IPCC WGII Fourth Assessment Report – Draft for Expert Review

Chapter 14: North America

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Executive summary

Climate change does not introduce fundamentally new types of challenges. It adds new dimensions and new complications to challenges for North American communities, businesses, governments, and individuals, especially if thresholds are exceeded and sudden changes occur. Climate change impacts and adaptation are occurring in parallel with large changes in population, technology, land-use, infrastructure, international relations and environmental quality. Impacts of climate change interact strongly with all of these and with extreme events.

Recent climate trends have had clear impacts on many aspects of North American ecosystems and economies. These impacts include a lengthening growing season, changes in the timing of plant and animal activities and range, increased forest growth, rapid growth in property damage, large increases in areas burned in wildfires, increased severity of drought, and decreased western snowpack.

The value of infrastructure and number of persons in areas sensitive to climate change in North America (e.g., coastal areas, river floodplains, and areas with scarce water supplies) has grown significantly over the last 50 years and continues to grow, making North American society more sensitive to current climate variability and to climate change over time. This has occurred despite the fact that the risks are known to be relatively high in these locations.

Increased coastal infrastructure and increased urbanization interact with rising sea level to amplify risks of coastal flooding, including damage to or loss of coastal ecosystems like salt marshes. Adaptation to coastal hazards under present climate is often inadequate and readiness for increased exposure is poor.

North American cities are important drivers of global change and a locus of diverse impacts of global change, with climate, heat islands, immigrations, impermeable surfaces, disease, water issues (flooding, water quality, water availability), and biological invasives. Climate change may reduce the overall use of energy in buildings in North America but will significantly increase the use of electricity.

The continuing trend in North America toward older, more urbanized populations will increase vulnerability to some impacts of climate change (e.g. flooding or heat waves) but decrease aggregate vulnerability to impacts on sectors that become less important components of the overall economy (e.g. economic viability of agriculture, fisheries, or forestry). An older population is likely to benefit from decreased cold-related illness and injury.

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. Changes in heat-related deaths will depend on the effectiveness of adaptation. There are increased risks from a number of warm-climate diseases, but these tend to be at least as sensitive to public health infrastructure as to climate. Changes in air quality may have widespread effects on human health. Warming-related increases in ozone concentrations could have serious impacts.

Climate change will have large effects on freshwater resources. In regions like California and the Rocky Mountains that are highly dependent on snowpack, water shortages are likely. These will intensify conflicts among water users, including agriculture, growing urban areas, and terrestrial and aquatic ecosystems. Where ground water resources are heavily utilized, warming will place additional stresses on resource availability. This could compromise sustainability of supply, create competition between human uses and environmental requirements as well as amongst agricultural, industrial and municipal uses, and affect individual and regional economic activities.

Impacts on agriculture will vary from region to region, with strong modulation by changes in technology, biotechnology, and water availability. Adaptation is likely to be most challenging in regions like California and Florida with a heavy emphasis on long-lived perennial crops. Continuing shifts in the global distribution of agricultural production may concentrate both the economic and social impact of changes in agriculture on crops and regions, with impacts heightened in areas with cultural and/or tourism value (e.g. wine grapes in California). Areas with increased competition over limited water supplies will be among those most impacted.

Climate change will have diverse impacts on tourism, including the possibility that some new regions will become preferred tourist destinations (or places people want to escape). Some opportunities for nature-based tourism will increase with longer warm seasons. Climate change will increase winter access to some northern areas, but will degrade some winter-based activities. Tourism values will be altered by climate change as well as other anthropogenic impacts.

Impacts of climate change (both temperature and water balance) on natural ecosystems are occurring and will occur in conjunction with changes in land use and biological invasives. Events that kill the dominant plants and animals (e.g. fire, disease, severe storms) enhance the potential for major changes in ecosystem structure and function. Risks of wildfire and insect outbreaks are likely to increase in a warmer future with drier soils and longer growing seasons. Over the 21st century, the tendency for species and ecosystems to shift north and to higher elevations may fundamentally rearrange the map of North American ecosystems.

North America has considerable adaptive capacity, but capacity does not guarantee its use. Society has largely responded to climate experience, but action is needed where future change exceeds experience. A key prerequisite for sustainability is mainstreaming climate issues into decision making. Successful adaptation is most evident where there is multi-dimensional support for local & community actions. Cultural traditions and institutions in North America are consistent with a range of individual, community, business, and government actions.

14.1 Introduction

Does it, in our increasingly interconnected world, make sense to consider impacts of climate change on a single region? Will the United States and Canada experience impacts of climate change mainly through direct effects of local patterns of temperature, precipitation and extreme weather events? Or will regional impacts of climate change be global in scope, through their effects on interconnected economies, human migrations, and international security? Complete answers to these questions are not yet available. Regional climate change will certainly have regional impacts and require local and regional adaptations. The impacts of a changing climate on Canada and the United States will certainly not, however, all flow from climate changes experienced directly within their borders. Many of the impacts of climate change and many of the required adaptations in Canada and the United States will be indirect, in response to direct impacts of climate change in other parts of the world. This chapter strives to consider a balance of direct and indirect impacts and adaptations.

Canada and the United States (called North America hereafter, based on the WMO definitions of regions) are nations with developed economies and massive infrastructure for transportation, communication, and construction, backed with extensive scientific and technical capabilities. One consequence of this is that the amount of infrastructure exposed to damage from climate change is large. Another is that the range of feasible strategies for dealing with climate change is broad. The region's technical capabilities and tradition of innovation provide the potential for novel solutions.

The scientific literature on climate change impacts and adaptation for North America is also large. This chapter synthesizes key elements of that literature but cannot discuss every study or every locale. We focus on impacts and adaptations that operate across large parts of the region or with the potential to influence large numbers of people, important ecosystem services, or expensive or culturally significant parts of the built environment. Even with this large foundation of scientific studies, many potentially important impacts and adaptations have not been adequately studied. This is especially true for impacts and adaptations that arise from interactions among multiple direct impacts of climate change or as indirect responses to impacts and adaptations in other regions.

Structurally, this chapter is parallel to the other regional chapters in this volume. We begin with a summary of the knowledge discussed in detail in the Third Assessment Report of the IPCC (McCarthy *et al.*, 2001) and follow that with a consideration of current sensitivity and vulnerability to climate change. Then, we map expected future trends onto the landscape, economy and culture of North America and examine the expected sensitivities, adaptive capacities, vulnerabilities, and impacts, of climate change on a variety of sectors, with and without adaptation. The chapter's next section more fully addresses options for adaptation, including likely constraints as well opportunities for win-win strategies that simultaneously achieve multiple goals. Finally, we consider the implications of climate change for sustainability of North American ecological, economic, and cultural well being.

14.2 Summary of knowledge assessed in the TAR

14.2.1 Key findings from TAR

Rising costs of natural disasters in North America illustrate vulnerability to climate variability and extreme events. Emerging adaptation strategies generally address current challenges, but there are few cases of implementing adaptation to meet future impacts and opportunities.

Resource and Ecosystems

Water Resources

- In western snowmelt-dominated watersheds, shifts in seasonal runoff are likely, with a larger proportion of runoff occurring in winter. Even with adaptive responses like conjunctive management, voluntary water transfers between users, and altered management of storage systems, it may not be possible to avoid adverse impacts on aquatic ecosystems or fully offset effects of reduced summer water availability to users or instream needs.
- Possible changes in the frequency/intensity/duration of heavy precipitation events may require changes in land-use planning and infrastructure design to avoid increased damages.

Forests

- The areal extent and productivity of forests are expected to increase, though carbon stocks could increase or decrease.

- Disturbance factors (e.g., fire, insect outbreaks) are expected to 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.
- Adaptation may make lands managed for timber production less susceptible than unmanaged forests to climate change.

Agriculture

- Warming generally benefits food production in North America but there will be strong regional effects with changes in comparative advantage.
- Because they have not accounted for farm- and agricultural market-level adjustments in agriculture, economic studies have probably overestimated negative effects of climate change.
- Outdoor tourism and recreation opportunities (e.g., winter sports, fishing, parks, beaches) will respond to shifts in temperature and precipitation patterns, with both increases and decreases in recreation value.

Marine Fisheries

- The abundance and spatial distribution of species important to commercial and recreational fisheries may be affected by impacts on coastal and marine ecosystems.
- Sustainable fisheries management will require timely, accurate scientific information on environmental conditions affecting fish stocks, as well as institutional flexibility to respond quickly.

Natural Ecosystems

- Losses of specific ecosystem types, such as coldwater ecosystems, high alpine areas and coastal (e.g., salt marshes) and inland (e.g., prairie “potholes”) wetlands are possible; effective mitigation is unlikely.

Human settlements and health

- Northern cities may experience 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. Investments in adapting infrastructure can reduce vulnerability, although rural, poor, and indigenous communities may not have necessary resources.
- More frequent extreme events may increase deaths, injuries, infectious diseases, and stress-related disorders, as well as 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 degradation in air quality (smog and particulate air pollution).
- Vector-borne (malaria and dengue fever) and tick-borne (Lyme) diseases may expand their ranges in North America. Public health measures and other socioeconomic factors have a large role in determining the existence or extent of such diseases.

Adaptation and Vulnerability

Extreme events

- Over the past three decades, weather-related losses have been increasing in North America; associated insured losses are increasing with affluence and as populations continue to move into vulnerable areas.
- Governments play a key role as insurers and/or providers of disaster relief, especially in cases deemed too risky by the private sector. Over the last two decades, Canadian government disaster relief programs have covered roughly 86% of flood losses. U.S. government crop and flood insurance programs have been unprofitable and may have encouraged more human activity in at-risk areas.

- Insurers have responded to recent extreme events by limiting insurance availability or increasing prices and by establishing new risk-spreading mechanisms. Advancing building codes, land use planning and disaster preparedness also help reduce disaster losses.

Long-term Adaptation

- Changing climate-society relationships are influencing the nature of vulnerability, impacts, and adaptive responses. Increased development may reduce vulnerability in some cases (e.g., agriculture) and increase or change vulnerability in others (e.g., Columbia River basin water management).
- Climate-related impacts are likely to require substantial changes in institutions and infrastructure. “Water markets” in the western U.S. illustrate a new trend in adaptive strategies, in which the use of market mechanisms to provide efficient distribution may lead to concerns about accessibility to water for lower income people and conflicts about social priorities in allocation.
- Developing adaptation responses to climate scenarios requires a long process of interdisciplinary and intercultural dialogue with stakeholders.
- Most stakeholders perceive changes in variability as more threatening than decadal-scale gradual changes.

14.2.2. Key differences from TAR

- Tendency for models to project future warming with little or no increase in precipitation, leading to increasing severity of water resource shortages
- Our understanding of impacts on water resources now expands to identify impacts on groundwater and water quality, as well as surface water.
- Expanding recognition of the role of multi-factor, interacting impacts
- Expanding recognition of the interactions among climate change impacts and other kinds of local, regional, and global changes
- Increased recognition of the role of adaptation and adaptive capacity, and their contribution to modulating impacts
- Increased recognition of the continuum between current vulnerabilities, adaptive capacity, and long-term adaptation

14.3 Current sensitivity/vulnerability

Annual mean air temperature for Canada (south of 60°N) increased 0.9°C during the period 1900 to 1998 while in the contiguous U.S. the increase was about 0.56°C/100 yrs from 1895 to 2002 (Zhang *et al.*, 2000c; Groisman *et al.*, 2004). However, there is strong regional variation with cooling in Atlantic and north-eastern Canada and southeastern U.S. and accelerated warming in the Arctic (see Chapter 15). The marked warming in North America during the latter half of the 20th century has been attributed to the effect of greenhouse gases and sulphate aerosols in addition to natural variation (Karoly *et al.*, 2003; Stott, 2003; Zwiers and Zhang, 2003). The most warming has occurred in spring and winter (Karl *et al.*, 1996; Bonsal *et al.*, 2001). Minimum (i.e., night-time) temperatures have warmed more rapidly than maximum (i.e. daytime) temperatures (Easterling *et al.*, 1997; Zhang *et al.*, 2000c; Bonsal *et al.*, 2001). The vegetation growing season as defined by continuous frost-free air temperatures has increased by on average 2 days/decade since 1948 in the conterminous US, with the largest change in the western US, and with most of the increase from earlier warming in the spring (Easterling, 2002; Feng and Hu, 2004) (Figure 14.1). The growing season in much of Canada has increased similarly, 2-3 days/ decade overall from 1950-1998, although north-eastern Canada has cooled slightly (Bonsal *et al.*, 2001) (Bonsal and Prowse, 2003).

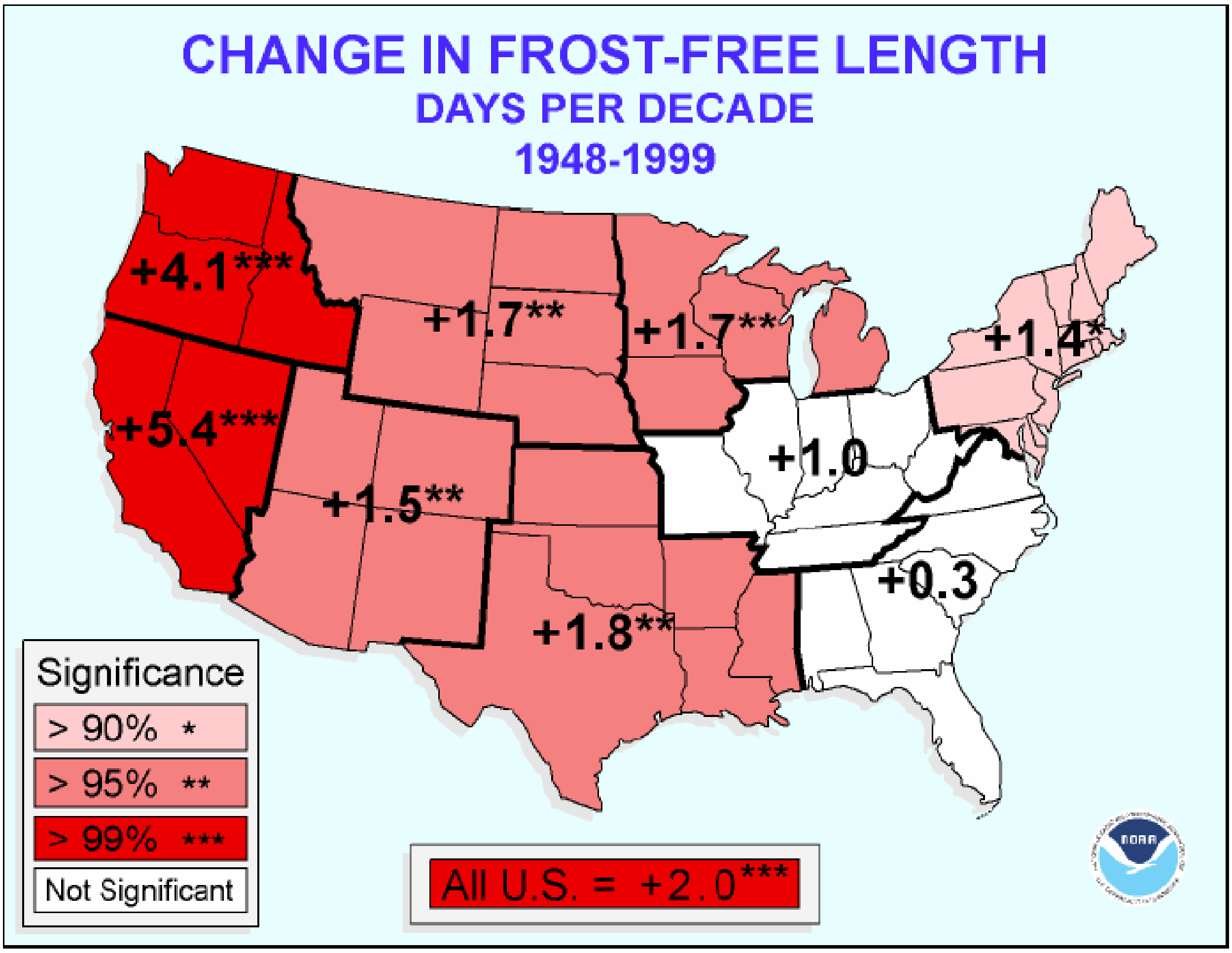


***Figure 14.1**: NA Growing season lengthening 1948-1999 (Easterling, 2002). Figure to be expanded to include Canada.*

Significant total annual precipitation increases of five to thirty percent have occurred across most of southern Canada (1900-1998) (Zhang *et al.*, 2000c). Annual total precipitation in the U.S. has increased seven percent from 1895 to 2002 (Groisman *et al.*, 2004). A recent analysis of long-term daily precipitation records (1895 to 2000) in the U.S. by Kunkel *et al.* (Kunkel *et al.*, 2004) found that heavy precipitation frequencies were at a minimum in the 1920s and 1930s and then increased to the 1990s. Increases in heavy precipitation were observed in the coterminous U.S during the past three decades (Groisman *et al.*, 2004).

Present rates of relative sea-level change range from rapid emergence (~10 mm/y) in Hudson Bay and southeast Alaska to slight emergence on the outer Pacific coast (Vancouver Island to northern California) and slow submergence in the Georgia-Puget basin (Vancouver, Seattle) and from San Francisco south. On the Atlantic seaboard, rates of relative sea-level rise increase northward from Florida to peak (>4 mm/y) in the region from Virginia to New Jersey and decrease again north to Maine (Zervas, 2001). In Atlantic Canada, many stations show rates between 3 and 4 mm/yr (Forbes, 2004). These patterns primarily reflect regional variations in the rates of postglacial isostatic vertical adjustment of the crust (Douglas and Peltier, 2002). Extraordinary rates of relative sea-level rise in Louisiana (e.g., about 10 mm/yr at Grand Isle) and Texas (e.g., ~7 mm/yr at Galveston) reflect added factors of compaction and induced subsidence from fluid extraction. Sea levels exhibit considerable variance over time scales of years to decades, but evidence suggests recent acceleration of sea-level rise at some stations (Donnelly and Bertness, 2001; Forbes, 2004). Sensitivity to sea-level rise has been mapped for Canada (Shaw *et al.*, 1998) and the eastern USA (Titus and Richman, 2001).

14.3.1 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) than at any time since ____. Areas in southern Canada affected by extreme dry and by extreme wet summer conditions both increased between 1900-49 and 1950-98 (Figure 14.2) (Zhang *et al.*, 2000b). Dai *et al.* (Dai *et al.*, 2004) found that global land areas in either very wet or very dry conditions increased from 20-38% of land area since 1972, suggesting more extreme hydrology. Streamflow has *increased* 25% in the last 60 years over the eastern U.S. (Groisman *et al.*, 2004), but has *decreased* in the western U.S. by about two percent per decade in the last century (Rood *et al.*, 2005). Walter *et al.* (2004) calculate that evapotranspiration (ET) increased by 55mm y^{-1} in the last 50 years in the conterminous U.S., however, their data show reduced stream discharge in the Colorado and Columbia river basins since 1950.

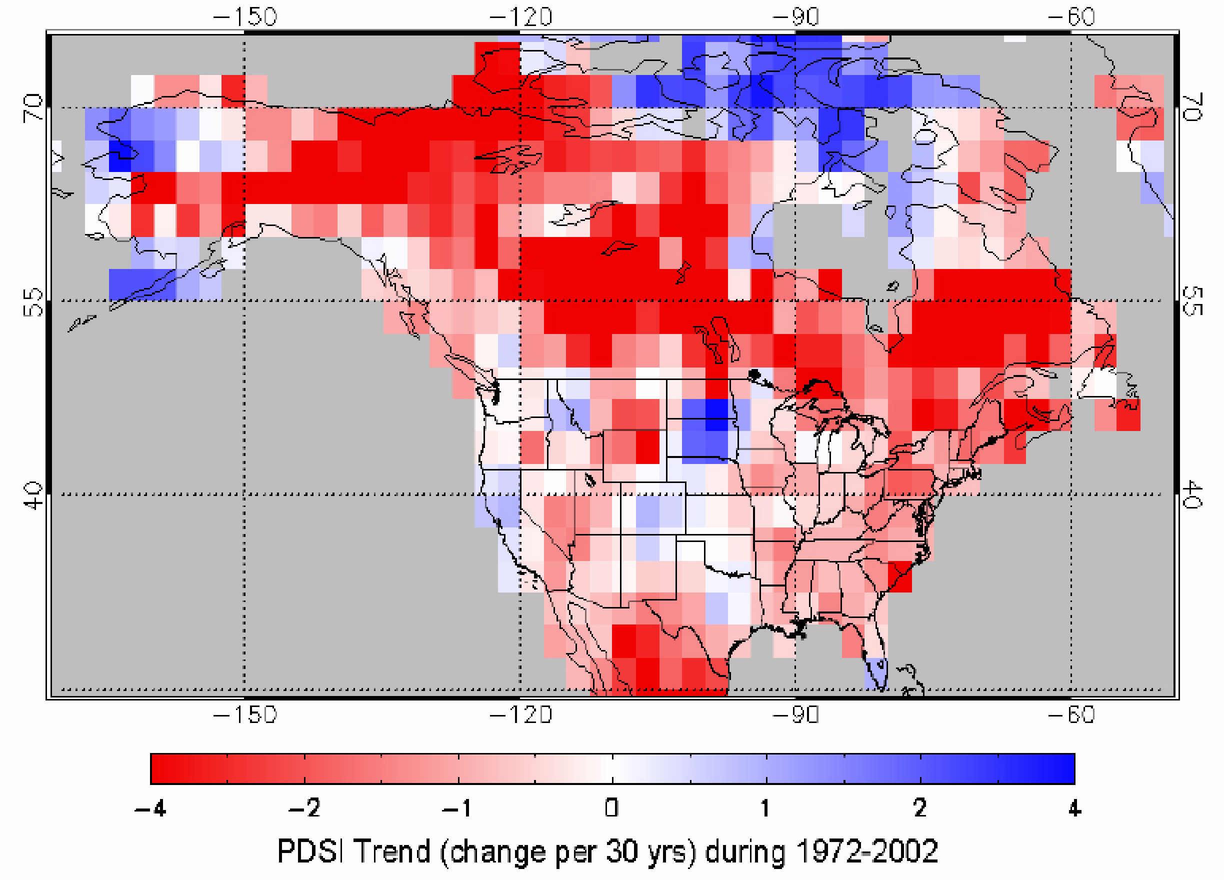


Figure 14.2: *NA Drought Index trend 1972 – 2002 (Dai et al., 2004)*

In snow melt regions, temperature increase has shifted the magnitude and timing of hydrologic events. 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 soil water equivalent (SWE) decreased 15-30% since 1950 in the Pacific Northwest particularly at lower elevations in spring (Mote *et al.*, 2003; Mote *et al.*, 2005) (Figure 14.3). Whitfield and Cannon (Whitfield and Cannon, 2000) reported an earlier onset of runoff and Zhang *et al.* (Zhang *et al.*, 2001) mapped a significant trend in earlier occurrence of the spring runoff across Canada. Stewart *et al.* (Stewart *et al.*, 2005) found streamflow peaks in the snowmelt dominated western mountains of the U.S. occurred 1-4 weeks earlier 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).

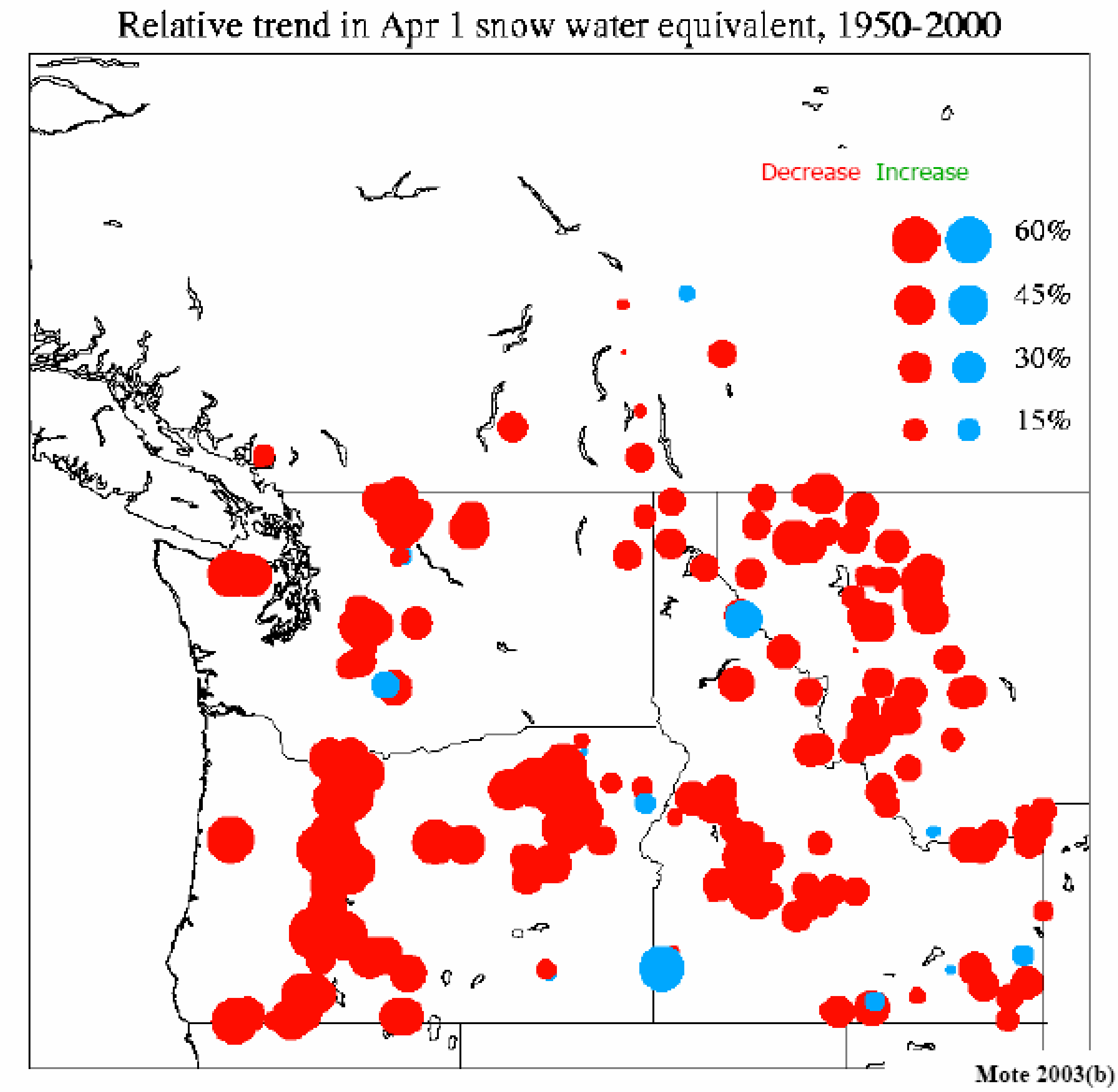


Figure 14.3: *Western U.S. April 1 snowpack trend, 1950-2000 (Mote et al., 2005). Figure to be expanded to include all of Western US and Canada*

Some of the trends in reconciling urban and ecosystem water demands are positive (Fitzhugh and Richter, 2004). In the U.S., water pollution control regulations have encouraged conservation, greater efficiency, and lower water- using technologies in industry. At the same time, several heavy water-using sectors (petroleum, coke, and steel) consolidated. As a result, industrial water demand declined by about 24% between 1985 and 2000 (Hutson *et al.*, 2004). Even in regions such as California, where previous drought has encouraged water conservation, there is considerable scope for increased water efficiency (approximately 39% of current industrial use; see (Gleick *et al.*, 2003). Some U.S. states have developed sector-specific water conservation guides (CDWR (California Department of Water Resources), 1994; NCDENR (North Carolina Department of Environment and Natural Resources), 1998). In Canada, industry groups and governments at all levels have fostered water conservation typically through pollution prevention programs. Many of the opportunities are in traditional industrial heavy process users of water.

Municipal and irrigation demand and pumping of ground water has already resulted in saltwater intrusion in coastal aquifers along the Atlantic coast from the Canadian Maritimes and Massachusetts to Florida (Foyle *et al.*, 2002; Gaswirth *et al.*, 2002; Barlow, 2003; Clarke, 2003; Price *et al.*, 2003), on the Gulf Coast (Gunterspergen *et al.*, 1998), and in California and British Columbia (Allen *et al.*, 2001; Allen and Suchy, 2001; Edwards *et al.*, 2002; Erskine and Fisher, 2002; Zektser *et al.*, 2005). Saline contamination of coastal aquifers by storm-surge flooding and storm overwash has been documented in the southeastern USA (Anderson and Evans, 2001; Conner and Ozalp, 2002).

14.3.2 Ecosystems

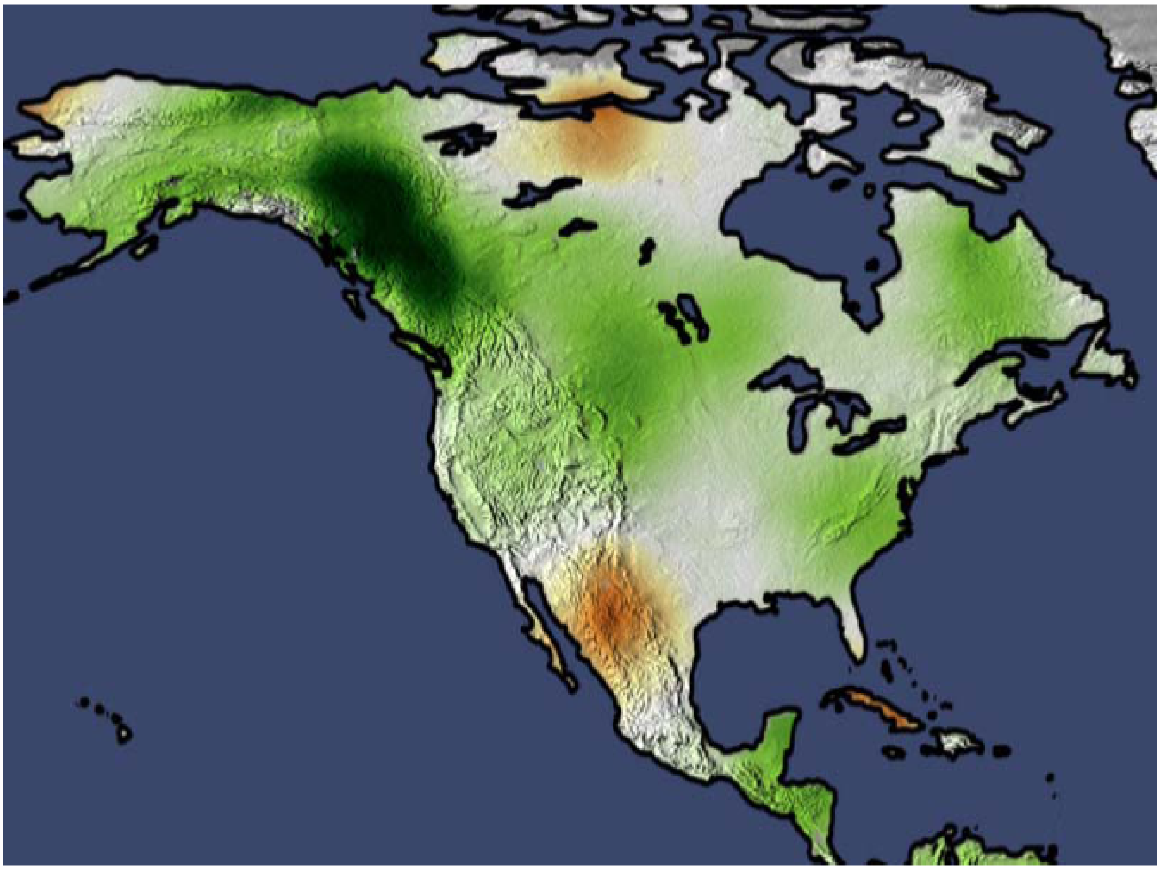
Three direct and observable connections between climate and terrestrial ecosystems are the seasonal timing of life-cycle events or phenology, responses of plant growth or primary production, and geographic distribution. Direct impacts on organisms interact with indirect effects of ecological interactions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

Phenology, Productivity and Biogeography

Global daily satellite data, available since 1981, has detected earlier onset of spring “greenness” of 10-14 days in 19 years , particularly over temperate latitudes of the northern hemisphere (Myneni *et al.*, 2001; Lucht *et al.*, 2002). Field phenological observations of vegetation have confirmed these satellite observations. (Schwartz and Reiter, 2000) reported an advance of 1.8 days/decade from 1959-1993 in lilac bloom dates from 800 sites across North America. Honeysuckle first bloom dates have advanced 3.8 days/decade at phenology observation sites across the western United States (Cayan *et al.*, 2001) and apple and grape leaf onset has advanced 2 days/decade at 72 sites in the north-eastern U.S.(Wolfe *et al.*, 2005). The first bloom of aspen trees in Edmonton now averages 26 days earlier than in 1901 (Beaubien and Freeland, 2000). Autumn leaf senescence timing is jointly controlled by temperature, photoperiod and water deficits, so shows weaker trends (Badeck *et al.*, 2004).

Global terrestrial net primary production has increased 6% during the 1982-1999 period of satellite record used for these estimates (Cao and Prince, 2002; Nemani *et al.*, 2003) (Figure 14.4). NPP increases of 10% from 1982-1999 in North America were concentrated in the central plains croplands and grasslands due to improved water balances (Lobell *et al.*, 2002; Nemani *et al.*, 2002; Hicke and Lobell, 2004). Higher NPP during this period, predominantly in northern Rocky Mountain forests was attributed to higher spring temperatures and a longer growing season (Hicke and Lobell, 2004). All of these continental scale estimates of NPP rely on satellite spectral indices of vegetation greenness, the Normalized Difference Vegetation Index, and surface weather data to compute a simple production efficiency model.

Change in Terrestrial NPP from 1982 to 1999



Nemani et al., Science June 6th 2003

Figure 14.4: *NPP trend from 1981 – 1999 (Nemani et al., 2003) Crop figure to North America only.*

Estimates of the net ecosystem exchange or carbon balance of North America can be developed from atmospheric inversion, carbon bookkeeping, and biogeochemical process models, augmented with satellite, field inventory, and flux tower data (House *et al.*, 2003). North America continues to be a carbon sink of 0.5 +/- 0.5 Pg C/yr, although human land management practices control much of the dynamics (Pacala *et al.*, 2001; Schimel *et al.*, 2001) These continental carbon budgets are limited mostly by different accounting details and availability of continent wide measurements rather than theoretical uncertainty, making greater accuracy difficult (Houghton, 2003). Goodale *et al.* (Goodale *et al.*, 2002) estimated a forest-sector carbon sink of 0.28Pg/yr for the conterminous U.S., but a source of 0.04Pg/yr for Canada because of low forest productivity rates and large wildfire emissions in the boreal forests. ENSO, AO and SO climate indices have all shown some correlation with temporal North American carbon fluxes (Potter *et al.*, 2003; Hashimoto *et al.*, 2004).

In recent decades, the area of forest burned in wildfire has increased substantially (Box 2). Early in the twentieth century, the area burned in North America was as high as 40,000,000 Ha y^{-1}, with large areas in boreal, western, and southeastern forests. This decreased to about 4,000,000 Ha y^{-1} in the middle of the century but is now increasing, with the largest increases in boreal regions (Mouillot and Field, 2005).

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). Increasing spring temperatures 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). Similarly, concurrent with increased temperatures during spring, several frog species now initiate breeding calls 10-13 days earlier than they did a century ago (Gibbs and Breisch, 2001). In lowland California, 70% of 23 butterfly species begin first spring flights an average of 24 days earlier (Forister and Shapiro, 2003).

Animals making phenological shifts might confront unfavourable microclimate conditions, as in a high elevation Colorado site where migrating robins are arriving earlier and marmots are emerging earlier from hibernation, only to confront snow persisting over their forage plants (Inouye *et al.*, 2000). Migration for North American wood warblers is initiated by photoperiod not temperature, so seven of eight species fail to migrate earlier in response to earlier springs. However, their caterpillar prey are shifting emergence with temperature, leading to a mismatch between the warbler migration and availability of their invertebrate food. Warblers are directly affected, and become less able to control insects that may defoliate host trees (Sillett *et al.*, 2000; Thomas *et al.*, 2001; Strode, 2003). 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 lead to changes in community composition and nutrient flow in ponds (Wilbur, 1997). Climate-induced reduction in water depth at western toad egg-laying sites in Oregon has increased exposure of eggs to UV-B radiation, leading synergistically to an increase in mortality by a deadly fungal parasite (Kiesecker *et al.*, 2001; Pounds, 2001).

Climate change has also shifted geographic ranges for a number of North American wildlife species. A review of long-term studies of 99 species in North America and Europe indicate that birds, butterflies and alpine herbs are shifting their range limits on average 6.1 kilometres northward or meters upward in altitude per decade (Parmesan and Yohe, 2003). Edith's checkerspot butterfly has undergone local extinctions in the southern part of their western North American range and at low elevations, resulting in a northward range shift of 90km and an upward elevation shift of 120m (Parmesan, 1996; Parmesan and Galbraith, 2004) see also (Crozier, 2003). Red foxes have expanded northward in northern Canada with warming temperatures, leading to retreat of arctic foxes which are competitively subordinate (Hersteinsson and Macdonald, 1992). Similarly, fire ants 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 (including bobwhite quail, a popular game species) and mammals, and disrupting mutualistic interactions (Holway *et al.*, 2002).

14.3.3 Coastal regions

North America has an extraordinary variety of coastal environments and ecosystems and more than 400 000 km of coast, 61% in Canada and 39% in the USA (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, in the Canadian Atlantic Provinces, and in the Beaufort Sea (Shaw *et al.*, 1998; Zervas, 2001). Relative sea level is falling in areas of crustal uplift, including Labrador, northern Quebec and Hudson Bay, the central Arctic, and outboard Pacific coast sites such as Vancouver Island (Dyke and Peltier, 2000; Forbes, 2004; Andalo *et al.*, 2005). Despite recent historical evidence of submergence, and tide-gauge records showing secular trends of rising relative sea level over the past 50-100 years at numerous locations (Zervas, 2001; Forbes, 2004), most coastal residents are unaware of these existing trends and their impacts.

Coastal regions of southern Canada and the conterminous USA have experienced growing development pressure over recent decades. A large proportion of the population and many of the largest cities are located close to the coast (Small *et al.*, 2000). As of 1998, total flood insurance in coastal counties of the United States (excluding the Great Lakes) exceeded US$466 billion (Heinz Center (The H. John Heinz III Center for Science, 2000). Titus and Richman (Titus and Richman, 2001) completed a compilation for the southern and eastern USA of lands below 1.5-m above the 1929 datum (somewhat below mean sea level today). This showed a total area of 56 000 km^2, primarily in Florida, Louisiana, North Carolina, and bordering Chesapeake and Delaware Bays. Of this area at risk of inundation, seventy-five percent was wetland and five percent urban and residential, with a total human population of approximately two million (Titus, 2005). Demographic trends support a growing demand for waterfront real estate (Small and Nichols, 2003), increasing the value of property at risk (Heinz Center (The H. John Heinz III Center for Science, 2000; Forbes *et al.*, 2002b). A recent inventory of impervious surface area (ISA), representing human alteration of the land surface through construction and paving, shows linear concentrations of high ISA effectively drawing the shoreline of the conterminous United States (Elvidge *et al.*, 2004). High concentrations of population immediately adjacent to the coast are most apparent in southern California; along the Gulf coast from Texas to Florida; the east coast of Florida; numerous urban centres along the Atlantic coast north to Long Island; and coastal population centres in New England. Vancouver and the Fraser Delta (British Columbia) have the highest concentration of population in the marine coastal zone in Canada. Beyond areas of urban concentration, vulnerable residential properties and public infrastructure, including industrial, municipal, fisheries, transportation, and tourism facilities, are widely dispersed. The extent of coastal hardening for shore protection or reclamation, combined with locally enhanced subsidence from groundwater pumping or hydrocarbon production, has resulted in extensive coastal wetland loss through 'coastal squeeze' (prevention of landward migration with sea-level rise) and submergence (Kennish, 2001; Kennish, 2002; Scavia *et al.*, 2002; Titus, 2005).

The effects of sea-level rise and climate change in the coastal zone are most clearly seen during storm events. Damage to coastal property resulting from tropical and extratropical storms along U.S. coasts has increased rapidly in recent decades (Zhang *et al.*, 2000a) and growing impacts have been seen in Canada (Forbes *et al.*, 2004; O'Reilly *et al.*, 2005). On the Pacific coast, 140 years of data from the San Francisco tide gauge suggests an increase in extreme winter storm events since 1950 (Bromirski *et al.*, 2003) During severe El Niño conditions, exceptionally high water levels can occur while winter storms tend to track further south along the Pacific coast, producing 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, submitted). Several exceptional storms since 2000 in eastern Canada, including a direct

Category 2 hurricane landfall at Halifax (Nova Scotia) in 2003, and four hurricanes in Florida during 2004, demonstrate that even well-prepared population centres in North America are highly vulnerable to severe weather and storm surges in the present climate. As this experience shows, impacts on natural coastal systems and coastal communities can be more severe when major storms recur at short intervals, allowing little opportunity to rebuild natural resilience or to reduce the exposure of property and infrastructure (Forbes *et al.*, 2004). Winter sea ice provides seasonal shore protection in parts of eastern Canada, but ice ride-up and pile-up events can cause severe damage to shorefront homes and infrastructure (Forbes *et al.*, 2002a; Forbes, 2004). The impacts of extreme events on natural coastal systems can result in thresholds of stability being exceeded, with potentially severe consequences for habitat conservation and ecological function (Scavia *et al.*, 2002; Burkett *et al.*, submitted). 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). Few coastal communities are well prepared for the possibility of unexpected, rapid, non-linear adjustments under a changing climate (Burkett *et al.*, submitted).

Municipal and irrigation demand and pumping of ground water has already resulted in saltwater intrusion in coastal aquifers along the Atlantic coast from the Canadian Maritimes and Massachusetts to Florida (Foyle *et al.*, 2002; Gaswirth *et al.*, 2002; Barlow, 2003; Clarke, 2003; Price *et al.*, 2003), on the Gulf Coast (Gunterspergen *et al.*, 1998), and in California and British Columbia (Allen *et al.*, 2001; Allen and Suchy, 2001; Edwards *et al.*, 2002; Erskine and Fisher, 2002; Zektser *et al.*, 2005). Saline contamination of coastal aquifers by storm-surge flooding and storm overwash has been documented in the southeastern USA (Anderson and Evans, 2001; Conner and Ozalp, 2002)

One aspect of coastal flooding that is rarely investigated is the release hazardous materials into the environment as a result of flooding. The Texas State Department of Health (Borders, 2003) looked at the injuries from hazardous substances in the environment as a result of tropical storm Allison. Several hazardous chemicals were released to water in the Houston-Beaumont, Texas area, including 15 million gallons of phosphoric acid, 85,000 gallons of sulphuric acid, 1,000 tons of urea fertilizer, and 3,600 gallons of ammonium nitrate fertilizer. There were also 18 fixed-facility air emission events. Events with water releases included containment failure, waste water overflows, and flooding.

Urban growth in the coastal zone (‘coastal sprawl’) has a deleterious effect on natural systems (Beach, 2002), reducing biodiversity and degrading wetlands (Eyles *et al.*, 2003). These added stresses 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, there is a tendency to increased coastal vulnerability on a broad scale (Pielke and Landsea, 1999; Heinz Center (The H. John Heinz III Center for Science, 2000). It is critical also to ensure that adaptation measures can be adaptive to changing understanding and conditions (Forbes *et al.*, 2002b; Brunner *et al.*, 2004).

14.3.4 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% y^{-1}. These yield trends include changes in technology, fertilizer, and seed stocks, plus any changes due to climate. In a large part of the Midwestern U.S., a cooling trend over the last twenty years has made a substantial positive contribution to yields of corn and soybeans (Hicke and Lobell, 2004). In northern Mexico and southern California, the contribution of recent cooling to yields of wheat explains all or nearly all of the yield changes since 1980 (Lobell *et al.*, 2005). In California, warmer nights have enhanced the production of high-quality wine grapes (Nemani *et al.*, 2001). For twelve major crops in California, climate changes over the last twenty years have not had large effects on yield, though they have been a positive factor for oranges and walnuts but a negative for avocados and cotton (Lobell *et al.*, 2005).

North American agriculture has been exposed to multiple severe weather events during the past decade. Recurring drought 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 the sector's future capacity to cope with more a 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. The key however is not whether North American agriculture will adapt to stresses such as climatic change but rather the extent to which prevailing economic and social constraints will limit the sector's capacity to cope and if necessary adapt (Edmonds and Rosenberg, 2005). It is in this light that recent assessments of current sensitivities and adaptive capacity of North American agriculture has been pursued in two broad ways: (a) modelling sensitivities to climate variability and (b) understanding adaptation as a process.

Understanding agricultural adaptation as a process has developed rapidly since 2000 (Reilly *et al.*, 2002). There has been an initial compilation of adaptations options that are currently employed within North American agriculture, including the grouping of specific adaptations into broader categories (e.g., technological, public policy and farm management) and while this has been an important step, a comprehensive understanding of adaptive behaviours remains elusive (Smit and Skinner, 2002). One of the key findings emerging from this research is that recent adaptations by the agricultural sector in North America are not typically a single discrete action (as if often implied within adaptation modelling studies) but it is a rather 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). And while there has 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 and if necessary adapt to climate change remains limited (Tol, 2002).

Forestry

Forest growth appears to be slowly accelerating (<1%/decade) in regions where tree growth is limited by low temperatures and short growing seasons that are gradually being alleviated (Casperson *et al.*, 2000; McKenzie *et al.*, 2001; Joos *et al.*, 2002). Black spruce at the forest-tundra transition in eastern Canada show acceleration of height growth, beginning in the 1970s (Gamache and Payette, 2004). However, radial growth of white spruce in Alaska has decreased over the last 90yr due to increased drought stress on the dry south aspects (Barber *et al.*, 2000). Semi-arid forests of the southwestern US also showed a decreasing growth trend since 1895, correlated with drought effects from warming temperatures (McKenzie *et al.*, 2001). Peterson and Peterson (Peterson and Peterson, 2001) and Peterson *et al.* (Peterson *et al.*, 2002) found complex topographic relationships between tree-ring growth and climate from 1895-1991 in subalpine forests in the Pacific Northwest. 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. Photographs at timberline in Colorado taken 100years ago have recently been repeated, and show advancement of aspen into the more cold tolerant spruce-fir forests (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).

Fisheries

To follow.

14.3.5 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 land use change can exacerbate climate exposures across populations (e.g., via the urban heat-island effect) requiring cross-sector risk assessment to determine site-specific vulnerability. For example, drought and fires in California can affect human safety, just as flooding and mudslides impact human health directly, in addition to their adverse effects on housing and infrastructure.

Trends in incidence of infectious diseases vary widely, with some of the patterns controlled by: transmission pathway (e.g. air, water, food, or insects). 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 was linked to variability in precipitation. The epidemic followed five years of drought in California (Kolivras and Comrie, 2003). Waterborne disease outbreaks from all causes in the US demonstrate a distinct seasonality, a spatial clustering in key watersheds, and an association with heavy precipitation (Curriero *et al.*, 2001). Certain watersheds, by virtue of the land use patterns and the presence of human and animal faecal contaminants, are at higher risk of surface water contamination after heavy rains, and this has serious implications for drinking water quality. Heavy runoff after severe rainfall can also contaminate recreational waters and increase the risk of human illness (Schuster *et al.*, in press). For example, heavy runoff leads to higher bacterial counts in rivers in coastal areas and at beaches along the coast. This association is strongest at the beaches closest to rivers (Dwight *et al.*, 2002), suggesting that the public health risk of swimming in beaches increases with heavy rainfall.

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.*, in press). This trend is independent of seasonal effects.

Many zoonotic diseases (natural life cycle being in animals) are sensitive to climate fluctuations (Charron, 2002). West Nile virus (WNV) emerged for the first time in the North America in July, 1999. While international travel is suspected as the cause of this event, the unseasonable heat wave that year (as well as in subsequent hot summers in the Midwest and West during peak years of 2002 & 2003 subsequently) raises the question of weather’s possible effect on WNV disease ecology and transmission. 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). Also, an outbreak of West Nile encephalomyelitis horses in the Midwest of the US peaked with high temperatures, and significantly dropped following decreasing ambient temperatures, suggesting a temperature effect (Ward *et al.*, 2004). Bird migratory pathways and WNVs recent march westward across the US and Canada are key factors as well, and must be considered in future assessment of temperature's role in disease dynamics. Its emergence in North America is influenced by several factors, but some evidence suggests a modulating effect of temperature (see Box 3). Saint Louis encephalitis (SLE) tends to appear during hot, dry La Niña years when hot summer temperatures 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, maximum, minimum, and mean temperatures as well as vapour pressure, significantly contribute to population maintenance of the tick, *Ixodes scapularis,* which functions as the microorganism's secondary host in the U.S. Also, an average monthly minimum temperature threshold above -7º C is required for tick survival (Brownstein *et al.*, 2003).

Current Adaptive Capacity

Air conditioning is one adaptation to heat waves, and increasing trends in air conditioning market saturation and may substantially offset direct risks of more frequent heat waves (Sailor and Pavlova, 2003). However, use will increase the demand for electrical power and subsequent production of pollution and greenhouse gases – potentially an unsustainable adaptation (uncertain).

Heat response plans and heat early warning systems (EWS) can save lives. For example, in the wake of 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.*, 2002a). As for EWS, currently, over two-dozen cities worldwide have a "synoptic-based" weather watch-warning system, which focuses monitoring on dangerous air masses (Sheridan and Kalkstein, 2004). However, variability in predictability between cities suggests that systems must be location specific, requiring the input of considerable amounts of health-related and meteorological data for each locale at considerable costs (Ebi *et al.*, 2004).

Current EWS for infectious diseases have not yet demonstrated their utility, and are only likely to improve if predictive accuracy through incorporation of both climatic and non-climatic determinants is achieved.

14.3.6 Human Settlements

Human settlements at a wide range of scales are dominant features of the landscape in many parts of North America, but extremely sparse in others (Figure 14.5). Many are concentrated along the coast and around the Great Lakes. Broad regional patterns are apparent in the map of urban land cover (a surrogate for population density). Extensive urban cover in the eastern half of the USA contrasts with much lower concentrations in the west, excluding the north-south corridor from southern California to Washington and the British Columbia lower mainland. The Canadian population is concentrated in a small number of medium-sized urban centres, with extremely low population densities elsewhere. Research published since the TAR shows that human settlements in North America are sensitive to climate variability and trends, both through effects on the economic base and through direct and indirect impacts of extreme events.

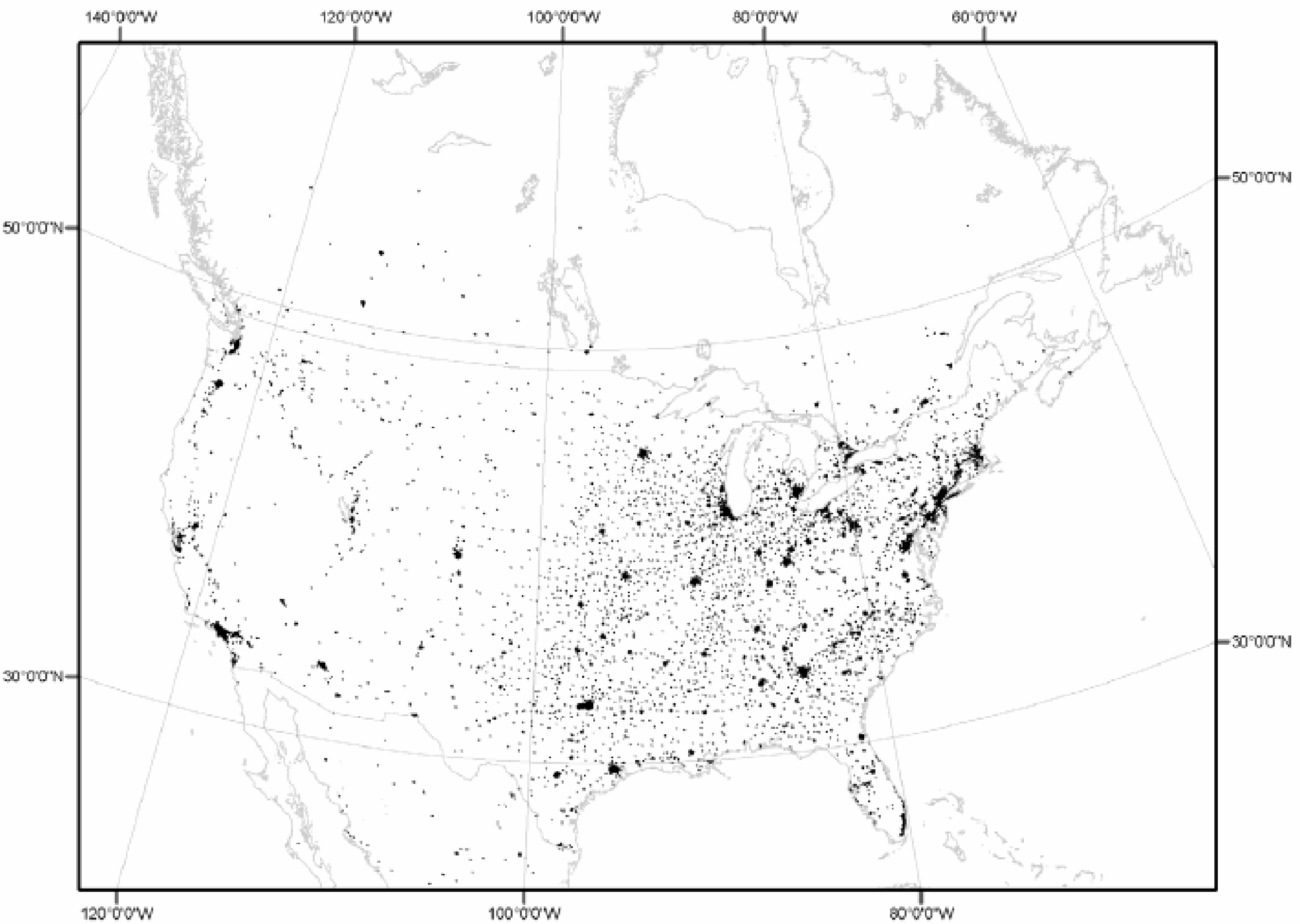


***Figure 14.5:** Constructed area in North America (Elvidge et al., 2004).*

Economic Base

Indigenous communities in North America include some Native American settlements in the Lower 48 United States where the residents largely inhabit their ancestral lands (the reminder probably would be better classified as “rural”), but mostly consist of Native American villages in Alaska and First Peoples’ settlements in Canada. Although residents may participate in the wage economy, many of the residents of these settlements engage in subsistence (hunting, fishing, trapping and gathering) activities on at least a part-time basis. These activities have social and spiritual as well as economic importance, and contribute to the cohesion of the settlement. Many such communities have a long history of adaptation to ecological change, but their high relative dependence on sometimes-fragile ecological systems makes them sensitive to climate change. For example, Alaskan Inupiat whaling and sealing communities are confronted with the loss of 15-20% of summer sea ice in the last 30 years and the near-total loss by late in the century (ACIA (Arctic Climate Impact Assessment), 2004). Inuit communities in the Canadian Arctic also face challenges associated with climate change (Fox, 2003). These include additional stress on caribou herds from insects and reduced pasturage, and less reliable sea ice for Inuit hunting and land and river ice for travel (NAST (National Assessment Synthesis Team), 2000a; CCME (Climate Change Indicators Task Group of the Canadian Council of Ministers of the Environment), 2003 Nature, People; ACIA (Arctic Climate Impact Assessment), 2004). Depending on location, their infrastructure could also be sensitive to flooding, drought, extreme weather, or storm surge. Further, infrastructure redundancy and robustness may be low, as are ability to exploit entirely new modes of resource use, levels of economic wealth, and adaptive capacity.

Rural settlements in North America such as fishing towns in maritime Canada, Pacific Northwest, and New England, have been seriously affected by the multi-causal decline of the resource base in recent years (CDLI (Centre for Distance Learning and Innovation), 1996) while some Alaska fishing communities benefited from warmer waters and rising salmon stocks after 1977 (CDLI (Centre for Distance Learning and Innovation), 1996). Some traditional resource regions have considerable institutional ability to marshal resources from higher levels of government and have been able to maintain themselves during long adverse trends in market conditions (e.g., dairy farming communities and dry land farming areas in the Great Plains) (Rathge *et al.*, 2001).

Urban Infrastructure and Extreme Events

Almost 80 % of the North American population lives in urban areas (U.S. Census Bureau, 2000). North American cities, while diverse in size, function, climate, and other factors, have a common operational “style” that affects how climate change will affect them.

Based on the automobile and low-rise, low-density living and sprawling infrastructure systems based on economies of scale, these cities are largely shielded from its natural environment by multiple technical systems designed for high-throughput of water, energy, and materials with just-in-time supplies. The systems make large demands on natural resources in the surrounding regions. For example, California South Coast water sources include the Colorado River (390 km distant); California State Water Project (612 km); Los Angeles aqueducts from Owens Valley and Mono Basin (552 km); and local sources. Electric power required to operate the 390 km Colorado River Aqueduct is two mega-watts per acre-foot delivered to the Los Angeles basin, more than 20%of the firm energy and contingent capacity of the Hoover Project, 50% of the Parker Project, and off peak purchases from electric utilities (California Regional Assessment Group, 2002). Over 90% of all electricity used in Vancouver is produced by hydro-electric dams in the interior of the province of British Columbia, some 400-500 km distant (Sheltair Group, 2003). New York’s mostly gravity-fed water system draws from three upstate reservoir systems over a distance of 120-200 km. The system includes 19 reservoirs and three controlled lakes with a total storage capacity of approximately 2200 billion litres. Urban systems are vulnerable to low-probability extreme events beyond their design basis, and to systemic failures (domino effects). For example, future extended drought could threaten the urban water systems of at least some cities in the southwest United States, despite elaborate and geographically extensive water supply infrastructure (Morehouse *et al.*, 2002) (see Sections 14.2.3, 14.2.8, and 14.4.8, Box 4)

North American cities contain ethnically diverse populations, with wide distributions of income, with low-income populations concentrated in city centres rather than on the peripheries (as in many developing countries). This leaves low-income populations vulnerable to some climate impacts such as air pollution and heat waves (Section 14.2.5; Box 4)

Because of their wealth, ability to draw additional resources from beyond their borders, large educated populations, and large cadres of trained personnel, these cities have high adaptive capacity. However, the large numbers of governmental units and the complex relationships between levels of government and between the private, NGO, and public entities make concerted regional adaptation difficult to achieve (Sections 14.5.3, Box 4)

The TAR noted the dramatically rising cost of natural disasters in North America at the end of the 20th century, as a result of increasing levels of development and, possibly, increasing storminess. Several studies published after the TAR confirm the rise in sensitivity as the likely principal source for past increases in damage (high agreement, much evidence). They generally do not attribute observed increased damage to increased storminess and instead emphasize that past increases in damage are a function of 1) increased wealth, with more valuable property at risk; 2) demographic shifts to coastal areas and storm-prone areas that are experiencing increased urbanization, and 3) aging infrastructure, substandard structures, and inadequate building codes (Easterling *et al.*, 2000; Balling and Cerveny, 2003; Changnon, 2003; Changnon, 2005). The frequency of hurricanes has not increased, but the energy released per storm (a function of wind speed and duration), has more than doubled in the last 30 years (Emanuel, 2005). Thunderstorms and hail activity peaked in the period 1936-1955, followed by a moderate decrease (Changnon and Changnon, 2000; Changnon and Changnon, 2001). There has been no discernable upward trend in the number of strong tornadoes F-3 or greater on the Fujita scale (although weak ones may be better reported over time (Grazulis, 2001; Hage, 2003). Damaging winter storms such as Nor'easters on the east coast of North America appear not to have been increasing (Hirsch *et al.*, 2001; Hage, 2003), with increases in damages from these events explained by societal factors (Kunkel *et al.*, 1999). Freezing rain incidence shows a very complex set of local patterns, but there is no general increase (Changnon and Bigley, 2005). The only exception was an increase in the intensity in heavy rains from thunderstorms (Changnon, 2001). Numerous shortcomings have documented for storm loss data and corrections have been attempted (Easterling *et al.*, 2000; Changnon *et al.*, 2001; Changnon and Hewings, 2001; Changnon, 2003; Changnon, 2005). North American economic losses from extreme weather, once carefully adjusted for reporting shortfalls and for societal factors such as increased wealth and inflation or some types of climate extremes (floods, hurricanes thunderstorms-hail and winter storms have trended upward (Changnon, 2001), but the number and intensity of the events themselves generally have trended downward or have held steady (Kunkel *et al.*, 1999; Balling and Cerveny, 2003; Changnon, 2003).

Regardless of any future trends in the number and intensity of extreme weather due to climate change, the impact of four hurricanes in Florida during the summer of 2004 (US$42 billion in property losses (NCDC (National Climate Data Center), 2004)) demonstrates that even relatively well-prepared areas in North America could suffer serious property losses even if extreme events simply vary in number and intensity and do not become more common or more severe in a warmer climate, due to growth in property values and numbers of people at risk (Pielke Jr. *et al.*, in press).

Since the TAR, additional effort has gone into mapping hazards associated with increased vulnerability of infrastructure in North America to climate change. Nelson *et al.* mapped hazards to population centres and settlements, roads, railroads, airfields, electrical transmission lines, and pipelines from potentially melting permafrost at 0.5° x 0.5° resolution under climate warming scenarios (ECHAM1-A,GFDL89, and UKTR models). Infrastructure at “moderate to high hazard” in North America included Nome and Barrow in Alaska, Inuvik in the Yukon, the Dalton Highway in Alaska and the Dempster Highway in the Yukon, airfields in the Hudson Bay region, the Alaska Railroad, and the Trans-Alaska oil pipeline (Nelson *et al.*, 2002). Several cities and populated coastlines on the U.S. Gulf Coast and Atlantic Coast are potentially sensitive to severe weather and storm surge due to their location within 3.5-m of sea level (high agreement, much evidence). This area has now been mapped in some detail in the U.S., and includes areas such as Miami to Palm Beach (FL), Tampa-St. Petersburg-Sarasota (FL), Savannah (GA)-Hilton Head (SC), Houston (TX), Galveston (TX), New Orleans (LA), Gulfport-Pascagoula (MS), Mobile (AL)-Pensacola (FL), Charleston (SC), Myrtle Beach (SC), Wilmington (NC), Virginia Beach-Hampton (VA), Ocean City (MD), Atlantic City (NJ), Point Pleasant-Perth Amboy (NJ), Long Island (NY), and the coastal communities of New England (Titus and Richman, 2001).

There have been other evaluations of impacts of past extreme events on human settlements and infrastructure since the TAR. These studies continue to emphasize the interaction between a variable and sometimes increasing flood hazard on the one hand and increasing numbers of people and value of property at risk, on the other. If some river basins become more flood-prone due to snowmelt or more intense precipitation there may be impacts in regions historically known for flooding challenges (e.g., the Sacramento (Miller, 2003), Fraser (Loukas *et al.*, 2002), and Red River of the North (Simonovic and Li, 2004)). The experiences with large property losses in the floods of the upper Mississippi basin in the summer of 1993 (Allen *et al.*, 2003), the Columbia River and Fraser River in 1948, and the Red River of the North (North Dakota-Minnesota-Manitoba) in 1997 (Pielke Jr., 1999) illustrate the sensitivity to climate associated with riverine flood plain location of key infrastructure and correctly interpreting forecasts of flooding. Also see section 14.2.1. As noted in 14.2.3 above, several cities and populated coastal areas on the US Gulf and Atlantic coasts are potentially sensitive to severe weather and storm surge due to their location within 3.5 meters of sea level.

14.3.7 Tourism and Recreation

The United States and Canada are an important component of the global tourism industry, ranking among the top ten nations for international tourism receipts (US$112 billion and US$16 billion (World Tourism Organization, 2002)). Both countries also possess domestic tourism markets that are several times larger than their international tourism markets. Extreme events such as forest fires, low water levels, and storms illustrate sensitivity of tourism and recreation to climate variability.

The wildfires in the state of Colorado during the summer of 2002 may provide an analogue of potential impacts on the tourism sector in the mountainous regions of western North America. Dangerous wildfire conditions and media coverage of major fires in parts of the state had a significant impact on summer tourism.

Below average water levels in the Great Lakes during 1999-2002 revealed the sensitivity of marinas and the recreational boating industry to climate variability (Lemmen and Warren, 2004). The Canadian Government created a US$9.9 million Great Lakes Water-Level Emergency Response Programme to aid marina owners and operators with emergency dredging costs.

In the United States, low water levels are restricting tourism and recreation in western regions of the country. Drought conditions in Colorado during the summer of 2002 impacted the sport fishing and rafting industries. Anglers were restricted from fishing in many state rivers because the fish populations were highly stressed by low water levels and higher water temperatures. The river-rafting season was also shortened, with economic losses to the rafting industry exceeded US$50 million (Kesmodel, 2002). The prolonged drought in western regions of the United States has also negatively affected reservoirs, a major tourism and recreation resource in the country. Lake Mead is the largest functional reservoir in the western United States and used for recreation by nearly ten million people annually. Water levels in the reservoir have dropped nearly 30-m since 1999 and a number of boat launches have been closed because they no longer extend to the water line. The National Park Service estimates that every six metre reduction in Lake Mead's surface water level costs six million dollars (U.S.) to mitigate (Allen *et al.*, 2003).

The U.S. EPA indicated that the ten day closure and clean-up period from Hurricane Georges (September 1998) resulted in tourism revenue losses of approximately US$32 million in the Florida Keys. The four hurricanes that struck Florida during a two month period in 2004 are anticipated to have cost the tourism industry over a billion dollars in infrastructure damage and lost business in 2004 and 2005.

14.3.8 Industry, energy supply

The TAR identified extreme weather impacts on power systems as one of the climate sensitivities of North American society. Empirical estimates of the costs of power outages in North America published since the TAR confirm the high costs of outages (e.g., \$30 billion-\$130 billion annually in the U.S.) (EPRI (Electric Power Research Institute), 2003; LaCommare and Eto, 2004).

Though not all power outages are caused by extreme weather, the impacts of weather-related disruptions can be severe. Edison Electric Institute (EEI) found that 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 was US\$890 million (EEI (Edison Electric Institute), 2005). Although it was not triggered specifically by the hot weather prevalent at the time, the 2003 summer outage in the northeast U.S. and southeast Canada also illustrates the costs to North American society to large-scale power interruptions. Over 50 million people were without power in the 2003 incident, 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 shut down by the 2003 outage (Bradford, 2003). Business losses can range from various forms of business interruptions; to property losses from consequent fires (61 more fires than normal during the 2003 U.S. blackout), data loss, equipment damage from power surges, and loss of perishable refrigerated products; to injury from evacuations; to liability for power suppliers deemed to have been able to avert the loss, and others (out of the area of the outage) were adversely impacted by disruptions to supply lines (Bradford, 2003). Business downtime is a major cost of power outages. A recent survey of companies found that power outages cost half of the surveyed companies US\$50,000 per hour of downtime, and an average of over US\$250,000 per hour in the top quartile (RMS (Risk Management Solutions), 2005).

14.4 Assumptions about future trends

14.4.1 Climate

The climate model simulations run for the Fourth Assessment Report of the IPCC (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 2010 time slice is in the range of one to three degrees Celsius. By the 2040-2069 time slice, winter warming across the northern part of the region is two to six degrees Celsius, approximately twice as much as in the summer months. In this mid-century time-slice, warming across the temperate and subtropical latitudes of North America is one to five degrees Celsius in summer and winter. Regional differences in the seasonality of warming continue through the latter 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. Differences among scenarios and models vary among regions. 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 is 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. This is not true across the temperate and subtropical latitudes. In this region, projected decreases in precipitation are as common as projected increases, across the array of seasons, models, and scenarios.

The climate of North America is strongly affected by natural modes of variability in the global coupled ocean-atmosphere system, including El Niño- Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), the Arctic Oscillation (AO) and related North Atlantic Oscillation (NAO), and the Quasi-Biennial Oscillation (QBO). Across Canada, ENSO strongly affects the frequency and duration of winter cold and warm spells, El Niño being associated with an increase in occurrence of warm temperatures across most of Canada and La Niña having the opposite effect (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997; Shabbar and Bonsal, 2004). Over eastern Canada and New England, AO influences winter temperatures, with a higher frequency of cold spells in years of positive AO, and the QBO has a comparable effect. The frequency of warm spells and extreme warm days increases in the southern Prairies during the westerly phase of QBO (Shabbar and Bonsal, 2004).

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).

14.4.2 Social and Economic Context

Canada and the U.S. have developed economies, extensive infrastructure, and access to working capital. These resources expand the pallet of potentially viable approaches for coping with a changing climate. But they also impose a broad range of challenges. The existence of a large quantity of infrastructure implies a large investment in protecting it.

In recent years, Canada and, especially, 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. Budget pressures associated with the costs of health care and an aging population are likely to intensify over several decades. 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.

14.4.3 Government and culture

Since 9/11, the U.S. has invested an increased fraction of its national budget and attention on national security, with the position of the federal government being that security threats from international terrorism are likely to continue over at least the next several decades. If responses to these threats continue to consume a large fraction of government budgets at all levels, then flexibility in dealing with climate change may be substantially constrained.

In recent decades, the economies of Canada and the U.S. have increased emphasis on services and technology and services, while decreasing emphasis on manufacturing. While this has led to substantial increases in the energy efficiency of GDP, it has also resulted in the loss of many well paid manufacturing jobs and in income stagnation among some groups of wage earners. Increasing inequality in income and wealth could lead to social unrest, though the persistence of the dream of making it big has been a powerful incentive to generate innovation and hard work.

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. The implications of this for continued economic leadership from North America are far from clear.

14.4.4 Technology

Canada and the U.S. are technologically advanced, with significant investments in a range of technologies relevant to addressing climate change. Some recent analyses suggest that the challenge of limiting carbon emissions over the next 50 years is mainly one of massively scaling existing technologies (Pacala and Socolow, 2004) while others emphasize the need for fundamentally new technologies (Hoffert *et al.*, 2002). Differences between these perspectives include both expected levels of increase in energy demand and assessments of the potential for scaling existing technologies. All of the analyses to date, however, conclude that meeting the energy demands of the 21st century will be a massive undertaking, whether or not the energy sources emit greenhouse gases (Caldeira *et al.*, 2004).

Some of the most potent new technologies developed in the last decade and likely to be developed in coming decades involve genetic engineering, in which organisms are altered for a wide variety of reasons, including producing new products, producing more of desired products, producing less of undesired products, or requiring less of expensive inputs. Technologies with genetically modified organisms (GMOs) have the potential to play key roles in energy technology, in areas ranging from improved efficiency of methanol production from biomass to increasing land area available for photovoltaics by reducing the land requirements for agriculture for food production. GMO-based technologies for exotic processes like light-driven hydrogen production are within the realm of possibility. In coming decades, however, the prospects for wide adoption of products from biotechnology, especially agricultural products, will depend on public acceptance, business practices, and environmental implications.

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

14.5.1 Freshwater Resources

For freshwater resources, climate change is an additional stressor interacting with population growth, urbanization, land use change and intensification, pollution, and rising water demand. National assessments indicate that freshwater resources are affected by climate change across Canada and the U.S. but the nature of the vulnerabilities varies depending on regional context (NAST (National Assessment Synthesis Team), 2001; NRCan (Natural Resources Canada), 2002; Lemmen and Warren, 2004). Drought and insufficient water supply, and floods and changing seasonal flow are pervasive issues while surface water quality, ground water quantity and quality, and ecosystem vulnerabilities are important in many areas.

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; Stone *et al.*, 2001; Rosenberg *et al.*, 2003; Sushama *et al.*, 2006). Rosenberg *et al.* (Rosenberg *et al.*, 2003), using HadCM2 scenarios (IS92a, 2030 and 2095) in HUMUS, showed an overall increase in annual water yield for the U.S., with reductions in the western Great Plains of Kansas, Colorado and Nebraska. Warming offsets the effects of more precipitation while magnifying the effects of less precipitation (Stonefelt *et al.*, 2000; Fontaine *et al.*, 2001). Simulated water yield also depended on the resolution of the climate model (Stone *et al.*, 2003).

Higher temperatures in snow-melt dominated watersheds are important drivers of the shift in the seasonal hydrologic cycle through earlier snowmelt with increased water yield during late winter and early spring, and, in some cases, reductions in summer water supply (Stonefelt *et al.*, 2000; Kim *et al.*, 2002; Rosenberg *et al.*, 2003; Sushama *et al.*, 2006). 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 (Canadian Regional Climate Model (CRCM), 2041-2070, A2 and IS92a) (Sushama *et al.*, 2006). Springtime snowmelt discharge advanced by 30-40 days in the Pacific Northwest, Sierra Nevada, and Rocky Mountains (Stewart *et al.*, 2004).

Projected warming and changes in the form, timing and amount of precipitation lead to significant reductions in snowpack at moderate elevations by mid 21st century. Winter flows and flooding potential are projected to increase with associated large reductions in summer flow during the dry season in coastal and inland mountainous areas draining to the Pacific (Kim *et al.*, 2002; Loukas *et al.*, 2002; Snyder *et al.*, 2002; Leung and Qian, 2003; Miller *et al.*, 2003; Mote *et al.*, 2003). In these simulations, the ratio of snowfall to rain declines, particularly at lower elevations (Loukas *et al.*, 2002; Leung and Qian, 2003; Mote *et al.*, 2003). Simulated annual mean snow pack decreases over the Cascade Range and Coast Mountains by up to 60% (Leung and Qian, 2003). In the Sierra Nevada region, late winter snow accumulation decreases by 50-90% by the late 21st century (Miller *et al.*, 2003), with larger impact from the HADCM3 than the PCM model and with the A1FI than the B1 scenario (Hayhoe *et al.*, 2004). Heavily-managed water systems of the western U.S. that rely on capturing snowmelt runoff, such as the Columbia River, are especially vulnerable (See Case Study x). These hydrologic changes are likely to affect design and operation of dams and reservoirs, require re-assessment of flood mitigation plans, and negatively affect summer water quality and ecosystem health.

In the Great Lakes – St. Lawrence Basin, recent assessments concur in projecting that climate change will lead to lower net basin supplies and reductions in water levels (high confidence) (Croley, 1990; Hartmann, 1990; Mortsch and Quinn, 1996; Chao, 1999; Mortsch *et al.*, 2000; Quinn and Lofgren, 2000; Lofgren *et al.*, 2002). Lower water levels lead to a number of interacting impacts (Figure 14.6). Hydropower producers in the regions could experience losses of US$437 to $660 million per year if water levels fall. In contrast, rising water levels lead to annual gains of only CDN$28 to $42 million per year (Buttle *et al.*, 2004). Commercial navigation into the deep-water port facilities Port of Montréal could be curtailed or re-routed to other eastern seaboard ports. Adaptation measures could be dramatic, including unprecedented channel dredging, and structural dams and navigation locks below Montréal (St. Lawrence River-Lake Ontario Plan of Study Team, 1999). The estimated cost of compensating for a 1.25 to 2.5-m drop in the 101 km stretch of the Illinois shoreline, including Chicago, was US$251 to $515 million over 50 years including harbour dredging and refitting bulkheads, slips and docks (Changnon, 1989 barges and diversion). Costs for dredging the small harbour in Goderich, Ontario to alleviate a 1 metre drop were CDN$6.84 million (Schwartz *et al.*, 2004b). The Great Lakes have a history of conflicts and controversies about diversions of water, particularly at Chicago. Contentious issues include water quality, navigation, domestic and industrial 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).

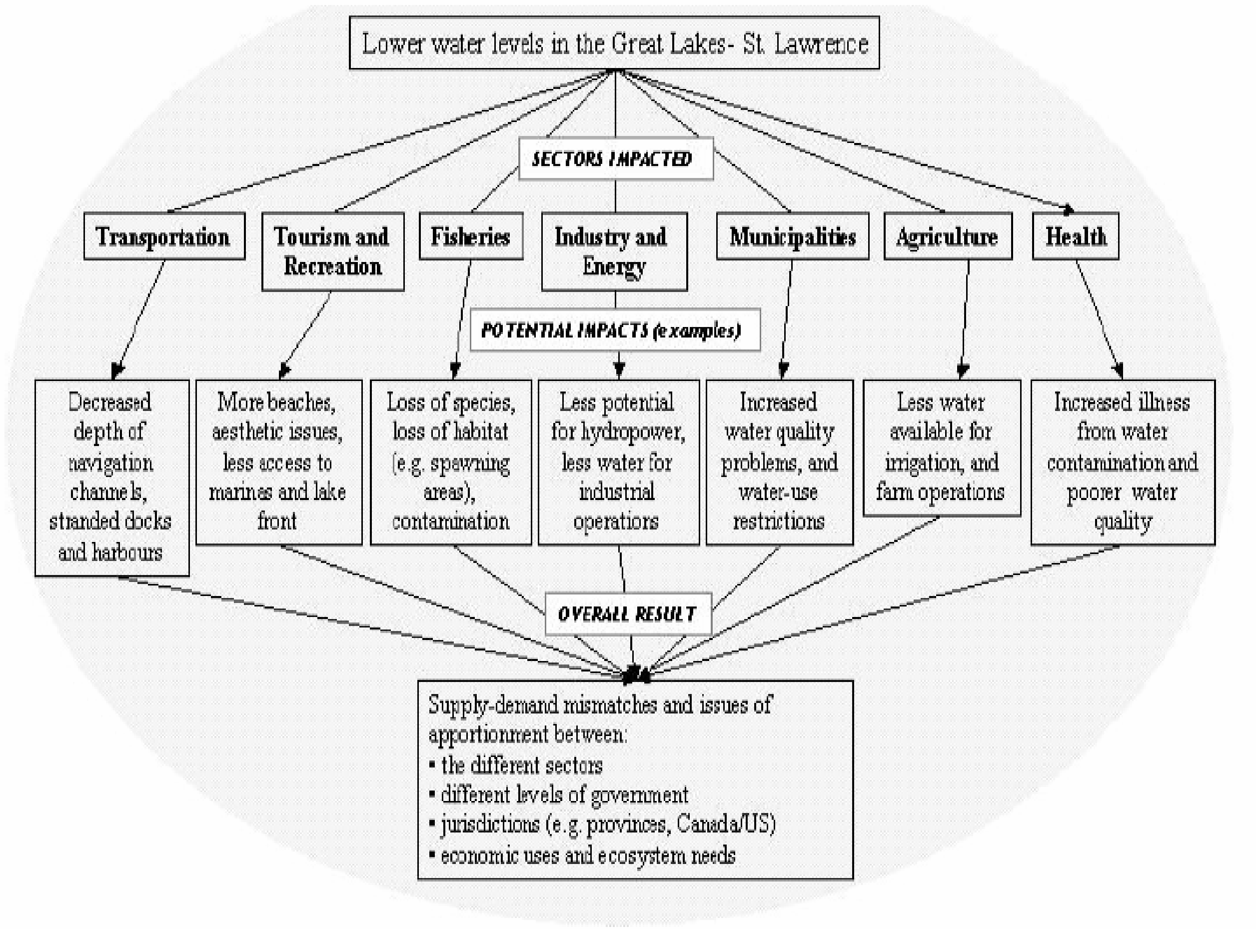


Figure 14.6: *Interconnected impacts of lowered Great Lakes water levels (Lemmen and Warren, 2004).*

Groundwater

Warmer temperatures (increases in evaporation), changes in timing, intensity and amount of precipitation, and changes in timing and amount of streamflow are key drivers of changes in regional groundwater systems. Responses are expected to be more rapid and pronounced in shallow, unconfined aquifers than in deeper, confined aquifers (Rivera *et al.*, 2004). With climate of 2030 simulated by CGCM1 with the IS92a scenario, projected annual base flow for a Michigan aquifer decreased 19.7%. Levels declined 0.3 to 1.2-m under current pumping and 0.3 to 2.3-m with future pumping demands. Recharge and levels increased 4.1% and 0.1 to 0.3-m, respectively, with a wetter climate model (HadCM2, IS92a, 2030), (Croley and Luukkonen, 2003). Based on results from the same two climate models, projected base flows for southwestern Ontario in 2080 decreased nineteen percent (CGCM1) and increased three percent (HadCM2) (Piggot *et al.*, 2003). For all precipitation projections, these studies showed an alteration in the seasonal cycle, probably due to temperature effects. Groundwater flow increased in winter (less snow cover, more winter rain and recharge) and decreased during spring and early summer. For aquifers in alluvial valleys (e.g., B.C.), temperature and precipitation scenarios had a smaller impact on the groundwater table and flows than on projected changes in river flooding and base flow (Allen *et al.*, 2004a; Allen *et al.*, 2004b).

Saltwater inundation is a “likely impact” of rising sea levels in Kouchibouguac National Park, New Brunswick (Scott and Suffling, 2000). Rising sea levels and increasing demands may exacerbate this issue (Boesch *et al.*, 2000; Barlow, 2003), causing shortages of potable groundwater supply in some coastal cities. This is more likely if recharge of freshwater is inadequate or lagged in time. Recharge is not well understood for many aquifers, but may be affected by extended drought (Alley *et al.*, 2002). Numerous studies assess the willingness of North Americans to pay for water quality improvements, but little analysis has been done on the specific effects of climate change and willingness to pay to avoid its adverse consequences.

Heavily utilized groundwater in the southwest U.S. will be put under additional stress by climate change (high confidence). Reductions in recharge could endanger water supplies, and regional water withdrawals may need to adjust to changing recharge conditions. The Edwards (Balcones Fault Zone) aquifer, utilized for irrigation, recreation, and municipal and industrial uses, is currently under pumping limits in order to preserve springs that support unique ecosystems. Simulations of 2xCO_2 conditions with six GCMs running the IS92a scenario indicate decreased spring flows and project water shortages and negative environmental impacts under average recharge conditions. With a 25% increase in pumping, violations of minimum spring flows occur frequently by the 2030s and spring flow ceases under drought conditions for some scenarios (Loáiciga, 2000). Assessments using the CGCM and HADCM2 running IS92a also projected decreases in spring flow of ten to sixteen percent in 2030 and twenty to twenty-four percent in 2090, with estimated regional welfare losses of US$2.2 to $6.8 million per year (Chen and Grasby, 2001). Net agriculture income decreased 16 – 30% (2030) and 30-45% (2090) as water allocation shifted to municipal and industrial uses. Reducing pumping nine to twenty percent to maintain springs and environmental amenities cost an additional US$0.5 to $2 million per year. In the Ogallala aquifer region, natural ground water recharge was affected negatively in all scenarios (GISS, UKTR, and BMRC) with the modest decreases ranging from 17 to 25% and others higher; precipitation gains were offset by greater evapotranspiration due to warmer temperatures (Rosenberg *et al.*, 1999). Reductions in recharge could endanger water supply in a region where recharge has not compensated for water withdrawals since the 1940s.

Water quality

Interactions between atmospheric, terrestrial and aquatic processes as well as the human use of water resources affect water quality. Climate change can influence these components leading to direct and indirect changes in water quality.

Modelled surface and bottom water temperatures of lakes, reservoirs, rivers, and estuaries throughout North America consistently increase using $2xCO_2$ and IS92a-based scenarios (Fang and Stefan, 1999; Hostetler and Small, 1999; Nicholls, 1999; Stefan and Fang, 1999; Lehman, 2002; Gooseff *et al.*, 2005). Significant warming occurs in Midwestern and southern lakes and reservoirs; simulated summer temperatures can exceed 30°C (ECHAM4 and CGCM1, IS92a) (Hostetler and Small, 1999). Warming extends and intensifies summer thermal stratification. In combination with warmer bottom waters, this can lead to anoxia. A shorter period of ice cover, in shallow northern lakes, however, 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 increasing above four degrees Celsius by 2090 (CGCM1 and HadCM2, IS92a) in the Great Lakes accelerate metabolic rates and accelerate oxygen depletion (Lehman 2002).

Warmer summer water temperatures and lower river flows may have direct effects on phosphorus reflux in sediments in shallow, eutrophic systems in north temperate latitude. With a three to four degrees Celsius temperature rise, simulated summer average total phosphorus concentrations in the inner portion of Bay of Quinte increased by seventy-seven to ninety-eight percent (Nicholls, 1999). Blue-green algae, favoured by higher water temperatures, are associated with summer taste and odour problems in drinking water, as well as health issues, and may require costly improvements to municipal water supply systems (Magnuson *et al.*, 1997; Anderson and Quartermaine, 1998). Warmer lake temperatures favour transfer of volatile and semi-volatile compounds (mercury, PCBs, dioxins, pesticides) from the water to the atmosphere, and warmer water affects bioaccumulation of toxins and toxicity of metals (Atkinson *et al.*, 1999; Murdoch *et al.*, 1999; Schindler, 2001).

Climate change may make it more difficult and expensive to achieve water quality goals. In the U.S., effluent discharge limits for point sources, Total Maximum Daily Loads (TMDL), are based, in part, on low-flow conditions. Projected reductions in flow may require more stringent TMDLs, necessitating costly upgrades in effluent treatment (Mortsch *et al.*, 2003). 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. Low flow violations increase by up to 100% (Eheart *et al.*, 1999). In the Bay of Quinte watershed in the Great Lakes basin, runoff decreases but non-point source loadings of phosphorus increase 25%, 10% and 15% in 2030, 2050 and 2090, respectively, in CGCM1 simulations with the _____scenario. With constant land use, average phosphorus concentration increases 25-35%, setting back achievement of phosphorus remediation targets (Scheffer *et al.*, 2001). Clean up and restoration of beneficial uses identified under the Great Lakes Water Quality agreement may be vulnerable to climate change (Mortsch *et al.*, 2003).

Risk to water quality, through erosion and combined sewer overflows, increase with projected higher annual rainfall and more frequent, intense precipitation events. Projected rainfall erosivity in the U.S. is geographically variable (HadCM2 and CGCM1 2050 and 2090). The mid-western U.S. is vulnerable to increases. For each one 1% in annual precipitation, erosion changes by 1.7% (Nearing *et al.*, 2004). Spring, because of fertilizer and pesticide application with little vegetative cover, is typically a high risk period for non-point source pollution. Projected decreases in snow cover, with more winter rain on bare soil, lengthens the erosion season, increases erosion, and results in more pollution (Atkinson *et al.*, 1999; Scheffer *et al.*, 2001; Soil and Water Conservation Society, 2003). Current soil management practices (e.g., crop residue, no-till, incorporating manure) in the cornbelt may not provide sufficient protection against future precipitation changes (Hatfield and Pruger, 2004). Antiquated combined wastewater and stormwater systems are common in older urban areas of North America. During heavy precipitation events, the high volume of runoff to the system causes wastewater and stormwater to mix, bypass treatment, and discharge to surface waters, degrading water quality and causing health risks (bacterial pollution) (NAST (National Assessment Synthesis Team), 2000a). Large investments are required to separate these systems or construct containment areas.

Water quality is also affected by cycles of dry and wet. Long dry periods allow build-up of nutrients, sediments, and chemicals on urban and agricultural land from atmospheric deposition or direct application. Heavy rainfall after a dry period releases a large pulse of pollutant- and sediment-rich runoff to receiving streams. Winter warming creating more runoff reduces the pulse of chemicals released during rapid melt of snowpack in spring (Atkinson *et al.*, 1999; Murdoch *et al.*, 1999; Fisher, 2000).

14.5.2 Ecosystems

Climatic constraints on ecosystem activity can be generalized as variable limitations of temperature, water availability and solar radiation, with every point on Earth exhibiting a different mix of these controlling factors every day of the year (Nemani *et al.*, 2003; Jolly *et al.*, 2005). Where a single climatic limiting factor clearly dominates, such as low-temperature constraints at high latitudes, growing seasons are generally getting longer, 2-3 days/decade in Alaska, resulting in increased ecosystem productivity (Keyser *et al.*, 2000). In ecosystems with severe water limitations like deserts, lower rainfall reduces ecosystem productivity (Dai *et al.*, 2004). However, where a seasonally changing mix of temperature and water constraints is possible, which includes most mid-latitudes, projection of ecosystem responses depends on the integrated influences of temperature trends and the land surface water balance, limiting the current confidence in projections of ecosystem change. Comparative analysis of seasonal NDVI and atmospheric CO_2 dynamics from 1982-2002 suggest that the photosynthetic enhancement from warmer early spring temperatures is being cancelled out by late summer drought in much of the Northern hemisphere (Angert *et al.*, 2005). Fung *et al.* (Fung *et al.*, in press) analyzing the trajectory of overall global carbon source/sink dynamics over the next century concluded that the temperature driven increases in carbon sinks at high latitudes will be nearly cancelled out by decreasing carbon sinks at low latitudes caused by water limitations and higher biological respiration losses. Berthelot *et al.* (Berthelot *et al.*, 2002) expects NEP of northern latitude ecosystems to increase 11% by 2100, but the tropics to decrease by 80% due to increasing water deficits.

Phenology, Productivity and Biogeography

The most advanced Dynamic Global Vegetation Models now project that the carbon sink of North America is contingent on two dynamics, the northward expansion of forests into the tundra and improved boreal NPP from longer growing seasons, and sufficient enhancement of precipitation in the mid-latitudes to sustain the land water balance as temperatures rise (Bachelet *et al.*, 2001; Berthelot *et al.*, 2002; Gerber *et al.*, 2004; Woodward and Lomas, 2004). Shrubs have invaded into the tundra on the North Slope of Alaska (Sturm *et al.*, 2001). Ecosystem-model projections are unanimous in projecting continued temperature-stimulated expansion of boreal and temperate forests into higher latitudes and altitudes (Berthelot *et al.*, 2002). The subarctic treeline of black spruce is rising 2-10 +/- 2 cm/yr in northern Quebec (Gamache and Payette, 2005). Tropical and mid-latitude ecosystem trajectories are much less clear, as the dominant dynamics will be determined by whether the land surface water balance trend is positive or negative. Bachelet *et al.* (Bachelet *et al.*, 2001) project areal extent of drought-limited ecosystems to increase 11%/ºC warming in the continental US. Bachelet *et al.* (Bachelet *et al.*, 2004) project that ecosystems in the Northeast and Southeast parts of the United States will become carbon sources, and the western United States a carbon sink by the end of the 21st century.

Population and Community Dynamics
Impacts on ecosystem structure and function may be amplified by changes in extreme meteorological events, and increased disturbance frequencies. Ecosystem disturbances, caused by either humans or natural events, accelerate both the loss of native species, and invasion of exotics (Sala *et al.*, 2000). Hot or cold temperature extremes and drought or flooding events may provide climatic triggers of disturbance for invasive and extinction dynamics. Alward *et al.* (Alward *et al.*, 1999) found that increased spring minimum temperatures from 1964-1992 correlated with decreasing NPP of the native C4 grass, allowing increased abundance of exotic C3 forbs in a Colorado grassland. An extreme drought year reduced nesting of passerine birds in California from 88% to 7%, as a result of low food availability (Bolger *et al.*, 2005) McLaughlin *et al.* (McLaughlin *et al.*, 2002) found that increasing variability of precipitation appeared to hasten extinction of two checkerspot butterfly populations in California from 1969-1998. A bioclimate modelling analysis by Currie (Currie, 2001) suggests mammal and bird richness will tend to decrease in the southern U.S. but increase in the western US mountains in the next century. Currie (Currie, 2001) also expects woody plant richness to increase in the north and west ecosystems but decrease in the southwestern deserts in the next century. Thomas *et al.*, (Thomas *et al.*, 2004) used three different approaches to estimating probabilities of species extinctions, concluding that 15-37% of plant and animal species in their global sample would be "committed to extinction" by 2050, although actual extinctions might take centuries to occur. Clearly, managed ecosystems can adapt to new climatic conditions more rapidly, substituting species or populations more appropriate to new climatic conditions.

14.5.3 Coastal regions

The coastal population in the USA is expected to increase by 25% (18 million) within the next 25 years, with most of this growth taking place in Washington, California, Texas, and Florida (Boesch *et al.*, 2000), areas already supporting large populations exposed to storm hazards in the coastal zone (Titus, 2005). Projections of future sea-level rise around North America vary widely between models and between regions for individual models. At the present time, it is difficult to provide adequate guidance on this critical issue. What is clear is that accelerated sea-level rise is expected (high confidence) with global mean sea level rising 0.09-0.88 m from 1990-2100 (update with AR4 WG1 estimates when available). The regional rates of sea-level rise will become more clear as scenarios and models are defined in future. Given the wide range in rates of relative sea-level rise observed over recent decades around the coast of North America (see 14.2 above), it is clear that vertical motion (as much as 10 mm/yr uplift or 2 mm/yr subsidence, locally much more) will be an important component and must be factored into estimates for any given location. In some areas, such as the Canadian Maritimes, the rates are highly variable within the region (Koohzare *et al.*, 2005), so that future rates of relative sea-level rise may be quite different in coastal communities less than 100 km apart.

Superimposed on scenarios of accelerated sea-level rise over coming decades, the projection of present storm climatology and storm-surge frequency distributions into the future leads to forecasts of more severe coastal flooding and erosion hazards. The water-level probability distribution is shifted to higher relative elevation, giving higher potential flood levels and more frequent flooding at levels rarely experienced today (high confidence) (Zhang *et al.*, 1997; Zhang *et al.*, 2000a; Forbes *et al.*, 2004). The risk of storm overtopping of coastal barriers and dunes can be assessed using digital elevation models derived from airborne laser altimetry data (Elko and A.H. Sallenger Jr, 2001; Elko *et al.*, 2002a; Elko *et al.*, 2002b). Higher mean relative sea levels are likely to be correlated with accelerated coastal erosion if coastal systems, including sediment supply, remain otherwise effectively unchanged (Hansom, 2001; Cowell *et al.*, 2003). However, appropriate large-scale modelling including uncertainty is rarely applied (Cowell and Zeng, 2003).

Present rates of coastal wetland loss, as documented in Chesapeake Bay and elsewhere (Kennish, 2002), will increase with accelerated relative sea-level rise, in part due to 'coastal squeeze' (high confidence).). There is also evidence to suggest that salt-marsh biodiversity will be diminished in northeastern marshes through expansion of cordgrass (*Spartina patens*) at the expense of high-marsh species (Donnelly and Bertness, 2001).

Potentially more intense storms (Gulf of Mexico, Atlantic Seaboard, Gulf of St. Lawrence) and possible changes in El Niño are expected to result in more coastal instability (moderate confidence) (Scavia *et al.*, 2002; Forbes *et al.*, 2004; Emanuel, 2005). Projections of more common 'El Niño-like' conditions (Timmerman *et al.*, 1999) may be correlated with lower Atlantic hurricane frequency (moderate confidence) but higher mean sea levels on the Pacific coast (high confidence) (Walker and Barrie, 2004). If El Niño-like conditions become more prevalent in future, increases in the rate of cliff erosion may occur along the Pacific coasts of the USA and Canada. This conclusion follows from observations that El Niño events raise sea level along the west coast and are marked by the presence of larger, and more damaging, waves, changes in wave direction, and resulting increases in coastal erosion, with serious implications for infrastructure and property (Komar *et al.*, 2000; Storlazzi *et al.*, 2000).

Damage costs from coastal storm events (storm surge, waves, wind), which have increased substantially in the past decade (Zhang *et al.*, 2000a), are expected to continue increasing at an accelerating rate (high confidence). The potential exists for greater loss of life unless there is further investment in transportation infrastructure to enable faster evacuation in some areas of the southern USA, such as Galveston (TX) and New Orleans (LA). Higher sea levels, coupled with storm surges, will cause more general problems for transportation in some coastal regions of North America, notably the Gulf and Atlantic coasts (Titus, 2002). Approximately 60 000 km^2 of land along the U.S. Atlantic and Gulf Coasts lies less than a metre above the present highest astronomical tide (Titus and Richman, 2001). As a consequence, the most costly water-related impacts of climate change for transportation in North America are likely to be associated with coastal flooding. In some areas, such as New York City (Gornitz *et al.*, 2001; Zimmerman, 2002) and Charlottetown, Prince Edward Island (Webster *et al.*, 2004; O'Reilly *et al.*, 2005), the facilities at risk have been inventoried. For NYC, they include surface roads and rail lines, bridges, tunnels, marine and airport facilities, and transit stations. In other cases, potential impact areas have not been mapped and/or the effects may unfold only as natural coastal defences or constructed embankments deteriorate.

Climate models suggest the probability of more winters with reduced sea ice in the Gulf of St. Lawrence over coming decades, resulting in more open water during the winter storm season (Forbes *et al.*, 2002a). This will result in a larger number of storm wave events per year on average, leading to further acceleration of coastal erosion beyond that expected with accelerated relative sea-level rise alone (moderate confidence) (Forbes *et al.*, 2004).

14.5.4 Agriculture, Forestry and Fisheries

Agriculture

Spatially refined climate scenarios have resulted in re-assessments of future sensitivities and have confirmed that yield sensitivities within a region are more spatially variable than earlier estimates. Further, the timing of key agro-climatic events such as last frost and rain events are critically important to understanding agricultural sensitivities (Mearns *et al.*, 2003). Winkler *et al.* (Winkler *et al.*, 2002) concluded that climatic change is expected to result in more favourable climates for fruit production in the Great Lakes region but the potential for early season frost remains. As a consequence, commercial fruit production in the Great Lakes region may remain vulnerable to springtime cold injury (Winkler *et al.*, 2002). Work on soybean production in the Midwest U.S. revealed that careful adjustment of seeding dates could more than compensate for yield sensitivities to climatic change (Southworth *et al.*, 2002), reinforcing the importance of identifying the timing of critical events in the agricultural calendar within sensitivity and adaptation studies.

Since the IPCC TAR, agriculture-climate change research has moved away from top-down, scenario-driven approaches focusing on primary agriculture production. Newer studies emphasize field-based, participatory approaches more suited to examining producers' vulnerability to climate change and their capacity to cope and adapt to climate variability and change (Wall *et al.*, 2004).

Recent assessments for major North American crops including 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.*, 2005) using finer resolution of climatic information "consistently yielded a less favourable assessment of the implications of climatic change (for U.S. agriculture)" (Adams *et al.*, 2003). This suggests that earlier assessments underestimated the effects of climatic change on crop yields and on the agricultural economy. For the southeastern U.S., high-resolution impact assessments, as compared to coarse-scale assessments, indicated that soybean and sorghum yields would be more adversely impacted (Carbone *et al.*, 2003). These new methods point to increased yield sensitivities for major crops in the southeast U.S. and the U.S. corn belt, but not in the Great Plains (Mearns *et al.*, 2003). Overall, recent research underscores assessments of agriculture's sensitivity to climate change and emphasizes the sensitivity to spatial scale. Future regional assessments need to consider spatial scale more carefully.

Vulnerability of North American agriculture to climatic change is multidimensional and is determined interactions among pre-existing conditions, stresses from climate change (and other environmental and socio-economic conditions), and the sector's capacity to cope with, and if necessary adapt to, multiple, interacting stresses (Choi and Fisher, 2003; Parson *et al.*, 2003). The role of pre-existing conditions can go unrecognized. For example, water access is the major factor limiting agriculture in southeast Arizona, but farmers in the region perceive that vulnerability of agriculture has declined through available technologies and larger societal-scale adaptations such as crop insurance (Vasquez-Leon *et al.*, 2002). Areas with the poorest financial and natural endowments are generally more vulnerable to climatic change (Antle *et al.*, 2004). Recent declines in coping capacity tend to increase the vulnerability of agriculture in the U.S. Great Plains to climate change (Polsky and Easterling III, 2001).

Forestry

The consensus of a panel of 11 leading ecologists interviewed to define an expert judgement about climate change impacts on ecosystems is that forest growth in North America will modestly increase (+10 to 20%) as a result of lengthening growing seasons and enhanced CO_2 over the next century (Morgan *et al.*, 2001). However provenance modelling of the strongly temperature-limited white spruce in Quebec predicts that while tree growth will be enhanced by a 1º C temperature increase, a 4º C increase would be beyond the genetic range of the current population and cause a growth decrease or species replacement. (Andalo *et al.*, 2005). Zolbrod and Peterson (Zolbrod and Peterson, 1999) project that a 2º C temperature increase in the Olympic Mountains of Washington, USA would cause dominant tree species to shift upward in elevation 300-600m causing the subalpine species to be replaced by temperate zone species over a period of 300-500 years. Biomass growth responses in these simulations had a complex relationship with elevation and aspect, where longer growing seasons enhanced tree growth only if adequate soil moisture was present. Rehfeldt *et al.* (Rehfeldt *et al.*, 2001) evaluated potential climate-driven growth responses for the entire biogeographical range of *Pinus contorta* throughout western North America, concluding that with present tree populations, a 3º C temperature increase would "increase productivity in the northern latitudes, decrease productivity in the middle latitudes and decimate forests on the southern" limits of the species' current range. With evolutionary adjustments or active forest management of the population to the changing climate, forest productivity losses could be moderated, but only if increases in temperatures were balanced by equivalent increases in precipitation. Otherwise widespread mortality and growth losses would occur.

The greatest impacts on the future of North American forests will probably be changing disturbance dynamics from insects, diseases, and wildfires (Box 2) (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; Gillett *et al.*, 2004).

14.5.5 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. Demographic trends influence vulnerability. According to the 2050 U.S. Census, 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

Heat waves are predicted to increase in frequency and severity. The key health-relevant environmental conditions that determine the severity of annual heat waves are stagnant, warm air masses and consecutive nights with high minimum temperatures. Heat waves with these characteristics will intensify in magnitude and duration over portions of the United States and Canada, where they already occur. Around 2090, Chicago may experience 25% more frequent heat waves annually and the average number of heat wave days in Los Angeles increases from 12 to 44-95 (for 2070-2099, with PCM and HadCM3 for A1FI and B1) (Hayhoe *et al.*, 2004). Large increases in heat waves are also projected for the western and southern U.S. (Meehl and Tebaldi, 2004 more frequent).

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). Time-series of morbidity across 12 U.S. cities showed that hot temperatures were associated with increased hospital admissions for cardiovascular disease (Schwartz *et al.*, 2004a).

Urban night-time heat retention can be a factor in the greater number of heat-related deaths in urban, compared to rural areas (Buechley *et al.*, 1972; Smoyer-Tomic *et al.*, 2003). Mean surface warming that has already occurred due to urban sprawl and land use change is estimated to be 0.27°C for the continental United States (Kalnay and Cai, 2003). Urban areas may therefore experience compounded problems of global warming and localized warming effects of the heat island effect. Also, during heat waves, when stagnant atmospheric conditions persist, air pollution often compounds the effects of hot temperatures.

Air Pollution

Ozone is an example of an air pollutant whose 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, which is a precursor of ozone (Lerdau and Keller, 1998). Isoprene production is controlled primarily by leaf temperature and light. Biogenic VOC emissions are so sensitive to temperature that an increase of as little as 2º C could cause a 25% increase in emissions (Guenther, 2002). Under the right circumstances, higher levels of isoprene result in higher levels of ozone. Other important sources of VOC pollution are fuel combustion, industrial processes, and vehicles (EPA (Environmental Protection Agency), 2003).

Using the A2 scenario, daily average ozone levels increase by 3.7 ppb across the eastern United States, with the most polluted cities today experiencing the greatest increase in temperature-related ozone pollution (Figure 14.7) (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). The large potential population exposed to outdoor air pollution (in the millions), translates this seemingly small relative risk into a substantial attributable health risk.

The Air Quality Index (AQI) gives an overall assessment of the health impacts of a particular day's pollution levels. The daily AQI is determined by assigning an individual index to each of several pollutants: ozone (8-hour and 1-hour averages); particulate matter (PM_{10} and $PM_{2.5}$); carbon monoxide, sulphur dioxide, and nitrogen dioxide. Figure 14.8 shows the percent of summer days under each AQI category for both current conditions and the A2 projected future climate scenario, on average across the 50 U.S. cities. No city had maroon levels, the worst category, under either current or projected future conditions. Even under the current climate, 37% of the summer days in these fifty cities had an ozone AQI of yellow or worse, and nine percent of the days had unhealthy conditions with an ozone AQI of orange or worse. Under the A2 scenario for the 2050s, 47% of the days had yellow or worse ozone AQIs and 16% were at orange or worse categories, on average across the cities. The climate change scenario changed the distribution of AQI categories, with more days in each of the categories with adverse health effects (yellow, orange, red, and purple) and fewer days in the good ozone level category (green).

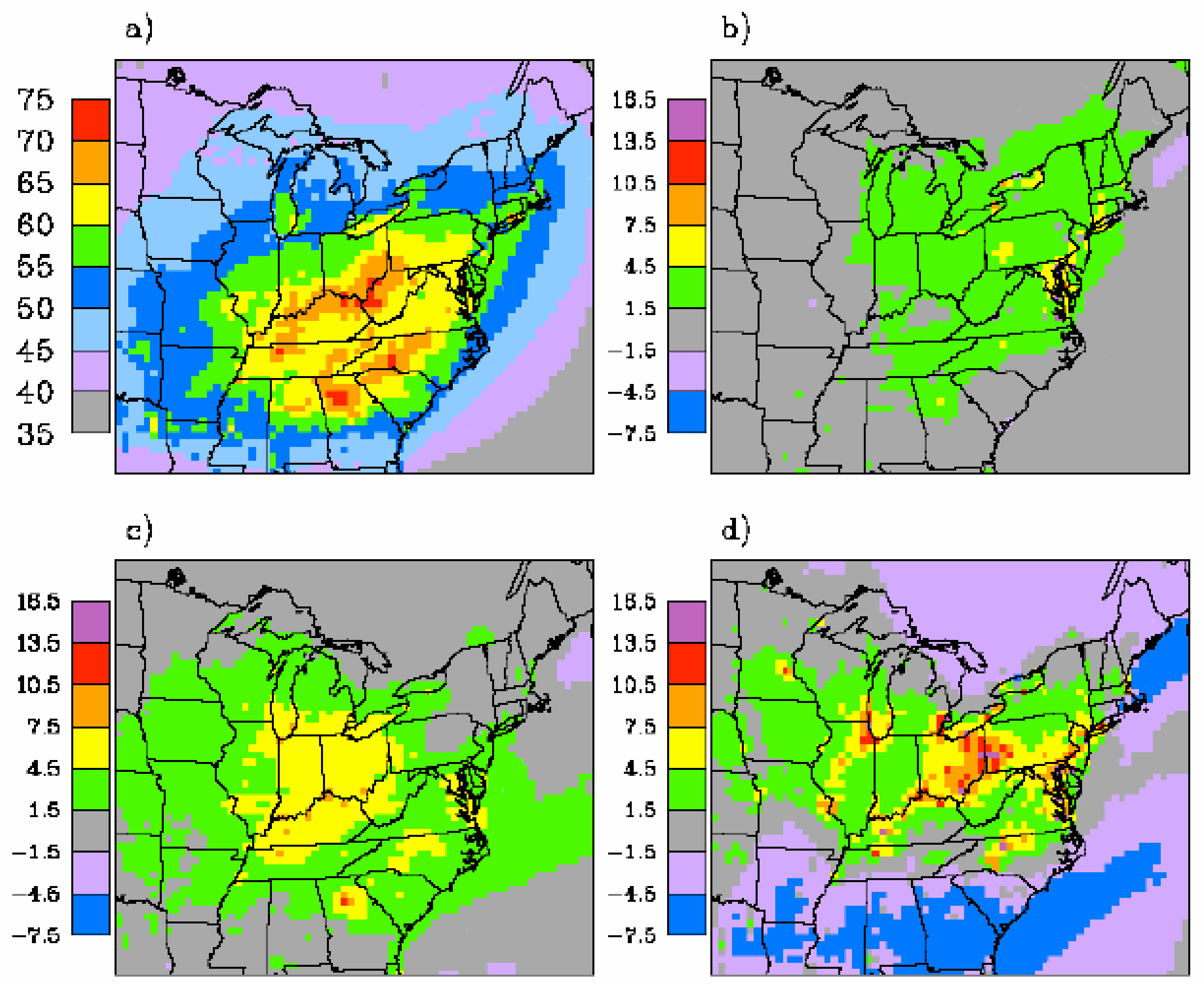


Figure 14.7: *Simulated ozone air pollution over the eastern United States by utilizing a downscaled climate model linked to a regional air pollution model (Hogrefe et al., 2004). Panel (a) shows baseline summertime average daily maximum 8-hour O_3 concentrations for the 1990s. The following panels show changes in summertime-average daily maximum 8-hour O_3 concentrations for (b) 2020s, (c) 2050s, and (d) 2080s over the region based on IPCC A2 scenario simulations relative to the 1990s, in parts per billion. Five consecutive summer seasons were simulated in each decade starting with the NASA Goddard Institute for Space Studies (GISS) Atmosphere-Ocean Global Climate Model, with results subsequently downscaled using the mesoscale regional climate model (MM5), and finally coupled to the Community Multiscale Air Quality (CMAQ) model. Simulation results for the 2020s, 2050s, and 2080s indicate that summertime average daily maximum 8-hour O_3 concentrations increase by 2.7, 4.2, and 5.0 ppb, respectively, as a result of regional climate change (Modified from (Bell et al., 2005)).*

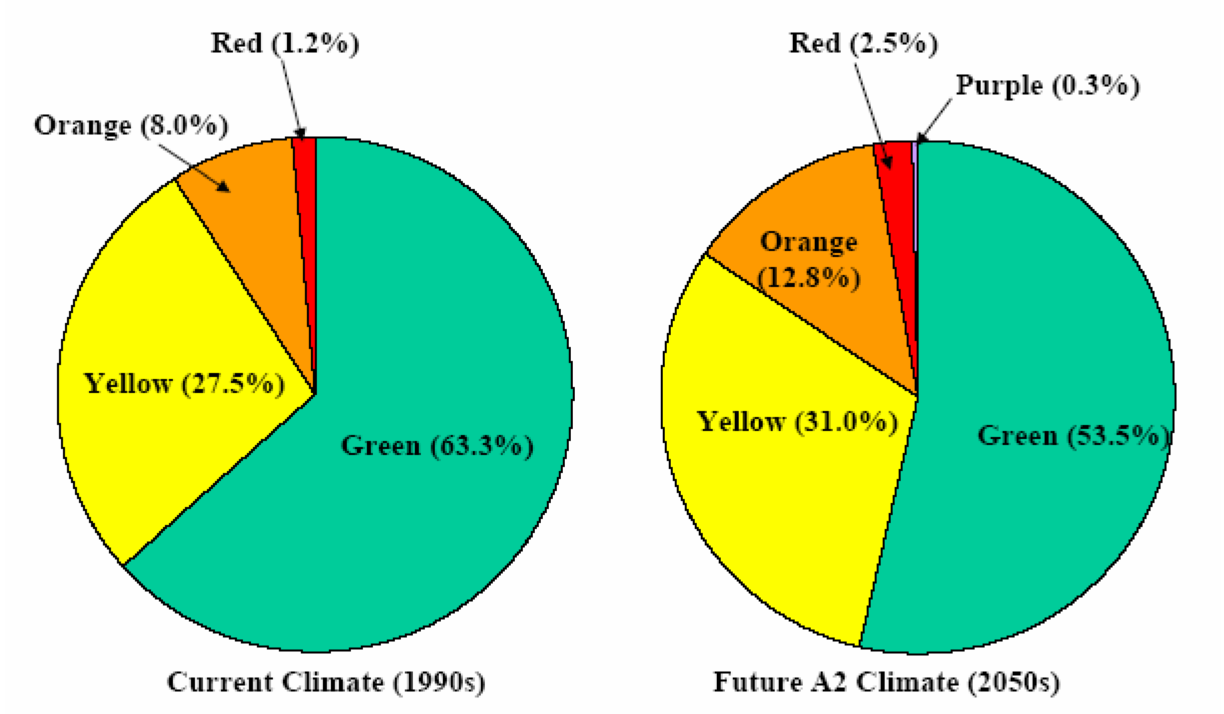


Figure 14.8: *The percent of summer days under each AQI ozone category for both current conditions and the A2 projected future climate scenario, on average across the 50 U.S. cities, with the categories defined as follows.*

Air Quality Index (AQI) Levels for Ozone (Modified from (US EPA (United States Environmental Protection Agency), 2003b))

AQI	Air quality	Colour code	Health advisory
0-50	Good	Green	None
51-100	Moderate	Yellow	Unusually sensitive people should consider limiting prolonged outdoor exertion.
101-150	Unhealthy for sensitive groups	Orange	Active children and adults, and people with respiratory disease (e.g. asthma) should limit prolonged outdoor exertion.
151-200	Unhealthy	Red	Active children and adults, and people with respiratory diseases (e.g. asthma) should avoid prolonged outdoor exertion; everyone else, esp. children, should limit prolonged outdoor exertion.
201-300	Very unhealthy	Purple	Active children and adults, and people with respiratory disease (e.g.asthma) should avoid all outdoor exertion; everyone else, especially children should limit outdoor exertion.
301-500	Hazardous	Maroon	Everyone should avoid physical activity outdoors due to emergency pollution conditions.

Pollen

Pollen, another air contaminant, may increase with climate change in North America. Higher levels of carbon dioxide promote growth and reproduction by many plants, including those that produce allergens. 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 locations than at rural locations (Ziska *et al.*, 2003).

14.5.6 Human Settlements

Although the United States is frequently visited by tropical cyclones (hurricanes) making landfall under current climate conditions, the Canadian provinces experience intense hurricanes only rarely and mostly experience the effects of offshore storms rather than storms making landfall at full force. Nor'easter extratropical storms are far more common (Canadian Hurricane Centre, 2005). It is not clear whether this would continue with a warmer climate. In a world-wide study of coastal flooding using 2080 SRES scenarios (A1FI and A2) under lagged evolving protection, low population growth, and low subsidence, only 100,000 additional North Americans were exposed to coastal flooding per year (Nicholls, 2004).

In contrast to the large body of research on sensitivity and/or vulnerability of settlements and infrastructure to climate change and extreme weather in North America since the TAR, relatively little has been done to assess the impacts of future climate change and extreme events on urban infrastructure. Since most extreme weather events are short duration and difficult to project even for current climate, the research community has largely focused its efforts elsewhere. There have been a few exploratory direct local and regional studies of the potential impacts of climate warming on infrastructure through extreme weather. For example, Suarez *et al.* (Suarez *et al.*, 2005) analyzed the economic impacts on the urban transportation network of the Boston metropolitan area using a GIS floodplain mapping and the Urban Transportation Modelling System (Meyer and Miller, 2001) for a gradual future 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 0.3-cm/y. Urban riverine and coastal flooding doubled delays and number of lost trips, but economic damage did not justify adapting the infrastructure to climate change (Suarez *et al.*, 2005). Choi and Fisher estimated impacts of flood loss in the mid-Atlantic region of the US, hurricane loss in North Carolina and derived a multi-equation regression model of national catastrophic insured loss, taking into account growth in population, inflation, and per capita real wealth, and 13.5% or 21.5% increases in annual precipitation (GENESIS and RegCM2) (Choi and Fisher, 2003). At the national level, a 1% increase in precipitation results in about a 2.8% increase in catastrophic losses.

The US National Assessment (NAST (National Assessment Synthesis Team), 2001) did not carry many of the potential physical impacts of climate change to financial impacts due to lack of data and tools (Changnon, 2005).

One aspect of flooding hazard that is rarely investigated is the release of hazardous materials into the environment as a result of increased heavy precipitation events or flooding of closed or abandoned hazardous waste sites. Kelly and Winchester developed a method of analyzing the potential of heavy precipitation to breach the cover system on hazardous waste landfills, based on a 24-hour, 100-year storm rather the current design standard of a 24-hour, 25-year storm (Kelly and Winchester, 2005). The Texas State Department of Health (Borders, 2003) estimated injuries from hazardous substances in the environment as a result of tropical storm Allison. Several hazardous chemicals were released to water in the Houston-Beaumont, Texas area, including 15 million gallons of phosphoric acid, 85,000 gallons of sulphuric acid, 1,000 tons of urea fertilizer, and 3,600 gallons of ammonium nitrate fertilizer. There were also 18 fixed-facility air emission events. Events with water releases included containment failure, waste water overflows, and flooding.

14.5.7 Tourism and Recreation

Many major recreation and tourism segments are highly seasonal and dependent on climate-sensitive natural resources. Climate change could have far-reaching consequences for this increasingly important economic sector (see (Nicholls and Scott, 2006) (for an overview of potential impacts).

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. Using a tourism climate index, Scott *et al.* (Scott *et al.*, 2004a) found that the number of cities in the U.S. with 'excellent' or 'ideal' ratings in the month of January tripled under an A1FI 2050s scenario and quadrupled in the 2080s. Florida and Arizona could face increasing competition for winter getaway travellers. In contrast, the number of Mexican cities with the same ratings decreased in the 2080s, suggesting Mexico could become a less competitive winter destination. Scott *et al.* (Scott *et al.*, 2004a) also hypothesized that the combined effect of an improved warm tourism season and reduced demand for winter getaway holidays (because of shorter and less severe winters) could benefit Canada's international travel deficit. Hamilton *et al.*'s (Hamilton *et al.*, 2006) analysis of tourism arrivals and departures under climate change scenarios supports this assessment. The 2025 scenario for Canada projected 14-16% fewer departures and 16-17% more arrivals. The projected impact of climate change was much more pronounced in 2050 (25-30% fewer departures, 33-43% more arrivals) and 2080 (32-44% fewer departures, 52-85% more arrivals).

Coastal zones are the most important recreation resource in North America. Some of the most important coastal zones for tourism in the southern United States are vulnerable to sea level rise. The health of south Florida's tourism industry is strongly dependant on the region's beaches. The cumulative cost of sand replenishment to protect Florida's coast from a 50cm rise in sea level by 2100 is estimated at US$1.7 to $8.8 billion (US EPA (United States Environmental Protection Agency), 2003a).

Nature-based tourism is an important component of North American tourism. National parks in Canada and the U.S. are central components of this tourism market. There were over 2.6 billion visitor days in parks and protected areas in Canada and the United States in 1996 (Eagles *et al.*, 2000). Tourism in many of the parks in the northern U.S. and Canada is constrained by climate. Visitation to Canada's national parks system could increase by 6-8% in the 2020s, 9-25% in the 2050s and 10-40% in the 2080s as a result of a lengthened and improved warm-weather tourism season (B2 and A1 scenarios respectively) (Scott *et al.*, forthcoming). The potential increase in park visitation from climate change, would have potential benefits for park revenues and the economies of communities near each park, but would exacerbate visitor-related ecological pressures in many parks.

Nature-based tourism will also be indirectly affected by biophysical change (e.g., loss of glaciers, reduced biodiversity, fire or disease impacted forests). Richardson and Loomis (Richardson and

Loomis, 2004) and Scott *et al.* (Scott *et al.*, forthcoming) explored the implications of environmental change scenarios in two Rocky Mountain parks for future tourism. Results were consistent for the 2020s, with the large majority of respondents (>90%) not changing their visitation patterns. Scott *et al.* (Scott *et al.*, forthcoming) also explored the potential impacts of greater environmental changes later in the 21st century and found that 56% of respondents indicated they may not visit the park or would visit less often.

Winter sports tourism in North America has been repeatedly identified as vulnerable to climate change due to decreased snow or a shorter winter season. An important limitation of widely cited earlier studies of the impact of climate change on the ski industry was the omission of snowmaking, which as been an integral climate adaptation for 20 years. Scott *et al.* (Scott *et al.*, 2003; Scott *et al.*, in press) reassessed the impact of climate change on the ski industry at six locations in eastern Canada and the U.S. with a method that integrated snowmaking and found much lower vulnerability. At most locations, projected losses to the ski season under the 'worst case' 2050s scenario approximated the 'best case' from earlier studies. The results pointed to two distinct possible futures for the ski industry in eastern North America, with the B2 scenario having negligible impacts through the 2050s, while the A1 scenario would seriously challenge the economic viability of many ski areas through a reduced ski season and increased snowmaking costs. The likely outcome is a continued contraction of the ski industry in this region, with multi-resort ski conglomerates potentially out-competing smaller ski tourism operators because they have higher adaptive capacity (regionally diversified, well diversified resort operations, advanced snowmaking systems, access to capital to support individual ski areas during poor business conditions) (Scott, 2005). Although the western mountain ranges are home to some of North America's internationally renowned winter tourism destinations, the implications for the ski industry in this region have not been examined. Impacts of climate-change on the ski industry in any region are likely to be quite sensitive to changes in other regions. For example, a region with a small degradation in snow quantity or quality might expect increased visits, if the impacts on competing regions more negative.

The US$10 billion (International Snowmobile Association, 2003) snowmobiling industry in North America is much more vulnerable to climate change than the ski industry, because it is entirely reliant on natural snowfall and lacks the adaptive capacity of snowmaking (Scott *et al.*, 2002; Scott *et al.*, 2006). Under the warmest A1 scenario for the 2050s, a reliable snowmobile season is largely eliminated from the regions of eastern North America with developed trail networks. Adaptation could occur through the substitution of recreational vehicles, from snowmobiles to all-terrain-vehicles.

Climate change presents many risks and opportunities for the North American recreation and tourism sector. The critical uncertainties regarding the magnitude of projected climate change and how these changes will affect different segments of the recreation and tourism marketplace, currently precludes any definitive statement regarding the net economic impact on this sector.

14.5.8 Energy, Industry, and Transportation

There has been some work done since the TAR on the potential impacts of future climate warming on energy demand and supply, industry, and transportation in North America. Form this work

Energy Demand

North American studies conducted during the last five years have confirmed earlier work that shows a small net change in the demand for energy in buildings as a result of average annual temperature increases of about two degree Celsius, but a significant increase in the demand for electricity, mainly for space cooling (high agreement, much evidence) (Sailor and Muñoz, 1997; Mendelsohn and Schlesinger, 1999; Morrison and Mendelsohn, 1999; Mendelsohn, 2001; Sailor, 2001; Sailor and Pavlova, 2003). None of these studies addressed the adaptive value of energy efficiency improvements or the interaction of climate and energy efficiency. Recent empirical studies of energy demand in buildings suggest: 1) reduced heating requirements offset higher fuel consumption to meet increased air-conditioning needs; 2) warmer climate conditions slightly reduce (Considine, 2000) or slightly increase (Mendelsohn, 2001) energy demand and carbon emissions in the United States; and 3) there has been a slight (0.2%) reduction in carbon emissions due to the warming trend since 1982 (Considine, 2000). Scott *et al.* (Scott *et al.*, in review) show that the IPCC projected warming in Ruosteenoja *et al.* (Ruosteenoja *et al.*, 2003) causes net decreases of energy consumption in U.S. residential and commercial buildings—about 5% in 2020 (0°C to 2.5°C warming) to as much as 20% in 2080 (for 3.5°C to 10°C warming). The study shows an increase of as much as 25% in temperature-sensitive electricity demand by 2080, even without increased market penetration of air conditioning (Scott *et al.*, in review). In this context, by 2020 U.S. building energy efficiency programs save 4.5%., more than enough to offset increases in energy consumption due to growth in space cooling and building stock. At the regional level, Sailor found a per capita increase in residential and commercial electricity consumption of five to fifteen percent for a three degree Celsius average temperature increase, but individual state and regional results are highly sensitive to the specific climate scenario (Sailor, 2001). A regional study in Massachusetts for the year 2020 (Ruth and Amato, 2002) shows 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% in annual cooling degree-days). Behavioural responses to global warming could be a very important determinant of energy consumption (high agreement, limited evidence). Increased market saturation of air conditioning may be two to three times more important than weather sensitivity in determining the response of per capita electricity consumption to climate warming (Sailor and Pavlova, 2003).

Energy Supply

Since the TAR, a variety of regional assessments have estimated impacts on hydropower in North America under climate change. For a two to three degree Celsius 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.*, 2000). There is high agreement and much evidence that winter flows, earlier spring melt, and possibly more winter rainfall can be expected in the western United States and Canada (Hamlet and Lettenmaier, 1999; Stewart *et al.*, 2004; Hamlet *et al.*, in review), leading to greater hydroelectric potential in the winter in the Columbia River system and less power in the summertime. Though based on fewer studies and therefore less certain, Colorado River hydropower yields would likely decrease significantly (Christensen *et al.*, 2004). In the Ontario and upper New York State area, the yield of Great Lakes hydropower likely would decline (Moulton and Cuthbert, 2000; Lofgren *et al.*, 2002; Mirza, 2004), while James Bay hydropower likely would increase (Mercier, 1998; Filion, 2000). There would be large annual losses $437-$660 million per year and small annual gains $28-$2 million per year for hydro producers depending on whether water levels decreased or a increased, respectively (Buttle *et al.*, 2004). Ouranos restates these conclusions for a two to three degree Celsius warming in Quebec, but acknowledges the uncertainty of precipitation on which these results depend (Ouranos, 2004). In particular it appears that Northern Quebec hydropower likely would benefit from greater precipitation and more open-water conditions. The run-of-the-river plants in Southern Quebec likely would face lower water levels from the Great Lakes, which are not expected to be offset by greater precipitation. Changes in seasonal distribution of flows (possibly advantageous) and changes in the timing of ice formation (impact uncertain) are also expected.

The viability of the wind resources is based on the speed and reliability of wind. There are a handful of studies since the TAR that examine the effect of climate change on North American wind resources. Breslow and Sailor (Breslow and Sailor, 2002) investigated projected wind speed changes resulting from the Hadley climate model, which suggested minimal climate change impact on wind resources, while their results from the Canadian model suggested potential reductions in wind power generation on the order of 30 to 40%. Using the Hadley Centre HadCM2 model and RegCM2 regional climate model, Segal *et al.* (Segal *et al.*, 2001) in what they describe as an "exploratory" analysis projected a 2040-2050 overall decreased daily average wind power availability in the U.S. of between 0 and 30% by roughly 2040-2050. In limited areas in the southern and northwestern U.S., they projected an increase of up to 30%, while northern Texas, western Oklahoma, and northwest were almost unaffected, and there was a simulated decline in north-central U.S. and the western mountainous region. The same set of authors, using similar climate techniques, also analyzed the impact of cloudiness on solar radiation for photovoltaics, and found an overall decrease ranging from 0% to 20% (Pan *et al.*, 2004). The largest decreases were in the west in the fall, winter and spring; there was a small increase in the northwest and southwest.

Future climate change likely will impact the geographic ranges of potential biomass crops. The United States Department of Energy and Department of Agriculture have systematically evaluated three major crops: switchgrass (*Panicum virgatum)*, a perennial grass; hybrid poplar (*Populus spp.)*; and willow (*Salix spp.)*. Research with an agricultural sector model has shown that the bioenergy crops could compete successfully with current climate for agricultural acreage at a farmgate price of $33/Mg, or about US$1.83/GJ (Walsh *et al.*, 2003). Only one study has addressed the effect of climate change on these tradeoffs. Brown *et al.* used a 2 X CO_2 scenario and the NCAR RegCM2 to provide estimates of seasonal climate warming of about 3.7° C to 7.5° C and precipitation increases ranging from 1mm to 115 mm to evaluate the effects of warming on biomass relative to traditional crops in the Missouri-Iowa-Nebraska-Kansas are of the central U.S. Switchgrass competes more successfully with traditional crops. The geographic range of corn would likely shift north, with switchgrass a potential replacement at the southern end of corn's range in the central United States. Switchgrass is less productive of biomass but can 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 and hurricanes, and additional progress has been since the TAR on documenting this vulnerability. No quantitative estimates have been made, however, of the future impact of climate change on energy infrastructure because of continuing uncertainty concerning the effect of climate change on the number, location, and intensity of extreme weather events such as ice storms and hurricanes. Improvements that reduce system sensitivity are still possible despite this uncertainty. Mirza (Mirza, 2004) summarizes several of the issues that led to the high damages in Quebec from the early 1998 ice storm in southeastern Canada and neighbouring areas in the northeastern United States. These include high reliance on electricity for space heat in Quebec, use of very high voltage long distance heavy transmission lines that are vulnerable to icing, lack of climatologically adequate or consistent standards for transmission towers (although they generally exceeded normal standards), lack of adequate backup power (many areas are served by only one power line), and lack of emergency plans for supplying and restoring power.

Water and Sewer

If water becomes less reliably available, this may pose challenges to certain "water-hungry" industries that depend on large volumes of water. In the United States, a survey of water managers indicated that 36 out of 47 states surveyed (excluding California, New Mexico, and Michigan) anticipated that they will face local, regional, or state wide water shortages some time during the next ten years. Some of the nation's highest population growth rates are projected for western states where water is already in short supply (GAO (General Accounting Office), 2003). See Freshwater Resources, Section 14.4.1 Based on an assumption of 15% increase in heavy precipitation developed from a literature survey, Watters *et al.* developed an assessment of urban stormwater infrastructure needs in Burlington and Ottawa, Ontario, Canada that consisted of both structural and non-structural measures. Effective retrofit options that provide the required peak discharge reductions included 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. In northern Canada and parts of northern Alaska, however, areas dependent on seasonal delivery of heavy goods such as construction materials will have a shorter period of time in which to achieve delivery. In addition, construction methods will have to change in northern Alaskan and Canadian areas currently underlain by permafrost (Cole *et al.*, 1998) at high expense. Replacement of individual support members for the Trans-Alaska Oil Pipeline, for example, costs about US$20 million (1998 dollars) (Cole *et al.*, 1998). More attention will have to be paid to adequate drainage and removal of peat. Some areas may become too wet to be usable. See Chapter 15 Polar Regions.

Transportation

For North America's transportation system, the most serious issue is likely to be coastal flooding, especially along the Gulf and Atlantic coasts, because of sea-level rise and storm surges (Burkett, 2002) (section 14.4.3).

The long-term viability of some inland navigation routes is in question because of projections of lower water levels, due mainly to increased evaporation. Reduced water depth in channels in the Great Lakes-St. Lawrence Seaway system would translate into the need for "light loading" with serious economic consequences, notwithstanding the likelihood of an extended shipping season due to reduced ice coverage (Quinn, 2002). Lower water levels would also create periodic 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).

Increased winter temperatures in the north, as already evidenced, would reduce the reliability of transport. Permafrost degradation reduces surface bearing capacity and potentially triggers landslides (Smith and Levasseur, 2002). Ice roads, which are constructed by clearing a route over frozen terrain and service remote communities, would have a shorter season (Lonergan *et al.*, 1993). Recent advances in design and construction have reduced disturbances in the thaw-sensitive permafrost, and solutions to permafrost melting and winter road access exist. But all of these are associated with high costs because of the harsh and fragile northern environment (Warren *et al.*, 2004).

An increase in the frequency, intensity and duration of heat spells is expected, and this raises concerns over pavement integrity because of the potential for softening and traffic-related rutting as well as the migration of liquid asphalt (flushing and bleeding) to pavement surfaces (Zimmerman, 2002). High temperatures are also of concern for rail operations, as track may buckle or kink (Rosetti, 2002). However, there are potential offsetting effects. At present, extreme cold is more problematic than heat for transport systems throughout Canada and northern parts of the U.S. (Warren *et al.*, 2004). Also, there is an opportunity to integrate current understanding of climate change into transportation infrastructure design and construction.

Potential changes in storm patterns may affect maintenance and safety. More frequent or intense winter rainfalls would potentially increase flood risks (e.g., in California) (du Vair *et al.*, 2002). Winter road maintenance needs are expected to be reduced overall but may increase in some regions (Pisano *et al.*, 2002). Less severe winters are also expected to generate mobility benefits, however, the safety effects are as yet undetermined, and may indeed be minimal, given risk estimates for different types and intensities of precipitation (Andrey and Mills, 2003). While re-engineering may solve some of the concerns about infrastructure, other adaptations are more likely to revolve around information systems that are being developed and implemented independent of climate change (Warren *et al.*, 2004). There is also the possibility that a movement toward a more sustainable transportation system will introduce added resilience to weather hazards.

There are concerns that future changes in hydroclimatic events, particularly extreme rainfall and snowmelt, could result in more frequent disruptions of the transportation corridors in the mountains of western Canada as a result of increased landslide (Evans and Clague, 1997). Changnon *et al.* (Changnon *et al.*, 2001), in a study of U.S. national economic losses and gains due to weather variability between 1950 and 1997, found an annual average national loss value of $17.5 billion and an average gain value of US$5.8 billion (1997 dollars), about 0.2% of U.S. GDP. Energy use costs (US$4.7 billion per year) ranked highest followed by those due to hurricanes, floods, and crop losses due to temperature and rainfall extremes (not storms). A recent economic assessment using three climate scenarios for 2060 (temperature increases between 1.5°C and 5.0°C with precipitation increases of 0 to 15%) estimated a range of economic impacts from $36 billion in benefits to $19 billion in losses (Mendelsohn and Smith, 2002), about 0.1% of GDP. The U.S. National Assessment in 2001 found somewhat smaller impacts (NAST (National Assessment Synthesis Team), 2001), but did not attach economic values to all identified impacts.

14.5.9 Integrative and Quality of Life Impacts

Climate change is one of many dynamics in a rapidly changing world. The challenge of projecting the impacts of climate change is amplified by the uncertainty of the context in which it is occurring and will occur. In general, challenges from climate change will not appear as isolated effects on a single sector, region, or group. They will, instead, appear as new dimensions of the broad set of issues associated with economic development, environmental sustainability, and personal fulfilment (quality of life). Most of the research on climate change impacts focuses on individual sectors or processes, with limited attention to interactions among suites of simultaneously changing processes and impacts. Integrated assessment models synthesize impacts across a range of economic activities, but typically with formulations not intended to accurately characterize interactions among individual impacts – other issue is that they produce net impacts often hiding the regional distributive and equity issues. Many integrated assessment studies have a regional focus (Edmonds and Rosenberg, 2005), but few are structured to explore consequences of interactions among regions.

Little of the literature reviewed in this chapter (or in this volume) 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. Consequences for North America from these two classes of climate-change impacts could potentially dominate direct, local impacts, or they could be of only secondary importance. Though quantitative information on interactive and indirect impacts is unavailable, a general picture of the kinds of effects with the potential to be important is emerging. The following examples introduce some of the possibilities.

Interactive Impacts

Most of the work on agriculture impacts has focused on rain-fed agriculture. While rain-fed agriculture dominates the planted area in North America, irrigated agriculture constitutes nearly half the total yield and is the dominant management practice for many high-value crops. For many of these crops, profitability is highly dependent on the price of water. Future increases in competing demands for water, including water for instream and ecological uses, could threaten the viability of irrigated agriculture in water limited regions.

Air conditioning provides a mechanism for modulating the impacts of hot weather on human health, but at the cost of increased electricity consumption. Increased use of air conditioning in North America in recent decades has already shifted peak electricity demand from winter to summer. In regions where hydropower is a major source of electricity (e.g. Eastern Canada, British Columbia and the US Pacific Northwest), altered precipitation and competing demands for water may limit hydropower generation, especially during the summer months. In a warmer climate, opportunities for evaporative cooling may increase, but these may also be constrained by water availability.

Biological invasives constitute some of the most serious threats to North American ecosystems, agriculture, and human health. Examples of invasives facilitated by climate change are rare. In the future, climate change, combined with changes in land use and long-distance transportation could substantially widen the range of targets for potential invasion. Where climate change stimulates changes in land use, both processes could create opportunities for invasives. In some cases, an invasive initiates a series of changes that lead to dramatic degradation of ecosystem services. Clear examples include insect pests and pathogens, including a number of agricultural diseases.

Indirect Impacts

Impacts of climate change on agriculture will be diverse, with climate change contributing to increased yields in some areas of North America and decreased yields in others. The increasingly global market for agricultural products means that the economic viability of agriculture is determined by more than local yields. Thus, the profitability of commodity agriculture in the Midwest of the US and Canada is likely to be strongly affected by international supply and demand, with international demand for meat exerting a strong influence. Improved transportation options and crop varieties optimized for transportation are likely to continue to expand the range of locations and crops competing in the global marketplace. Subtle changes in agricultural productivity and costs around the world could lead to dramatic changes in the profitability and/or the crops utilized for North American agriculture.

In an increasingly globalised world, the health of North American economies is not independent of the health of the global economy. If climate change slows global economic growth, the effects could impact the economies of Canada and the US, even in the absence of direct effects. Alternatively, global costs of climate change mitigation could also have indirect effects on North American economies (Boehmer-Christiansen, 2003).

Changes in the environment, especially in the distribution of resources like water, could lead to conflicts (Koshida *et al.*, 2005), perhaps including armed conflicts (Soffer, 2000; Rogers, 2004). The literature on conflicts linked to environmental problems is highly speculative. Neither empirical evidence nor a strong theoretical foundation supports the hypothesis that environmental degradation or changes in the distribution of environmental quality leads consistently to armed conflict (Barnett, 2003).

Environmental scarcity may play a factor in migration patterns, but it is rarely the sole driver of migration (Barnett, 2003). To the extent that climate change creates environmental winners and losers, it may encourage migrations. Migration out of regions that become uninhabitable as a consequence of sea level rise are especially likely. The implications of these for the economy and security of the US and Canada will depend on a number of other factors, especially institutional and cultural responses (Goldstone, 2001).

Globalization tends to create economic winners and losers. Climate change may have much the same effect (O'Brien and Leichenko, 2000). If the negative impacts of these two large-scale global trends are both focused in the same regions, the implications could profoundly reinforce the global distribution of income inequality (O'Brien and Leichenko, 2003). Although North America is unlikely to be at the eye of this storm of negative effects, the possibility that there are centres of highly negative impacts may have important implications for future global economic growth, equity, and security.

14.6 Adaptation

In the context of climate change, adaptation refers to adjustments in behaviour due to projected climatic conditions or extreme events, seeking to reduce the cost of adverse impacts or to realize positive opportunities (Easterling *et al.*, 2004) Many adaptive choices and actions are evident in Canada and the United States (NAST (National Assessment Synthesis Team), 2000b; Lemmen and Warren, 2004). Most are reactive, driven by experience with recent changes in climate or extreme events (Paavola and Adger, 2002). Some adaptation is proactive, influenced by expected changes in the climate. A third approach may be the absence of an adaptive response – inaction (Smit and Pilifosova, 2003).

There is considerable adaptive capacity in Canada and the United States (NAST (National Assessment Synthesis Team), 2000b; Lemmen and Warren, 2004). However, capacity must be mobilized to realize adaptive action. Changes in behaviour and practices are essential to reduce the threat of adverse impacts of climate change or to realize potential benefits. In Canada and the United States the decision makers who can implement adaptive practices include individuals, businesses, communities and government.

14.6.1 Practices and Options

Canada and the United States are market-based economies, so much adaptive behaviour is based on decisions made by individuals, business and communities. They react to local or regional climatic events, and may proactively anticipate future changes. Governments adapt their own practices and formulate policies that provide incentives for others to change behaviour and practice. Governments also support development of adaptive capacity of individuals, businesses and communities by sharing knowledge about the climate and information about adaptive practices and options. The process of learning and adapting, however, needs to be promoted, more than simply identifying certain tools or technologies (Hagmann and Chuma, 2002). Despite many examples of adaptive practices in North America, further adaptation is needed to better manage the risk of loss due to current perils. This adaptation deficit is evident in the rapid increase in property damage across Canada and the U.S. over the past several decades.

Individuals invest in adaptation

Individuals in North America pursue a wide range of practices when adapting to weather, including variability and extremes. Some regularly check the weather forecast to support short-term decisions like what clothing to wear (Lemmen and Warren, 2004). Vacation and other longer term decisions are influenced by seasonal forecasts (Kunreuther and Kleindorfer, 2001). Extreme weather warnings can trigger safety behaviour, like evacuations or relocation to a shelter (Simmons *et al.*, 2002b). Judgements about adaptations are typically relative to normal conditions for the location and time of year, with some deviation from the norm deemed acceptable.

Short-term forecasts and current weather can have other affects on behaviour. When a storm strikes, for example, driving behaviour changes (Andrey, 2005). Average speed decreases and the distance between vehicles increases. The adjustment in driving behaviour is, however, often not sufficient to fully address the peril, because the number of collisions increases by 70% during inclement weather like fog, rain or snowfall, and traffic fatalities more than double during extreme precipitation (Andrey, 2005).

Climate experience also influences decisions about shelter. Some people choose homes in the United States and Canada that are designed to address expected local weather conditions (Kunreuther and Kleindorfer, 2001; Kovacs, 2005). Expected weather conditions such as cold, humid, hot, dry or hail affect choices about foundation, roof, wall-cladding or other design elements (Building Science, 2005). The slope of the roof, for example, is partially determined by the expected loading from snow or heavy rain. The choice of roofing materials is influenced by the threat of wildfire, hail or severe wind. Also, attention to concerns about heating systems and insulation is greater in regions with cold winters, and to cooling in regions with warm summers (USGCRP, 2004).

Adaptive choices by individuals are entwined in climate, social and economic considerations. The growing investment in air conditioning in both vehicles and homes across North America reflects both climate and economic considerations. The number of houses in the United States with central air-conditioning 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). These changes may have been influenced by warming, but with a role for declining costs for equipment and changing expectations.

Businesses invest in adaptation

It is estimated that 70% of businesses face weather risk of some sort, and the impact of climate on businesses in the United States is an estimated US$200 billion per year (Lettre, 2000). Through effects on customer demand or the production process weather can affect almost any industry. This includes resource industries like agriculture and forestry, manufacturing, and most service industries, like tourism. Expected changes in the climate will present businesses with new risks, but also new opportunities (Byers and Snowe, 2005).

A changing climate can influence both demand for and supply of a product. For example, the golfing season is expected to start earlier and end later in the season, but there will be an increased loss of days due to inclement weather (Singh, 2005). Ski resort operators are investing in lifts to reach higher altitudes and snow-making equipment (Elsasser *et al.*, 2003). With advanced weather forecasts, some farmers adjust crops planted, irrigation strategies, and other aspects of management, including crop varieties planted (Smit and Wall, 2003).

Some organizations are taking a proactive approach to adapting to climate change. Insurance companies have begun introducing incentives for homeowners and businesses that invest in loss prevention strategies (Kim, 2004). Rising hazard damage to insured property has led the insurance industry to invest in research to prevent hazard loss, and adjust traditional pricing models (Kovacs and Wakeford, forthcoming). Georeferenced information is particularly useful, as it can be used to identify recurrent damage patterns, and to resolve insurance claims (Munich Re., 2004).

In agriculture, the conceptual divide between adaptation and mitigation approaches to climatic change has become less pronounced, with greater recognition that mitigation measures such as carbon sequestration and improved agricultural soil and water-conservation provide co-benefits that expand the adaptive capacity of farmers, improve water quality in adjacent water bodies, and help sustain compelling rural landscapes (Boehm *et al.*, 2004; Butt and McCarl, 2004; Dumanski, 2004; Feng *et al.*, 2004; Murray, 2004).

However, there are few examples of companies in North America proactively adapting their practices in anticipation of future changes in the climate. Most evidence of adaptive actions reflects responses to changes in current climate norms or extremes.

Communities invest in adaptation

Some adaptation strategies are most effective when addressed at the community level. These include adaptations to the risk of damage due to flood, wildfire, or tornado. These actions may be supported by land use planning, local regulations, building code enforcement, community education and investments in critical infrastructure.

Many communities across North America are working to address the threat of flood damage. This may involve land-use planning, as well as engineered structures, like dams, dykes and levees to reduce the risk of overland or coastal flooding (Duguid, 2002). Flood losses persist in many communities despite efforts over many decades. The city of Peterborough, Canada, after being struck by two 100-year flood events within three years, invested in new infrastructure and land-use planning (Hunt, 2005). The flooding had four causes: unprecedented rainfall, insufficient storm sewer capacity, poorly defined overland flow routes and floodwater getting into the sanitary sewer system (UMA Engineering, 2005). To combat these causes, the city has flushed the drainage systems and replaced the trunk sewer systems so they are now designed to meet the current five-year flood criteria (Hunt, 2005). This city has not, however, moved the design to cope with 10-year, 20-year or more infrequent extreme floods.

A comprehensive wildfire and interface fire management strategy has many dimensions with community-scale components. These include healthier forests managed with controlled burns and thinning, and resilient communities that use appropriate roofing materials and maintain a defensible space around each building. FireWise and FireSmart are programs promoting wildfire safety in the U.S. and Canada (FireSmart, 2005; FireWise, 2005). Individual homes and businesses can pursue these strategies, but the greatest reduction in the risk of fire damage will be in communities that work together (McGee and Reinholdt, 2003). The District of Langford in British Columbia, Canada, has established a planning model that requires the expedient removal of debris, and requires that proposals for new development include assessments prepared by a registered biologist and a registered engineer on the interface fire risk (District of Langford, 2004).

Rapid coastal development and population growth are occurring in many areas that are physically sensitive due to low backshore elevation and easily eroded coastal deposits or rocks. Some of the most aggressive adaptation measures to past extreme events have taken place in Galveston, Texas, with its massive seawall and raised grade, an engineering response to devastating storm impacts in 1900 (Bixel and Turner, 2000). Yet fading memories, new arrivals, and high demand for waterfront property have resulted in growing coastal development along the low-lying, unprotected, sandy barrier coast to the west of this city.

Some large centres (such as New Orleans) and important infrastructure (such as the only highway and rail link between Nova Scotia and the rest of Canada) are behind dykes that provide progressively less protection unless raised on an ongoing basis. Some potential damages may be averted through enhanced protection (for example, raising dykes), redesigned structures (as in the case of Confederation Bridge between New Brunswick and Prince Edward Island; (Warren *et al.*, 2004), raising the grade (as in Galveston, TX, following the 1900 storm; (Bixel and Turner, 2000), or relocation (Titus, 2002). Protection strategies should be broadly re-evaluated on a regular basis, given the life expectancy of most transport facilities, and the value of the infrastructure at risk.

Some communities are involved in public awareness and education programs to better inform residents of climate extremes and variability. Many people recognize climate change as an issue, but they do not understand that solutions may require lifestyle changes. Adaptation yields greater benefits when those at risk become acquainted with the potential effects of climate change (Government of Manitoba, 2002). Climate change is now part of the high school curriculum in the province of Manitoba, Canada. To reach a broader audience, the Manitoba Climate Change Connection was established to promote public education and outreach (Government of Manitoba, 2002)

Community-focused approaches are generating other benefits like engagement of a wide variety of stakeholders, including individuals, local government, local decision-makers, and NGOs (Murphy, 2004; CIDA (Canadian International Development Agency), 2005). A challenge is that stakeholders may bring conflicting interests to community discussions about adaptation. This is often evident in debates about water use during periods of drought. Also, adaptive decisions in the best interest of the community frequently restrict the actions of property owners, leading to conflict in market-based societies like Canada and the U.S.

Governments invest in adaptation

Governments and their agencies in Canada and the U.S. provide information to support efforts by individuals, businesses and communities to make appropriate decisions about adaptation (NAST (National Assessment Synthesis Team), 2000b; Lemmen and Warren, 2004). This includes impact studies, historic weather data, weather warnings and local climate forecasts. Decision makers need information about a broad range of climate elements, like temperature extremes for heat alerts, frost free days for agriculture, and extreme events for insurance, severe wind and snow load for home building, and heavy rainfall for storm sewer construction.

Governments in North America support adaptation research, seeking to share information about options, impacts and the consequences of adaptation. For example, the U.S. will invest US$5 billion in 2005 alone (USGCRP, 2004). As well, the U.S. (NAST (National Assessment Synthesis Team), 2001) and Canada (Lemmen and Warren, 2004) have both published national assessments exploring the impact of climate change on society and adaptive options.

Public institutions can shape incentives or confront disincentives for decision makers considering investments in adaptation. Options include tax assistance and grants. Incentives to improve resilience to extremes would reduce government costs for disaster management. In the U.S., Oklahoma provides US$500 cash incentives to homeowners that invest in tornado shelters (Simmons *et al.*, 2002b). As well, the National Flood Insurance Program is changing its policy to reduce the risk of multiple flood claims. The Program paid over US$200 million per year in losses to properties that sustained flood damage on multiple occasions (Howard, 2000). The 'two and you're out rule' has been implemented to require households that have made two flood-related claims to elevate their structure to one inch above the 100-year flood level, or relocate. To complement this, there has been more than US$500 million invested in flood mapping over the last three years (Larson, 2004).

Governments have also invested in structural projects to protect citizens from climate hazards (Kovacs and Kunreuther, 2001). The Canadian and U.S. Governments have established national Doppler radar networks. Among other benefits, the Doppler radar systems improve tornado warnings. One study found that as lead time on tornado warnings in Oklahoma increased from 5.3 minutes to 9.5 minutes, injuries declined by 40 percent, and fatalities decreased by 45% (Simmons *et al.*, 2002b). Another study found that the full benefits of the new radar system for Canada were not realized because of significant cutbacks in the staff available to assess weather information, and the elimination of local weather offices (Murphy *et al.*, 2005).

14.6.2 Integration Issues

Human society adapts to change, although frequently with some resistance and delay. Integrating climate considerations into the array of factors that influence adaptive decisions is a continuing challenge. It is also one of the most important components of preparing society to deal effectively with the future. Three areas where integration challenges are evident involve the role of experience in shaping expectation, the influence of socio-economic factors, and the importance of establishing means for self-organization. An unexpected social or economic change, including a major shift in technology or political priorities, could affect society's ability to respond to climate change (NAST (National Assessment Synthesis Team), 2000b).

Experience and knowledge shape adaptive behaviour

Experience and knowledge shape expectations, and expectations shape behaviour (Slovic, 2000). Individuals, businesses, communities and governments develop their practices and systems based on climate norms, and, to a lesser extent, the risk of extremes. Unless systems are already at their limits, minor variations in the weather do not bring significant benefits or costs for society. Major deviations from the norm can be very disruptive (Lettre, 2000; Munich Re., 2004).

The behaviour of people and systems in North America reflects local climate experience (Schipper *et al.*, 2003). An integration challenge is to support adaptation of governments, communities, industries and individuals to future climate events that may exceed historic climate norms. Decision-making related to climate change is a collective process in which a variety of concerns such as equity, ecological protection, economics, ethics and poverty-related issues, are of special significance for current and future generations (IPCC, 2005).

Experience and knowledge shape coping strategies (Blaiklie *et al.*, 1994; Adger and Vincent, 2005). Canadians and Americans, for example, have invested in flood management systems and well-constructed buildings that reflect historic climate experience (UMA Engineering, 2005). Experience generally has a greater influence over decision makers than do projections of future climate trends and impacts (Co-operative Programme on Water and Climate, 2005). For example, building codes in North America require new construction capable of coping with historic local climate conditions, but not with climate projections.

Specific examples of adaptive behaviour that have been significantly influenced by projections of future changes in the climate are still rare. An example of proactive adaptation is the establishment of heat-health alert systems in Philadelphia, Toronto and some other communities across North America (Kalkstein, 2002). These systems identify climate conditions dangerous to people's health and warn the public (Koppe *et al.*, 2004). Fatalities from past heat waves influenced the decision to establish these programs, but predictions that the frequency and severity of heat waves will increase was also a critical factor.

Climate extremes often reveal a community's vulnerability or resilience (RMS (Risk Management Solutions), 2005). A resilient system has likely proven its ability to adapt to historic climate fluctuations. This would include communities, industries and individuals that have responded socially, economically and politically to past extremes. These experiences provide insights into potential adaptive responses to future events. For example, since the 1998 ice storm in Canada and New England, Canada's two most populous provinces, Ontario and Quebec, have taken significant measures to strengthen emergency preparedness and response capacity. These include mandating that all municipalities prepare and submit comprehensive, risk-based emergency management strategies, so they are better positioned to cope with future extreme events. In two communities with similar exposure to tornadoes, adaptive behaviour was greater in the community that experienced a tornado three years earlier than in the community with no direct experience (Murphy *et al.*, 2005). But adaptive actions do not always follow significant emergencies, cautioning that the nature of the event influences how society integrates the exposure into its behaviour (Murphy, 2004).

Socio-economic factors

Socio-economic trends over the past few decades include rising affluence, increasing income inequality (OPHA (Ontario Public Health Agency), 2002), an ageing population (Burleton, 2002), changing energy prices, and growth of major urban centres (Munich Re., 2005). Combined with new trends that will emerge, life in North America is expected to be as different in fifty years from now as the transformation experienced over the past fifty years (Kovacs and Wakeford, forthcoming). Changes in climate, and extreme weather, represent one more factor competing for the attention of decision-makers.

Wealth is a key determinant of adaptive capacity. Wealthier societies tend to have access to technology, schooling and training, information, infrastructure, and stable institutions (Easterling *et al.*, 2004). These factors 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 countries like Canada and the United States – which are well adapted in aggregate – the poor and marginalized have historically been most at risk from climatic shocks (Turner II *et al.*, 2003).

There is evidence of a positive relation between income inequality and vulnerability (Yohe and Tol, 2002). Even within the wealthiest developed countries, some regions, localities, or social groups, have lower capacity to adapt (O'Brien and Vogel, submitted). Finally, complacency can prevent wealthy societies from taking action when it is preduct or economically efficient.

Adaptive practices are an integral element of observed behaviour, and relatively few actions can be designated solely as adaptation to climate change (Smit and Pilifosova, 2003). Indeed, climate considerations may be largely ignored, even when they are potentially important. For example, most coastal communities in North America are increasingly vulnerable to climate perils. Yet the coastal population grew by more than 33 million between 1980 and 2003, with the growth driven by a combination of economic opportunity and lifestyle preferences (ABI (Association of British Insurers), 2005). Even experience with extreme events, like the impact of hurricanes in Florida and tornadoes in Oklahoma, has not diminished population growth and economic expansion.

Capacity for self organization

Emergency response systems in North America are based on the philosophy that households are primarily responsible for their own safety after a disaster (Kovacs and Kunreuther, 2001). When a household is overwhelmed it looks to its community for support, relying on friends, family and other social networks that can be an important source of physical and emotional support (Cutter *et al.*, 2000; Enarson, 2000).

Social capital can enhance the ability of a community to cope with extreme climate hazards (Mohan and Mohan, 2002). Communities with a rich stock of social networks and civic associations are better positioned to confront vulnerability, resolve disputes and realize new opportunities (Buckland and Rahman, 1999; Hutton, 2001). Social capital can also have some negative effects. For example, 'old boys clubs' may act as barriers to social inclusion and mobility, and networks may divide some communities as outsiders are treated with suspicion (Fukuyama, 2002; Kawachi, 2002). The benefit of networks is that they tend to help neighbours and family, while the disadvantage is that the needs of strangers and isolated individuals may not be met.

Social cohesion increases in the immediate aftermath of extreme events. Lasting effects are, however, few. Perceptions can return to pre-disaster levels in as little as a month (Sweet, 1998), though they may persist for three years or more after an event (Murphy *et al.*, 2005).

Adaptation practices more effective when they accommodate the needs and priorities of vulnerable groups in a manner that fosters positive change in everyday life (Hutton, 2001). Building resilience and strengthening coping capacity can prevent hazards from becoming disasters (Trujillo *et al.*, 2000).

Adaptation to minimize the adverse effects or realize the potential benefits of climate change often requires a capacity for self organization. Associations, networks and other institutions contribute to adaptive capacity (Adger, 2003 collective action). This is evident when a community responds to climate extremes and institutions in North American, like the Red Cross and Mennonite Disaster Service, organize community members to minimize the adverse impact. In addition, organizations in the United States, like the National Voluntary Organizations Active in Disaster, can help support community-based efforts.

14.6.3 Constraints

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

Social and cultural barriers

Adaptive capacity is high in Canada and the United States. A system with high adaptive capacity is better able to cope with, or benefit from, changes in the climate. Capacity, however, does not ensure positive action or any action at all. Societal values, perceptions and levels of cognition shape adaptive behaviour (Schneider, 2004). Beyond the important role of information and experience, public opinion and social norms influence the implementation of adaptation measures.

Information about the climate is often a small part of the overall decision-making process (Slovic, 2000; Leiss, 2001). The concept of mainstreaming climate risk describes processes that would bring explicit consideration of climate into decision-making processes (Dougherty and Elasha, 2004). Within government, this may include revising national policies, programs, and plans; or revising local development projects and activities.

After the extensive property damage in Florida during Hurricane Andrew in 1992, significant improvements were made to the building code in some counties. If all properties in south Florida met this stricter code, not just new construction, then property damage from a repeat of Hurricane Andrew would drop by nearly 45 percent (AIR (Applied Insurance Research, 2002). However, Florida is still experiencing increases in damage from hurricanes. This is due to Florida having one of the highest population growth rates in the United States (ABI (Association of British Insurers), 2005). Property damage from a repeat of Hurricane Andrew would double as a consequence of increased development and rising property values. Climate considerations are not yet a central element for decision makers.

Financial and market barriers

Most adaptive decisions are made by individuals, industry and communities acting to preserve their perceived self-interest. This includes zoning regulations, land use restrictions and other community planning. Property owners and communities are motivated to protect and preserve the value of their assets. Their decisions are influenced by the actions of public agencies that provide climate information and warnings, as well as knowledge about adaptive options, costs and feasibility. The situation is less clear with respect to non-market goods, including critical public infrastructure. Further complicating this issue, is the question of who should pay to adapt public goods?

A number of communities in North America have made substantial investments in adaptation. For example, despite considerable public opposition, the government of Manitoba and the government of Canada invested in a floodway to redirect occasional excess water flow in the Red River around the city of Winnipeg. The water diversion project cost C$63 million. Since construction was completed in 1968 the floodway has successfully been used thirteen times to avoid several billion dollars in damage (Duguid, 2002). The 1997 flood almost exceeded the peak capacity of the floodway, leading to a decision to invest further in flood protection for Winnipeg. The cost of enlarging the floodway will be more than ten times the cost of the original project (Duguid, 2002).

All societies have developed coping mechanisms in response to extreme events. Some of these are quite successful, but others are not, as is evident in loss of life and injuries attributed to climate risk, economic impacts, and time before the impact of these shocks fade and economies return to their previous growth paths (Yohe and Tol, 2002).

Adaptation is not always timely despite significant adaptive capacity. For example, despite adaptations to heat stress in residences and health services (Weisskopf *et al.*, 2002b), heat waves in North America continue to cause high levels of mortality even though relatively inexpensive adaptations are available.

Informational and technological barriers

Individuals, businesses and communities regularly adapt their practices, primarily as a result of socio-economic developments. Adaptation decisions should be supported with complete information about climate projections and technological options. A number of private, academic and public agencies in Canada and the United States provide some information of this nature, although its penetration into action is questionable. Expanded information on climate impacts, daily and seasonal weather forecasts, severe weather warnings, customized local climate information, climate research, and assessments of adaptive practices could all increase the effectiveness of adaptations.

Confidence in the assessment of climate risks depends on the availability of historic climate records, and the capacity to forecast future events. Weather records in the United States and Canada are generally reliable, but the absence of historical data can be a barrier to support for adaptation (Mehdi, 2003). For example, the reduction in budget and staffing at the Meteorological Service of Canada in the late 1990s, including the closure of all local weather offices, is a barrier to the capacity to examine and forecast dangerous weather events in Canada (Murphy *et al.*, 2005). Improvement in the ability to forecast hazards and provide disaster information is a high-priority in the United States (National Science and Technology Council *et al.*, 1996).

The lack of understanding of climate change is another barrier to adaptation. The uncertainty surrounding both the future projections of climate change and the effectiveness of planned responses to it is often used as justification for inaction. Knowledge gaps in homeowners' awareness of insurance coverage for climate extremes (Kovacs, forthcoming) and awareness of disaster safety options (Murphy, 2004; Murphy *et al.*, 2005) further constrain adaptive behaviour.

Hidden adaptations tend to be undervalued, relative to obvious ones. For example, it costs about US$5,000 to add storm shutters to a home located in a region that is regularly confronted by the threat of hurricane damage (Simmons *et al.*, 2002a). This adaptation is visible to anyone who looks at the home, including prospective buyers should the home be offered for sale. Indeed, homes with storm shutters in vulnerable regions typically sell for about US$5,000 more than homes without this adaptation. However, non-visible retrofits, such as stronger tie-down straps better secure roofing in high winds, are not well recognized in the resale market.

14.6.4 Conclusion

The US and Canada have developed economies, extensive infrastructure, and mature public and private institutions that create a wide range of adaptive capabilities. These capabilities have led to numerous adaptations across a wide range of historical conditions, with notable successes and failures. A dominant theme in adaptive strategies is implementation based on past experiences, including climate. Resources for basing adaptation on projections of future climate are relatively immature. One key limitation is tools for decision-making under uncertainty. Another is assessing the appropriate scale for implementing adaptations, especially choosing between responses practical at the scale of the individual property owner and actions that involve land-use and regional planning. Moving from reactive adaptations based on experiences with past weather to proactive, anticipatory adaptations in response to projected changes in climate presents a wide range of challenges. Progress on meeting these challenges is just beginning.

14.7 Case Studies

Box 1: The Columbia River System

Fundamental climate change problem in the Columbia River basin is the projected radical decline in snowpack. Combined with this challenge is an extremely complex set of carefully balanced uses among hydropower, navigation, flood control, irrigation, municipal uses and maintenance of several populations of threatened and endangered species, whose current and projected needs for water over-commit even existing supplies. Finally, the institutions are complex, 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 (Amlety, 2003). Moreover, there are significant issues of watershed management and (mainly non-point source) pollution in many of the tributaries, especially setting water quality and flow minimums for in-stream uses. Also, because the first-in-time first-in–right provisions of U.S. western water law prevail in the U.S. part of the basin, rights to withdraw water for offstream use (mainly irrigation, but also some municipal and industrial use, inflexible allocation schemes govern water distribution in some of the principal tributaries, significantly reduce the water available to junior water users (Gray, 1999; Scott *et al.*, 2004c)). Temporary water trading has been suggested as a method to avoid conflict between instream and irrigation uses under current climate variability (Huffaker *et al.*, 1993; Scott *et al.*), but this method has limits if climate changes (Scott *et al.*, 2004a). The Pacific Northwest Chapter and foundation report for the U.S. National Assessment (Parson *et al.*, 2001; Miles *et al.*, 2002) indicate the complexities of some of the tradeoffs among multiples objectives for management of the Columbia River under climate change.

Projections of changes in reliability for six objectives under present operational rules, using two climate models for the 2020s,and one for the 2090s,are shown in Table 1 (Hamlet and Lettenmaier, 1999). Under present rules, reliability of firm energy is projected to remain near 100%, while other uses suffer reliability losses up to 10%, similar to the effect of Pacific Decadal Oscillation (PDO). The effects of rule changes, which will interact with both climate change and variability, are likely to be even larger. For example, "fish-first" rules would reduce firm power reliability by 10% even under present climate, and by 17% in warm-PDO years. Adding the projected long-term climate trend would very likely reduce reliability even more, but these interactions have not yet been quantified. Increasing stresses on the system are highly likely to coincide with increased water demand, principally from regional growth but also induced by climate change itself. For example, an analysis of Portland's municipal water demand for the 2050s projected that climate change would impose an additional 5-8% increase in total summer demand (5% - 10% in peak day demand) on top of a 50% increase in summer demand from population growth (Mote *et al.*, 1999).

Table 1: *Changes in Reliability of Various Columbia Management Objectives, Assuming Present Operating Rules (Mote et al., 1999)*

		2020s		2090s
Objective	Base Case	Hadley	Max-Planck	Hadley
Flood Control	98%	92%	96%	93%
Firm Energy	100%	100%	98%	99%
Non-firm Energy	94%	98%	87%	90%
Snake River Irrigation	81%	88%	76%	75%
Lake Roosevelt Recreation	90%	88%	79%	78%
McNary Fish Flow	84%	85%	79%	75%

While only small changes are projected in annual Columbia flow, seasonal flow shifts markedly toward larger winter and spring flows, and smaller summer and fall flows (Mote *et al.*, 1999), which could create significant challenges for future management of the river. Long-lead climate forecasts are being considered in the management of the river (Payne *et al.*, 2000; Hamlet *et al.*, 2002; Lettenmaier and Hamlet, 2003). Management of the tributaries of the Columbia for fish production, hydropower, irrigation, and recreation is extremely complex, already, and little thought has been given to the long term consequences of climate change to the management regime. For example, each of 43 sub-basins of the system has its own sub-basin management plan for fish and wildlife, none of which currently address the much reduced summertime flows expected under climate change in more than a superficial manner (Independent Scientific Review Panel and Independent Scientific Advisory Board (ISRP/ISAB)).

The interaction of land and water issues is covered in Cohen et al 2003. Figure 9 illustrates the growing complexity of the integration problem for management of the Columbia and its associated resources, only one part of which is climate change.

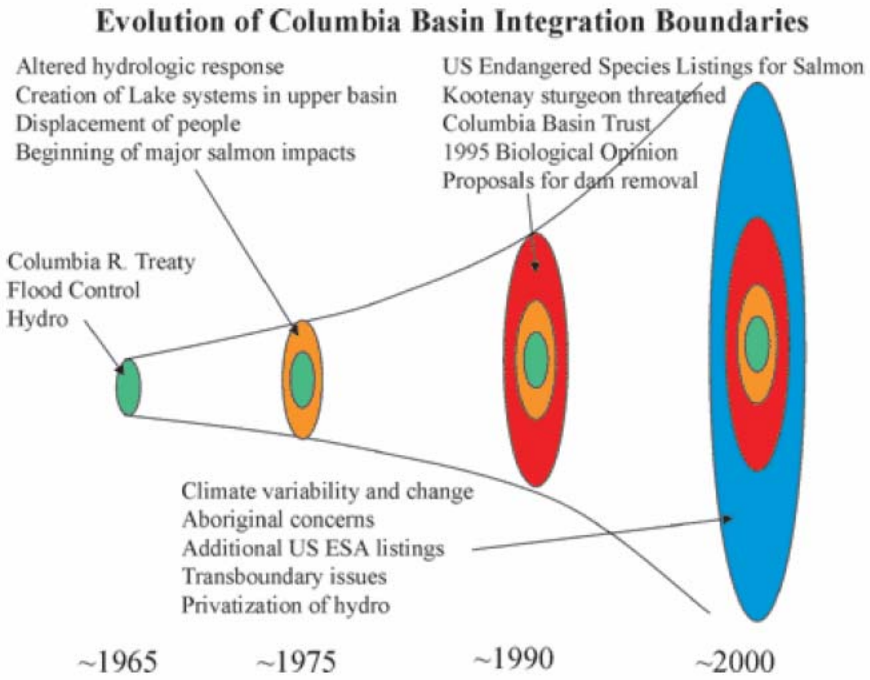


Figure 14.9: *Expanding range of issues impacting decision-making on management of Columbia Basin water resources (Cohen et al., 2003)*

Box 2: Wildfire and Disturbance dynamics

From 1920 to 1980, the area burned in wildfires in the US averaged about 13,000km^2/yr. Since 1980 average annual burned area has almost doubled to 22,000km^2 /yr, and 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 for the period 1970-1986, with a higher fraction burning at higher elevations (Westerling *et al.*, 2003). In Canada, area burned has averaged 30,000km^2/yr but with three peak years of 60-76,000km^2 since 1990 (Stocks *et al.*, 2002). Warming climate encourages wildfires by drying the land surface, allowing more fire ignitions, and desiccated vegetation and hot dry weather allow fires to grow exponentially more quickly, ultimately determining the area (Westerling *et al.*, 2003). Gillett *et al.* (Gillett *et al.*, 2004) found a correlation of r = 0.77 between warming summer temperatures of 0.8º C and the acceleration of wildfire burned area since 1970 in Canada (Figure 14.10). More active fire years in the southwestern US have been 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). Relating climatic trends to fire activity is complicated by regional differences in seasonality of fire activity. Most fires occur in April – June in the SW and SE United States, and in July-August in the Pacific Northwest, Alaska, and Canada. Earlier snowmelt, longer growing seasons and higher summer temperatures, particularly in western North America, are synchronized with the increase of wildfire activity, along with dead fuel build-up from previous decades of fire suppression activity (Westerling *et al.*, 2003).

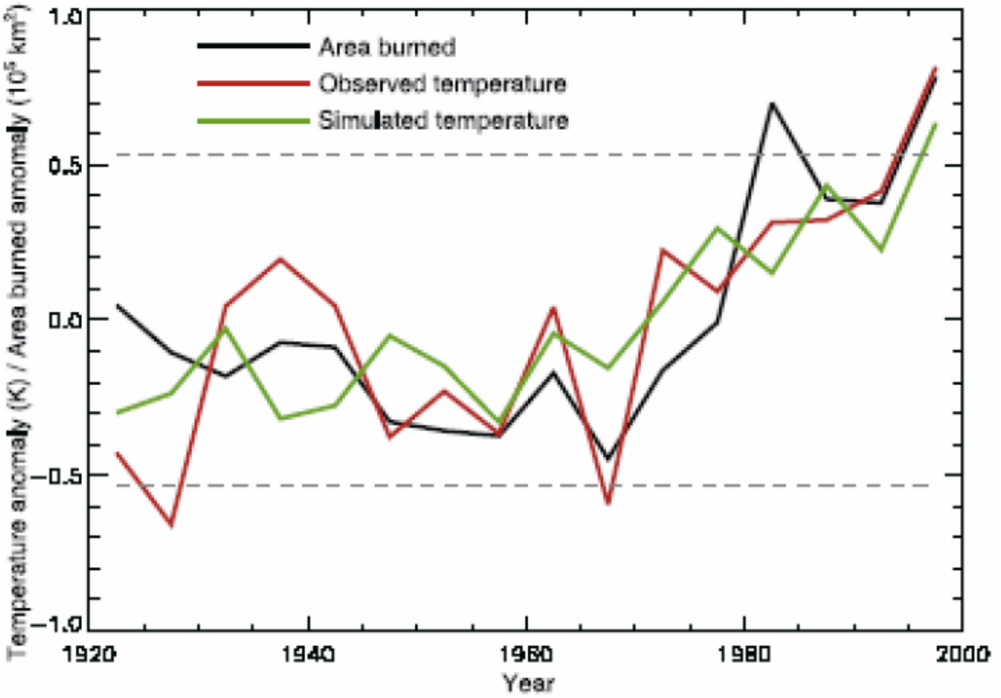


Figure 14.10: *Temperature trend vs. Canadian fire area burned, 1920 - 1999 (Gillett et al., 2004)*

Insects and diseases are a natural part of all ecosystems, however in forests, periodic insect epidemics can erupt and kill millions of hectare of trees, providing dead, desiccated fuels for large wildfires. The dynamics of these epidemic outbreaks are related to insect life cycles that are tightly tied to climate fluctuations and trends (Williams and Liebhold, 2002). Many of the northern

insects have a two year life-cycle, and warmer winter temperatures allow a higher percentage of over-wintering larvae to survive. Recently, spruce budworm in Alaska have successfully completed their life cycle in one year, rather than the previous two (Volney and Fleming, 2000). Earlier warming spring temperatures allow a longer active growing season, and higher temperatures directly accelerate the physiology and biochemical kinetics of the life cycles of the insects (Logan *et al.*, 2003). Mountain pine beetle has expanded its range in British Columbia into areas previously too cold to support their survival (Carroll *et al.*, 2003). Multi-year droughts also reduce the available carbohydrate balance of trees, and their ability to generate defensive chemicals to repel insect attack (Logan *et al.*, 2003). Recent dieback of aspen stands in Alberta is caused by a complex interaction of light snowpacks and drought in the 1980s triggering defoliation by tent caterpillars, followed by wood-boring insects and fungal pathogens (Hogg *et al.*, 2002).

Box 3: Climate and West Nile virus

West Nile virus (WNV) emerged for the first time in the North America in July, 1999. While international travel was suspected as the cause of this event, the unseasonable heatwave that year suggests that weather may have an effect on WNV disease ecology and transmission. Dohm and Turell (Dohm and Turell, 2001) examined the effect of simulated over-wintering temperatures on West Nile (WN) virus replication in the major mosquito vector, *Culex pipiens L.*, collected during the autumn 1999 epizootic in New York. Virus was recovered from most mosquitoes held exclusively at 26 °C. In contrast, none of the mosquitoes held exclusively at the lower temperatures had detectable infections. Furthermore, the incubation temperatures (18, 20, 26, or 30 °C) directly influenced *Culex pipiens L.* transmission of a strain of WN virus obtained from a crow that died during the New York 1999 outbreak. In mosquitoes held at 30° C, virus was recovered from nearly all mosquitoes tested. Disseminated infections were detected as early as 4 days after the infectious blood meal, and >90% of all mosquitoes had a disseminated infection 12 or more days after the infectious blood meal. In contrast, for mosquitoes held at 18 °C, disseminated infections were not detected until 25 days after the infectious blood meal, and even after 28 days, <30% contained a disseminated infection. Results for mosquitoes held at 20 and 26°C were intermediate for both infection and dissemination rates (Dohm *et al.*, 2002). Also, an outbreak of West Nile encephalomyelitis horses in the Midwest of the U.S. peaked with high temperatures, and significantly dropped following decreasing ambient 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.

Box 4. Climate Change Impacts and North American Cities

North American cities are integrators of impacts over many sectors and considerable distances. The variety of impacts and adaptive responses can be illustrated by the examples of the metropolitan areas of Los Angeles, California and New York, New York in the United States and Vancouver, British Columbia in Canada.

Sea Level Rise, Riverine Flooding

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. Portions of the Lower Fraser River Delta, Vancouver, and Vancouver International Airport are vulnerable to a combination of riverine flooding and sea level rise (Lemmen and Warren, 2004). The largest SLR flood danger to Los Angeles area property occurs if high tides, El Nino conditions, and storms were to coincide more frequently. Coastal groundwater aquifers such as the Ventura-area Santa Clara-Calleguas groundwater basin may be adversely affected by SLR (California Regional Assessment Group, 2002). Future hurricane and nor-easter storms would cause the most significant SLR-related damage to New York City (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 dozens of the region's most significant infrastructure features at increased risk (Jacob *et al.*, 2001; Major and Goldberg, 2001). Locally unwanted land uses (LULU) and transportation infrastructure are put across and along the edges of wetlands, bays, and estuaries, are especially vulnerable.

Water Supply Systems

Water supply systems can draw from great distances, so climate impacts need not be local to affect cities. 41% of the year 2020 supply to Southern California (Colorado River, Los Angeles Viaduct, and especially the State Water Project) is vulnerable to warming due to loss of Sierra Nevada and Colorado River basin snowpack (Beuhler, 2003). Vancouver: Reduced mountain snowpack and lack of summer runoff could reduce summer water supplies for Vancouver, requiring additional conservation measures and water restrictions, expanding existing reservoirs, and developing additional water supply sources (Schertzer *et al.*, 2004). The New York area should experience greater hydrologic variability in the future (Solecki and Rosenzweig, 2005). The New York City system could likely accommodate this (Major and Goldberg, 2001), while the region's smaller systems may be vulnerable. There is a need to evaluate enhanced intra-regional water distribution protocols, including the integration of Delaware River water, to reduce regional vulnerability to drought (Hansler and Major, 1999).

Energy Supply and Demand

Decreases in winter energy demand due to climate change are likely to be offset by increases in summer demand for electricity. Providing additional electricity causes additional problems. Conflicts between flood-control functions and hydropower objectives, and human-induced climate change in California may require more water to be released from California reservoirs in spring to avoid flooding. This can adversely affect the ability of hydroelectric systems to deliver power in the summer, when costs are already high (California Regional Assessment Group, 2002). In New York, lower winter demand for energy will be more than offset by an estimated increase in summer electricity demand, particularly for air conditioning (Hill and Goldberg, 2001). Minority sections of New York City experienced brownouts and a one-day extended blackout during a heat wave of 1999. Environmental justice demands were made to ensure that disadvantaged communities will not be disproportionately affected by similar future events (Wilgoren and Roane, 1999).

Health Effects

Urban populations may experience enhanced exposure to heat stress and, higher concentrations of secondary air pollutants, resulting in the increased frequency of respiratory ailments and attacks, such as asthma. The large population of the poor, elderly, very young, and immuno-compromised will be at greatest risk, especially those without air conditioning. Air conditioning use, though, would increase cooling demand and could increase blackouts. In New York, peak electricity demand for air conditioning during heat waves could result in an increase in primary air pollutants, for example nitrogen oxides (NOx), that convert into secondary air pollutants, such as ozone. The latter are associated with higher numbers of respiratory-related health attacks and hospitalizations (Kinney *et al.*, 2001; Knowlton *et al.*, 2005). Further exacerbating health impacts, global climate change also will interact with local urban heat island conditions (Rosenzweig *et al.*, 2005).

Adaptation

The complex nature of potential climate change impacts in urban regions poses tremendous challenges to the large number of government agencies, private entities, and other stakeholders. In spite of this, Los Angeles, New York, and Vancouver have committed to a range of adaptations, including some with multi-decade time horizons. In the future, the need for cooperation, flexibility, and long decision-making timeframes will continue to increase (Solecki and Rosenzweig, 2005). The state of California has used regulatory mandates and the leverage of its large market to require special grades of gasoline, air pollution control equipment on industrial and transportation equipment (California Air Resources Board, 2005), and energy-efficient appliances and buildings (CEC (California Energy Commission), 2005). The local water districts have developed incentive and information programs to mobilize the private sector and encourage the purchase and use of water-saving appliances by residents, reduction of garden and commercial landscape water use, improvements in process water efficiency in industry, and the building of "California-friendly" homes (MWD (Metropolitan Water District of Southern California), 2005). Market methods for transferring water among uses have also been implemented. Despite a population increase of slightly over 35% (or nearly one million people) since 1970, water use in Los Angeles has grown by only 7%, and per capita usage has been reduced by 15%" (California Regional Assessment Group, 2002). New York's water system now consumes 27% less water and 34% less per capita than it did in the early 1980s (City of New York, 2005). Some of the key concepts in the cities^{PLUS} 100-year plan for Vancouver include connecting natural areas and waterways, developing locally resilient, smaller "loop" systems that do not require extensive amounts of energy and travel to maintain and require smaller throughputs. Cool Vancouver is aimed at reducing the energy use in the area, with the aim mitigating carbon emissions. It has the added benefit of also adapting the city to climate change. Smart growth in Vancouver complements the cities^{PLUS} initiative by reducing the suburban sprawl. A drainage infrastructure study of North Vancouver suggests that the system can be adapted to more intense rainfall events by gradually upgrading key sections of pipe during routine, scheduled infrastructure maintenance (Denault *et al.*, 2002).

Box 5: Adaptation to rising sea levels and climate-change impacts: Canadian Maritimes and U.S. Eastern Seaboard

Atlantic coast provinces and states from southern Québec to Florida are all subject to rising relative sea levels expected to accelerate in coming decades. In Prince Edward Island (PEI), relative sea-level rise was projected to be 0.7 ±0.4 m from 1990 to 2100, based on IPCC/TAR and estimated vertical crustal motion (McCulloch *et al.*, 2002). Present and future flooding risk was assessed using digital elevation models derived from airborne laser altimetry (LiDAR) mapping to simulate the highest observed storm-surge flood (providing validation) and potential flooding at higher sea level (Figure 14.11a) (Webster *et al.*, 2004).

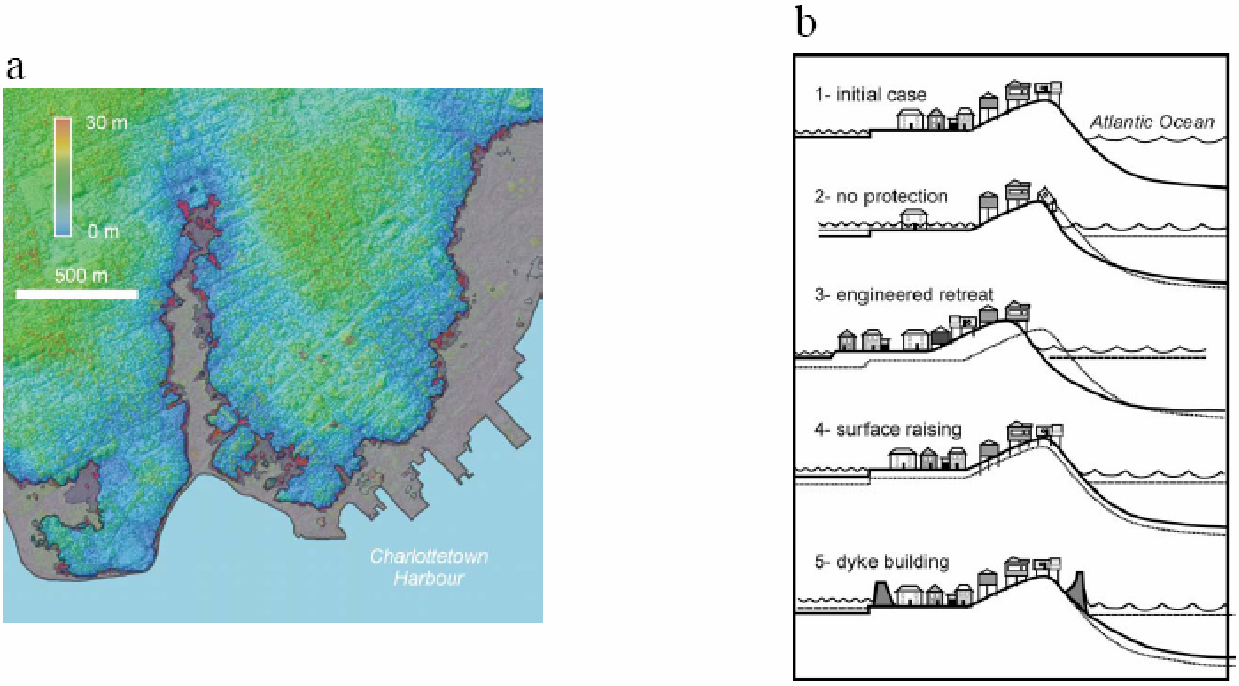


Figure 14.11: *a) (in pale grey) extent of January 2000 surge in the downtown core of Charlottetown, Prince Edward Island, and the same event superimposed on 0.5 m (dark grey) and 0.7 m (red) relative sea-level rise. b) Overview of strategies for adapting coastal communities to future risks of coastal flooding.*

Additional impacts identified in the southern Gulf of St. Lawrence include accelerated shoreline retreat from storms (possibly more intense) superimposed on rising sea levels, with more open-water fetch and larger waves during the winter storm season if the extent of sea ice declines in future decades (Forbes *et al.*, 2002a; Forbes *et al.*, 2004). In a representative area, this could lead to loss of as much as 49% of present assessed value for shorefront properties on the North Shore of PEI (McCulloch *et al.*, 2002).

Adaptation measures to minimize future impacts include beach nourishment, enhancing natural resilience (e.g., dune replenishment), managed or engineered retreat, raising land and/or foundation levels, and protection using sea walls or dykes (Figure 14.11b) (Forbes *et al.*, 2002b; Titus, 2005). Managed retreat has been initiated in many jurisdictions in both Canada and the USA, but protection may be required or justified for cultural heritage sites or where the capital value is high. Habitat conservation in coastal wetlands is another common objective requiring specific adaptation measures.

14.8 Implications for sustainability

Climate change creates a broad range of difficult challenges. Several of the most difficult emerge from the long time scale over which the changes occur and the possible need for action well before the magnitude of the impacts is clear. Other difficult problems arise from the intrinsic global scale of climate change. 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 (Field *et al.*, 2004), 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. On the other hand, the daunting magnitude of the climate change challenge calls for a major flowering of technological and social innovation, areas in which Canada and the United States have traditionally excelled.

The challenge of addressing climate change in ways that are sustainable, efficient, and ethical has many dimensions. Some of these are grounded in consumer preferences. Modest shifts in consumer preferences, for example toward more efficient cars (Jackson and Schlesinger, 2004), could play a major role in creating incentives for sustainable technologies. Consumer preferences for energy from non-emitting sources can also provide incentives, though the cumulative magnitude of these is certainly limited (Caldeira *et al.*, 2004). Other kinds of incentives, ranging from removal of subsidies on fossil fuel based energy systems to tax credits for and direct investment in non-emitting technologies will also be necessary. In particular, approaches for facilitating long-term transitions from fossil to non-emitting energy sources are likely to play a crucial role (Edmonds, 2004). Incentives that encourage international spread of non-emitting technologies have win-win potential, if they can strengthen North American economies at the same time they decrease fossil emissions in other parts of the world.

Many of the challenges for future sustainability concern our ability to balance competing priorities. Climate change is likely to complicate the challenge of maintaining sustainable economic growth at the same time we protect the environment, preserve rare species, and maintain opportunities for indigenous lifestyles. Conflicting demands for freshwater resources may be especially severe in Canada and the U.S., where much of the population, industry, and agriculture are in arid regions. Continued progress in accounting for the value of ecosystem services (Daily *et al.*) can play a critical role in effectively balancing these competing demands.

14.9 Key uncertainties, confidence levels, unknowns, research gaps and priorities

Canada and the United States have large and sophisticated science enterprises, plus a distinguished record of serious commitments to climate change science. Still, our understanding of regional climate changes, impacts of these changes, and options for adapting to the changes that do occur is far from complete. Uncertainty in the amount and rate of climate change in coming decades is still substantial. Key areas that impact the assessment of impacts are the sensitivity of the amount of warming to changes in policy and the link between the amount of climate change and the frequency and intensity of extreme events. The developed economies and infrastructure of North America may limit the loss of human life from extreme weather events, but they play an increased stock of economic resources at risk.

Likely impacts of particular aspects of climate change are increasingly known, though our understanding of impacts of interactions among multiple impacts, adaptations, and other responses is still rudimentary (Edmonds, 2004). We have a limited understanding of, for example, the way that warming, increased atmospheric carbon dioxide, and decreased water availability will affect agriculture, but we also have a limited appreciation of the extent to which investments in water efficient irrigation can ameliorate (or exacerbate) problems associated with warming. Similarly, we have little information on the way that biological invasives will interact with climate change in constraining options for protecting endangered species, but we similarly have few tools for assessing co-benefits of strategies for dealing with invasives. The transition from single sector to multi sector impacts assessment is one of the key priorities for future research.

Many of the greatest uncertainties in climate over the next century concern the responsiveness of policy to the scientific information, especially on a relevant time scale. Policy decisions that delay effective action have the potential to increase the magnitude of the changes, increase the strength of interactions among changes, and decrease the suite of effective adaptations (Field *et al.*, 2004).

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