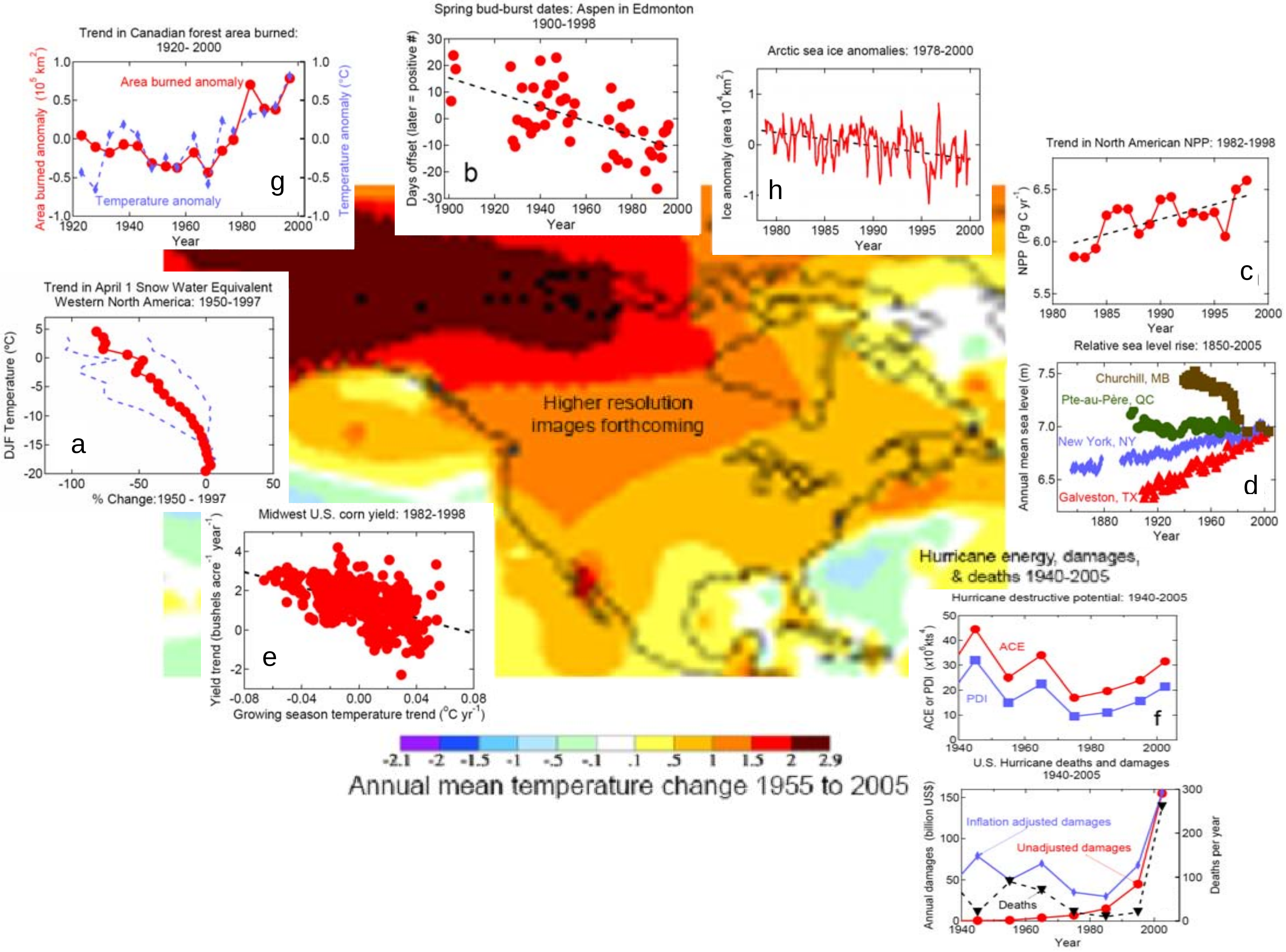

Fig. 14.1: *Background: annual average temperate change from 1955 to 2005. Insets: (a) trend in April 1 snow water equivalent across western North America from 1950-1997, plotting midwinter temperature against % change (modified from (Mote et al., 2005)), (b) Spring bud-burst dates for aspen in Edmonton since 1900 (modified from (Beaubien and Freeland, 2000)), (c) trend in North American net primary production (NPP) from 1981 to 1998 (modified from (Hicke et al., 2002)), (d) relative sea level rise from 1850-2000 for Churchill, MB, Pte-au-Pere, QB, New York, NY, and Galveston, TX, (e) response of corn yield to temperature anomalies in the Midwest U.S. from 1981-1998 (modified from (Lobell and Asner, 2003)), (f) hurricane energy (ACE and PDI), economic damages, and deaths from Atlantic hurricanes since 1940 (modified from (Emanuel, 2005a) (NAST (National Assessment Synthesis Team), 2001), (g) area burned annually in wildfires in Canada since 1930, plus observed and modelled summer temperature (modified from (Gillett et al., 2004)), and (h) anomalies in the area of Arctic sea ice since 1978 (modified from (ACIA, 2004)).*

The frequency and duration of North Atlantic hurricanes increased significantly from 1970 to 2004 (Webster *et al.*, 2005). Energy released per storm (a function of wind speed and duration) has more than doubled in the last 30 years (Emanuel, 2005b), with a larger number of powerful category 4 and 5 storms (Webster *et al.*, 2005). Thunderstorms and hail activity peaked in 1936-1955, followed by a moderate decrease (Changnon and Changnon, 2000) (Changnon and Changnon, 2001). There has been no clear trend in the number of strong tornadoes (F-3 or greater on the Fujita scale) (Grazulis, 2001; Hage, 2003). Damaging winter storms such as Nor'easters on the east coast of North America have not been increasing (Hirsch *et al.*, 2001; Hage, 2003). Rising damages from these events may be explained in part by changes in the value and exposure of coastal developments (Kunkel *et al.*, 1999). Incidence of freezing rain has complex local patterns but no general increase (Changnon and Bigley, 2005). Intensity of heavy rains from thunderstorms has increased (Changnon, 2001; Adamowski and Bougadis, 2003; Groisman, 2005; Stone, 2005)(WGI Chapter 3).

14.2.1 Freshwater Resources

During the last few decades of the 20th century, a greater proportion of the U.S. was either in severe drought or severe moisture surplus (Dai *et al.*, 2004). Areas in southern Canada affected by extreme dry and by extreme wet summer conditions both increased between 1900-49 and 1950-98 (Zhang *et al.*, 2000b). Streamflow has *increased* 25% in the last 60 years over the eastern U.S. (Groisman *et al.*, 2004), but has *decreased* in the western North America by about 2%/decade in the last century (Rood *et al.*, 2005). Walter *et al.* (Walter *et al.*, 2004) calculate that evapotranspiration (ET) increased by 55mm in the last 50 years in the conterminous U.S.; in addition, their data show reduced stream discharge in the Colorado and Columbia river basins since 1950.

In snow melt regions, temperature increase has shifted the magnitude and timing of hydrologic events (Mote et al., 2005; Regonda et al., 2005; Stewart et al., 2005). A greater fraction of annual precipitation is falling as rain rather than snow at 74% of the weather stations studied in the western mountains of the U.S. (Knowles *et al.*, 2005). Since the 1970s, winter snow depth and spring snow cover have decreased in Canada, particularly in the west, where air temperatures have consistently increased (Brown and Braaten, 1998). Spring and summer snow cover is decreasing in the U.S. west (Groisman *et al.*, 2004). April 1 snow water equivalent (SWE) decreased 15-30% since 1950 in the western mountains of North America particularly at lower elevations in spring, and primarily due to warming rather than changes in precipitation (Mote *et al.*, 2003; Mote *et al.*, 2005) (Fig.14.1a). Whitfield and Cannon (2000) reported an earlier onset of runoff and Zhang *et al.* (2001) mapped a significant trend in earlier occurrence of the spring runoff across Canada, and declining annual flows across southern Canada. Schindler and Donahue (2006) found summer (May –August) flows of the Athabasca River, the largest free-flowing river in western Canada declined 20% since 1958. Stewart *et al.* (2005) found streamflow peaks in the snowmelt dominated western mountains of the U.S. occurred 1-4 weeks earlier by 2002 than in 1948. River and lake ice break up dates advanced by 0.2 – 12.9 days in North America over the last 100 years (Magnuson *et al.*, 2000).

14.2.2 Ecosystems

Three direct and 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 geographic distribution. Direct impacts on organisms interact with indirect effects of ecological mechanisms (competition, herbivory, disease), and disturbance (wildfire, human activities).

Phenology, Productivity and Biogeography

Global daily satellite data, since 1981, indicates earlier onset of spring "greenness" by 10-14 days in

19 years, particularly over temperate latitudes of the northern hemisphere (Myneni *et al.*, 2001; Lucht *et al.*, 2002). Field studies confirm these satellite observations (Fig. 14.1b). Many species are leafing flowering earlier, including lilac blooms (1.8 days/decade, 1959-1993, 800 sites across North America)(Schwartz and Reiter, 2000)), honeysuckle blooms (3.8 days/decade, western U.S.) (Cayan *et al.*, 2001), apple and grape leaf onset (2 days/decade, 72 sites in northeastern U.S.) (Wolfe *et al.*, 2005), and aspen bud-burst (2.6 days/decade since 1900, Edmonton) (Beaubien and Freeland, 2000). The timing of Autumn leaf senescence, which is controlled by a combination of temperature, photoperiod and water deficits, shows weaker trends (Badeck *et al.*, 2004).

Net primary production (NPP) in North America increased nearly 10% from 1982-1998 (Fig. 14.1c), with the largest increases in the central plains croplands and grasslands due to improved water balance (Lobell *et al.*, 2002; Nemani *et al.*, 2002; Hicke and Lobell, 2004). Higher NPP in northern Rocky Mountain forests was attributed to warmer spring temperatures and a longer growing season (Hicke and Lobell, 2004).

Wildfire and epidemics of insects and disease are major, potentially climate-change-sensitive, controllers of North American forest processes. The area burned in wildfires has increased dramatically over the last 3 decades (Box 14.1).

Box 14.1: Wildlife Population and Community Dynamics

North American wildlife 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 10-13 days earlier than a century ago (Gibbs and Breisch, 2001). In lowland California, 70% of 23 butterfly species begin first spring flights an average 24 days earlier (Forister and Shapiro, 2003). Climate-induced reduction in water depth at western toad egg-laying sites in Oregon has increased exposure of eggs to UV-B, leading to an increase in mortality from a fungal parasite (Kiesecker *et al.*, 2001; Pounds, 2001).

North American species with documented range shifts include Edith's checkerspot butterfly, which has become locally extinct in the southern, low elevation portion of its western North American range but has extended its range 90km north and 120m higher in elevation (Parmesan, 1996; Parmesan and Galbraith, 2004) (Crozier, 2003). Red foxes have expanded northward in northern Canada, leading to retreat of competitively subordinate arctic foxes (Hersteinsson and Macdonald, 1992). Fire ants, introduced from South America, have spread throughout the southeastern U.S., damaging crops and other plants, displacing native ants and other invertebrates, causing nest failure and mortality in birds and mammals, and disrupting mutualistic interactions (Holway *et al.*, 2002).

14.2.3 Coastal regions

With more than 400 000 km of coast, 61% in Canada and 39% in the U.S., North America has a diversity of coastal environments (Shaw *et al.*, 1998; Scavia *et al.*, 2002). Relative sea level is rising slowly on some parts of the Pacific coast and more rapidly along the U.S. Gulf and Atlantic coasts, and in the Canadian Atlantic Provinces (Fig. 14.1d) (Shaw *et al.*, 1998; Zervas, 2001). Relative sea level is falling where there is crustal uplift, including Hudson Bay and some Pacific coast sites (e.g. Vancouver Island) (Dyke and Peltier, 2000; Forbes, 2004; Andalo *et al.*, 2005). Even where sea level has been rising over the past 100 years (Zervas, 2001; Forbes, 2004), most coastal residents are unaware of the trends and their impacts, including coastal retreat and more frequent flooding (O'Reilly *et al.*, 2005). In the Great Lakes, low and high water levels have affected erosion, hydro-power production, navigation and boating, water supply, and wetland ecosystems (Moulton and Cuthbert, 2000)

Many parts of the Atlantic and Gulf of Mexico coasts in the U.S. and the Gulf of St. Lawrence in Canada, are at risk of inundation by storm surges. Of 56 000 km^2 less than 1.5 m above sea level in the U.S. south and east (Titus and Richman, 2001) 75% is wetland and 5% urban and residential with a population of approximately two million (Titus, 2005). Some major urban centres on large deltas are below maximum sea level (e.g. New Orleans on the Mississippi; Richmond and Delta on the Fraser), exposing large populations to flooding hazards. Breaching of New Orleans floodwalls following passage of Hurricane Katrina in 2005 (RMS, 2005b; Select Bipartisan Committee, 2006), and suburban flooding following storm-wave breaching of a dike in Delta BC in early 2006 demonstrate the vulnerability.

Demand for waterfront real estate continues to grow (Small and Nichols, 2003), increasing the value of property at risk (Heinz Center, 2000; Forbes et al., 2002b) in the U.S. and Canada. During severe El Niño conditions, high water levels combined with changes in winter storm tracks along the Pacific Coast can produce severe coastal flooding, and wave and erosion impacts (Griggs and Brown, 1998; Komar et al., 2000; Scavia et al., 2002; Walker and Barrie, 2004; Abeysirigunawardena and Walker, 2006) . At San Francisco, 140 years of tide gauge data suggest an increase in extreme winter storm events since 1950 (Bromirski *et al.*, 2003). Several villages on Alaska's west coast are sufficiently threatened by increased erosion and inundation that they must be protected or relocated. Present plans include constructing a $4-$6M sea wall in Shishmaref (a 10-15 year interim solution), and relocating Kivalina to higher ground at an estimated cost of $54M (Parson *et al.*, 2001a). Recent damaging hurricanes, in Nova Scotia (2003) and the southern U.S. (2004, 2005) demonstrate that North American urban centres with assumed high adaptive capacity remain vulnerable to severe weather and storm surges. This vulnerability also extends to impacts of major extratropical storms in northern areas such as Atlantic Canada and the Pacific coast (Walker and Barrie, 2004)(Forbes et al., 2002b; Forbes et al., 2004; O'Reilly et al., 2005). Winter sea ice can provide seasonal shore protection, but ice can also cause severe damage to shorefront homes and infrastructure (Forbes *et al.*, 2002a; Forbes, 2004). Recent winters with less ice in the Great Lakes and Gulf of St. Lawrence have increased coastal exposure to damage from winter storms (Mick, 2006).

Impacts on coastal communities and ecosystems can be more severe when major storms recur in short intervals, allowing little opportunity to rebuild natural resilience or reduce exposure (Forbes *et al.*, 2004). Adaptation to coastal hazards under 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 in coastal ecosystems (Scavia *et al.*, 2002; Burkett *et al.*, 2006) including shoreline development and associated nitrogen eutrophication (Bertness *et al.*, 2002). Already, more than 50% of the original tidal salt marsh habitat in the U.S. has been lost (Kennish, 2001). Accelerating sea-level rise, can lead to 'coastal squeeze' where shore protection structures or fill prevent landward migration of a salt marsh and submergence, where rates of vertical marsh accretion cannot keep pace with sea level rise (Kennish, 2001; Kennish, 2002; Scavia *et al.*, 2002; Chmura and Hung, 2004; Titus, 2005)(see 14.4.3). Mid- to high marsh species in some parts of New England are increasingly vulnerable to drowning under future sea-level rise (Donnelly and Bertness, 2001).

14.2.4 Agriculture, Forestry, and Fisheries

Agriculture

Over the last century, yields of major commodity crops in North America have increased consistently, typically at rates of 1-2%/yr (Troyer, 2004). These yield trends are a result of changes in technology, fertilizer, and seed stocks, plus any changes due to climate. In the Midwestern U.S. from 1970-2000 corn yield increased 58% (Fig. 14.1e) and soybean yields increased 20%, with annual weather fluctuations resulting in year-to-year variability (Hicke and Lobell, 2004). Heavy rainfalls have reduced the value of the U.S. corn crop by an average of $20 billion/yr between 1951 and 1998 (Rosenzweig *et al.*, 2002). In the corn and wheat belt of the U.S. over the period from 1982-1998, yields of corn and soybeans decreased by 17% for each 1ºC 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). 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 but negative for avocados and cotton (Lobell *et al.*, 2005).

North American agriculture has been exposed to multiple severe weather events during the past decade. More variable weather coupled with out-migration from rural areas and economic stresses on the agricultural sector have 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). North American agriculture is dynamic, and adaptation to change, including climate change, 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 *et al.*, 2005) Recent adaptations by the agricultural sector in North America are not typically a single discrete action (as is often implied within adaptation modelling studies) but a set of decisions that can transcend multiple years and occur in a dynamic and changing environment (Smit and Skinner, 2002) including changes in public policy (Goodwin, 2003). While there have been a few attempts to capture the dynamics of adaptation within a climatic change context (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 (<1%/decade) in regions where tree growth has historically been limited by low temperatures and short growing seasons (Casperson *et al.*, 2000; McKenzie *et al.*, 2001; Joos *et al.*, 2002). Black spruce at the forest-tundra transition in eastern Canada shows acceleration of height growth, beginning in the 1970s (Gamache and Payette, 2004). Growth is slowing, however, in areas subject to drought. Radial growth of white spruce on dry south slopes in Alaska has decreased over the last 90 yr due to increased drought stress (Barber *et al.*, 2000). Semi-arid forests of the southwestern U.S. also show a decreasing growth trend since 1895, correlated with drought from warming temperatures (McKenzie *et al.*, 2001). Relationships between tree-ring growth and climate from 1895-1991 had complex topographic influences in subalpine forests in the Pacific Northwest (Peterson and Peterson, 2001; Peterson *et al.*, 2002). On high elevation north aspects, growth of subalpine fir and mountain hemlock was negatively correlated with spring snowpack depth and positively correlated with summer temperatures, indicating growing season temperature limitations. However, on lower elevation sites, 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 W.L.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 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 First Nations peoples often taking a major role. Recreational inland fisheries are also significant and increasing (DFO-MPO, ; USDOI-FWS, 2002). Climate change increasingly has both direct and indirect impacts through interactions 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 homogenization due to invasions and introductions (Rahel and McGinn, 2002), and overexploitation (Post et al., 2002; Cooke and Cowx, 2004) Salmonids are the most vulnerable and most valued group of fish species. The sea-run salmon stocks are already in steep decline throughout 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 (K., 2002). Lake Char in an Ontario lake suffered recruitment failure due to El Nino-linked warm temperatures (Gunn, 2002). 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.*, 2004).

Ecological sustainability of fishes and fisheries productivity is closely tied to temperature and water supply (flows, and lake levels). Lake Ontario year-class productivity is strongly linked to temperature, with a shift in favour of warm water species (Casselman, 2002). Walleye yield in lakes is predicted by thermal-optical habitat supply (Lester *et al.*, 2004). Northern pike abundance depends on thermal habitat supply in Minnesota lakes (Pierce and Tomcko, 2005). The maximum size and age at maturity of yellow perch scale with growing degree-days greater than 5^{o}C in Ontario lakes (Purchase *et al.*, 2005), with similar controls in many other fishes. Success of spawning and young-of-the-year brook trout is closely linked to groundwater seeps, which provide preferred temperature refuges for lake-dwelling populations (Borwick *et al.*, 2006). Fish egg development and mortality rates increase as temperatures rise within species-specific tolerance ranges (Kamler, 2002).

14.2.5 Human Health

Many prevalent human diseases are sensitive to climate fluctuations, from cardiovascular mortality and respiratory illnesses due to heat waves, to altered transmission of infectious diseases. Synergistic effects of other activities can exacerbate climate 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 to changing climatic conditions. In the early 1990s, California experienced an epidemic of Valley Fever that followed five years of drought (Kolivras and Comrie, 2003). Waterborne disease outbreaks from all causes in the U.S. are distinctly seasonal, clustered in key watersheds, and associated with heavy precipitation (Curriero *et al.*, 2001). In May, 2000, an estimated 2,300 people became ill and 7 died from exposure to *E. coli* 0157:H7 and *Campylobacter jejuni* in the drinking water of Walkerton, Ontario (Holme, 2003) (Hrudey *et al.*). 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 the 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.*, 2005). This trend is independent of seasonal effects.

Many zoonotic diseases (with a natural life cycle in animals) 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 2002-2004 in the U.S. were linked to above-average temperatures (Reisen *et al.*, 2006). Lab studies of virus replication in the major mosquito vector, *Culex pipiens L* show high viral titers in mosquitoes held at warmer temperatures (Dohm and Turell, 2001; Dohm *et al.*, 2002). An outbreak of West Nile encephalomyelitis in horses in the U.S. Midwest peaked with high temperatures and significantly dropped following cooler temperatures, suggesting a temperature effect (Ward *et al.*, 2004). Bird migratory pathways and WNVs recent march westward across the U.S. and Canada are key factors as well, and must be considered in future assessment of temperature's role in disease dynamics. A virus closely related to WNV, Saint Louis encephalitis (SLE), tends to appear during hot, dry La Niña years, when conditions facilitate transmission by reducing the extrinsic incubation period (Cayan *et al.*, 2003).

Lyme disease is a prevalent zoonotic disease in the North America for which there is new evidence of an association with temperature (Ogden *et al.*, 2004). In the field, temperature and vapour pressure contribute to population maintenance of the tick, *Ixodes scapularis,* which functions as the microorganism's secondary host in the U.S. An average monthly minimum temperature threshold above -7ºC is required for tick survival (Brownstein *et al.*, 2003).

Heat response plans and heat early warning systems (EWS) can save lives. After the 1995 heat wave, 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 a "synoptic-based" weather watch-warning system, which focuses on monitoring for dangerous air masses (Sheridan and Kalkstein, 2004). EWS for infectious diseases are not yet proven. Improving their predictive accuracy will require integrating both climatic and non-climatic determinants.

14.2.6 Human Settlements

Research published since the TAR provides further evidence that human settlements in North America are sensitive to climate variability and trends (e.g., loss of resource base), both through effects of warming or precipitation on infrastructure (e.g., permafrost melting or drought), and through direct and indirect impacts of extreme events.

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 (Chapter 15). The U.S. federal government recognizes more than 565 tribal and Alaska Native governments as "domestic dependent nations." 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 indigenous government program budgets depend heavily on agriculture, forest products, and cultural-, ecological-, or recreation-based tourism, which are likely to be affected by climate change (NAST (National Assessment Synthesis Team)). A 1993 hantavirus outbreak related indirectly to heavy rainfall led to a significant reduction in tourist visits to the Southwest, especially Pueblo areas (NAST (National Assessment Synthesis Team), 2000). Native water rights are established in a variety of treaties, agreements, and court decisions but climate change may complicate exercise of these rights (NAST (National Assessment Synthesis Team)). 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 travel, 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; ACIA, 2004). In the North, there may be limited ability to exploit new resources or economic opportunities (Moser, 2005; ACIA, 2004).

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). Still, not all communities have suffered as some Alaskan fishing communities have benefited from warmer waters and rising salmon stocks since 1977 (CDLI, 1996)

Infrastructure and Extreme Events

About 80% of North Americans live in urban areas (U.S. Census Bureau, 2000; Statistics Canada, 2001). North American cities, while diverse in size, function, climate, and other factors, have a common operational "style" that influences how climate change affects them. Primarily based on the automobile, and low-rise, low-density living and sprawling infrastructure, these cities are largely shielded from the natural environment by technical systems designed for high throughput of water, energy, and materials. The devastating effects of hurricane Ivan in 2004 and Katrina, Rita, and Wilma in 2005, illustrate that North American infrastructure and urban systems are vulnerable to events beyond their design thresholds (RMS (Risk Management Solutions), 2005). When protective systems fail, the impacts can be widespread and multidimensional, affecting local, regional and national systems through effects on waterborne transportation and supply of oil and natural gas (Business Week, 2005; EEA, 2005; Levitan and Associates Inc., 2005; RMS (Risk Management Solutions), 2005). Costs include loss of lives (over 1300 in 2005), billions of dollars in damaged property (only some of which is insured), costs of decontamination and cleanup, loss of key facilities (e.g. hospitals and ports), business interruptions, continent-wide price increases for commodities such as oil and natural gas, and national-level price increases from the surge in demand for rebuilding supplies (RMS (Risk Management Solutions)). The federal impacts of Katrina and Rita so far have included the cost of emergency response during the storms and in the immediate aftermath, US$7.7 billion in emergency housing assistance, plus US$17 billion in National Flood Insurance Program claims to policyholders in Louisiana alone. Disproportionate impacts of Hurricane Katrina on the poor, infirm, elderly, and other dependent populations were amplified by inadequate public sector planning and/or execution of plans for evacuation and emergency services (Cutter, 2006; Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina U.S. House of Representatives (Select Committee), 2006).

Costs of weather-related natural disasters in North America rose at the end of the 20th century, mainly as a result of increasing value of infrastructure at risk (Changnon, 2001). Key factors in the increase in exposure include increased wealth, demographic shifts to coastal areas and urbanization in storm-prone areas, and aging infrastructure, sometimes with substandard structures and inadequate building codes (Easterling *et al.*, 2000; Balling and Cerveny, 2003; Changnon, 2003; Changnon, 2005). Trends in the number and intensity of extreme events in North America are variable, with many holding steady or even decreasing (Kunkel *et al.*, 1999; Balling and Cerveny, 2003; Changnon, 2003)(Section 14.3) (McCabe *et al.*, 2001)(WG1 Chapter 3).

North America could continue to suffer serious losses of life and property simply due to growth in property values and numbers of people at risk (Pielke Jr. *et al.*, 2005). Of the US$19 trillion value of all insured residential and commercial property in the U.S. states subject to North Atlantic hurricanes, US$7.2 trillion (41%) is located in coastal counties. This includes 79% of the property in Florida, 63% of the property in New York, and 61% or the property in Connecticut (AIR (Applied Insurance Research, 2002). Cumulative decadal hurricane intensity in the U.S. has risen in the last 25 years, following a peaked in the mid 20th century and a later decline (Fig. 14.1f). US Mortality from hurricanes in the 20th century is dominated by three storms: Galveston in 1900, Okeechobee in 1926, and Katrina in 2005 (Fig. 14.1f).

Flood hazards are, of course, not limited to the coastal zone. River basins with a history of major floods (e.g. the Sacramento (Miller, 2003), the Fraser (Loukas *et al.*, 2002), the Red River of the North (Simonovic and Li, 2004), the upper Mississippi (Allen *et al.*, 2003), and the Columbia) illustrate the sensitivity of riverine flooding to extreme events and highlight the critical importance of good infrastructure, planning, and forecasts (Pielke Jr., 1999).

14.2.7 Tourism and Recreation

The United States and Canada rank among the top ten nations for international tourism receipts (US$112 billion and US$16 billion, respectively (World Tourism Organization, 2002) with domestic tourism markets that are several times larger. Climate variability can potentially affect many segments of the tourism industry, but it impacts on the industry in North America have not been comprehensively analyzed (Scott *et al.*, 2005b).

Wildfires in Colorado (2002) and British Columbia (2003) clearly affected tourism. Colorado State Parks recorded a 30% decline in reservations (Butler, 2002), and Colorado River Outfitters Association experienced a 40% decline in business, with an estimated impact of US$50 million (Associated Press, 2002). Impacts in British Columbia included destruction of some tourism infrastructure and attractions, a decline in seasonal occupancy rates, and restricted access to some parks (BC Stats, 2003).

Drought in Colorado during the summer of 2002 restricted angling because fish were stressed by low water levels and high water temperatures (losses of US$50 million) (Kesmodel, 2002). Due to prolonged drought, water levels in the Lake Mead, the largest western U.S. reservoir with ten million visitors annually, have dropped nearly 30-m since 1999. Each six-metre reduction in water level costs US$6 million for adapting infrastructure (Allen *et al.*, 2003). With below average water levels in the Great Lakes during 1999-2002, a US$9.9 million programme assisted marina owners and operators with emergency dredging costs (Fisheries and Oceans Canada, 2000).

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 (United States Environmental Protection Agency, 1999). The economic impact of the four hurricanes that struck Florida in 2004 is estimated to be several times larger. Evacuees, however, generated an additional US$240 million in spending in nearby Alabama (Deravi and Smith, 2005). Hurricane Katrina caused extensive damage to tourism infrastructure in New Orleans, a major centre for business conventions and riverboat gambling (Bhatnagar, 2005).

14.2.8 Industry, energy supply

Empirical estimates of the costs of power outages in North America confirm their high cost (e.g., $30-130 billion annually in the U.S.) (EPRI, 2003; LaCommare and Eto, 2004). The multiple hurricane strikes in Florida in the summer of 2004 resulted in a direct system restoration costs of US$1.4 billion to the four Florida public utilities involved (EEI (Edison Electric Institute), 2005). Fourteen EEI member utilities experienced 81 other major storms between 1994 and 2004, which cost an average of US$49 million per storm. The highest impact of a single storm to EEI utilities was US$890 million (EEI (Edison Electric Institute), 2005). Data for 2005 are not yet available but are likely to dwarf current record values in destructiveness.

Although not triggered specifically by the concurrent hot weather, the 2003 summer outage in the northeast U.S. and southeast Canada illustrates the type of costs to North American society that result from large-scale power interruptions. 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. More than half of Ford Motor Company’s 44 plants in North America, plus major installations of other automakers in the Detroit area, were closed by the

2003 outage (Bradford, 2003). A recent survey of companies found that power outages cost half of the surveyed companies US$50,000 per hour of downtime, and over US$250,000 per hour in the top quartile (RMS, 2003).

The impacts of hurricanes Katrina, Rita, and Wilma in 2005 and Ivan in 2004 demonstrate that the Gulf of Mexico offshore oil and natural gas platforms and pipelines, petroleum refineries, and electrical and transportation infrastructure necessary to support the industry can be seriously harmed by major hurricanes and have recovery times stretching to months or longer (Business Week, 2005; EEA, 2005; EIA (U.S. Energy Information Administration), 2005b; Levitan and Associates Inc., 2005; RMS, 2005b; Swiss Re, 2005c; Swiss Re, 2005e; Swiss Re, 2005d; Swiss Re, 2005b).

14.3 Assumptions about future trends

14.3.1 Climate

The climate model simulations for the AR4 (Ruosteenoja *et al.*, 2003) indicate that by the 2010-2039 time slice, year-round temperatures across North America will be outside the range of natural variability, based on 1000-year AOGCM simulations with either the CGCM2 or HadCM3 climate models. For most combinations of model, scenario, season, and region, warming in the 2020 time slice is in the range of 1-3ºC. By the 2040-2069 time slice, winter warming across the northern part of the region is 2-6ºC, approximately twice as much as the summer months. In this mid-century time-slice, warming across the temperate and subtropical latitudes of North America is 1-5ºC in summer and winter. Regional differences in the seasonality of warming continue through the later decades of the century, with comparable summer and winter warming in the southern part of the region (2-8 ºC) but greater winter (2-10 ºC) than summer (1-7 ºC) warming at high latitudes. By the 2070 to 2099 time slice, a scenario with high emissions early in the century (A1FI) produces more warming than lower emissions scenarios (B1 and B2), especially after the 2010-2039 time slice.

Trends in precipitation are much less consistent. In the 2010-2039 time slice, no part of the region has changes in precipitation across models, scenarios, and seasons that are significantly outside the range of natural variation (Ruosteenoja *et al.*, 2003). Later in the century, changes in temperature and precipitation are positively correlated across the northern part of the region.

Timmerman *et al.* (Timmerman *et al.*, 1999) suggested that greenhouse forcing will result in more frequent El Niño-like warm conditions (but more intense La Niña cold intervals). This situation would favour less frequent (but possibly more intense) Atlantic hurricanes. However, this may be modulated by strong interdecadal variability related to other factors, whereby conditions of higher hurricane activity, such as 1941-1965 and the 1990s, may persist for decades (Bengtsson, 2001; Goldenberg *et al.*, 2001). Strong El Niño events are associated with increased precipitation and severe storms in some regions, such as the U.S. southeast, and higher precipitation in the Great Basin, 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).

14.3.2 Social, Economic, and Institutional Context

In recent years, Canada and the U.S. have faced a range of economic and geopolitical challenges that have put great pressure on government budgets, sharpening the discussion on the kinds of programs and strategies that are or are not within our means [ref]. Budget pressures associated with the costs of health care and an aging population are likely to intensify over several decades (Burleton, 2002). Future population growth driven mainly by immigration will create both opportunities and challenges, as citizens of both countries accommodate diverse cultures, backgrounds, economic resources, educational requirements, and aspirations for the future. Interests of indigenous peoples are important in both Canada and the U.S., especially in relation to questions of land management.

The economies of Canada and the U.S. are mostly based on activities with limited direct sensitivity to climate (Nordhaus, 2006). North America does, however, have massive agricultural (2004 value XXX billion US$) and transportation (2004 value XXX billion US$) sectors (discussed in section 14.4). Recent increases in the fraction of economic activity in the service and technology sectors have, in addition to decreasing direct sensitivity to climate change, led to substantial increases in the energy efficiency of GDP (Nakicenovic and Swart, 2000).

The economies of Canada and the U.S. are strongly based on free market mechanisms and the philosophy of private ownership. If strong trends toward globalization in the last several decades continue through the 21st century, it is likely that the means of productions, markets, and ownership will all be thoroughly international, with policies and governance increasingly designed for the international marketplace (Stiglitz, 2002). The implications of this for impacts of climate change on North America are far from clear.

14.4 Summary of expected key future sensitivities, vulnerabilities, impacts and adaptation options

14.4.1 Freshwater Resources

Freshwater resources are affected by climate change across Canada and the U.S., but the nature of the vulnerabilities varies from region to region (NAST, 2001; Parson et al., 2001a; NRCan (Natural Resources Canada), 2002; Adamowski and Bougadis, 2003; Environment Canada, 2004; Lemmen and Warren, 2004).

Surface water

Simulated annual water yield in basins shows regional changes that are linked to the precipitation patterns in the GCM and RCM scenarios (Stonefelt et al., 2000; Fontaine et al., 2001; Parson et al., 2001b; Stone et al., 2001; Adamowski and Bougadis, 2003; Rosenberg et al., 2003; Jha et al., 2004; Sushama et al., 2006) and on the resolution of the climate model (Stone *et al.*, 2003). Rosenberg *et al.* (Rosenberg *et al.*, 2003) using HadCM2 scenarios (IS92a, 2030 and 2095) in HUMUS, modelled an overall increase in annual water yield for the U.S., with reductions in the western Great Plains of Kansas, Colorado and Nebraska. Statistically significant increases in modelled winter flow occurred in northern and mid-continent basins (Mackenzie, Fraser, Yukon, Nelson and Churchill), due to earlier snowmelt and increased frequency of rain (CRCM, 2041-2070, A2 and IS92a) (Sushama *et al.*, 2006). Warming offsets 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 lead to significant reductions in snowpack at moderate elevations by mid 21st century in the western cordillera (Loukas *et al.*, 2002; Leung and Qian, 2003; Mote *et al.*, 2003). The Cascade Range and Coast Mountains annual snowpack decreases up to 60% (Leung and Qian, 2003) and late winter snow accumulation in the Sierra Nevada region, decreases by 50-90% by the late 21st century (Miller *et al.*, 2003), with larger impact using the HadCM3 than the PCM model and the A1FI than the B1 scenario (Hayhoe *et al.*, 2004). In snowmelt dominated watersheds, snowmelt discharge advances, winter and early spring flows and flooding potential are projected to increase with associated large reductions in summer flow during the dry season in western coastal and inland mountainous areas (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). Heavily-managed water systems of the western U.S. and Canada that rely on capturing snowmelt runoff, such as the Columbia River, are especially vulnerable (See Box 14.2).

Box 14.2: Great Lakes water levels

Assessments of the Great Lakes – St. Lawrence Basin project both lower and higher net basin supplies and water levels (Croley, 1990; Hartmann, 1990; Mortsch and Quinn, 1996; Chao, 1999; Mortsch et al., 2000; Quinn and Lofgren, 2000; Lofgren et al., 2002), reflecting uncertain effects of. poleward moisture transport, evaporation/precipitation balance, and atmosphere-lake interactions (Wetherald and Manabe, 2003; Kutzbach *et al.*, 2005). Lower water levels lead to a number of interacting impacts across sectors (Fig. 14.2) (Lemmen and Warren, 2004). Hydropower generation decreases and producers incur losses (Buttle *et al.*, 2004) (see 14.4.8). Overseas commercial navigation into the deep-water Port of Montréal could be maintained with extensive adaptation, or it could be re-routed to other eastern ports (St. Lawrence River-Lake Ontario Plan of Study Team, 1999). Adapting infrastructure and dredging to cope with altered water level entails a range of costs(Changnon, 1993; Parson et al., 2001b; Christensen et al., 2004; Schwartz et al., 2004b) The Great Lakes have a history of controversies about diversions of water, particularly at Chicago, to address issues of water quality, navigation, water demand, and drought mitigation outside the region; climate change is expected to exacerbate all these issues and create a new set of challenges for bi-national cooperation (Changnon and Glantz, 1996; Koshida *et al.*, 2005).

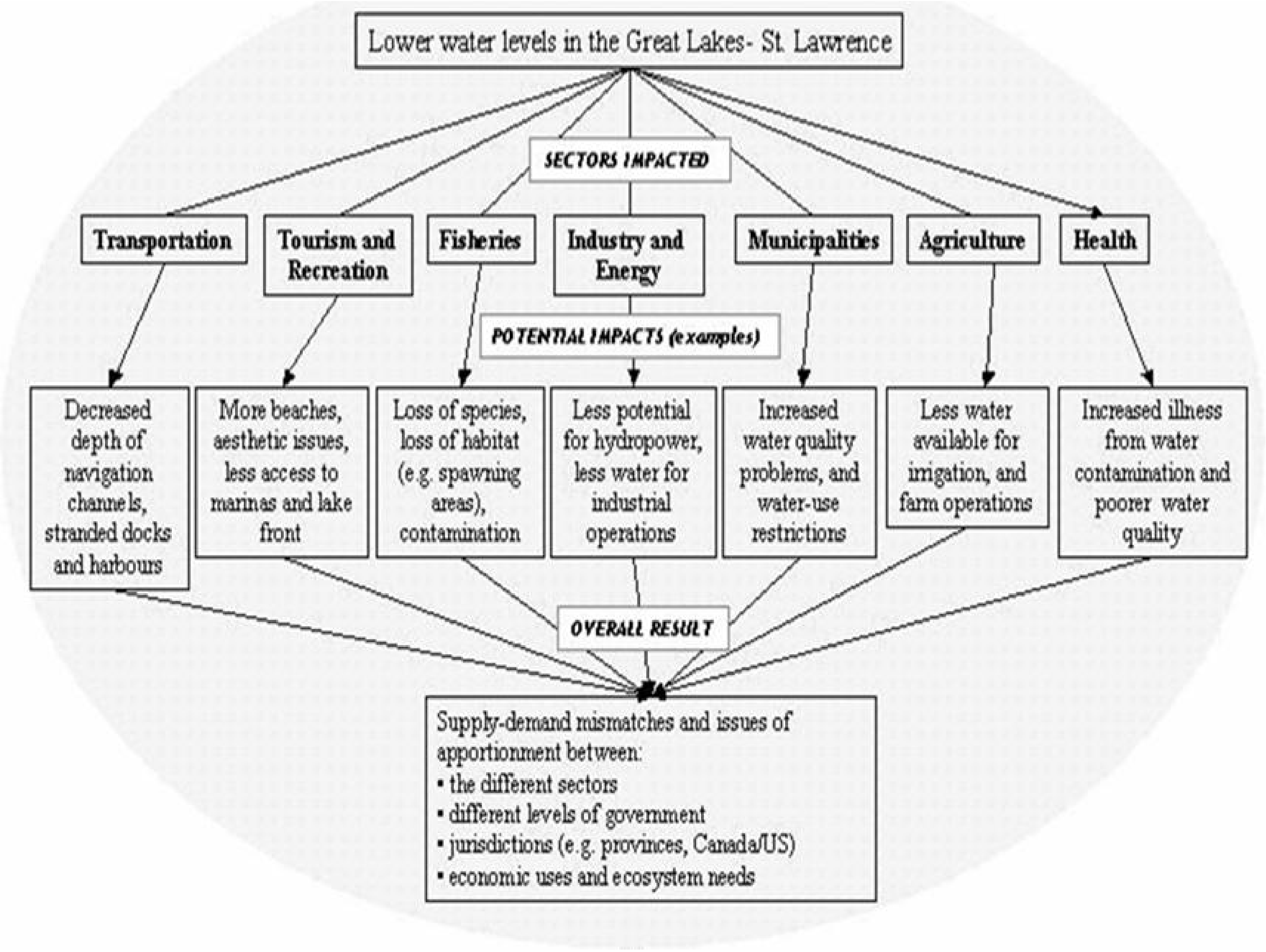

Fig.14.2: *Interconnected impacts of lowered Great Lakes water levels (Lemmen and Warren, 2004).*

Groundwater

With climate change, availability of groundwater depends on withdrawals (which depend on economic activity and the availability of other sources), temperatures, the timing and amount of precipitation, and streamflow (Rivera *et al.*, 2004). Projected annual base flow for a Michigan aquifer decreased 19.7% while levels declined 0.3-1.2m under current pumping and 0.3-2.3m with future pumping demand (CGCM1, IS92a, 2030) while base flow and levels increased 4.1% and 0.1-0.3-m, respectively for the wetter HadCM2 scenario (IS92a, 2030), (Croley and Luukkonen, 2003). Similarly, base flows for southwestern Ontario decreased 19% (CGCM1) and increased 3% (HadCM2) in 2080. Yet, in all scenarios, base flow increased in winter and decreased during spring and early summer (Piggot *et al.*, 2003). For aquifers in alluvial valleys (e.g., south-central B.C.), temperature and precipitation scenarios had a smaller impact on groundwater recharge and levels than did projected changes in river stage, which was influenced by timing and flow of spring floods and subsequent flow regime (Allen *et al.*, 2004a; Allen *et al.*, 2004b).

Heavily utilized groundwater-based systems in southwest U.S. may experience additional stress from climate change as reductions in recharge could endanger water supplies and necessitate adjustments in withdrawals. In Texas, the Edwards aquifer is currently under pumping limits to preserve flow from springs. Simulations under average recharge projected lower spring flows, water shortages, and negative environmental impacts. With pumping increased 25%, violations of minimum spring flows were frequent by the 2030s and spring flow could cease (Loáiciga *et al.*, 2000) (Loáiciga, 2000). Another assessment of the same aquifer projected flow reductions from springs of 10-16% in 2030 and 20-24% in 2090 (CGCM and HADCM2, IS92a). Associated regional welfare losses were estimated to be US$2.2-$6.8 million/year with net agriculture income decreasing 16–30% (2030) and 30-45% (2090) as water allocation shifted to municipal and industrial uses (Chen and Grasby, 2001). In the Ogallala aquifer region, natural groundwater recharge was affected negatively by all scenarios (GISS, UKTR, and BMRC) with decreases greater than 17%. Effects of precipitation increases were offset by higher evapotranspiration due to warming (Rosenberg et al., 1999).

Water quality

Modelled surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries throughout North America consistently show increases from 2-7°C ($2xCO_2$ and IS92a) (Fang and Stefan, 1999; Hostetler and Small, 1999; Nicholls, 1999; Stefan and Fang, 1999; Lehman, 2002; Gooseff *et al.*, 2005), pushing summer temperatures over 30°C in Midwestern and southern lakes and reservoirs (ECHAM4 and CGCM1, IS92a, 2070-2079) (Hostetler and Small, 1999). Warming extends and intensifies summer thermal stratification, contributing to anoxia, while 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). Longer duration of thermal stratification, stronger stability of stratification, and bottom water temperatures above 4°C by 2090 (CGCM1 and HadCM2, IS92a) accelerate metabolic rates and oxygen depletion in the Great Lakes (Lehman, 2002). Simulated summer phosphorus concentrations in the Bay of Quinte in the Great Lakes increased 77-98% with a 3-4°C water temperature rise (Nicholls, 1999).

Climate change may make it more difficult and expensive to achieve water quality goals. U.S. Total Maximum Daily Loads (TMDL) defining discharge limits for point sources factor in low-flow conditions. A 25% decrease in mean precipitation in the Midwest leads to a 63% reduction in design TMDL flow, which reaches 100% when irrigation demands are incorporated (Eheart *et al.*, 1999). In the Bay of Quinte watershed in the Great Lakes basin, simulated average phosphorus concentration increased 25-35% (CGCM1, IS92a, 2030, 2050 and 2090) setting back phosphorus remediation targets (Walker, 2001). Restoration of beneficial uses (e.g., loss of habitat, eutrophication, beach closings) identified under the Great Lakes Water Quality agreement may be vulnerable to climate change (Mortsch *et al.*, 2003).

Rainfall erosivity in the U.S. is projected to increase but varies across the U.S (HadCM2 and CGCM1 2050 and 2090) with the mid-western U.S. the most vulnerable (Nearing *et al.*, 2004). Decreases in snowcover and more winter rain on bare soil lengthen the erosion season, increase erosion, and result in more pollution (Atkinson et al., 1999; Walker, 2001; Soil and Water Conservation Society, 2003). Current soil management practices (e.g., crop residue, no-till) in the cornbelt may not provide sufficient protection against future precipitation changes (Hatfield and Pruger, 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 is likely to sustain forest carbon sinks in North America, cancelling decreased sink strength resulting from water limitations and higher respiration in the tropics (medium confidence).

Primary Production

At high latitudes, several models simulate increased net primary production (NPP) as a result of expansion of forests into the tundra, plus 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 sustain the water balance (Bachelet *et al.*, 2001; Berthelot *et al.*, 2002; Gerber *et al.*, 2004; Woodward and Lomas, 2004). Bachelet *et al.* (Bachelet *et al.*, 2001) project areal extent of drought-limited ecosystems to increase 11%/ºC warming in the continental U.S. By the end of the 21st century, ecosystems in the Northeast and Southeast 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 modestly increase (10-20%) as a result of extended growing seasons and elevated CO_2 over the next century (medium confidence) (Morgan *et al.*, 2001), but with important spatial and temporal variation. Growth of white spruce in Quebec 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 300-600m, causing temperate species to replace subalpine species over 300-500 years (Zolbrod and Peterson, 1999). For a widespread species like 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 ecosystem structure and biodiversity are sensitive to a wide range of climate drivers (Sala *et al.*, 2000). These include non-climate factors like extreme events and biological invasives that may be influenced by climate, leading to the possibility of indirect effects. 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 (Currie, 2001) suggests that, over the next century, vertebrate and tree species richness will decrease in most parts of the conterminous U.S. (medium confidence), even though long-term trends (millennia) may favour increased richness in some taxa and locations. Based on relationships between habitat area and biodiversity 15-37% of plant and animal species in a global sample would be "committed to extinction" by 2050, although actual extinctions might take centuries to occur (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 (Boesch *et al.*, 2000) will reduce the effectiveness of natural protective features, leading to impaired resilience (Forbes *et al.*, 2002b; Dolan and Walker, 2004). As property values and investment continue to rise, coastal vulnerability tends to increase on a broad scale (Pielke and Landsea, 1999; Heinz Center, 2000), with a sensitivity that depends on the commitment to and flexibility of adaptation measures (Forbes *et al.*, 2002b; Brunner *et al.*, 2004). Disproportionate impacts due to socioeconomic status may be exacerbated by rising sea levels and storm severity (Wu *et al.*, 2002; Rygel *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 SRES scenario A1B, global mean sea level is projected to rise by 0.12 ± 0.06m (2000-2050) and 0.29 ± 0.15m (2000-2100) or possibly higher, with a scenario spread of 0.2m at 2100 (WG1 Chapter 10). Regional rates of sea-level rise will become clearer as scenarios and models are refined (Church *et al.*, 2004). Vertical land motion will decrease (uplift) or increase (subsidence) the relative sea level rise at any one site (Douglas and Peltier, 2002)

Superimposed on accelerated sea-level rise, the projection of present storm and wave climatology and storm-surge frequency distributions leads 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 (high confidence) (Zhang *et al.*, 2000a; Forbes *et al.*, 2004). Although appropriate modelling including uncertainty is rarely applied (Cowell and Zeng, 2003) higher sea levels are likely to be correlated with accelerated coastal erosion if coastal systems, including sediment supply, remain otherwise unchanged (Hansom, 2001; Cowell *et al.*, 2003).

Up to 21% of the remaining coastal wetlands in the U.S. mid-Atlantic region will be inundated between 2000 and 2100 (Najjar *et al.*, 2000). Present rates of coastal wetland loss, as documented 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 may be diminished in northeastern 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 may be able to keep pace with sea-level rise (to some limit) through vertical accretion (Walker, 2001; Morris et al., 2002; Chmura et al., 2003)Chmura, 2004, accretion}. However, where rapid subsidence increases rates of relative sea-level rise, as in the Mississippi Delta, even heavy sediment loads cannot compensate for inundation losses (Rybczyk and Cahoon, 2002).

Potentially more intense storms (Gulf of Mexico, Atlantic Seaboard, Gulf of St. Lawrence) and possible changes in El Niño are likely to result in more coastal instability (moderate confidence) (Scavia *et al.*, 2002; Forbes *et al.*, 2004; Emanuel, 2005a). Damage costs from coastal storm events (storm surge, waves, wind), which have increased substantially in recent decades (Zhang *et al.*, 2000a) are expected to continue rising (high confidence). Higher sea levels, coupled with storm surges, will cause widespread problems for transportation in some coastal regions of North America, notably the Gulf and Atlantic coasts (Titus, 2002)

Climate models suggest the probability of more winters with reduced sea ice in the Gulf of St. Lawrence by 2020 over the coming decades, resulting in more open water during the winter storm season (Forbes *et al.*, 2002a). This is also an issue for the summer and shoulder seasons in the Arctic (see Chapter 15). Less ice will result in a larger number of storm wave events per year on average, leading to further acceleration of coastal erosion (moderate 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 rainfed agriculture, but with smaller increases and more spatial variability than in earlier estimates (high confidence) (Reilly *et al.*), a pattern confirmed in 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 spatial heterogeneity; Thomson et al., 2005a). High-resolution assessments (Carbone *et al.*, 2003) identify increased climate sensitivity in the southeastern U.S. and in the U.S. corn belt, 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; Jones *et al.*, 2006a).

The critical importance of specific agro-climatic events (e.g. last frost) injects 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 (Winkler *et al.*, 2002). For U.S. soybean yield, adjusting planting date can more than compensate for direct effects of climate change (Southworth *et al.*, 2002).

Vulnerability of North American agriculture to climatic change is multidimensional and is determined by interactions among pre-existing conditions, stresses from climate change, and the sector’s capacity to cope with multiple, interacting stresses, including economic competition from other regions (Choi and Fisher, 2003; Parson et al., 2003). Water access is the major factor limiting agriculture in southeast Arizona, but farmers in the region perceive that technologies and adaptations such as crop insurance have 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 III, 2001).

Forestry

The greatest impacts on the future of North American forest ecosystems will probably be changing disturbance dynamics from insects, diseases, and wildfires (Box 14.1) (Dale *et al.*, 2001). 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 (Brown *et al.*, 2004; Flannigan *et al.*, 2005). Breshears et al. (Breshears *et al.*, 2005) found a >90% dieoff over 12,000 km^2 of normally drought tolerant Pinyon pine forest after prolonged drought in the Southwest U.S. The southern boundary of the boreal forest in Canada, limited by water balance, is expected to move northward 100-200 km by the 2041-2070 time period (Hogg and Bernier, 2005). Warmer winters with more sporadic freezing and thawing are expected to increase erosion and landslides on forest roads, and reduce access for winter harvesting (Spittlehouse and Stewart, 2003).

Freshwater Fisheries

Coldwater fisheries will be the most negatively effected by climate change, warm water fisheries will generally gain, and the results for cool water fisheries will be mixed with gains in the northern portions of the ranges and losses in the southern portions (high confidence) (Stefan *et al.*, 2001; Rahel and

McGinn, 2002; Shuter *et al.*, 2002; Mohseni *et al.*, 2003; Fang *et al.*, 2004). Salmonids, which prefer cold, clear water, will be the most affected group of fishes (Gallagher and Wood, 2003), and Arctic freshwaters will be most affected as they will experience the greatest changes (Wrona *et al.*, 2005). Many warm water and cool water species will shift their ranges northwards, or to higher altitudes (Clark *et al.*, 2001; Mohseni *et al.*, 2003). In the continental U.S., coldwater species will 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 (Stefan *et al.*, 2001). Species already listed as threatened will either be forced to extinction or their ranges will contract further (Chu *et al.*, 2005). Expansion of predatory species like smallmouth bass will lead to the loss of cyprinid biodiversity (Jackson *et al.*, 2002). In Lake Erie, river-spawning walleye will both gain and lose in larval recruitment, but lake-spawning stocks will mostly lose from warming and lower lake levels (Jones *et al.*, 2006b). The thermal habitat of yellow perch will expand, as the thermal habitat of lake trout contracts (Jansen and Hesslein, 2004). While temperature increases may favour warm water fishes like smallmouth bass, changes in water supply and flow regimes may 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. The aging of the North American population and patterns of immigration and or emigration will also be major factors (United Nations Population Division, 2003). Across North America, the 65-plus population 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 heat waves.

Heat Waves and Health

Severe heat waves, characterized 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. Around 2090, Chicago may experience 25% more frequent heat waves annually (Meehl and Tebaldi, 2004 more frequent), and the average number of heat wave days in Los Angeles could increase from 12 to 44-95 (PCM and HadCM3, A1FI and B1, 2070-2099) (Hayhoe *et al.*, 2004).

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 were associated with increased hospital admissions for cardiovascular disease (Schwartz et al., 2004a), and admissions to emergency rooms has been directly related to extreme heat in Toronto, Canada (Dolney and Sheridan, 2006).

Air Pollution

Surface ozone concentration may increase with a warmer climate. Ozone damages lung tissue, and causes 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 will generally increase at higher temperature, 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). Other important sources of VOC pollution are fuel combustion, industrial processes, and vehicles (EPA (Environmental Protection Agency), 2003).

For 2050, daily average ozone levels increase by 3.7 ppb across the eastern U.S (A2 scenario), with the most polluted cities today experiencing the greatest increase in temperature-related ozone pollution (Fig. 14.3) (Hogrefe *et al.*, 2004). Assuming constant population and dose-response characteristics, ozone-related deaths from climate change increase by approximately 4.5% for the mid-2050s, compared with 1990s levels (Knowlton *et al.*, 2004; Bell *et al.*, 2005). Across 50 cities in the eastern U. S., summertime 1-hour maximum ozone may increase by 4.8 ppb, with the largest increase (9.6 ppb) occurring in currently polluted cities. The number of summer days exceeding the 8-hour regulatory U.S. standard is projected to increase by 68% (Bell et al., 2006). The large potential population exposed to outdoor air pollution (in the millions), translates this seemingly small relative risk into a substantial attributable health risk.

Pollen

Pollen, another air contaminant, may increase with climate change in North America. A doubling of the atmospheric CO_2 concentration stimulated ragweed-pollen production by 61% (Wayne *et al.*, 2002). Ragweed grew faster, flowered earlier, and produced significantly greater above-ground biomass and ragweed pollen at urban than at rural locations (Ziska *et al.*, 2003).

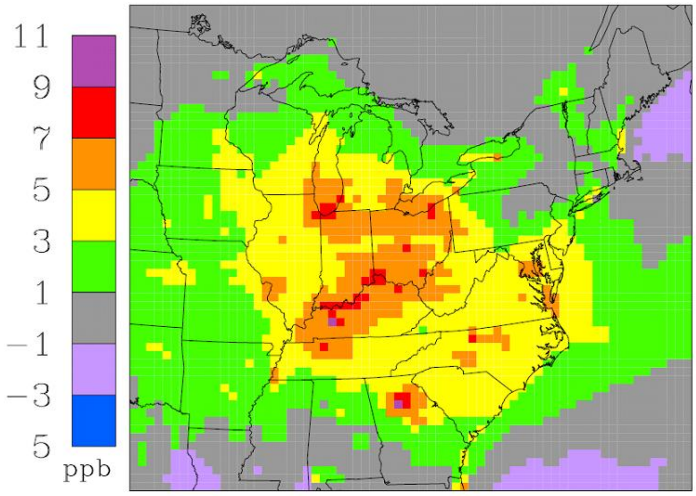

Fig. 14.3: *Simulated ozone air pollution over the eastern U.S. based on simulations from a downscaled climate model linked to a regional air pollution model (Hogrefe et al., 2004). Projected change in summertime average daily maximum 8-hour O_3 concentrations (ppb) for 2050s over the region based on A2 scenario simulations relative to the 1990s.*

Lyme disease

The Northern boundary of tick-borne Lyme disease is limited by cold temperature effects on the tick, *Ixodes scapularis*. Based on simulations with two GCMs (CGCM2 and HadCM3) running the A2 scenario, the northern range limit for this tick could shift north by 200km by the 2020s, and 1000km by the 2080s (Ogden *et al.*, 2006).

14.4.6 Human Settlements

Economic Base

The economies of resource-dependent communities and indigenous communities in North America are unusually 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). Although relatively few people are affected, residents of northern Canada and Alaska are among those likely to experience the most disruptive impacts of climate change, including impacts of shifts in the range or abundance of important prey species crucial to the livelihoods and well-being of indigenous peoples (Houser et al., 2001; Parson et al., 2001a; ACIA, 2004). For further details, see Chapter 15.

Infrastructure, Climate Trends, and Extreme Events

Many of the impacts of climate change on infrastructure in North America depend on future changes in regional precipitation or extreme events, which are very uncertain (WG I Chapters 3, 10, 11). Infrastructure in northern areas of both Canada and the U.S. is, in contrast, vulnerable to warming. The most sensitive areas are those affected by coastal erosion (due in part to projected loss of ice cover (NAST, 2000a; ACIA, 2004) and areas affected by melting of permafrost (Arctic Research Commission, 2003). Building, designing, and maintaining foundations, pipelines, and road and railway embankments would be more expensive due to permafrost thaw (ACIA, 2004). Infrastructure at "moderate to high hazard" in North America includes Shishmaref, Nome, and Barrow in Alaska, Inuvik 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 (ECHAM1-A,GFDL89, and UKTR, mid-21st century) (Nelson *et al.*, 2002).

Since the TAR, a few studies have addressed the potential impacts on infrastructure from extreme weather related to climate warming. Examples include the New York Metropolitan Region (Rosenzweig, ; Rosenzweig, 2001a), the Mid-Atlantic Region (Fisher, 2000; Barron, 2001; Wu et al., 2002; Rygel, 2005), and the urban transportation network of the Boston metropolitan area (Suarez et al., 2005), and the urban transportation network of the Boston metropolitan area (Suarez *et al.*, 2005) (see Box 14.5). For Boston, a gradual increase (0.31% per year) in the probability of the 100-year storm based on the CGCM1 model, as well as sea level rise of 0.3cm/yr, led to urban riverine and coastal flooding. It also doubled delays and the number of lost trips. In this study, however, economic damage did not justify adapting the infrastructure to climate change (Suarez *et al.*, 2005). Accounting for growth in population, inflation, and per capita real wealth in a study of potential hurricane losing North Carolina, Choi and Fisher (Choi and Fisher, 2003) concluded that a 1% increase in precipitation results in about a 2.8% increase in catastrophic losses (GENESIS and RegCM2).

It is not clear whether North America will experience more hurricanes and/or Nor'easters in a warmer climate (Canadian Hurricane Centre, 2005), although for the last couple of decades, potential damage has tracked sea surface temperature (Emanuel, 2005a). In simulations involving GCM scenarios for 2080 (A1FI and A2), lagged changes in protection, low population growth, and low subsidence, 100,000 additional North Americans were exposed to coastal flooding (Nicholls, 2004)

The U.S. National Assessment (NAST, 2001) did not carry forward many of the potential identified physical impacts of climate change to estimate financial impacts, due to lack of data and tools (Changnon, 2005).

14.4.7 Tourism and Recreation

One of the major tourism flows in North America is from the northern U.S. and Canada to the 'winter getaway' destinations in the southern U.S., Mexico and Caribbean. Based on a tourism climate index (Scott *et al.*, 2004a) the number of cities in the U.S. with 'excellent' or 'ideal' ratings in January triples by 2050 and quadruples by 2080 (A1FI), suggesting increasing competition for winter getaway travellers. The combined effect of an improved warm tourism season and reduced demand for winter getaway holidays could benefit Canada's international travel deficit (Scott *et al.*, 2004a), but decrease tourism in Mexico (Hamilton *et al.*, 2006).

Coastal zones are the most important recreation resource in North America. Some of the most important coastal zones for tourism in the southern U.S. are vulnerable to sea level rise. The cost of sand replenishment to protect Florida's coast from a 50cm rise in sea level by 2100 could be US$1.7 to

8.8 billion (US EPA (United States Environmental Protection Agency), 2003).

Nature-based tourism is also a central component of North American tourism, with over 900 million visitor days in national/provincial/state parks in 2001. Tourism in many of the parks in the northern U.S. and Canada is limited by winter conditions. Visits to Canada's national parks system could increase by 6-8% (2020s), 9-25% (2050s), and 10-40% (2080s) solely as a result of a lengthened and improved warm-weather tourism season (model, B2 and A1) (Scott *et al.*, 2005a). This would have benefits for park revenues and the economies of nearby communities, but could exacerbate visitor-related ecological pressures in some parks.

Nature-based tourism will also be indirectly affected by environmental change (e.g., loss of glaciers, reduced or changed biodiversity, fire- or disease-impacted forests). Based on interviews, a large majority of respondents would not change their intended visit patterns in response to projected environmental changes for the 2020s or the late 21st century scenarios provided (Richardson and Loomis, 2004; Scott *et al.*, 2005a).

Winter sports tourism in North America may be vulnerable to climate change due to a shorter winter season, but early studies of the impact of climate change on the ski industry did not account for snowmaking, which substantially lowers vulnerability in eastern North America for modest (B2) but not severe (A1) warming (model, 2050s) (Scott *et al.*, 2003; Scott *et al.*, 2005b). The likely outcome is a continued contraction of the ski industry in this region, in the face of diverse climate dependent and climate independent challenges (Scott, 2005). Without snowmaking, the ski season in western North America is likely to shorten substantially in many regions, with projected changes of 3-6 weeks (2050) and 7-15 weeks (2080) in the Sierra Nevada of California (PCM and HadCM3, B1 and A1FI) (Hayhoe *et al.*, 2004) and by 7-10 weeks at low elevation and 2-14 weeks at higher elevation (in the 2050's) at Banff, Alberta. With advanced snowmaking, the season still shortens at low but not at high altitudes (Scott *et al.*, 2005a). Resorts at high altitudes or in cold microsites are much less vulnerable and may draw visitors away from regions where climate change degrades skiing options. The US$10 billion (International Snowmobile Association, 2003) snowmobiling industry in North America is much more vulnerable to climate change than is the ski industry, because it is entirely reliant on natural snowfall (Scott *et al.*, 2002; Scott *et al.*, 2006a). Under severe warming (model, A1, 2050s), a reliable snowmobile season disappears from most regions of eastern North America with developed trail networks.

14.4.8 Energy, Industry, and Transportation

Studies since the TAR on the potential impacts of future climate change on energy demand and supply, industry, and transportation in North America mostly add detail to the broad conclusions of earlier work.

Energy Demand

Recent North American studies generally confirm earlier work showing a small net change in the demand for energy in buildings as a result of a 2°C average annual warming, but a significant increase in demand for electricity, mainly for space cooling (high confidence) (Sailor and Muñoz, 1997; Mendelsohn and Schlesinger, 1999; Morrison and Mendelsohn, 1999; Mendelsohn, 2001; Sailor, 2001; Sailor and Pavlova, 2003). These studies do not account for improvements in energy efficiency or changes in per capita building area. Energy consumption in U.S. residential and commercial buildings is likely to decrease by about 5% in 2020 (0-2.5°C warming) and as much as 20% in 2080 (for 3.5-10°C warming) (11 GCMs, 8 scenarios), but with an increase of up to 25% in temperature-sensitive electricity consumption by 2080, even without increased market penetration of air conditioning. By 2020, U.S. building energy efficiency programs are projected to save 4.5%, more than enough to offset increases in energy consumption due to growth in space cooling and building stock (Scott *et al.*, 2006b). An overall per capita increase in residential and commercial electricity consumption of 5-15% for a 3°C average temperature increase summarizes individual state and regional results that are variable and sensitive to the specific climate scenario (Sailor, 2001). For Massachusetts in 2020, Ruth and Amato (Ruth and Amato, 2002) projected a 6.6 % decline in annual heating fuel consumption (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 32 PJ, or 9.4 % of 2001 levels by 2100 (CGCM IS92a). Residential heating falls by 15% and air conditioning increases nearly four-fold. Commercial-institutional heating demand falls by 13% and air conditioning demand doubles. Peak electricity demand in Québec would decline, while summer peak demand would increase about 7%-17% in the New York metropolitan region (Ouranos, 2004b).

Energy Supply

Since the TAR, a variety of regional assessments have estimated impacts of climate change on hydropower in North America. For a 2-3°C warming in the Columbia River Basin and B.C. Hydro service areas, the firm hydroelectric supply for the winter peak demand season likely would conflict with flow targets established under the Endangered Species Act (Payne *et al.*, 2004). Accumulating evidence of reduced snowpack in the Western U.S. mountain ranges (Mote *et al.*, 2005; Hamlet *et al.*), combined with projections of increased winter flows, earlier spring melt, and possibly more winter rainfall in the western United States and Canada (Hamlet and Lettenmaier, 1999; Stewart *et al.*, 2004; Hamlet *et al.*, 2006), all suggest greater winter but reduced summer hydroelectric potential in the Columbia River system (high confidence), with potentially adverse effects on salmon restoration (Parson *et al.*, 2001b) (Box 14.4). Colorado River hydropower yields would likely decrease significantly (medium confidence) (Christensen *et al.*, 2004). In Ontario and upper New York State, the yield of Great Lakes hydropower likely will decline (Moulton and Cuthbert, 2000; Lofgren *et al.*, 2002; Mirza, 2004), while James Bay hydropower may increase (Mercier, 1998; Filion, 2000). Decreased water levels could lead to large losses (Can$437-$660 million per year), with increased water levels leading to small gains (Can$28-$42 million per year) (Buttle et al., 2004; Ouranos, 2004a). Regionally, northern Québec hydropower likely would benefit from greater precipitation and more open-water conditions, but run-of-the-river plants in southern Québec likely would face lower water levels. Consequences of changes in seasonal distribution of flows and in the timing of ice formation are uncertain (Ouranos, 2004a).

The viability of wind resources depends on the speed and reliability of wind, which is not well constrained in GCM outputs. A handful of studies since the TAR conclude that the effects of climate change on North American wind resources are sensitive to model and scenario. Projected wind speed changes from one model (HadGCM2, CGSa4) suggest minimal impact of climate change on wind resources, while results from another model (CGCM1, GHG+A1) suggest potential reductions of 30-40% (Breslow and Sailor, 2002). Segal *et al.* (Segal *et al.*, 2001) projected decreased daily average wind power availability in the U.S. of 0-30% by 2040-2050 (HadCM2 and RegCM2, 1%/yr CO_2 increase). In limited areas in the southern and northwestern U.S., wind resources increased by up to 30%. Northern Texas and western Oklahoma were almost unaffected, but wind resources declined in the north-central U.S. and the western mountains. Future cloudiness is also poorly known, but increased cloudiness could decrease the potential energy output of photovoltaics by 0%-20% (HadCM2 and RegCM2, 1%/yr CO_2 increase, 2040-2050) (Pan *et al.*, 2004).

The potential of bioenergy is climate sensitive, through direct impacts of climate on crop growth and through indirect effects on the availability of irrigation, as well as demand for other agricultural products. Under current conditions, bioenergy crops are projected to compete successfully for agricultural acreage at a farm gate price of $33/Mg, or about US$1.83/GJ (Walsh *et al.*, 2003). In the single study that has addressed the effect of climate change on these tradeoffs, warming of 3.7-7.5° C and precipitation increases ranging from 1-115 mm allow switchgrass to compete effectively with traditional crops in the central U.S. (RegCM2, 2 x CO_2, 4.2-5.0°C summer temperature change, 1 to 52 mm increase in summer precipitation). Switchgrass produced less biomass than the traditional crops, but could survive warmer temperatures and lower water availability (Brown *et al.*, 2000).

Energy infrastructure, particularly electric power systems, is vulnerable to extreme weather, such as ice storms, lightning strikes, and hurricanes, and additional progress has been made since the TAR on documenting this vulnerability. Impacts of climate change on energy infrastructure have not been quantified, largely because of the effects of climate change on the number, location, and intensity of extreme weather events such as ice storms and hurricanes is unknown. Especially at high latitudes, energy infrastructure, including the Trans-Alaska oil pipeline, may be vulnerable to thawing permafrost (ECHAM1-A,GFDL89, and UKTR, no specific scenario or date) (Nelson *et al.*, 2002).

Water and Sewer

Decreased reliability of water supplies, a possible but unproven consequence of climate change, would create challenges for managing water systems (see Box 14.4) as well as industries that depend on large volumes of water. Water managers in the U.S. anticipate that they will face local, regional, or state-wide water shortages during the next ten years (GAO (General Accounting Office), 2003). Threats to reliable supply are complicated by the concentration of some of the nation's highest population growth rates in western states where water is already in short supply (GAO (General Accounting Office), 2003) (Section 14.4.1). Potential increases in heavy precipitation, together with increases in the extent of impervious surfaces, could increase flood risks and create additional challenges for stormwater management (Easterling and Karl, 2001). Coping with a 15% increase in heavy precipitation in Burlington and Ottawa, Ontario, Canada could require both structural and non-structural measures, including downspout disconnection (50% of connected roofs), increased depression storage (by 45 m^3/impervious hectare), and increased street detention storage (by 40m^3/impervious hectare) (Waters *et al.*, 2003).

Construction

As projected in the TAR, the construction season in the northern United States and southern Canada will lengthen with increases in temperatures. Increasing depth of the "active layer" or loss of permafrost in specific permafrost areas in Canada and Alaska (Lawrence and Slater, 2005) may lead to substantial decreases in soil strength (ACIA, 2004). Construction methods will have to change in areas currently underlain by permafrost (Cole *et al.*, 1998) potentially increasing construction and maintenance costs (ACIA, 2004). Replacement of individual support members for the Trans-Alaska Oil Pipeline, for example, costs about US$20 million (1998 dollars) (Cole *et al.*, 1998).

Transportation

For North America's transportation system, serious future issues will include coastal flooding (Burkett, 2002), reduced water depth in inland waterways (Quinn, 2002), decreased availability or strength of ice roads (Smith and Levasseur, 2002), degraded integrity of pavement (Zimmerman, 2002), and changes in storminess. In general, however, extreme cold is more problematic than heat for transport systems throughout Canada and much of the U.S. (Warren *et al.*, 2004).

Lower water levels in inland navigation routes, especially channels in the Great Lakes-St. Lawrence Seaway system could translate into the need for "light loading". This could have serious economic consequences, partially offset by an extended shipping season due to reduced ice coverage (Quinn, 2002; Millerd, 2005). Lower water levels would also create acute challenges for river traffic, reminiscent of the stranded barges on the Mississippi River in 1988 (du Vair *et al.*, 2002). Adaptive measures, such as deepening channels, would need to address both institutional and environmental challenges (Warren *et al.*, 2004).

Warmer winters at high northern latitudes (Nelson *et al.*, 2002) will likely reduce the reliability of transport. Permafrost degradation reduces surface bearing capacity and potentially triggers landslides (Allard *et al.*, 2002; Smith and Levasseur, 2002; Beaulac and Doré, 2005). Ice roads, which are constructed by clearing a route over frozen land and water bodies to service remote communities would have a shorter season (Lonergan et al., 1993; Welch, 2006), even with costly improvements in design and construction (Stiger, 2001; McBeath, 2003; Warren et al., 2004).

An increase in the frequency, intensity, or duration of heat spells could impact rail transport, causing railroad track to buckle or kink (Rosetti, 2002), and affect pavement integrity through softening and traffic-related rutting, as well as the migration of liquid asphalt (flushing and bleeding) to pavement surfaces (Zimmerman, 2002). Some of these problems can be ameliorated with altered road design, construction and management, including changes in the asphalt mix or the timing of spring load restrictions (Mills *et al.*, 2006).

Potential changes in storms and fog may affect the reliability, maintenance and safety of the transportation system. More frequent or intense winter rainfall would increase flood risks in California (du Vair *et al.*, 2002). Extreme rainfall or rapid snowmelt could result in more landslides, disrupting the transportation corridors in the mountains of western Canada (Evans and Clague, 1997). Climate change is likely to decrease the overall need for winter road maintenance but with local exceptions (Pisano *et al.*, 2002). Warmer or less snowy winters would reduce delays and improve ground and air transportation reliability, but more intense winter storms could require increased snow removal, with unknown risks for traveller safety (Andrey and Mills, 2003). Continuation of the declining fog trend across most of North America (Muraca *et al.*, 2001; Hanesiak and Wang, 2005) should have positive implications for transport. Improvements in technology and information systems, including efforts to develop a more sustainable transportation system, will likely modulate vulnerability to climate change (Warren *et al.*, 2004).

14.4.9 Interacting Impacts

Impacts of climate change on North America will not occur in isolation, but in the context of technological (Edmonds, 2004), economic (Nakicenovic and Swart, 2000), social (Lebel, 2004), and ecological changes (Sala *et al.*, 2000; Reid *et al.*, 2005). 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.

A recent set of coordinated 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., 2005b; Thomson et al., 2005c; Thomson et al., 2005e; Thomson et al., 2005d), concluding that scenarios with decreased precipitation create important challenges, restricting the availability of water for irrigation at the same time they increase the demand for irrigated agriculture and for water for urban and ecological users (Fig. 14.4).

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.*, 1999), fire (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 temperature

(WG1, chapter X), further expands the range of possible futures for North American ecosystems (Fig. 14.4)

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 heath system (Kinney *et al.*, 2001), and exposure to conflict (Barnett, 2003) all have the potential to either exacerbate or ameliorate vulnerability to climate change (Fig. 14.6). 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).

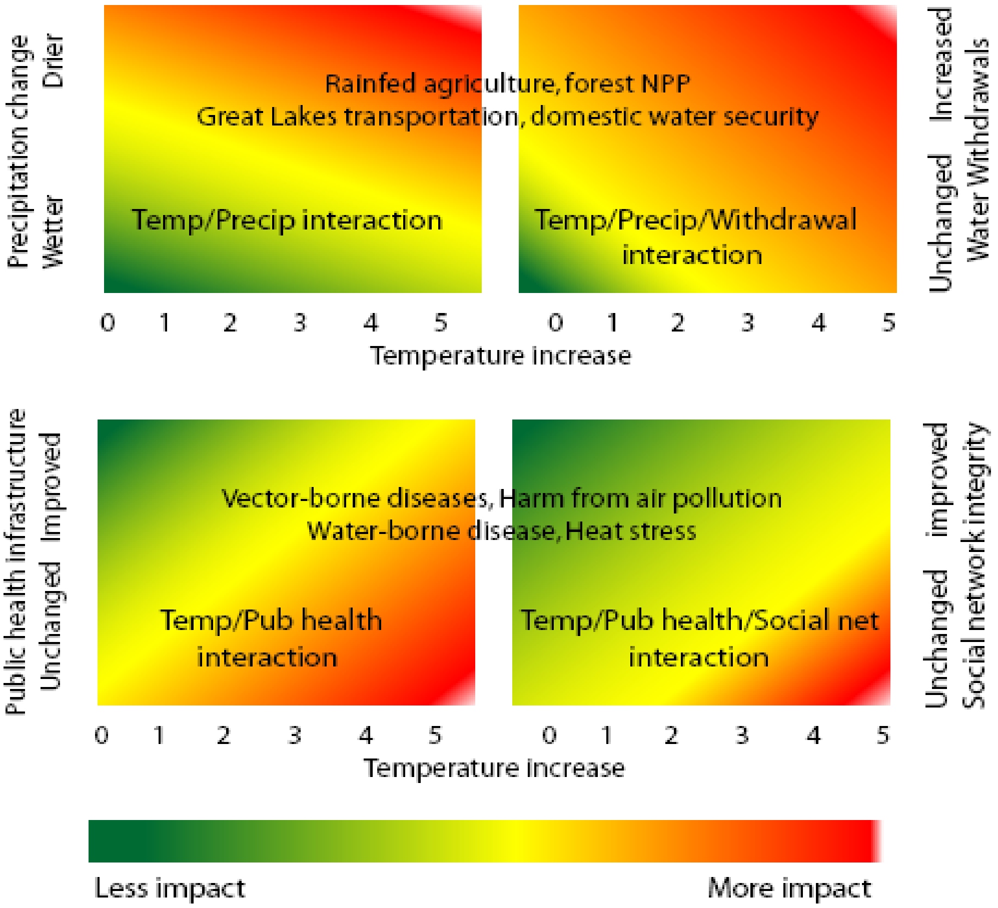

Fig.14.4: *Possible interactions between warming and other factors influencing North America in the future. Potentially important interaction factors include changes in precipitation, changes in extreme events, changes in other aspects of the social, ecological, or economic setting, adaptation, and the rapidity of the temperature change. Note that trends in these interacting factors can aggravate or moderate the impact of a given level of warming.*

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 impacts on North America of climate change in other regions is very limited.

14.5 Adaptation

The U.S. and Canada are developed economies with extensive infrastructure and mature institutions, with important regional and socioeconomic variation in the capacity to adapt (NAST, 2000b; 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 adaptive strategies documented in the research literature involve implementation based on past experiences (Paavola and Adger, 2002). Examples of adaptation based on future projections are rare (Smit and Pilifosova, 2003) (Devon, 2005). Expanding beyond reactive, adaptation to proactive, anticipatory adaptive strategies in response to projected changes in the climate presents many challenges and progress toward meeting these challenges is just beginning in North America.

14.5.1 Practices and Options

Canada and the U.S. are market-based economies. Governments often play a role implementing large-scale adaptive measures, and they can provide information and incentives to support development of adaptive capacity by private decision makers (United Nations Development Program, 2001). In practice, this means that individuals, businesses and community leaders act on perceived self interest, subject to constraints and opportunities influenced by awareness and knowledge about change processes and adaptive options. Despite many examples of adaptive practices in North America, underinvestment in adaptation is evident in the recent rapid increase in property damage due to climate extremes (Burton and Lim, 2005; Epstein and Mills, 2005), illustrating the current adaptation deficit.

Adaptation by Individuals and Private Businesses
Research on the extent of adaptive behaviour for coping with projected climate change is minimal, though several studies address adaptations to historic variation in the weather. Some people, for example, choose homes that are designed to address expected local weather conditions, like the ‘safer living’ program championed by the insurance industry, identifying disaster-resilient home design and construction practices (Kunreuther and Kleindorfer, 2001; Building Science, 2005; Kovacs, 2005a). Renovation spending by homeowners to enhance stormworthiness increased after the hurricane seasons of 2004-05 in the southeast United States (Kopp and Bartlett, 2005) (Kunreuther, 2006). Though probably driven by declining costs for equipment and rising living standards rather than by climate change, the number of houses in the U.S. with central air-conditioning has tripled in the last 25 years (United States Census Bureau, 2003). In 2000, most of the cars produced in North America had air-conditioning (Ward’s Automobile Report, 2002).

About 70% of businesses face some weather risk and the impact of weather on businesses in the United States is an estimated US$200 billion/year (Lettre, 2000). Climate change may also create business opportunities, as the use of catastrophe bonds increased 30% after the 2004 and 2005 Atlantic hurricanes (Dlugolecki, ; CERES, 2004; Byers and Snowe, 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 have begun introducing incentives for homeowners and businesses that invest in loss prevention strategies (Kim, 2004; Kovacs, 2005a).
- Insurance companies are investing in research to prevent future hazard damage to insured property, and to adjust traditional pricing models (Munich Re., 2004; Kovacs and Wakeford, 2005).
- Ski resort operators are investing in lifts to reach higher altitudes and in snow-making equipment (Elsasser *et al.*, 2003; Scott, 2005; Scott *et al.*, 2006a).
- With advanced weather forecasts, farmers are adjusting crop and variety selection, irrigation

strategies, and pesticide application (Smit and Wall, 2003).

- The forest resources sector is moving toward adaptive management options involving gene management, 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, through efforts to minimize damage due to heat waves, drought, flood, wildfire, or tornado. These actions may entail land-use planning, building code enforcement, community education, and investments in critical infrastructure (Multihazard Mitigation Council, 2005).

Flooding and drought present recurring challenges for many North American communities, despite progress with land-use planning, design codes, and engineered structures (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).

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 provide progressively less protection unless raised on an ongoing basis. Some potential damages may be averted through redesigned structures, raising the grade, or relocation (Titus, 2002). Following the catastrophic damage in New Orleans from Hurricane Katrina, more communities are expected to re-examine their hazard management systems (Kunreuther, 2006).

Rapid development and population growth are occurring in many coastal areas that are sensitive to storm impacts due to low backshore elevation and easily eroded substrate (Moser, 2005a). While there have been some aggressive adaptation measures in response to past extreme events (e.g. Galveston, Texas) (Bixel and Turner, 2000) with the passage of time, new residents, and high demand for waterfront property can push coastal development into vulnerable areas.

Climate change may bring increased risks of wildfire (Box 14.3). FireWise and FireSmart are programs 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 be in communities that manage forests with controlled burns and thinning, and promote or mandate the use of appropriate roofing materials and maintenance of a defensible space around each building (McGee and Reinholdt, 2003).

Some communities are involved in public awareness and education programs to better inform residents (NAST, 2000b; Lemmen and Warren, 2004), including information about vulnerability, impact and adaptation studies, historic weather data, analysis of climate trends, weather warnings and local climate forecasts. The U.S. Global Change Research Program has provided over 150 workshops and seminars about climate change (GRCEO, 2006), and climate change is now part of the high school curriculum in the province of Manitoba, Canada (Government of Manitoba, 2002).

Public institutions are responsible for adapting their own legislation, programs and practices to ensure that they appropriately anticipate change in the climate. They can also use a range of incentives to encourage or to overcome disincentives to investments by private decision makers (Moser, 2006). These options, including tax assistance, loan guarantees and grants, can improve resilience to extremes and reduce government costs for disaster management (Moser, 2005b). For example, the U.S. National Flood Insurance Program is changing its policy to reduce the risk of multiple flood claims, which cost the program more than US$200 million/year (Howard, 2000). Households with two flood-related claims are now required to elevate their structure one inch above the 100-year flood level, or relocate. To complement this, more than US$500 million has been invested in flood mapping over the last three years (Larson, 2004). However, delays in the implementation of appropriate zoning have been seen to result in accelerated inappropriate (maladapted) development.

North American governments have also invested in structural projects to protect citizens and property from severe weather hazards (Kovacs and Kunreuther, 2001) (Multihazard Mitigation Council, 2005), though generally not for weather hazards thought to be climate-change sensitive. This includes support for warning systems like national Doppler radar networks, increasing the lead time on tornado warnings in Oklahoma (Simmons *et al.*, 2002b) Recent upgrading of the flood diversion channel around Winnipeg, Manitoba, represents a capital-intensive adaptation to accommodate revised risk assessment related to climate change.

14.5.2 Mainstreaming adaptation

One of the greatest challenges in adapting North America to climate change is that many people resist and delay change (Bacal, 2006). 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 (Dow *et al.*, 2006; Yarnal *et al.*, 2006).

Experience and Knowledge

The behaviour of people and systems in North America largely reflects local climate experience (Schipper *et al.*, 2003). Historic experience has been institutionalized through development of building codes, flood management, water systems, and a variety of other programs. For example, community water managers make decisions based on historic experience, not projected trends in climate (Dow *et al.*, 2006) (Rayner *et al.*, 2005). Set-back regulations in coastal areas often take historical erosion rates into account but fail to incorporate information about the impact of rising sea levels on the rate of erosion (Moser, 2005a). Decision makers lack the tools and perspectives to integrate future climate, particularly events that may exceed historic norms (United Nations Development Program, 2001).

Experience and knowledge shape coping strategies (Wisner et al., 2004; Brooks and Adger, 2005). Canadians and Americans have invested in buildings, infrastructure, water, and flood management systems (UMA Engineering, 2005; Dow *et al.*, 2006) designed for acceptable performance under historical conditions (Co-operative Programme on Water and Climate, 2005). Building codes in North America require that new construction be capable of coping with historic local climate experience, but do not include climate projections (Bruce, 1999).

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 has been taken by the engineering community, some insurance companies, water managers, forestry, public health officials and hydroelectric producers. Philadelphia, Toronto and a few other communities have introduced warning programs to manage the health threat of heat waves (Kalkstein, 2002). The introduction of Toronto's heat/health warning program was influenced by both climate projections and fatalities from past heat waves (Koppe et al., 2004; Ligeti, 2006).

Weather extremes reveal a community's vulnerability or resilience (RMS, 2005a) and provide insights into potential adaptive responses to future events. For example, since the 1998 ice storm, Canada's two most populous provinces, Ontario and Quebec, have strengthened emergency preparedness and response capacity. Measures include phasing in a requirement that all municipalities prepare comprehensive mitigation and loss prevention strategies to reduce the vulnerability to extreme events.

These should include both public information programs and long-term strategies to invest in safety infrastructure (Emergency Management Ontario, 2003). In two communities with similar exposure to tornadoes, adaptive behaviour was greater in the community that recently experienced a tornado (Murphy *et al.*, 2005). But responses to the 2003 blackout in Eastern North America demonstrated that adaptive actions do not always follow significant emergencies, cautioning that the nature of the event influences how society integrates the experience into its behaviour (Murphy, 2004).

Socio-economic Factors

Wealthier societies tend to have access to technology, schooling and training, information, infrastructure, and stable institutions (Easterling *et al.*, 2004), which build capacity for individual and community action to adapt to climate change. But wealth is not a sufficient determinant of adaptive capacity (Moss *et al.*, 2001). Even in Canada and the U.S. the poor and marginalized have historically been most at risk from weather shocks (Turner *et al.*, 2003), with a direct relationship between income inequality and vulnerability (Yohe and Tol, 2002). Differences in individual capacity to cope with extreme weather were evident in New Orleans during and after Hurricane Katrina (Kunreuther, 2006), when the sizeable population who were poor, elderly, disabled or otherwise unable to function well on their own, lacked the ability to evacuate without assistance (Murphy *et al.*, 2005; Kumagi, 2006; Tierney, 2006).

Within the U.S. and Canada some regions, localities, or social groups, have lower capacity to adapt (O’Brien and Vogel, 2006). Moreover, complacency can prevent wealthy societies from taking action (IPCC, 2001).

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, as well as those provided by public service organizations, 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).

Adaptation to minimize adverse impacts or realize the potential benefits of climate change requires a capacity for local organization and coping. Associations, networks and other institutions contribute to adaptive capacity (Adger, 2003). When a North American community responds to weather extremes, non-governmental organizations often coordinate community efforts to minimize the adverse impact. In the U.S. organizations like the National Voluntary Organizations Active in Disaster serve to coordinate support community-based initiatives (National Voluntary Organizations Active in Disaster, 2006).

An active dialogue among stakeholders and political institutions has the potential for clarifying 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 in North America have focused public discussion on mitigation and energy strategies, with less attention to adaptation (Moser, 2005b). Some public funds were directed to support research into 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. As a result, there has been little public discussion in North America about adaptation to climate change (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, 2005), public flood insurance in the U.S. (Crichton, 2003), guidance on preservation of wetlands, and emergency management. Further research would clarify the extent to which climate information can influence practices in these areas.

14.5.3 Constraints and Opportunities

The main constraints to the development and application of adaptive capacity are social and cultural barriers, informational and technological barriers, and financial and market barriers (Brooks, 2003).

Social and Cultural Barriers

A region with high adaptive capacity, like most of North America, should be better able to cope with or benefit 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). The concept of mainstreaming climate risk describes processes that bring explicit consideration of climate into decision-making (Dougherty and Elasha, 2004). In North America, information about climate is often a small or absent part of the overall decision-making process (Slovic, 2000; Leiss, 2001), leading in some cases 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 recognize the vulnerability, unless the forecast information can be fit into their everyday management decisions (Dow *et al.*, 2006).

Informational and Technological Barriers

Uncertainty about the local impacts of climate change is a barrier to action (National Research Council, 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 specific 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 the purchase of reinsurance (Swiss Re, 2005a). Some electrical utilities have begun to integrate climate model output into their management of hydro-electrical facilities (Ouranos, 2004b).

Financial and Market Barriers

A comprehensive study of the benefits and costs of adaptation to extremes demonstrates that recent spending in the U.S. was a sound investment, contributing to reduced fatalities, injuries and significant economic benefits. The Multihazard Mitigation Council found that US$3.5 billion in spending between 1993 and 2003 on programs to reduce future damage caused by flooding, severe wind and earthquakes contributed to US$14 billion in societal benefits (Multihazard Mitigation Council, 2005). The greatest savings were in flood (5-fold) and wind (4-fold) damage reduction programs. Adaptation is also in government's self interest, as each dollar of spending resulted in $3.65 in savings or increased tax revenue for the federal government. This is consistent earlier case studies; the C$65 million invested in 1968 to create the Manitoba Floodway has prevented several billion dollars in flood damage (Duguid, 2002).

Economic resource issues are frequently the dominant decision factor influencing adaptive choices. 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.*, 2002a; Kunreuther, 2006), and changes in insurance practices (Kovacs, 2005b). The cost and availability of economic resources clearly influence choices (WHO (World Health Organization), 2003), as does the private versus public identity of the beneficiaries (Moser, 2000).

Sometimes, the financial barriers interact with the slow turnover of existing infrastructure (Fig. 14.5). Extensive property damage in Florida during Hurricane Andrew in 1992 led to significant revisions in the in building code. If all properties in south Florida at the time met this stronger code, then property damage from Hurricane Andrew would have been lower by nearly 45% (AIR (Applied Insurance Research, 2002). However, Florida is still experiencing extensive damage from hurricanes due 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 and less visible adaptations tend to be undervalued, relative to obvious ones. 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.*, 2002a).

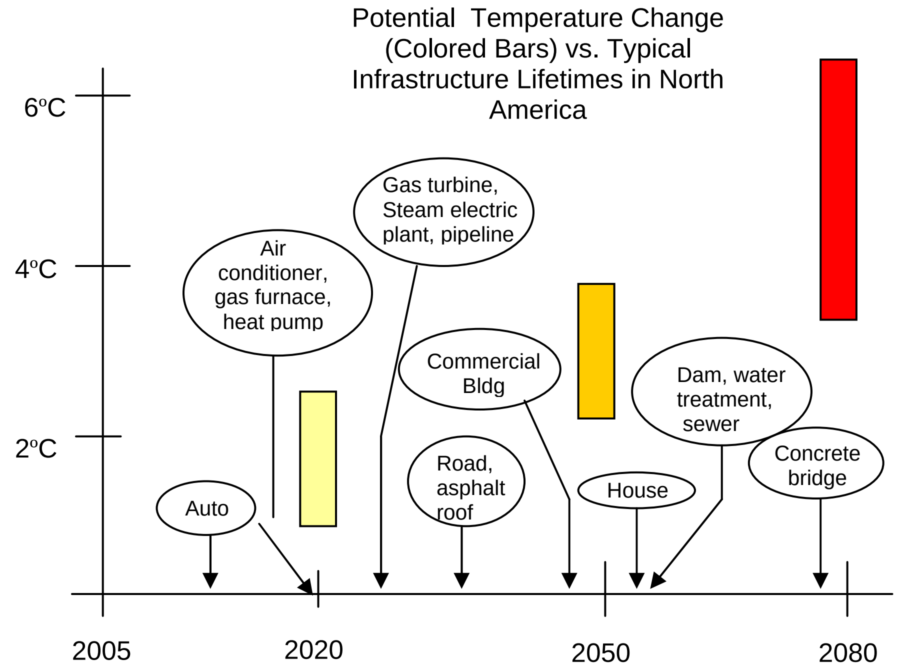

Fig. 14.5: *The possible range of mean global temperature change for 2020, 2050, and 2080, in relation to typical infrastructure lifetimes in North America. (data from (Lewis, 1987; Bettigole, 1990; U.S. Energy Information Administration, 1999; Statistics Canada, 2000; U.S. Energy Information Administration, 2001; U.S. Bureau of Economic Analysis, 2003)).*

14.6 Case Studies

Box 14.3: Wildfire and Disturbance Dynamics

Since 1980 average annual area burned in U.S. wildfires area has been 22,000km^2/yr, almost twice the 1920-1980 average of 13,000km^2/yr. Three major fire years have exceeded 30,000km^2 (Schoennagel *et al.*, 2004). The forested area burned from 1987-2003 is 6.7 times the area burned from 1970-1986, with a higher fraction burning at higher elevations (Westerling *et al.*, 2003). In Canada, burned area has exceeded 60,000km^2/yr, twice the long-term average, three times since 1990 (Stocks *et al.*, 2002). Human vulnerability to wildfires has increased in western North America as people have moved into suburbs, and built homes in the wildland-urban interface.

A warming climate encourages wildfires through drier fuel, easier ignition, and faster growth of fires in hot dry weather (Westerling *et al.*, 2003). In Canada, warmer summer temperatures are highly correlated with area burned (Fig. 14.1g) (Gillett *et al.*, 2004). In the southwestern U.S., fire activity is correlated with ENSO positive phases (Kitzberger *et al.*, 2001; McKenzie *et al.*, 2004), and higher Palmer Drought Severity Indices (Westerling *et al.*, 2003; Westerling and Swetnam, 2003). Earlier snowmelt, longer growing seasons, and higher summer temperatures, particularly in western North America, are synchronized with the increase of wildfire activity, along with accumulation of dead fuel previous from previous fire suppression activity (Westerling *et al.*, 2003).

Insects and diseases are a natural part of all 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 strongly controlled by climate (Williams and Liebhold, 2002). Many northern insects have a two-year life-cycle, and warmer winter temperatures allow a higher percentage of overwintering larvae to survive. Recently, spruce budworm in Alaska have completed their life cycle in one year, rather than the previous two (Volney and Fleming, 2000) (Logan *et al.*, 2003), and mountain pine beetle has expanded its range in British Columbia into areas previously too cold (Carroll *et al.*, 2003). Susceptibility of the trees to insects is increased when multi-year droughts degrade the trees’ ability to generate defensive chemicals (Logan *et al.*, 2003).

Box 14.4: The Columbia River System

Current management of water in the Columbia River basin involves balancing a complex set of often competing demands for hydropower, navigation, flood control, irrigation, municipal uses and maintenance of several populations of threatened and endangered species (e.g., salmon) (Fig. 14.6). Current and projected needs for these uses over-commit even 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 (especially after the “Boldt decision” in United States vs. Washington in 1974), numerous federal, state, provincial, and local government agencies (Hamlet, 2003). Pollution (mainly non-point source) is an important issue in many of the tributaries. The first-in-time first-in-right provisions of U.S. western water law in the U.S. part of the basin complicate management and reduce water available to junior water users (Gray, 1999; Scott *et al.*, 2004b). Complexities extend to different sets of responsible institutions when flows are high than when they are low, or when dependent protected species are in the tributaries, main stem, or ocean (Mote et al. 2003).

With climate change projected annual Columbia River flow changes little, but seasonal flow shifts markedly toward larger winter and spring flows and smaller summer and fall flows (Mote *et al.*, 1999), creating additional challenges for future management. These changes in flows will likely coincide with increased water demand, principally from regional growth but also induced by climate change itself. For example, climate change could increase Portland’s total summer water demand for the 2050s by additional 5-8% (5-10% in peak day demand) in addition to a 50% increase in summer demand from population growth (Mote *et al.*, 1999). A 2°C warming in the 2040s would increase Portland’s demand for water by 1.5 billion gallons/year, on top of 5.5 billion for population growth, while decreasing supply by 1.3 billion gallons (Mote *et al.*, 2003). Long-lead climate forecasts are increasingly considered in the management of the river (Hamlet et al., 2002; Lettenmaier and Hamlet, 2003; Payne *et al.*, 2004) but in a limited way. For example, each of 43 sub-basins of the system has its own subbasin 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 (Parson *et al.*, 2001b; Miles *et al.*, 2002), due to changes in snowpack and seasonal flows. The ability of managers to meet operating goals (reliability) will likely drop substantially under climate change (HadCM2, ECHAM4/OPYC3; IS92A, 2020s, 2090s) (Hamlet and Lettenmaier, 1999). By the end of the century, reliability losses may reach 25% (Mote *et al.*, 1999). Rule changes would interact with these changes. For example, "fish-first" rules would reduce firm power reliability by 10% under present climate and 17% in warm-PDO years. A later study of adaptive measures showed a smaller decrease in April snowpack, but showed 10%-20% losses of firm hydropower and still left summer flows for fish at lower levels than under current conditions (Payne *et al.*, 2004). Consequences of interactions between effects of changing climate and management goals have not be en quantified.

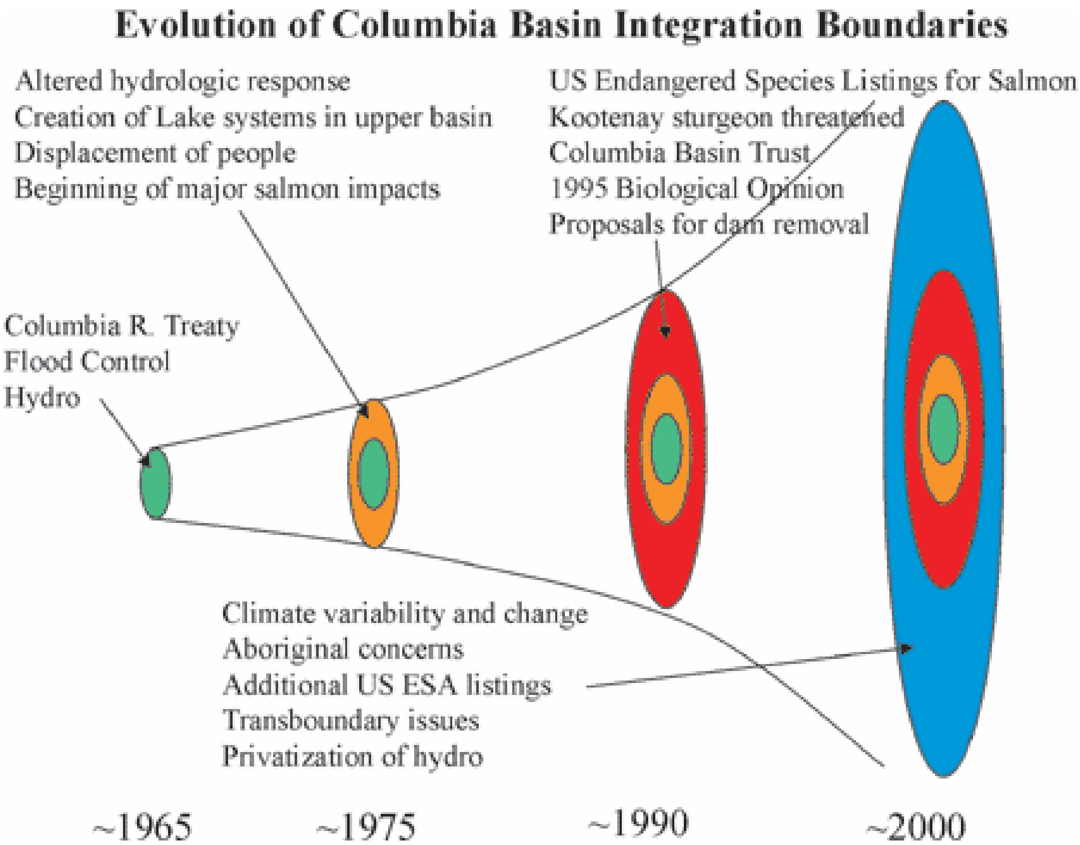

Fig. 14.6: *Expanding range of issues affecting decision-making for management of Columbia River Basin water resources. Originally river flow was managed to reduce downstream flooding and to produce hydropower. Public management has since been challenged by a series of other increasingly salient issues. Climate change is expected to change the distribution of seasonal flows around which previous policy was developed (Parson et al., 2001b; Cohen et al., 2003).*

Box 14.5: North American Cities Integrate Impacts Across Multiple Scales and Sectors

Impacts and adaptation in the metropolitan areas of Los Angeles, California, New York, New York and Vancouver, British Columbia will be different in some respects but similar in many others, especially as a result of interlinked, interacting, and compounding effects of climate change.

Coastal Infrastructure
Since most large North American cities are on tidewater or rivers or both, climate impacts include effects of sea level rise (SLR) and/or riverine flooding on multiple sectors. The largest SLR impacts on Los Angeles occur if high tides, El Niño conditions, and storms coincide more frequently (California Regional Assessment Group, 2002). Future hurricane and Nor'easter storms pose the greatest risk of damage to New York, where flooding from the combination of SLR and storm surge could be up to several meters deep (Gornitz *et al.*, 2001; Gornitz *et al.*, 2002). By 2090, in the worst-case scenario, a 100-year flood could occur as frequently as every 3-4 years, and 500-year floods could be as frequent as every 50 years, putting much of the region's most significant infrastructure at increased risk (Jacob *et al.*, 2001; Major and Goldberg, 2001). Portions of the built-up area of Vancouver in the Lower Fraser River Delta, including Vancouver International Airport also are vulnerable to a combination of riverine flooding and SLR (Lemmen and Warren, 2004).

Energy Supply and Demand
Decreases in winter energy demand due to climate change will likely be offset by increases in summer demand for electricity. In California, additional demand for electricity in summer intensifies inherent conflicts between hydropower and flood-control objectives. Climate change may require increased releases in spring to avoid flooding, decreasing the ability of hydroelectric systems to deliver power in the summer (California Regional Assessment Group, 2002). In New York, increased summer electricity demand, particularly for air conditioning (Hill and Goldberg, 2001), could increase air pollutants, such as ozone (Kinney *et al.*, 2001; Knowlton *et al.*, 2005). Further exacerbating health impacts, climate change will interact with urban heat islands (Fig. 14.5) (Rosenzweig *et al.*, 2005). Unreliable electric power, as in minority sections of New York that experienced brownouts and a one-day extended blackout during a heat wave of 1999, can amplify health concerns and motivate demands for improved environmental justice (Wilgoren and Roane, 1999). Over 90% of all electricity used in Vancouver is produced by hydroelectric dams 400-500 km distant in the Columbia River Basin (Sheltair Group, 2003) the operation of which is complicated by climate change (see Box 14.4).

Water Supply Systems
North American city water supply systems can draw from considerable distance (e.g., southern California from 400-600km and New York from 100-200 km), so climate impacts need not be local to affect cities. By 2020, 41% of the supply to southern California is vulnerable to warming due to loss of Sierra Nevada and Colorado River basin snowpack (Section 14.4.1). Similarly, less mountain snowpack and summer runoff could reduce summer water supplies for Vancouver, requiring additional conservation measures and water restrictions, expansion of existing reservoirs, and development of additional water supply sources (Schertzer *et al.*, 2004). The New York area will likely also experience greater increasing variability in water availability with climate change (Solecki and Rosenzweig, 2005). Even if the New York system can accommodate this (Major and Goldberg, 2001), the region's smaller systems may be vulnerable, leading to a need for enhanced regional water distribution protocols (Hansler and Major, 1999).

Adaptation
Climate change will require a range of adaptations, including some with multi-decade time horizons (Solecki and Rosenzweig, 2005). A range of adaptations to limited water supply is already occurring,

spurred by historical experience. In California, local water districts have incentive and information programs to encourage the use of water-saving appliances, reduce landscape water use, improve process water efficiency in industry, and build "California-friendly" water-efficient homes (MWD (Metropolitan Water District of Southern California), 2005). As a consequence, a population increase of over 35% (or nearly one million people) since 1970 has led to only 7% increased water use in Los Angeles. Per capita usage has fallen 15%" (California Regional Assessment Group, 2002). Efficiency measures in New York have reduced total water consumption by 27% and per capita consumption by 34% since the early 1980s (City of New York, 2005). Some of the key concepts in the 'CitiesPLUS' 100-year plan for Vancouver involve upgrading the drainage system through connecting natural areas and waterways, developing locally resilient, smaller systems, and gradually upgrading key sections of pipe during routine maintenance (Denault *et al.*, 2002).

14.7 Implications for sustainability

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 (14.3) and the possible need for action well before the magnitude (and certainty) of the impacts is clear (14,5). Other difficult problems arise from the intrinsic global scale of climate change (EIA (U.S. Energy Information Administration), 2005a). 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 kinds of free-market mechanisms and short-term political decision making that historically characterize Canada and the United States (14.5). On the other hand, the daunting magnitude of the climate change challenge calls for proactive adaptation – technological and social innovation – where Canada and the United States have abundant capacity. Key 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 extremes, especially hurricanes, heat waves, 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, confidence levels, unknowns, research gaps and priorities

The major gaps in understanding of climate change impacts on North America, and on the ability of its people, economics, and ecosystems to adapt to these changes, can be grouped into 7 main areas.

- The climate changes are uncertain, especially on a regional scale [WG1]. 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 [14.4.2], hydrology and water resources [14.4,1, 14,4,7], and on the industries [14.4.6, 14.4.7] that rely on them.
- North American people, economies, and ecosystems tend to be much more sensitive to extreme events than to average conditions [14.2]. Incomplete understanding of the relationship between changes in average and extreme conditions [WG1] 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 the extreme events with the greatest potential impact on North America, including hurricanes, other severe storms, heat waves, and prolonged droughts.
- For most impacts of climate change, we have at least some tools for estimating gradual change [14.4], but we have few tools for assessing the conditions that lead to tipping points, where a system 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 [14.4.9].
- Most of the past research has focused on climate change either in isolation or combination with adaptation. Very little work 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 [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 [14.2.3], increasing demand on freshwater resources [14.4.1], the accumulation of fuel in forest ecosystems susceptible to wildfire [Box 14.3], and continued introductions of invasive species with the potential to disrupt agriculture and ecosystem processes [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 organization could exacerbate or ameliorate impacts of climate change, even in the absence of intentional adaptation [14.4.9].
- Indirect impacts of climate change are poorly understood. In a world of ever-increasing globalization, 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 [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.
- While there are many North American examples of adaptation to climate-related impacts, understanding of the options for and the consequences of efforts to adapt proactively to conditions outside the range of historical experience is limited [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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