North America

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EXECUTIVE SUMMARY

Within the North American region (defined for the purposes of this report as the portion of continental North America south of the Arctic Circle and north of the U.S.-Mexico border), vulnerability to climate change varies significantly from sector to sector and from subregion to subregion. Recognition of this variability or subregional "texture" is important in understanding the potential effects of climate change on North America and in formulating viable response strategies.

The characteristics of the subregions and sectors of North America suggest that neither the impacts of climate change nor the response options will be uniform. This assessment suggests that there will be differences in the impacts of climate change across the region and within particular sectors. In fact, simply considering the relative climate sensitivity of different sectors or systems within a particular subregion (i.e., climate-sensitive, climate-insensitive, or climate-limited) would suggest differentiated impacts. This diversity also is reflected in the available response options. Sectors and subregions will need to adopt response options to alleviate negative impacts or take advantage of opportunities that not only address the impacts but are tailored to the needs and characteristics of that subregion.

Comprising most of Canada and the contiguous United States, this large area is diverse in terms of its geological, ecological, climatic, and socioeconomic structures. Temperature extremes range from well below -40°C in northern latitudes during the winter months to greater than +40°C in southern latitudes during the summer. The regional atmospheric circulation is governed mainly by upper-level westerly winds and subtropical weather systems, with tropical storms occasionally impacting on the Gulf of Mexico and Atlantic coasts during summer and autumn. The Great Plains (including the Canadian Prairies) and southeastern U.S. experience more severe weather—in the form of thunderstorms, tornadoes, and hail—than any other region of the world.

Our current understanding of the potential impacts of climate change is limited by critical uncertainties. One important uncertainty relates to the inadequacy of regional-scale climate projections relative to the spatial scales of variability in North American natural and human systems. This uncertainty is compounded further by the uncertainties inherent in ecological, economic, and social models—which thereby further limit our ability to identify the full extent of impacts or prescriptive adaptation measures. Given these uncertainties, particularly the inability to forecast futures, conclusions about regional impacts are not yet reliable and are limited to the sensitivity and vulnerability of physical, biological, and socioeconomic systems to climate change and climate variability.

Within most natural and human systems in North America, current climate—including its variability—frequently is a limiting factor. Climate, however, is only one of many factors that determine the overall condition of these systems. For example, projected population changes in North America and associated changes in land use and air and water quality will continue to put pressure on natural ecosystems (e.g., rangelands, wetlands, and coastal ecosystems). Projected changes in climate should be seen as an additional factor that can influence the health and existence of these ecosystems. In some cases, changes in climate will provide adaptive opportunities or could alleviate the pressure of multiple stresses; in other cases, climate change could hasten or broaden negative impacts, leading to reduced function or elimination of ecosystems.

Virtually all sectors within North America are vulnerable to climate change to some degree in some subregions. Although many sectors and regions are sensitive to climate change, the technological capability to adapt to climate change is readily available, for the most part. If appropriate adaptation strategies are identified and implemented in a timely fashion, the overall vulnerability of the region may be reduced. However, uncertainties exist about the feasibility of implementation and efficacy of technological adaptation.

Even when current adaptive capability has been factored in, long-lived natural forest ecosystems in the east and interior west; water resources in the southern plains; agriculture in the southeast and southern plains; human health in areas currently experiencing diminished urban air quality; northern ecosystems and habitats; estuarine beaches in developed areas; and low-latitude cold-water fisheries will remain among the most vulnerable sectors and regions. West coast coniferous forests; some western rangelands; energy costs for heating in the northern latitudes; salting and snow clearance costs; open-water season in northern channels and ports; and agriculture in the northern latitudes, the interior west, and west coast may benefit from opportunities associated with warmer temperatures or potentially from carbon dioxide (CO_2) fertilization.

The availability of better information on the potential impacts of climate change and the interaction of these impacts with other important factors that influence the health and productivity of natural and human systems is critical to providing the lead time necessary to take full advantage of opportunities for minimizing or adapting to impacts, as well as for allowing adequate opportunity for the development of the necessary institutional and financial capacity to manage change.

Key Impacts to Physical, Biological, and Socioeconomic Systems

Ecosystems: Nonforest Terrestrial (Section 8.3.1). The composition and geographic distribution of many ecosystems will shift as individual species respond to changes in climate. There will likely be reductions in biological diversity and in the goods and services that nonforest terrestrial ecosystems provide to society.

Increased temperatures could reduce sub-arctic (i.e., tundra and taiga/tundra) ecosystems. Loss of migratory wildfowl and mammal breeding and forage habitats may occur within the taiga/tundra, which is projected to nearly disappear from mainland areas. This ecozone currently is the home of the majority of the Inuit population. It also provides the major breeding and nesting grounds for a variety of migratory birds and the major summer range and calving grounds for Canada's largest caribou herd, as well as habitat for a number of ecologically significant plant and animal species critical to the subsistence lifestyles of the indigenous peoples. Current biogeographic model projections suggest that tundra and taiga/tundra ecosystems may be reduced by as much as two-thirds of their present size, reducing the regional storage of carbon in the higher latitudes of North America—which may shift the tundra region from a net sink to a net source of CO_2 for the tundra region.

The relatively certain northward shift of the southern boundary of permafrost areas (projected to be about 500 km by the middle of the 21st century) will impact ecosystems, infrastructure, and wildlife in the altered areas through terrain slumping, increased sediment loadings to rivers and lakes, and dramatically altered hydrology; affected peatlands could become sources rather than sinks for atmospheric carbon. Projections suggest that peatlands may disappear from south of 60°N in the Mackenzie Basin; patchy arctic wetlands currently supported by surface flow also may not persist.

Elevated CO_2 concentrations may alter the nitrogen cycle, drought survival mechanisms (e.g., the rate of depletion of soil water by grasses), and fire frequency—potentially decreasing forage quality and impacting forage production on rangelands. Increases in CO_2 and changes in regional climate could exacerbate the existing problem of loss of production on western rangelands related to woody and noxious plant invasions by accelerating the invasion of woody C_3 plants (many crop and tree species) into mostly C_4 (tropical grasses, many weed species) grasslands. Mechanisms include changes in water-use efficiency (WUE), the nitrogen cycle (increase in carbon-to-nitrogen ratio and concentrations of unpalatable and toxic substances), drought survival mechanisms, and fire frequency. Growth and reproduction of individual animals could decrease as CO_2 concentrations rise, without dietary supplementation. However, the data are ambiguous, and production may increase in some grassland ecosystems. Uncertainty exists in our ability to predict ecosystem or individual species responses to elevated CO_2 and global warming at either the regional or global scale.

Arid lands may increase. Current biogeographical model simulations indicate up to a 200% increase in leaf area index in the desert southwest region of North America and a northern migration and expansion of arid-land species into the Great Basin region of North America. Although uncertainty exists in predictions of regional climate changes and simulations of ecosystem responses to elevated CO_2 and global warming, long-term change in ecosystem structure and function is suggested.

Landslides and debris flows in unstable Rocky Mountain areas and possibly elsewhere could become more common as winter wet precipitation increases, permafrost degrades, and/or glaciers retreat. Water quality would be affected by increased sediment loads. Fish and wildlife habitat, as well as roads and other artificial structures, could be at increased risk.

Ecosystems: Forested (Section 8.3.2). Changes are likely in the growth and regeneration capacity of forests in many subregions. In some cases, this process will alter the function and composition of forests significantly.

Forests may die or decline in density in some regions because of drought, pest infestations, and fire; in other regions, forests may increase in both area and density. Models suggest that total potential forest area could increase by as much as 25–44%. For some individual forest types, however, range expansions could be preceded by decline or dieback over 19–96% of their area while the climate and ecosystems are adjusting, but before an equilibrium is attained. Even though total forest area could increase, northward shifts in distribution could produce losses in forest area in the United States.

Geographic ranges of forest ecosystems are expected to shift northward and upward in altitude, but forests cannot move across the land surface as rapidly as climate is projected to change. The faster the rate of climate change, the greater the probability of ecosystem disruption and species extinction. Climate-induced dieback could begin within a few decades from the present and might be enhanced by increases in pest infestations and fire. Alternatively, forest growth might increase in the early stages of global warming, followed by drought-induced forest dieback after higher temperatures have significantly increased evaporative demand. Migration into colder areas may be limited by seed dispersal (e.g., barriers may exist because of urbanization and changing land-use patterns), seedling establishment, and poor soils. As forests expand or contract in response to climate change, they will likely either replace or be replaced by savannas, shrublands, or grasslands. Imbalances between rates of expansion and contraction could result in a large pulse of carbon to the atmosphere during the transition.

Longer fire seasons and potentially more frequent and larger fires are likely. Because of decades of fire suppression—resulting in higher forest densities and increased transpiration—forests in the continental interior are experiencing increased drought stress; pest infestations; and catastrophic, stand-replacing fires, potentially resulting in changes in

species composition. Future climate could result in longer fire seasons and potentially more frequent and larger fires in all forest zones (even those that currently do not support much fire), due to more severe fire weather, changes in fire management practices, and possible forest decline or dieback.

Hydrology and Water Resources (Section 8.3.3). Water is a linchpin that integrates many subregions and sectors. Water quantity and quality will be directly affected by climate change. Available water supplies also will be affected by changes in demand from multiple sectors competing for water resources. Changes in the hydrological cycle will cause changes in ecosystems—which will, in turn, affect human health (e.g., by altering the geographic distribution of infectious diseases) and biological diversity.

Increases or decreases in annual runoff could occur over much of the lower latitudes and in midcontinental regions of mid and high latitudes. Increases in temperature lead to a rise in evapotranspiration—which, unless offset by large increases in precipitation or decreases in plant water use, results in declines in runoff, lake levels, and groundwater recharge and levels. The greatest impact of declines in supply will be in arid and semi-arid regions and in areas with a high ratio of use relative to available renewable supply, as well as in basins with multiple competing uses. Alternatively, regions that experience substantial increases in precipitation are likely to have substantial increases in runoff and river flows.

Climate projections suggest increased runoff in winter and early spring but reduced flows during summer in regions in which hydrology is dominated by snowmelt. Glaciers are expected to retreat, and their contributions to summer flows will decline as peak flows shift to winter or early spring. In mountainous regions, particularly at mid-elevations, warming leads to a long-term reduction in peak snow-water equivalent; the snowpack builds later and melts sooner. Snow- or glacier-fed river and reservoir systems that supply spring and summer flow during the critical periods of high agricultural and municipal demand and low precipitation may tend to release their water earlier in the year, which would reduce supplies during summer droughts. Water supplies and water quality, irrigation, hydroelectric generation, tourism, and fish habitat, as well as the viability of the livestock industry, may be negatively impacted. The Great Plains of the United States and prairie regions of Canada and California are particularly vulnerable.

Altered precipitation and temperature regimes may cause lower lake levels, especially in midcontinental regions and, along with the seasonal pattern and variability of water levels of wetlands, thereby affect their functioning—including flood protection, water filtration, carbon storage, and waterfowl/ wildlife habitat. The response of an affected wetland varies; it might include migration along river edges or the slope of a receding lake and/or altered vegetation species composition. Long-term lake levels would decline to or below historic low levels in the Great Lakes under several climate change scenarios. Prairie pothole lakes and sloughs may dry out more fre-

quently in the north-central regions of North America. These wetlands currently yield 50–75% of all waterfowl produced annually in North America. In the Mackenzie delta of arctic Canada, many lakes could disappear in several decades because of decreased flood frequency and less precipitation.

Ice-jam patterns are likely to be altered. In New England, the Atlantic provinces, the Great Lakes, and central Plains areas, as well as northern regions susceptible to spring flooding, changes in late winter-early spring precipitation patterns could result in diminished frequency of ice jams and flooding. Damages caused by these events currently are estimated to cost Canadians CAN$60 million and Americans US$100 million annually, though northern deltas and wetlands appear to depend on the resulting periodic recharge. Depending on the specific pattern of altering climate, mid-latitude areas where ice jams presently are uncommon—such as the prairies; central Ontario and Quebec; and parts of Maine, New Brunswick, Newfoundland, and Labrador—may suffer from an increase in frequency and/or severity of winter breakup and associated jamming.

Increases in hydrological variability (larger floods and longer droughts) are likely to result in increased sediment loading and erosion, degraded shorelines, reductions in water quality, reduced water supply for dilution of point-source water pollutants and assimilation of waste heat loads, and reduced stability of aquatic ecosystems. Projected changes in snowfall and snowmelt—as well as suggested increases in warm-period rainfall intensity—could shift the periodicity of the flood regime in North America, possibly stressing the adequacy of dams, culverts, levees, storm drains, and other flood prevention infrastructures. The impacts of flooding are likely to be largest in arid regions, where riparian vegetation is sparse; in agricultural areas during winter, when soils are more exposed; and in urban areas with more impervious surfaces. Increases in hydrological variability may reduce productivity and biodiversity in streams and rivers and have large impacts on water resources management in North America, with increased expenditures for flood management. Increases in water temperature and reduced flows in streams and rivers may result in lower dissolved oxygen concentrations, particularly in summer low-flow periods in low- and mid-latitude areas.

Projected increases in human demand for water would exacerbate problems associated with the management of water supply and quality. Managing increased water demands will be particularly problematic in regions experiencing increases in variability and declines in runoff. Improved management of water infrastructure, pricing policies, and demand-side management of supply have the potential to mitigate some of the impacts of increasing water demand.

Food and Fiber: Agriculture (Section 8.3.4). As the climate warms, crop patterns will shift northward. Most studies of these shifts have focused on changes in average climate and assume farmers effectively adapt. They have not fully accounted for changes in climate variability, water availability, and

imperfect responses by farmers to changing climate. Future consideration of these factors could either increase or decrease the magnitude of changes projected by these earlier studies.

Climate modifications that lead to changes in daily and interannual variability in temperatures and, in particular, precipitation will impact crop yields. Although changes in average temperature and precipitation can be expected to impact agriculture, few studies have considered the effects of increased climate variability on crop and livestock production. Increased variability in daily and interannual temperature and precipitation are likely to be as important or more important than the effects of mean changes in climate. Droughts, floods, and increased risks of winter injury will contribute to a greater frequency and severity of crop failure. An increased reliance on precision farming has increased vulnerability to climate variability outside a narrow range of change. These impacts are projected to be both site- and crop-specific; reliable forecasts for such occurrences, however, are not yet regionally available.

The direct effects of a doubling of CO_2 on crop yields are largely beneficial. Food and fiber production for crops like cotton, soybean, and wheat are expected to increase an average of 30% (range -10% to +80%) in response to a doubling of CO_2 concentration. The magnitude of this response will be highly variable and will depend on the availability of plant nutrients, temperature, and precipitation.

Crop losses due to weeds, insects, and diseases are likely to increase and may provide additional challenges for agricultural sector adaptation to climate change. Less severe winters due to climate change may increase the range and severity of insect and disease infestations. Increasing pressure to reduce chemical inputs (i.e., pesticides) in agriculture will necessitate a greater emphasis on concepts of integrated pest management and targeted application of agricultural chemicals through precision agricultural technologies.

Recent analyses of issues of long-run sustainability associated with agricultural adaptation to climate change from an arbitrary doubling of equivalent CO_2 concentrations have concluded that there is considerably more sectoral flexibility and adaptation potential than was found in earlier analyses. Much of this reassessment arises from a realization that the costs and benefits of climate change cannot be adequately evaluated independently of behavioral, economic, and institutional adjustments required by changing climate. Although scientific controversy over the nature and rate of climate change remains, most existing scenarios suggest gradual changes in mean climate over decades—providing ample opportunities for adaptation measures to be implemented within vulnerable subregions of North America. However, uncertainties remain about the implications of changes in climate variability, as well as crop responses to increases beyond a doubling of equivalent atmospheric CO_2 concentrations.

Existing studies that have looked at changes in mean temperature and precipitation suggest that climate change is not likely to harm agriculture enough to significantly affect the overall economy of North America. The economic consequences of climate change to U.S. agriculture are expected to be both positive and negative, depending on the nature of temperature and precipitation changes that occur in specific subregions. Subregions of North America that are dependent on agriculture may be more vulnerable than areas offering economic diversity. The Great Plains area, for example, relies heavily on crop and livestock production and, as a result, is potentially vulnerable to climate change, with negative consequences projected for southern extremes and potential positive impacts in northern areas as temperatures rise. Warmer temperatures at northern latitudes may lessen the adverse effects of frost damage, but the risk of early- and late-season frost will remain a barrier to the introduction of new crops.

Consumers and producers could gain or lose; the long-term stability of the forest-products market is uncertain. Consumer prices could increase by 100–250% with severe forest dieback, producing losses of 4–20% of the net value of commercial forests. Alternatively, consumer prices could decrease with increased forest growth and harvest in Canada, and producers could sustain economic losses. With exports from Canada to the United States, however, the net changes (consumers plus producers) could be negative for Canadians and positive for the U.S. market.

Food and Fiber: Production Forestry (Section 8.3.5). *The most intensively managed industry and private forestlands may be least at risk of long-term decline from the impacts of climate change because the relatively high value of these resources is likely to encourage adaptive management strategies.* Private forest managers have the financial incentive and the flexibility to protect against extensive loss from climate-related impacts. They can use several available techniques: short rotations to reduce the length of time that a tree is influenced by unfavorable climate conditions; planting of improved varieties developed through selection, breeding, or genetic engineering to reduce vulnerability; and thinning, weeding, managing pests, irrigating, improving drainage, and fertilizing to improve general vigor. Such actions would reduce the probability of moisture stress and secondary risks from fire, insects, and disease. However, the more rapid the rate of climate change, the more it may strain the ability to create infrastructure for seeding or planting of trees, or to support the supply of timber if there is a large amount of salvage. A fast rate of warming also may limit species constrained by slow dispersal rates and/or habitat fragmentation, or those that are already stressed by other factors, such as pollution.

Food and Fiber: Fisheries and Aquatic Systems (Section 8.3.6). Aquatic ecosystem functions will be affected by climate change, although the effects are likely to vary in magnitude and direction depending on the region.

Projected increases in water temperature, changes in freshwater flows and mixing regimes, and changes in water quality could result in changes in the survival, reproductive capacity,

and growth of freshwater fish and salmonid and other anadromous species. In larger, deeper lakes—including the Great Lakes and many high-latitude lakes—increases in water temperature may increase the survival and growth of most fish species. In smaller, mid-latitude lakes and streams, however, increased water temperatures may reduce available habitat for some cold-water and cool-water species. Increased production rates of food (e.g., plankton) with warmer water temperature (e.g., plankton production increases by a factor of 2–4 with each 10°C increase) also may increase fish productivity. However, shifts in species composition of prey with warming may prevent or reduce productivity gains if preferred prey species are eliminated or reduced. Warmer freshwater temperatures and changes in the pattern of flows in spawning streams/rivers could reduce the abundance of salmon, although individual size may increase from improved growth in the warmer water. Increases in temperature in freshwater rearing areas and increased winter flows may increase mortality for stocks in southern rivers on the west coast.

Freshwater species distributions could shift northward, with widespread/subregional species extinction likely at the lower latitudes and expansion at the higher latitudes of species ranges. For example, a 3.8°C increase in mean annual air temperature is projected to eliminate more than 50% of the habitat of brook trout in the southern Appalachian mountains, whereas a similar temperature increase could expand the ranges of smallmouth bass and yellow perch northward across Canada by about 500 km. Whether fish are able to move or will become extinct in response to changes in or loss of habitat will depend on the availability of migration routes.

Recreational fishing is a highly valued activity that could incur losses in some regions resulting from climate-induced changes in fisheries. The net economic effect of changes in recreational fishing opportunities is dependent on whether the gains in cool- and warm-water fish habitat offset the losses in cold-water fish habitat. The loss of fishing opportunities could be severe in some parts of the region, especially at the southern boundaries of fish species' habitat ranges. Although gains in cool- and warm-water fishing opportunities may offset losses in cold-water fishing opportunities, distributional effects will cause concern.

There will likely be relatively small economic and food supply consequences at the regional/national level as a result of the impacts on marine fisheries; however, impacts are expected to be more pronounced at the subregional and community levels. The adaptability of fisheries to current climate variability and the relatively short time horizons on capital replacement (ships and plants) will minimize the regional- and national-level impacts of projected climate change. At the subregional and community levels, however, positive and negative impacts can be significant as a result of suggested shifts in the centers of production and ensuing relocation of support structures, processors, and people.

Projected changes in water temperatures, as well as salinity and currents, can affect the growth, survival, reproduction, and spatial distribution of marine fish species and the competitors and predators that influence the dynamics of these species. Growth rates, ages of sexual maturity, and distributions of some marine fish species are sensitive to water temperatures (e.g., cold temperatures typically result in delayed spawning, whereas warm temperatures result in earlier spawning), and long-term temperature changes can lead to expansion or contraction of the distribution ranges of some species. These changes generally are most evident near the northern or southern species boundaries (i.e., warming resulting in a distributional shift northward, and cooling drawing species southward).

The survival, health, migration, and distribution of many North American marine mammals and sea turtles are expected to be impacted by projected changes in the climate through impacts on their food supply, sea-ice extent, and breeding habitats. Although some flexibility exists in their need for specific habitats, some marine mammals and sea turtles may be more severely affected than others by projected changes in the availability of necessary habitat, including pupping and nesting beaches; in food supplies; and in associated prey species. Concerns are the result primarily of projected changes in seasonal sea-ice extent and accelerated succession or loss of coastal ecosystems as a result of projected rises in sea level.

Coastal Systems (Section 8.3.7). The implications of rising sea level are well understood, in part because sea level has been rising relative to the land along most of the coast of North America for thousands of years. Some coastal areas in the region will experience greater increases in sea level than others. Adaptation to rising seas is possible, but it comes at ecological, economic, and social costs.

In the next century, rising sea level could inundate approximately 50% of North American coastal wetlands and a significant portion of dry land areas that currently are less than 50 cm above sea level. In some areas, wetlands and estuarine beaches may be squeezed between advancing seas and engineering structures. A 50-cm rise in sea level would cause a net loss of 17–43% of U.S. coastal wetlands, even if no additional bulkheads or dikes are erected to prevent new wetland creation as formerly dry lands are inundated. Furthermore, in the United States, 8,500–19,000 km^2 of dry land are within 50 cm of high tide, 5,700–15,800 km^2 of which currently are undeveloped. Several states in the United States have enacted regulations to adapt to climate change by prohibiting structures that block the landward migration of wetlands and beaches. The mid-Atlantic, south Atlantic, and Gulf coasts are likely to lose large areas of wetlands if sea-level rise accelerates.

Coastal areas in the Arctic and extreme North Atlantic and Pacific are less vulnerable, except where sea ice and/or permafrost currently is present at the shoreline. Recent modeling suggests that projected increases in ocean fetches as a result of decreases in the period and extent of sea-ice cover could increase wave heights by 16–40% and therefore increase coastal erosion during the open-water season. Maximum coastal erosion rates are expected to continue in those areas

where permafrost contains considerable pore, wedge, or massive ice or where the permafrost shoreline is exposed to the sea.

Rising sea level is likely to increase flooding of low-lying coastal areas and associated human settlements and infrastructure. Higher sea levels would provide a higher base for storm surges; a 1-m rise would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm. Sea-level rises of 30 cm and 90 cm would increase the size of the 100-year floodplain in the United States from its 1990 estimate of 50,500 km^2 to 59,500 km^2 and 69,900 km^2, respectively. Assuming that current development trends continue, flood damages incurred by a representative property subject to sea-level rise are projected to increase by 36–58% for a 30-cm rise and by 102–200% for a 90-cm rise. In Canada, Charlottetown, Prince Edward Island appears to be especially vulnerable, with some of the highest-valued property in the downtown core and significant parts of the sewage systems at risk.

Saltwater is likely to intrude further inland and upstream. Higher sea level enables saltwater to penetrate farther upstream in rivers and estuaries. In low-lying areas such as river deltas, saltwater intrusion could contaminate drinking water and reduce the productivity of agricultural lands.

Human Settlements and Industry (Section 8.3.8). Climate change and resulting sea-level rise can have a number of direct effects on human settlements, as well as effects experienced indirectly through impacts on other sectors.

Potential changes in climate could have positive and negative impacts on the operation and maintenance costs of North American land and water transportation systems. Higher temperatures are expected to result in lower maintenance costs for northern transportation systems, especially with fewer freeze-thaw cycles and less snow. However, some increased pavement buckling is a possibility because of projected longer periods of intense heat. Problems associated with permafrost thawing in the Bering Sea region could be particularly severe and costly. River and lake transportation could be somewhat more difficult, with increases in periods of disruption as a result of projected decreases in water levels (e.g., the Mississippi River and the Great Lakes-St. Lawrence Seaway system). Increases in the length of the ice-free season could have positive impacts for commercial shipping on the inland waterways and in northern ports (e.g., Arctic Ocean ports).

Projected changes in climate could increase risks to property and human health/life as a result of changes in exposure to natural hazards (e.g., wildfire, landslides, and extreme weather events). A large and increasing number of people and their property in North America are vulnerable to natural hazards. Projected changes in wildfires and landslides could increase property losses and increase disruptions and damages to urban and industrial infrastructure (e.g., road and rail transportation and pipeline systems). Although some questions remain regarding the extent and regional reflections of changes in extreme weather events as a result of climate changes, project-

ed changes in the frequency or intensity of these events are of concern because of the implications for social and economic costs in a number of sectors. For example, extreme weather events can cause direct physical harm to humans; disrupt health infrastructure, causing contamination of water systems and creating breeding sites for insects or favorable conditions for rodents that carry diseases; and affect construction costs, insurance fees and settlement costs, and offshore oil and gas exploration and extraction costs.

Climate warming could result in increased demand for cooling energy and decreased demand for heating energy, with the overall net effect varying among geographic regions. Changes in energy demand for comfort, however, are expected to result in a net saving overall for North America. Projected increases in temperature could reduce energy use associated with space heating [e.g., a 1°C increase in temperature could reduce U.S. space-heating energy use by 11% of demand, resulting in a cost saving of $5.5 billion (1991$US)]. It also has been projected that a 4°C warming could decrease site energy use for commercial-sector heating and cooling by 13–17% and associated primary energy by 2–7%, depending on the degree to which advanced building designs penetrate the market. If peak demand for electricity occurs in the winter, maximum demand is likely to fall as a result of projected temperature changes, whereas if there is a summer peak, maximum demand will rise.

The technological capacity to adapt to climate change is likely to be readily available in North America, but its application will be realized only if the necessary information is available (sufficiently far in advance in relation to the planning horizons and lifetimes of investments) and the institutional and financial capacity to manage change exists. Some adaptations can be made without explicit climate predictions through increasing the resilience of systems, such as greater flood control, larger water reservoirs, and so forth, but these approaches are not without social and economic costs. Rapid changes in climate and associated acceleration of sea-level rise would limit adaptation options, thereby putting considerable strain on social and economic systems and increasing the need for explicit adaptation strategies.

Human Health (Section 8.3.9). Climate can have wide-ranging and potentially adverse effects on human health through direct pathways (e.g., thermal stress and extreme weather/climate events) and indirect pathways (e.g., disease vectors and infectious agents, environmental and occupational exposures to toxic substances, and food production).

Direct health effects include increased heat-related mortality and illness and the beneficial effects of milder winters on cold-related mortality. Under a warmer North America, current models indicate that by the middle of the next century, many major cities could experience as many as several hundred to thousands of extra heat-related deaths annually. The elderly, persons with preexisting health conditions, and the very young (0–4 years) are most vulnerable to heat stress. Gradual acclimatization to increasing temperatures, the use of air con-

ditioners, and an adequate warning system for heat waves may help reduce heat-related deaths. Conversely, it has been suggested that winter mortality rates may decrease in the future with warmer winter temperatures.

Climate warming may exacerbate respiratory disorders associated with reduced air quality and affects the seasonality of certain allergic respiratory disorders. Concurrent hot weather and exposure to air pollutants can have synergistic impacts on health. Recent studies show a positive correlation between ground-level ozone and respiratory-related hospital admissions in the United States and Canada. Increased temperatures under climate change could lead to a greater number of days on which ozone levels exceed air quality standards. Global warming also may alter the production of plant aero-allergens, intensifying the severity of seasonal allergies.

Changing climate conditions may lead to the northward spread of vector-borne infectious diseases and potentially enhanced transmission dynamics due to warmer ambient temperatures. Vector-borne infectious diseases (e.g., malaria, dengue fever, encephalitis) and waterborne diarrheal diseases currently cause a large proportion of global fatalities. Temperature increases under climate change are expected to enlarge the potential transmission zones of these vectors into temperate regions of North America. Some increases in waterborne diseases may occur due to changes in water distribution, temperature, and microorganism proliferation under climate change. However, the North American health infrastructure likely would prevent a large increase in the actual number of vector-borne and waterborne disease cases.

Integrative Issues (Section 8.4). Taken individually, responses to any one of the impacts discussed here may be within the capabilities of a subregion or sector. The fact that they are projected to occur simultaneously and in concert with changes in population, technology, and economics and other environmental and social changes, however, adds to the complexity of the impact assessment and the choice of appropriate responses.

This assessment highlights a number of the uncertainties that currently limit our capability to understand the vulnerability of subregions and sectors of North America and to develop and implement adaptive strategies to reduce that vulnerability. The following research and monitoring activities are considered key to reducing these uncertainties:

- Improve regional and subregional projections of climate change that consider the physiographic characteristics that play a significant role in the North American climate (e.g., the Great Lakes, the nature of the coasts, and mountain ranges), and incorporate biosphere-atmosphere feedbacks.
- Improve projections of changes in weather systems and variability, including extremes.
- Develop a better understanding of physiological and ecosystem processes, with particular emphasis on direct CO_2 effects and how the CO_2 effects might be enhanced or diminished by nitrogen-cycle dynamics.
- Identify sensitivities and relative vulnerabilities of natural and social systems, including the availability of the necessary physical, biological, chemical, and social data and information.
- Identify beneficial impacts or opportunities that may arise as a result of climate change.
- Develop integrated assessments of impacts.
- Define viable response options that recognize the differentiated and integrative nature of the impacts and response options and the specific needs of sectors and subregions of North America.

8.1. Regional Characterization

North America, for the purposes of this regional assessment, is defined as continental North America north of the border between the United States and Mexico and south of the Arctic Circle. Comprising most of Canada and the United States, this area totals approximately 19.42 million km², with a combined population of approximately 292.7 million in 1995 (Annex D, Table D-6). Canada is the second-largest country in the world but one of the most sparsely populated, with nearly 90% of the population located along the border with the United States (Figures 8-1 and 8-2). The United States is the world's fourth-largest country in both area and population. Approximately 75% of the North American population is urban. North America is geologically and ecologically diverse and spans a full spectrum of land cover types and physiography (Figure 8-3 and Annex C). About 12% of the land area of the North American region is cropland, and 32% is forest and woodlands; the rest is divided among rangelands and other lands, including mountains, desert, wetlands and lakes, and wilderness. As such, management of croplands, forests, and rangelands within North America is a key part of sustainable development.

Canada and the United States rank among the wealthiest countries in the world in terms of per capita income and natural resources. In fact, there is a strong link between the region's economic prosperity and well-being and that of its natural resources. For example, Canada, more than most industrialized nations, depends on the land for its economic well-being, with one in three workers employed directly or indirectly in agriculture, forestry, mining, energy generation, and other land-based activities (Government of Canada, 1996). In the

United States, although dependence on primary production is lower, agricultural production and marketing account for 16% of employment, and almost half of the total land area (excluding Alaska) is dedicated to agriculture-related purposes (PCSD, 1996).

North America has abundant energy resources—including uranium, oil, natural gas, and coal—and leads the world in the production of hydropower. It also is the world's largest consumer of energy, but because of more rapid growth in other regions of the globe, emissions from North America have shrunk from 45.1% of the global total in 1950 to 24.3% in 1994. The region historically and currently leads the world in greenhouse gas emissions, contributing 1509 million metric tons of carbon in 1994 (Canada, 122 million metric tons; the United States, 1387 million metric tons) (Marland and Boden, 1997).

Water availability and quality are among the most common concerns expressed by North Americans (UNEP, 1997). Despite an overall abundance, water shortages occur periodically in some localities (e.g., arid sections of the western United States, the Canadian prairies, and some of the interior valleys of the Rocky Mountains). Compared with people in most other regions, North Americans are among the world's leaders in per capita water consumption, and the region enjoys relatively good water quality. Nevertheless, the availability of safe water remains a problem in a number of areas, particularly in rural and remote areas. Improper agricultural practices and by-product and waste disposal practices in some areas have contributed to impaired water quality of rivers, lakes, and estuaries. For example, large concentrations of industrial capacity and agricultural production (nearly 25%
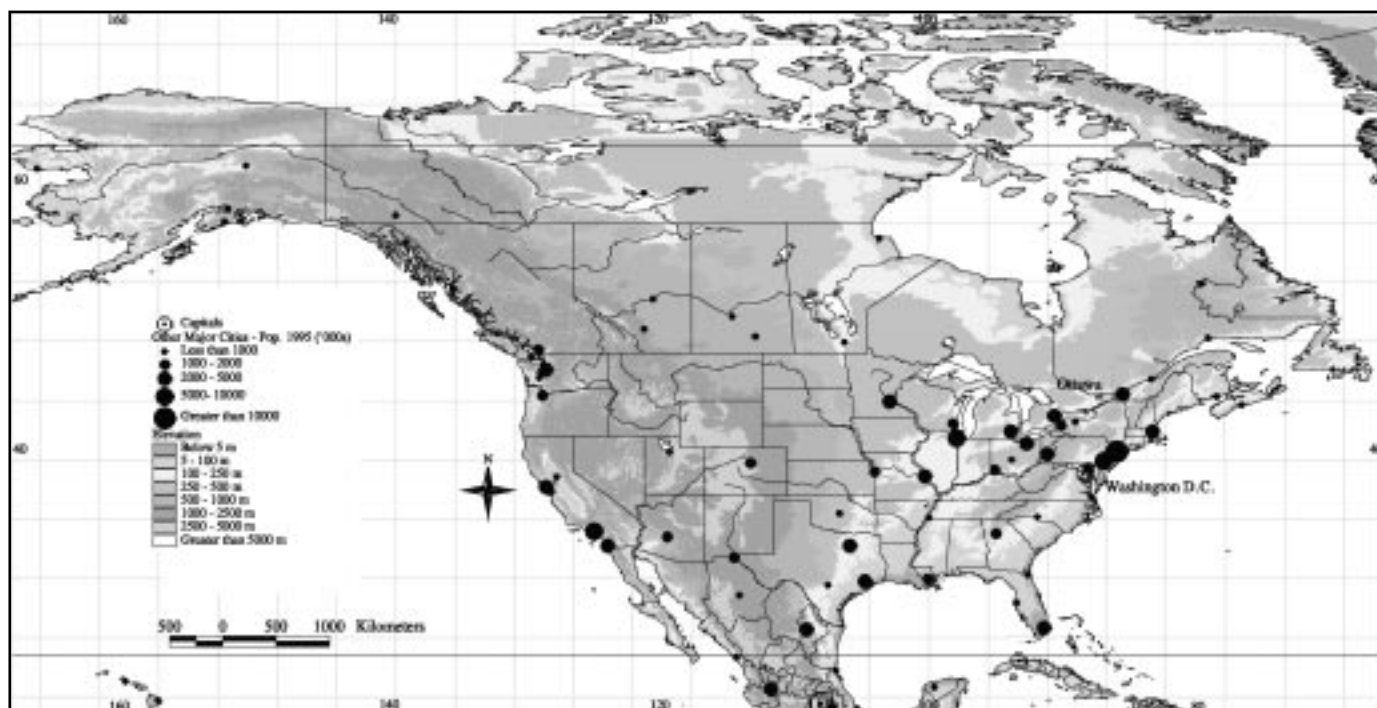
Figure 8-1: The North America region [compiled by the World Bank Environment Department Geographic Information System (GIS) Unit; see Annex E for a color rendition].
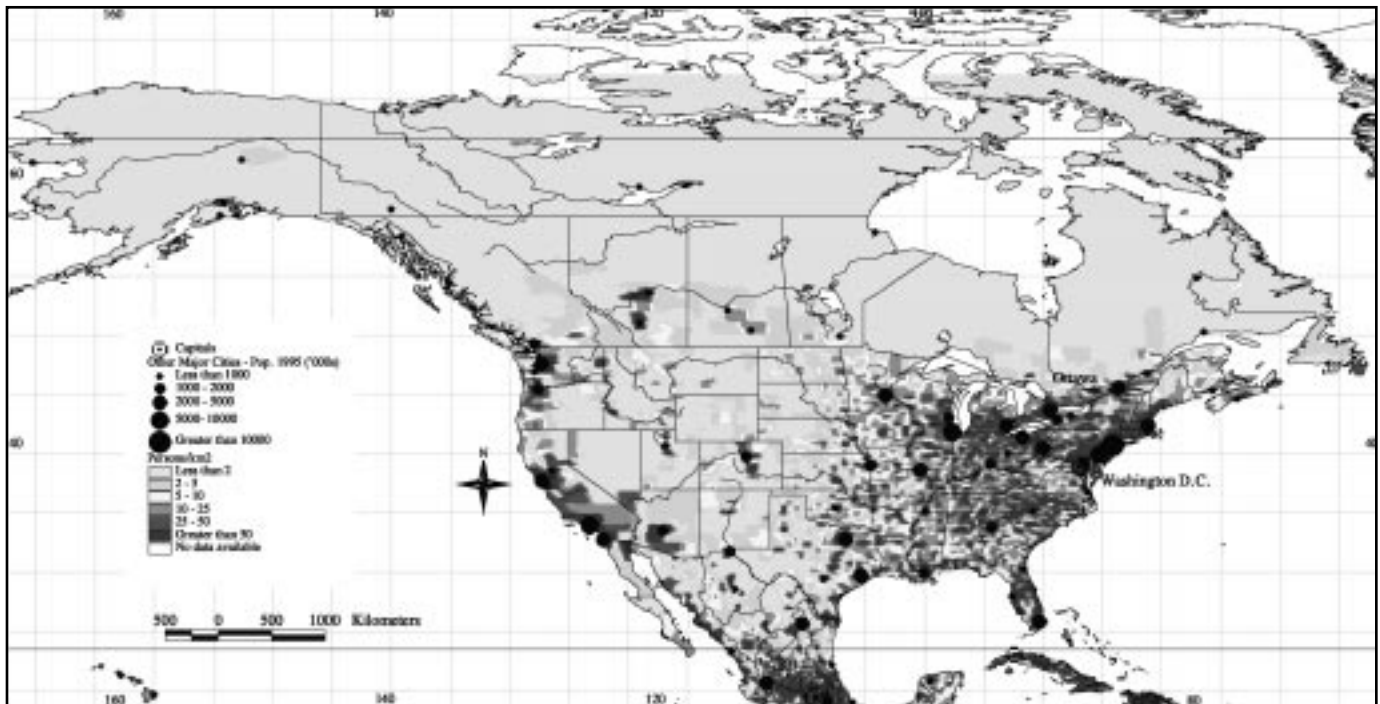
Figure 8-2: North American population density [compiled by the World Bank Environment Department Geographic Information System (GIS) Unit; see Annex E for a color rendition].

of the total Canadian agricultural production and 7% of the U.S. production) are located within the Great Lakes–St. Lawrence basin and have contributed to the reduced quality of the water contained within that basin (U.S. EPA and Environment Canada, 1995).

As in other regions of the globe, a number of pressures are being brought to bear on North America that are affecting the region's progress toward sustainability (e.g., population dynamics, land-use changes, changes in the global and regional economy, air and water pollution, consumption, and technological changes). Modern social and ecological systems, for the most part, have evolved and adapted to the prevailing local climate and its natural variability. Climate change, however, is an additional factor that will affect the evolution and adaptation (i.e., sustainability) of these systems. It acts in combination with these other pressures, resulting in either a negative impact or, in some cases, an opportunity that could benefit an area or sector. Climate change impacts and the ability of North America to adapt, therefore, must be assessed within the broader context of these other changes and development trends.

Another factor for consideration is the relative sensitivity of any activity, resource, or area of the region to climate and how these other changes and pressures will affect that sensitivity. Population growth, changing demographics, and the movement of a large proportion of that population to coastal communities are projected to increase the sensitivity of North Americans to climate change and variability. For example, by the year 2000, more than 75% of the U.S. population (PCSD, 1996) and approximately 25% of the Canadian population (Government of Canada, 1996) will reside in coastal communities. Projected

increasing demands on water resources—in terms of absolute amounts and multiplicity of demands—are expected to increase the climate sensitivity of these resources. On the other hand, increased energy efficiency and related technological advances are projected to decrease climate sensitivity through their positive impacts on reducing energy demands (e.g., energy for lighting, heating, and cooling).

Some of the key issues that need to be considered when interpreting the results of this assessment or deciding how to respond are as follows.

*There are uncertainties associated with climate change and with the responses of natural and social systems to climate change, particularly at the regional and subregional scales (*IPCC 1996, WG I, Summary for Policymakers*).* Because of inherent uncertainties in our knowledge of the processes affected, our understanding of the magnitude of the responses is equally, or more, uncertain. These uncertainties are compounded further by uncertainties about how landowners and other decision makers will respond to associated risks. Assumptions about how people will respond to risks associated with climate change can significantly affect estimates of associated socioeconomic impacts.

Differentiated impacts can occur across North America. As this assessment notes, particular areas and sectors within North America are projected to experience negative impacts, whereas other areas and sectors could benefit from the projected changes. Similarly, because of differences in adaptive capacity within North America, different areas and sectors will be better able to respond to climate change.
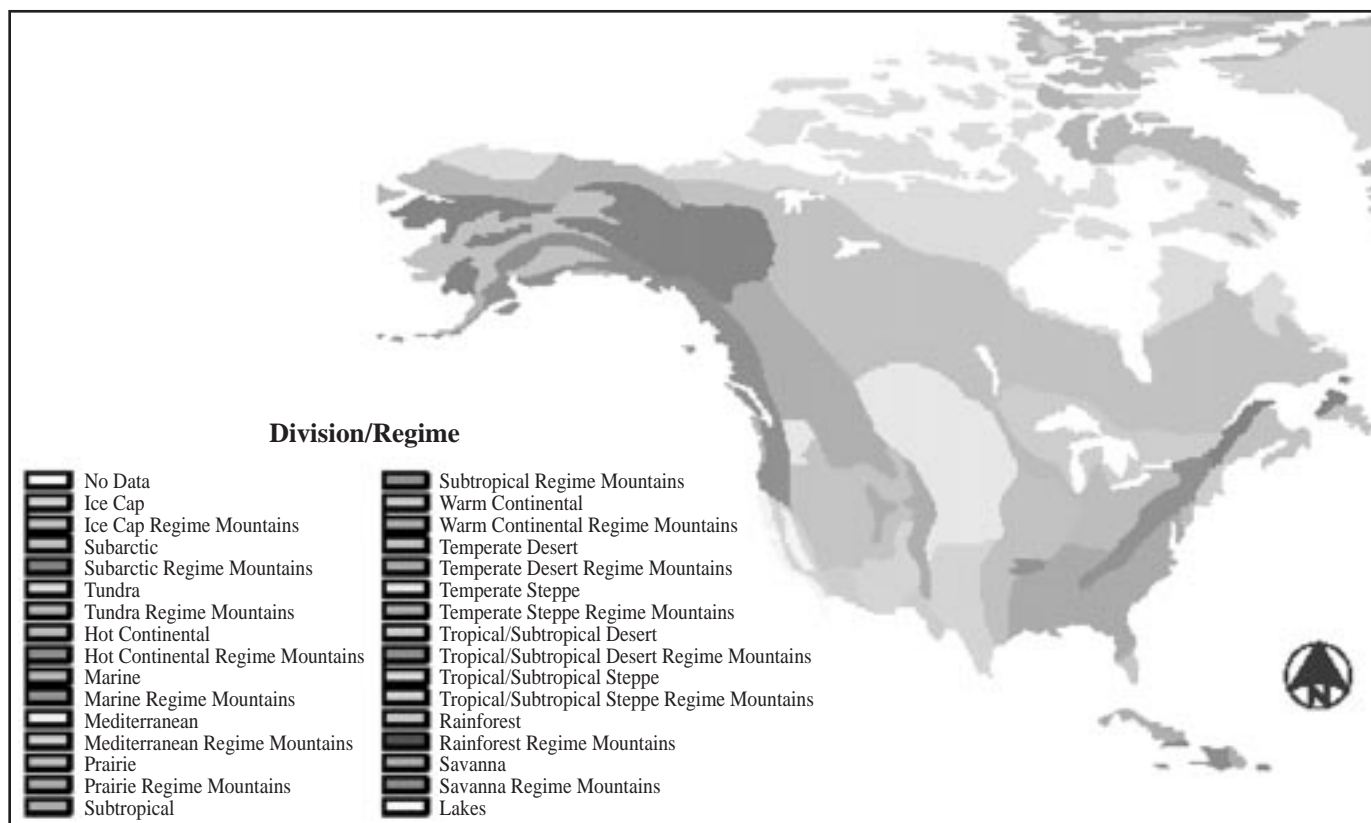
Figure 8-3: Ecoregions for North America (courtesy of R.A. Washington-Allen/ORNL), based on data provided by the National Geophysical Data Center (see Annex E for a color rendition).

Climate change is a dynamic process that will occur over time. Although most of the literature on impacts, including the analysis in this assessment, has focused on a $2xCO_2$ world, it is reasonable to expect that some of the kinds of impacts that have been discussed would begin to manifest themselves before atmospheric concentrations of CO_2 doubled. It also is important to recognize that $2xCO_2$ is not a magic concentration; it is likely that, unless action is taken, we will pass $2xCO_2$ on our way to even higher concentrations. It is not unreasonable to suggest that at these higher levels the negative and beneficial impacts (e.g., the benefits of CO_2 fertilization effects on vegetation) could be significantly different, even a nonfactor, in a $4xCO_2$ world.

*Many of the changes in climate that currently are being observed are consistent with the changes one would expect with greenhouse gas-induced climate change (*IPCC 1996, WG I, Summary for Policymakers*).*

Many of the actions that might be taken today to address existing stresses might also help reduce vulnerability to potential climate change and variability. Options include, but are not limited to, actions such as the following:

• Improve management of water infrastructure, pricing policies, and demand-side management of supply to support the competing needs of domestic water supply, agriculture, industrial cooling, hydropower, navigation, and fisheries and habitat.

• Introduce accommodating adaptation options in the transportation sector, as the industry copes with other significant changes, through new technologies, markets, and products.

• Introduce effective land-use regulations that also help reduce vulnerabilities and direct population shifts away from vulnerable locations such as floodplains, steep hillsides, and low-lying coastlines.

Failure to consider climate change when making long-range decisions to manage stress response in any sector could increase the risk of taking actions that would prove ineffective or even counterproductive in the long run. Examples where consideration of climate change could prove prudent are:

• Actions taken currently that would reduce weather-related deaths associated with heat waves in urban areas also could reduce vulnerability to potential climate change that might increase the frequency and intensity of heat waves (IPCC 1996, WG I, Summary for Policymakers).

• Introducing sustainable water-supply management concepts today, whether to deal with shortages or excesses of water, could reduce vulnerability to potential climate change.

The concept of "effective" adaptation by any given sector assumes that those affected have the ability and the foresight to

discern changing climate trends from short-term weather patterns and to make strategic anticipatory adaptations accordingly. It is not clear that, if changes in climate and weather patterns or variables fall outside people's experience, they will be able to adapt effectively in the near term. If they are not able, there may be short-term transitional impacts on those individuals and decision makers (e.g., resource managers, farmers, fishermen, loggers, or ranchers).

8.2. Regional Climate Information

8.2.1. Current Climate

North America possesses a multitude of diverse regional climates as a consequence of its vastness, its topography, and its being surrounded by oceans and seas with widely varying thermal characteristics. The North American region as analyzed in this report (see Figure A-3 in Annex A) extends latitudinally from approximately the Arctic Circle to the Tropic of Cancer and longitudinally from the Aleutian Islands in the west to the Canadian maritime provinces in the east. The regional atmospheric circulation is dominated by disturbances (waves) in the upper-level westerly winds. The development of these waves defines the position of the main upper-level jet stream over the continent and thus the position of the so-called Polar Front at the surface, which generally separates colder, drier air to the north from warmer, moister air to the south. In the colder half of the year, the position of the Polar Front can vary greatly, from southern Canada to the southern reaches of the United States. Such large shifts in the Polar Front are associated with long, high-amplitude waves that often cause one part of the continent to experience warm, moist, southerly airflow while another part experiences a blast of dry and cold Arctic air (meridional flow). These conditions may persist for lengthy periods because of the typically slow movement of these longer waves. At other times, however (mainly in the fall and spring), shorter, weaker waves move more quickly across the continent—producing highly variable weather with rapidly changing, but not extremely high or low, temperatures and short wet and dry periods. In the summer, the Polar Front retreats well into Canada, for the most part, and two oceanic semipermanent high-pressure systems tend to dominate the North American weather; as a result, there typically are fewer and weaker synoptic-scale disturbances in the westerlies. In summer and autumn, tropical storms of Atlantic, Caribbean, or Gulf of Mexico origin occasionally impact the Atlantic and Gulf coasts.

The temperature regime over North America varies greatly. Over all seasons, mean temperatures generally increase from the extreme north along the Arctic Ocean to the southern United States. Mean annual and wintertime temperatures along the west coast of the continent generally are higher than at equivalent latitudes inland or on the east coast because of the warming influence of Pacific air. During the winter in the far north, the long polar nights produce strong radiative cooling over the frozen Arctic Ocean and the typically snow-covered reaches of Alaska and Canada. This results in very cold surface

temperatures and a temperature inversion that acts to inhibit cloud development, creating a positive feedback on the radiational cooling process. In this way, vast pools of cold, dense air (Arctic high-pressure systems) are formed and move over central and eastern North America; they sometimes move southward as far as the Gulf of Mexico. These extreme cold air outbreaks usually are confined to areas east of the Rocky Mountains; they often can produce temperatures below -40°C in the heart of the continent, with attendant sea-level pressure readings in excess of 1050 mb. To the west of the Rockies, warmer maritime airflow off the Pacific Ocean produces milder winters along the coast; the western cordillera effectively restricts this mild air from reaching and thus modifying temperatures in the interior. The eastern maritime regions of the continent enjoy much less warming influence from the Atlantic Ocean during these cold air outbreaks because the prevailing air flow is off the land (Schneider, 1996). Nevertheless, in winter the east and west coastal regions of Canada and the United States usually are warmer than inland regions, with the Pacific and Gulf coasts and Florida experiencing the shortest and mildest winters (Schneider, 1996).

In summertime, the large amount of insolation received over the very long days in the northern reaches of North America acts to raise temperatures there so that these areas are more in line with much of the rest of the continent, thus decreasing the north-south temperature gradient. The coldest areas are found in the western Canadian mountains and along the Labrador coast (Schneider, 1996). The highest continental temperatures are found in the U.S. desert southwest and southern plains states, where temperatures routinely exceed 38°C (~100°F). Occasionally, extreme summer heat waves spread over much of the central United States and parts of central and eastern Canada. These conditions can persist for days or weeks when occasional blocking high-pressure ridges form; these ridges may extend from the central United States to the western Atlantic. The hot air can be extremely humid because of low-level southerly airflow off warm Gulf of Mexico waters. The combination of heat and humidity produces dangerous health conditions that have resulted in significant numbers of fatalities (e.g., the July 1995 heat wave over the midwestern United States).

Annual precipitation amounts over North America show large spatial variations. The wettest regions lie along the Pacific coast, extending generally from Oregon to southern Alaska—with mean annual totals exceeding 300 cm at several Canadian locations (Environment Canada, 1995). The other main continental maximum in annual precipitation is located in the southeastern United States. It is centered mainly along the central Gulf coast states during winter, spring, and autumn and over Florida in the summer (Higgins *et al.*, 1997). Mean annual precipitation amounts along the central Gulf coast exceed 150 cm.

Another precipitation maximum typically is observed over the midwestern United States (centered roughly over Missouri and Iowa) (Higgins *et al.*, 1997) in the summer months, where

mean rainfall (mainly convective in nature) typically exceeds 25 cm. This feature is associated with convection that often is fueled by a strong low-level southerly jet stream bringing abundant moisture from the Gulf of Mexico. The active convection often begins in the spring and continues through the summer, causing severe local- to regional-scale flooding. The convective activity observed over the Midwest, the Great Plains, and the southeastern United States also is responsible for the fact that this part of the United States experiences more severe weather (in the form of thunderstorms, tornadoes, and hail) than any other part of the world. Although North American annual precipitation is much more climatologically consistent than in many other parts of the world (e.g., northern Africa and eastern Australia), extremely damaging large-scale droughts and floods sometimes occur, often in association with blocking patterns in the large-scale circulation.

8.2.2. Climate Trends

A number of studies have examined long-term (century-scale) records of climate variables over the North American region. Most of this work has pertained to analyses of near-surface air temperature and precipitation. Gridded analyses of annual near-surface North American air temperatures for the period 1901–96 (see Figure A-2 in Annex A) show trends toward increasing temperatures over most of the continent. Temperature increases over land are greatest over an area extending from northwestern Canada, across the southern Canada/northern United States region, to southeastern Canada and the northeastern United States. These increases range mainly from 1–2°C/100 years. Decreases in annual temperature on the order of 1°C/100 years are observed along the Gulf coast and on the order of 0.5°C/100 years off the northeast coast of Canada (Environment Canada, 1995). Sea-surface temperatures appear to have warmed off both the west and east coasts of the continent, especially in the Gulf of Alaska.

The time series of anomalies in mean annual temperature for the entire North American region is depicted in Figure A-10 in Annex A. The record reveals temperatures increasing through the 1920s and 1930s, peaking around 1940, and then gradually decreasing through the early 1970s. From this point through the late 1980s, temperatures increased to levels similar to the 1940 era; they have remained mainly above normal since, with the exception of 1996. The more recent warmth has been accompanied by relatively high amounts of precipitation (see below), unlike the dry and warm 1930s. The value of the overall linear trend for 1901–96 is 0.57°C/100 years, a trend significant at better than the 99% confidence level.

The generally increasing temperatures of recent decades, both around the globe and across North America, have been found to result mainly from increases in daily minimum temperature (T_{min}); increases in daily maximum temperature (T_{max}) have less influence on the observed increase in the daily mean temperature (Karl *et al.*, 1993; Horton, 1995). This trend has caused the diurnal temperature range (DTR) to decrease in

many areas. Over North America, Karl *et al.* (1993) found that T_{min} increased greatly over the western half of the continent from 1951 to 1990—in many locales by as much as 2–3°C/100 years. Increases in T_{max} were smaller, for the most part, with T_{max} actually decreasing somewhat in the desert Southwest. The combined effect of these changes resulted in decreases in DTR of 1–3°C/100 years for much of western North America over the period 1951–90. [Trends are reported in Karl *et al.* (1993) as degrees per century to allow for direct comparison between regions with slightly different periods of record and should not be construed as representing actual trends over the past century.] Environment Canada (1995) also found that, over a longer period of record (1895–1991), maximum and minimum temperatures for Canada have been changing at different rates (Figure 8-4), with the minimum temperatures rising more than twice as much as maximum temperatures for the country as a whole.

Annual precipitation amounts from 1901 to 1995 over North America as a whole show evidence of a gradual increase since the 1920s, reaching their highest levels in the past few decades (see Figure A-10 in Annex A). Figure A-1 (Annex A) indicates that the regions experiencing the largest increases are portions of northwestern Canada (>20%), eastern Canada (>20%), and the Gulf coast of the United States (10–20%). The increases in eastern Canada shown in Figure A-1 are corroborated by Groisman and Easterling (1994) and Environment Canada (1995). The analysis of U.S. Historical Climatology Network data by Karl *et al.* (1996) for 1900–94 reveals the increases along the U.S. Gulf coast and also shows 10–20% increases over the central and northern Plains states, much of the Midwest and Northeast, and over the desert Southwest.
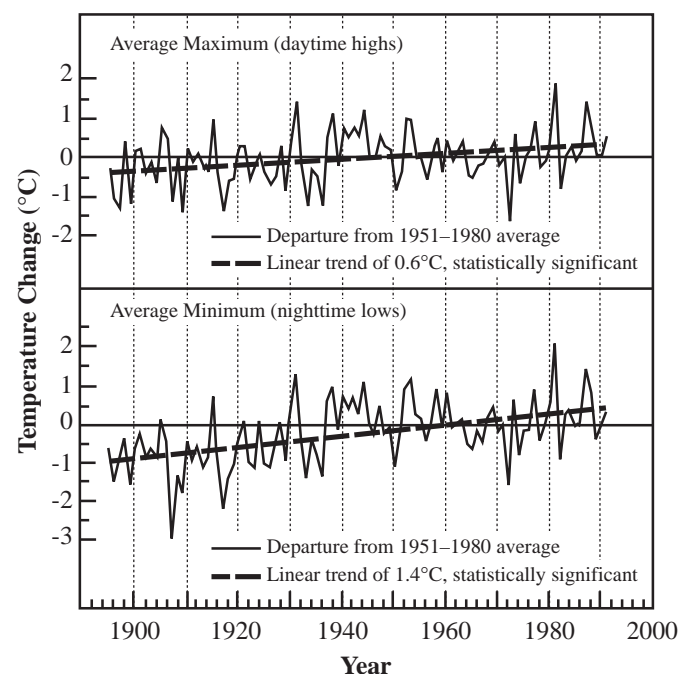
Figure 8-4: Canadian annual average maximum and minimum temperature trends for 1895–1991 (adapted from Environment Canada, 1995).
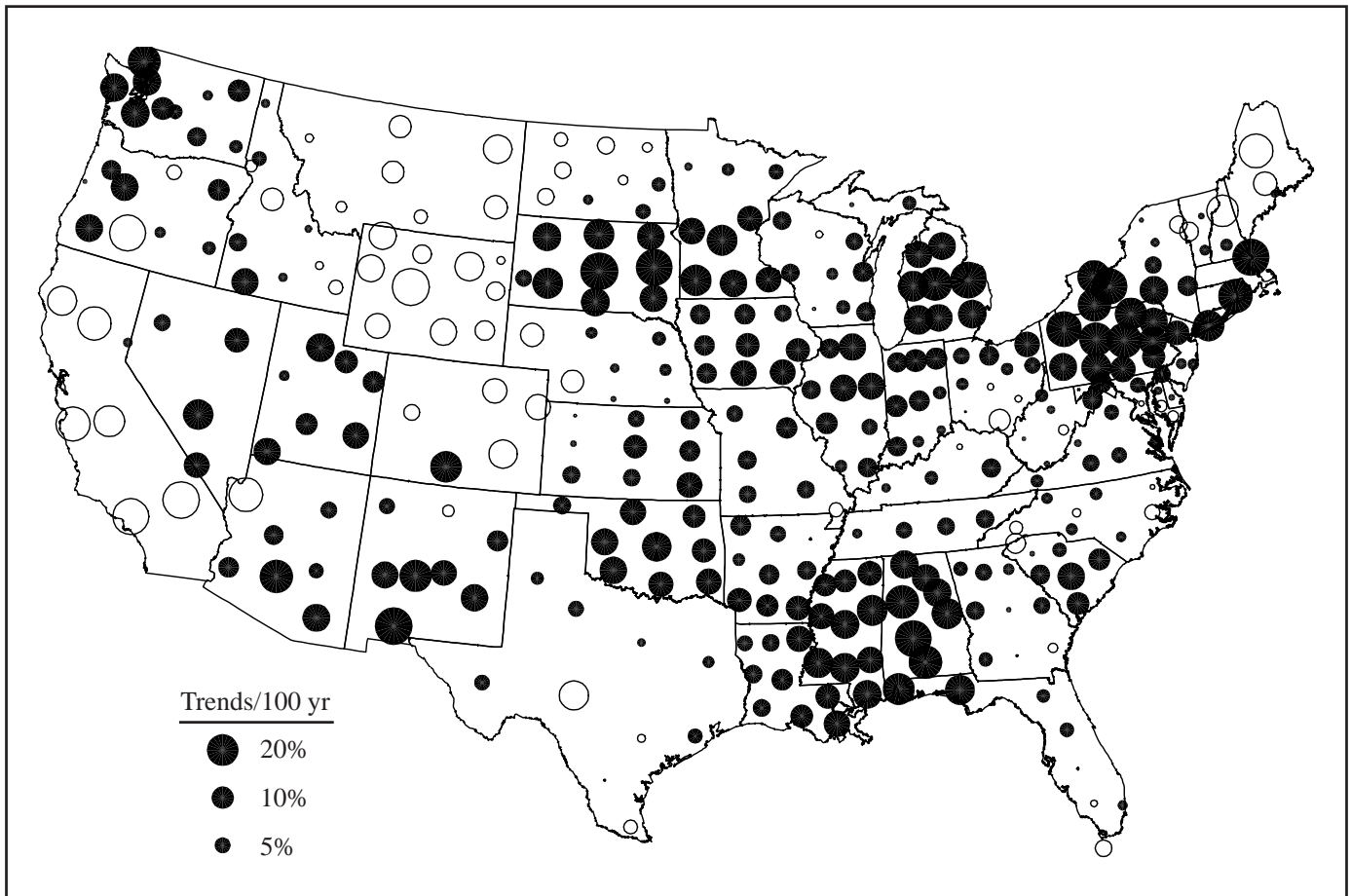
Figure 8-5: Conterminous U.S. precipitation trends for 1900–94 (converted to %/century), centered within state climatic divisions. The trend magnitude for each climatic division is reflected by the diameter of the circle. Solid circles represent increases, and open circles decreases.

Decreases of 10–20% are apparent over California and the northern Rocky Mountain states (Figure 8-5).

As part of an effort to monitor extreme weather events around the globe, some recent studies have examined the intensity of rainfall events. Karl *et al*. (1995) found a trend toward higher frequencies of extreme (>50.8 mm) 1-day rainfalls over the United States. The results pertained to the period 1911–92; the increasing frequency of such events was found to be a product mainly of heavier warm-season rainfall. Karl *et al*. (1996) also found a steady increase from 1910 to 1995 in the percentage area of the contiguous United States with a much above-normal (defined as the upper decile of all daily precipitation amounts) proportion of total annual precipitation coming from these extreme 1-day events (Figure 8-6). This area increased by 2–3%, and it was determined that there is less than 1 chance in 1000 that this change could occur in a quasi-stationary climate. To date, however, there is no similar evidence of an increase in the proportion of Canadian precipitation from extreme 1-day events (Hogg and Swail, 1997).

Although sea-level rise usually is not considered a climatic variable, it is arguably one of the most important potential impacts of global climate change in terms of environmental

and social consequences (IPCC 1996, WG I, Section 7.1). Therefore, a brief summary of sea-level trends is appropriate. Global mean sea level is estimated to have risen 10–25 cm over the past 100 years (IPCC 1996, WG I, Section 7.2). These
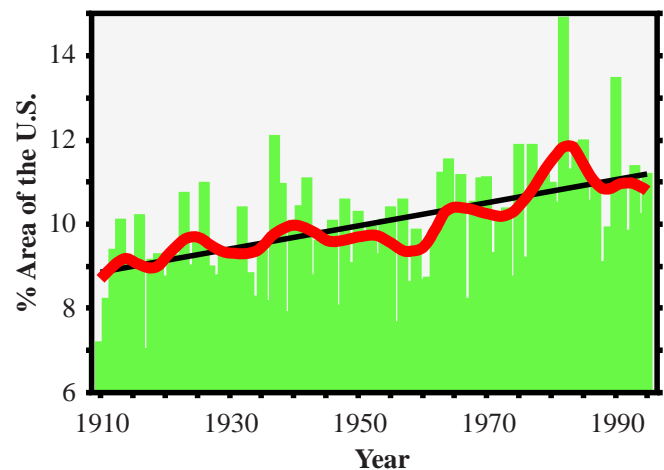
Figure 8-6: Percentage of the conterminous U.S. area with a much above normal proportion of total annual precipitation from 1-day extreme (more than 2 in. or 50.8 mm) events (Karl *et al.*, 1996).

estimates are based on tide gauge records; the increase is thought to result largely from the concurrent increase observed in global temperatures, which causes thermal expansion of the ocean and contributes to the melting of glaciers, ice caps, and ice sheets. In general, there is broad agreement that both thermal expansion and glaciers have contributed to the observed sea-level rise, but there are very large uncertainties regarding the role of the ice sheets and other hydrological factors (IPCC 1996, WG I, Section 7.4). There are differences in century-scale sea-level trends across regions of the globe because of vertical land movements such as "postglacial rebound." Figure 8-7 depicts sea-level trends for several North American sites. Sea level has risen 2.5–3.0 mm/year along parts of the U.S. Gulf coast and along the Atlantic coast south of Maine. Along the Texas-Louisiana coasts, sea level has been increasing about 10 mm/year as a result of rapid land subsidence in this region. Sea level is stable or dropping along much of the Canadian and Alaskan coasts because of postglacial rebound.

8.2.3.   *Climate Scenarios*

As discussed in IPCC (1996, WG I, Section 6.6), output from transient runs of atmosphere-ocean general circulation models (hereafter referred to simply as GCMs) has become available that can be used as the basis for improved regional analysis of potential climate change. The main emphasis of current analyses is on the simulation of seasonally averaged surface air temperature and precipitation. Climate scenario information for North America is available from several GCMs. In IPCC (1990, WG I), one of the five regions identified for analysis of regional climate change simulation was central North America
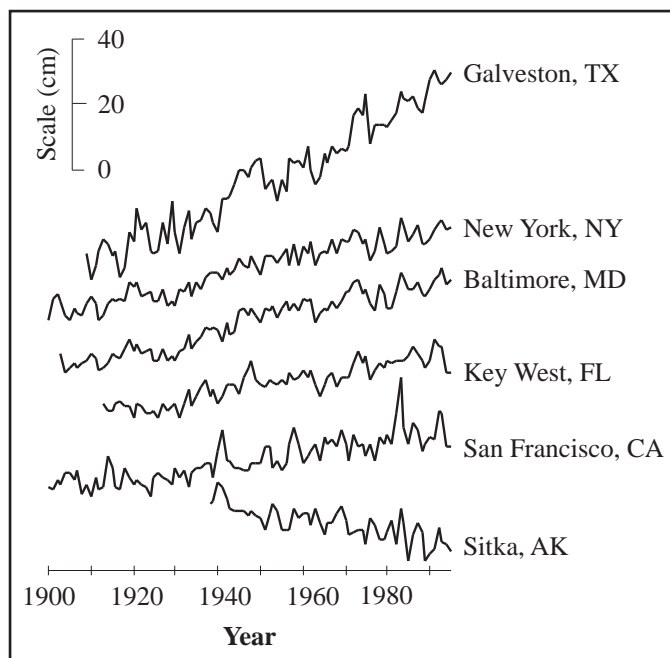
Figure 8-7: Relative sea-level trends for selected North American sites (adapted from Titus, 1997).

(35–50°N, 85–105°W). Output for this region from different coupled model runs with dynamic oceans was analyzed by Cubasch *et al.* (1994) and Kittel *et al.* (1998). Results for central North America, as well as the other identified regions, are depicted in Figure B-1 (Annex B), which shows differences between region-average values at the time of CO_2 doubling and the control run, as well as differences between control run averages and observations (hereafter referred to as bias) for winter and summer surface air temperature and precipitation. These model results reflect increasing CO_2 only and do not include the effects of sulfate aerosols. The biases in Figure B-1 (Annex B) are presented as a reference for interpretation of the scenarios because it can be generally expected that the better the match between control run and observed climate (i.e., the lower the biases), the higher the confidence in the simulated change scenarios. A summary of these transient model experiments is given in Table B-1 (Annex B). Most experiments use a rate of CO_2 increase of 1%/year, yielding a doubling of CO_2 after 70 years.

Scenarios produced for central North America by these transient experiments vary quite widely among models for temperature but less so for precipitation. GCM simulations also have been conducted that consider the effect of combined greenhouse gas- and direct sulfate aerosol-forcing on temperature, precipitation, and soil moisture (see Annex B). For central North America, the inclusion of sulfate aerosols results in a projected warming of 0–0.5°C in the summer and 1.4–3.4°C in the winter by the year 2100. In the case of precipitation, the inclusion of sulfate aerosol-forcing has little effect on the projections (see Annex B).

Using the Canadian Climate Centre (CCC) GCM (see Annex B), Lambert (1995) found a 4% decrease in cyclones in the Northern Hemisphere, though the frequency of intense cyclones increased. Lambert hypothesized that the latent heat effect is responsible for the greater number of intense storms. No change in storm tracks was evident. A few areas showed increased frequencies, such as off Cape Hatteras, over Hudson Bay, and west of Alaska. These results are similar to those of Rowntree (1993), who found a 40% increase in Atlantic gales, though fewer intense storms over eastern North America. Hall *et al.* (1994) and Carnell *et al.* (1996) found an intensification and northward shift of storm tracks.

Regarding sea-level rise scenarios, for IPCC Scenario IS92a, global mean sea level is projected to be about 50 cm higher by 2100 than today, with a range of uncertainty of 20–86 cm (IPCC 1996, WG I, Section 7.5). It is possible that for much of the North American coastline, future sea-level rise will be greater than the global average, given the higher historical rates of sea-level rise along the Gulf of Mexico and Atlantic coasts (see Section 8.2.2). By contrast, future sea-level rise along the Pacific coast may be less than the global average rise because of this region's generally lower historical rates. Even less sea-level rise might be expected in extreme northern North America, given the historical drop in sea levels at many locations (Titus and Narayanan, 1996).

8.3. Impacts and Adaptation

8.3.1. Ecosystems: Nonforest Terrestrial

8.3.1.1. Distribution and Sensitivities

Nonforest terrestrial ecosystems are the single largest type of land surface cover (>51%) in North America. They are extremely diverse and include nontidal wetlands (bogs, fens, swamps, and marshes), ecosystems of the polar domain (tundra and taiga), traditional rangeland ecosystems (grasslands, deserts, and savannas), and improved pastures. These ecosystems are major components of every region of North America; they constitute about 80% of the land cover of western North America and nearly 100% of the land cover above the 75th parallel. They provide forage for 80 million cattle, sheep, and goats and 25 million deer, elk, antelope, caribou, and buffalo, as well as most of the breeding and feeding grounds for waterfowl in North America (Child and Frasier, 1992; WRI, 1996). Nonforest ecosystems are the source of most surface flow and aquifer recharge in the western Great Plains and the extreme northern regions of North America. Municipal, agricultural, and industrial sectors in these regions depend on nonforest ecosystems for the quantity and quality of water required for economic sustainability. The quality and quantity of water derived from nonforest ecosystems depend on the management these lands receive and the average annual and extreme climatic events they encounter.

Nontidal wetlands in North America include a variety of ecosystems such as bogs, fens, swamps, marshes, and floodplains. Classification systems are many and varied. These wetlands are distributed throughout North America, principally in a band extending from the New England states to Alaska. There are additional significant areas in the Mississippi Valley, the "Prairie Pothole" region, the many coastal wetlands (e.g., the Mississippi River delta, the Everglades, and the Okefenokee), the Atlantic coastal marshes and Fraser River estuary, the former Great Kankakee and Great Blackwater swamps, the Hudson Bay Lowlands, the Peace-Athabasca-Slave delta, the Mackenzie delta, and the Queen Maud Gulf on the Arctic Ocean (Mitsch and Gosselink, 1986; Ecological Stratification Working Group, 1995; IPCC 1996, WG II, Chapter 6). See Section 8.3.3 for a more detailed discussion of wetlands impacts.

Rangelands are characterized by native and introduced vegetation—predominantly grasses, grasslike plants, forbs, shrubs, and scattered trees. These lands are extremely varied: They include the tallgrass, mixed, and shortgrass prairie regions of central North America; tundra and taiga areas in the polar domain; annual grasslands of California; chaparral regions of Arizona and California; sagebrush shrub steppe and pinyon-juniper woodlands in the intermountain region of western North America; and the Chihuahuan, Sonoran, and Mojave deserts in the southwestern portion of North America. The associated ecosystems are complex and are affected by many interacting biotic and abiotic components, and their health depends on the interaction of climate, soils, species competition, fire, grazing,

and management. These ecosystems provide a wide array of goods and services, including forage, water, and habitat for wildlife and domesticated livestock and open space for recreational activities, and they are the source of many of the raw materials needed to sustain our industrial society (i.e., pharmaceuticals, precious metals, minerals, construction materials, natural gas, oil, and coal) (Heady and Child, 1994).

Although some rangelands are fragile and easily disturbed by anthropogenic activity (Belnap, 1995), others are resistant to change. Semi-arid and arid ecosystems are considered among the most sensitive because these ecosystems often are water-limited and have marginal nutrient reserves (OIES, 1991; IPCC 1996, WG II, Chapter 2).

Current levels of uncertainties associated with the functioning and adaptive capacity of nonforest ecosystems under variable and changing climate and the possibility of critical thresholds limit our ability to identify the relative sensitivities of these ecosystems (and the potential impacts of changing climates). It is understood, however, that these ecosystems are sensitive to climate variability and that the impacts can vary depending on the resilience and resistance of the ecosystem to the stresses applied (e.g., changes in precipitation, CO_2, temperature, fire, land use, and land cover and management). Researchers also believe that the impacts of CO_2 enrichment and shifts in temperature and precipitation regimes are likely to be greatest when they are reinforced by other destabilizing forces. Lack of information about how these other factors interact with climate change also limits our understanding of ecosystem response. Also of concern are the relative sensitivities of species at the ecotones between vegetation types, such as between grasslands and woodlands and between woodlands and forests (Polley, 1997).

8.3.1.2. Impacts, Vulnerabilities, and Adaptation

The projected northward shift of the southern boundary of permafrost areas will alter ecosystem structure and functioning, with subsequent impacts on associated infrastructure and wildlife through terrain slumping, increased sediment loadings in rivers and lakes, and dramatically altered hydrology.

Approximately half of the wetland areas of North America are located in Alaska, the Northwest Territories, and the Yukon (Table 8-1). Most of these wetlands rest on continuous or discontinuous permafrost, the distribution of which would be altered by climate warming.

The northward shift of the southern boundary of discontinuous and continuous permafrost areas is projected to be about 500 km by the middle of the 21st century (Anisimov and Nelson, 1996; IPCC 1996, WG II, Chapter 7; Prowse, 1997). This shift would have profound effects within the altered areas (as summarized by Prowse, 1997). The melting of widespread ground ice will result in downslope soil movement, bank failure, and massive terrain slumping, leading to increases in sediment loads to rivers and lakes. This process will in turn affect spawning

areas, oxygen levels, and stream/wetland sediment budgets. A deeper active layer will reduce overland flow as infiltration and active layer storage capacity increase. Peatlands are projected to disappear from south of 60°N in the Mackenzie Basin (Cohen, 1997a); patchy arctic wetlands currently supported by surface flow would not persist. Lakes and ponds, which have permafrost hydrological divides, are more likely to drain laterally or to groundwater systems.

Landscape alteration on this scale has serious implications for hydrology, wildlife, cultural values, and lifestyles. The effects will likely extend to infrastructure and transportation—including the integrity of foundations (pipelines, bridges, and buildings), water-control structures, ice-roads, and tailings. Altered flooding patterns and sediment loadings will impact internationally significant wetland habitat such as the Peace-Athabasca-Slave delta, the Mackenzie delta, and habitats associated with Hudson Bay and Queen Maud Gulf lowlands.

Many northern peatlands could become sources rather than sinks for atmospheric carbon.

A primary impact of future climate change in nonforest terrestrial ecosystems is the projected reduction of subarctic (tundra/taiga) ecosystems (IPCC 1996, WG II, Chapter 2). Neilson *et al.* (see Annex C) estimate that tundra and taiga ecosystems may be reduced by as much as one- to two-thirds of their present size. This reduction will have an impact on regional storage of carbon in the higher latitudes of North America and may result in a shift from a net sink to a net source of CO_2 for the tundra region (Anderson, 1991; Oechel *et al.*, 1993). Climate warming also may cause reduction in total species biodiversity and total surface area covered by tundra vegetation, as well as decreased releases of methane from tundra plant communities as a result of alterations in the hydrological cycle, drier surface soils, and an increase in surface oxidation (IPCC 1996, WG II, Chapter 2).

Loss of migratory wildfowl and mammal breeding and forage habitats will occur within the southern Arctic ecozone, which is projected to nearly disappear from mainland areas.

The Queen Maud Gulf lowlands contain one of the largest sites (over 6 million ha) designated under the Ramsar Convention on

Table 8-1: Estimated wetland area in North America.

	Area (Mha)	Reference
Alaska	90.0	OTA, 1984
Yukon and NWT	29.3	Environment Canada, 1986
Subtotal	119.3	
U.S. Lower 48	40.1	Frayer *et al.*, 1983
Rest of Canada	97.9	Environment Canada, 1986
Subtotal	138.0	

Wetlands of International Importance. They are part of the southern Arctic ecozone, a transitional area between the taiga forest to the south and the treeless arctic tundra to the north. The ecozone includes the major summer range and calving grounds for Canada's largest caribou herds, as well as habitat for bear, wolf, moose, arctic ground squirrels, and lemmings. It is a major breeding and nesting ground for a variety of migratory birds, including yellow-billed, arctic, and red-throated loon; whistling swan; snow goose; oldsquaw; gyrfalcon; ptarmigan; and snowy owl (Ecological Stratification Working Group, 1995). It also is home to Canada's Inuit, whose subsistence lifestyle includes a diet dependent on this wildlife diversity. According to the U.S. Department of Agriculture (USDA) Forest Service MAPSS biome model using a variety of GCM simulations, this ecozone will nearly disappear from mainland North America under a climate brought about with CO_2 doubling (Neilson, 1993a,b,, 1995; Neilson and Marks, 1994; see also Annex C in this report).

Elevated CO_2 concentrations may have a negative influence on forage quality and species diversity within North American rangeland ecosystems.

Based on studies of plants grown in CO_2-enriched environments (Owensby *et al.*, 1993; IPCC 1996, WG II, Chapter 2), it has been suggested that forage quality in rangeland ecosystems may decrease with increasing CO_2 levels as a result of associated increases in carbon-to-nitrogen ratios and in concentrations of unpalatable and toxic substances, as well as decreases in mineral concentrations in the forage. There is evidence from field studies that low soil nitrogen—a common constraint on rangelands (McNaughton *et al.*, 1988; Seastedt *et al.*, 1991)—can limit plant growth responses to elevated CO_2 (Owensby *et al.*, 1994; Schäppi and Körner, 1996). Several studies have suggested that litter produced at increased levels of CO_2 will be nitrogen poor or that increased CO_2 concentrations slow nitrogen mineralization and reduce nitrogen availability to plants (Díaz *et al.*, 1993; Morgan *et al.*, 1994; Gorissen *et al.*, 1995). This decreased decomposition, mineralization, and uptake of nitrogen could initiate a negative feedback on nitrogen availability that reduces plant growth and forage production.

Without dietary supplementation, the growth and reproduction of individual animals could decrease as CO_2 concentrations rise (Owensby *et al.*, 1996). Rates of nitrogen input, litter quality, and frequency of events (like fire) that promote substantial nitrogen loss all mediate how quickly nitrogen accumulation and cycling approach the maximum at any given CO_2 concentration (Aber *et al.*, 1991). Potential production and forage quality on many rangelands therefore may be constrained by management practices that promote nitrogen loss or preclude nitrogen accumulation by limiting species change (Polley, 1997).

The existing data on the effect that rising CO_2 concentrations will have on the nitrogen cycle are ambiguous. Rising CO_2 may increase nitrogen input to rangelands directly or indirectly by promoting nitrogen fixation. Some of the most successful woody invaders in grasslands are legumes (e.g., species of the

Acaia and *Prosopis* genera). Symbiotic fixation of nitrogen in these species can be significantly stimulated (+400%) by elevated CO_2 concentrations (Polley *et al*., 1994; Polley *et al*., 1997). By adding fixed nitrogen to rangelands in litterfall or root turnover, these woody invaders could potentially increase productivity if the nitrogen gains are not offset by losses or conversion of nitrogen to recalcitrant forms (Polley, 1997). Kemp *et al*. (1994) reported that the ambient CO_2 concentration at which plants were grown had little effect on the decomposition of standing dead material of three tallgrass prairie species. O'Neill and Norby (1996) concluded that decomposability of naturally abscissed leaf litter was not greatly affected by the CO_2 concentration at which the litter was produced.

On grasslands where the effects of increased WUE are not negated by an increase in leaf temperature and leaf area, rising CO_2 concentration should slow the depletion of soil water by grasses and potentially favor shrubs/woody plants that otherwise might succumb to water stress (Polley *et al*., 1997). There is evidence that rising CO_2 also could contribute to species change by altering seedling survival rates during drought. Polley *et al*. (1996) found that more than twice as many honey mesquite tree seedlings survived soil-water depletion at elevated CO_2 levels than at ambient CO_2 levels. In the absence of fire or browsing, woody plants likewise would be expected to increase in size and abundance by exploiting the greater availability of soil water (Polley, 1997). Grass production and transpiration often decline following woody plant invasion (Vallentyne, 1971; Scifres, 1980; Knoop and Walker, 1985; Sala *et al*., 1989).

By increasing the growth rates of woody seedlings or improving their ability to survive drought, rising CO_2 could act as a positive feedback to overgrazing in promoting woody plant invasion (Polley *et al*., 1997). An increase in woody plants may result in decreased forage availability in mid-latitude grassland ecosystems and increased soil erosion, leading to a nearly irreversible loss of productive potential of the soil (Parton *et al*., 1993).

Since the turn of the century, mesic and arid grasslands in North America have had increases in C_3 woody plants (Branson, 1985; IPCC 1996, WG II, Chapter 2). This change often has been accompanied by changes in runoff, accelerated soil erosion, and loss of the grazing resource (Rauzi and Fly, 1968; Spaeth *et al*., 1996). Increases in CO_2 and changes in regional climate could exacerbate the existing problem of loss of production on western rangelands by accelerating the invasion of woody plants. Mayeux *et al*. (1991) discuss evidence that C_4 grasslands are being increasingly invaded by C_3 woody plants—a process that may have been abetted by the rise in CO_2 and changes in WUE over the past two centuries. However, conclusive evidence for this effect is not available (IPCC 1996, WG II, Chapter 2).

Consistent with trends from individual plants, many natural ecosystems (including grasslands) show little or no increase in standing crop or production at elevated CO_2 when temperatures are low or nutrients are limiting (Oechel *et al*., 1993;

Fredeen *et al*., 1995; Schäppi and Körner, 1996). In the Arctic tundra there is little expected change in plant growth from increased CO_2, although there is an expected decrease in insect-pollinated forbs (IPCC 1996, WG II, Chapter 2). However, elevated CO_2 has been shown to increase aboveground net primary productivity in tallgrass prairies, shortgrass steppe, and coastal salt marshes (Curtis *et al*., 1989; Owensby *et al*., 1993; Hunt *et al*., 1996) and root biomass in grasslands (Owensby *et al*., 1993; Jongen *et al*., 1995; Newton *et al*., 1995) when essential elements like nitrogen are plentiful or water begins to limit growth and the positive effects of CO_2 on water relations are expressed.

Changes in species composition emerge as a major unknown with the potential to affect ecosystem processes (productivity, forage quality, and nitrogen cycling) in ways that are not evident from studies that consider the direct effects of elevated CO_2 concentration alone. Given that the geographic distribution of rangeland vegetation and aboveground net primary productivity are highly correlated with precipitation, temperature, nutrient status, and soil-water availability on rangelands (Sala *et al*., 1988; Stephenson, 1990; Bailey, 1996; IPCC 1996, WG II, Chapter 2; Myneni *et al*., 1997; Polley *et al*., 1997), interactions among global warming, changes in precipitation, grazing, fire, rising CO_2 concentration, and species competition must be more clearly understood before we will be able to predict with confidence changes in forage quantity for North American rangelands.

On improved pastures, the alteration of species composition through reseeding with adapted grass species or the introduction of legumes to grass-dominated pastures is the most likely method to reduce the impacts of climate change. This approach would have the additional benefit of improving forage value for livestock while possibly reducing the average methane emission per head of livestock because of improved forage quality (IPCC 1996, WG II, Chapter 2). For native rangelands, active interventions to reduce impacts from increases in temperature or CO_2 or changes in precipitation frequency and amount are limited because of the large areal extent of rangelands and the low economic return per acre of land. Introduction of nonnative adapted species may be able to compensate for the loss of some forage production and watershed protection if native species decrease. However, the application and extent of this technology on federal lands may be limited by existing rules, regulation, and pending and future court cases.

Climate-induced variability and extreme events will increase the complexity of managing rangelands.

Rangeland vegetation is found where precipitation, temperature, and soil development provide suitable habitat for grasses, forbs, shrubs, and open stands of trees. Generally, these lands are characterized by extremes in temperature or in the timing, intensity, and amount of precipitation the site receives; these extremes drive rangeland ecosystems (Griffin and Friedel, 1985; Westoby *et al*., 1989). Precipitation is the major determinant of the structure, function, and sustainability of natural

ecosystems (Branson *et al.*, 1981). Current human activity on rangelands significantly alters plant species abundance and distribution and the hydrological cycle, accelerates erosion rates, and can overwhelm any change in regional or global climate (Thurow *et al.*, 1986; Weltz and Wood, 1986; IPCC 1996, WG II, Chapter 2; Williams and Balling, 1996). Small changes in the frequency or extent of extreme events may have a disproportionate effect on what management must cope with to sustain rangeland ecosystems (IPCC 1996, WG II, Chapter 2). Short-term variations in local or regional precipitation—upon which management planning often is based—are greater than the predicted change in the mean value of precipitation for North America (Shuttleworth, 1996). With the addition of climate change to existing stresses on rangelands, they may become more sensitive to extreme events such as drought, 100-year floods, and insect outbreaks that could reduce their long-term sustainability and escalate the desertification process in arid and semi-arid lands in North America (IPCC 1996, WG II, Chapters 2 and 4).

The most promising adaptive approach is to provide incentives to use management techniques that reduce the risk of these lands becoming degraded during extreme climatic events (i.e., droughts). The most cost-effective strategy is to improve lands already under stress and to strengthen their resistance to future extreme events. This approach could include changes in livestock type and number, changes in season of use, complete rest, or the development of additional infrastructure (new watering locations, fencing, etc.) to achieve proper stocking density.

A second promising avenue of adaptation is to provide arid and semi-arid land managers with more accurate predictions of regional precipitation on a seasonal to interannual basis. This information is particularly important prior to droughts or extremely wet years. Provision of these types of predictions is becoming more likely because recent research indicates that improvements in coupled ocean-atmosphere models make it possible to predict climatic conditions related to the El Niño-Southern Oscillation (ENSO) phenomenon more than a year before the event (Chen *et al.*, 1995). Predicted precipitation patterns can be used as inputs to ecological and hydrological models and thereby could provide the capability to assess the impacts of changing rainfall on flood frequency, surface hydrology, soil erosion, and forage and crop production and allow managers to develop mitigation plans to reduce degradation to rangeland ecosystems by altering grazing systems and purchasing supplemental feed before the onset of droughts.

Arid lands may increase.

Lane *et al.* (1994) reported that trend analyses for the period 1901–87 suggest that mean annual temperatures increased globally at the rate of 0.5°C per century, in the United States at 0.3°C per century, and in the southwestern desert region at about 1.2°C per century. Early climate change predictions suggested that a temperature increase of up to 17% in desert lands could occur in North America (Emanuel *et al.*, 1985). VEMAP Members (1995) considered climate change and doubled CO_2 from computer simulations of three different biogeographic models (see Annex C) and three different climate scenarios; a general result was that grasslands would contract and move eastward into the broadleaf forest and that shrublands would decrease within the United States. Potentially large increases (185%) in subtropical arid shrublands could occur in the southwest region of North America. Depending on the model and climate scenario, however, there could be a potential decrease (-56%) in subtropical arid shrublands (VEMAP Members, 1995). The most recent projections from the MAPSS model (Annex C) indicate up to a 200% increase in leaf area index in the desert southwest region of North America and a northern migration and expansion of arid-land species into the Great Basin region of North America. Various combinations of vegetation redistribution and altered biogeochemical cycles could result in novel plant communities and increases in arid regions.

Desertification is a function of human activities and adverse climate conditions. Recovery of desert soils from disturbance and desertification is a slow process. More than 50 years may be required to reestablish the nitrogen fixation capability of the soil, and 200 years may be required to completely reestablish the vegetation community in the arid southern region of North America (Belnap, 1995). During the recovery period, the site is at increased risk of wind and water erosion (Belnap, 1995; IPCC 1996, WG II, Chapter 4). Although long-term measures may need to be developed to cope with climate change, research that deals with annual and interannual fluctuations in precipitation must continue to receive attention because precipitation fluctuations directly affect North American strategic food and fiber supplies (grain production and forage for wildlife and livestock) (Oram, 1989).

Box 8-1. Examples of Effects on Birds

The distribution of birds in Canada shows strong correlation with habitat distribution, which in turn is influenced by climate as well as human land-use practices. Thus, changes in climate are expected to have significant effects on breeding and winter distributions. A combination of temperature and moisture considerations is the best predictor of the beginning of the nesting period, defining a "climate space" that can be extended to describe the limits of the breeding range (James and Shugart, 1974). In winter, the northern boundaries of many species coincide with January isotherms, reflecting daily energy requirements. For marine birds, shifts in the distribution of water masses of different temperature and salinity characteristics—supporting different species of prey—are expected to generate the most obvious responses to changing climates (Brown, 1991). For arctic nesting birds, such as geese and many shore birds, the timing of snowmelt is a critical variable that drives the success of nesting, as well as its timing (Boyd, 1987).

Box 8-2. Examples of Effects on Wildlife

Changes in the amount, type, and timing of winter precipitation will have considerable consequences for large ungulates (e.g., moose, caribou, elk, deer, and bison), as well as their most important predators (wolves and coyotes). Current distributions of ungulate communities correspond well with their adaptations to the type and depth of snow in the regions in which they occur. Shifts in winter climate could, based on past experience, lead to shifting suitability of ranges for these species. Predator-prey relations also could shift with changing distributions of snow types and amounts; wolves flounder in deep snow that caribou can cross, but moose are no better suited to travel through soft snow.

Landslides in mountain areas could be more frequent.

Catastrophic geomorphic processes in mountain terrain are heavily influenced by climate (e.g., precipitation). As a result, the occurrence of these processes—which include landslides and outburst floods—is sensitive to climate change. The frequency of debris flows and other landslide types can be expected to increase under conditions of increased precipitation, debuttressing of mountain slopes due to glacier ice losses, and the decay of mountain permafrost during recent and projected warming. As in the past, these events should be expected to impact on settlements, infrastructural elements, resources, and the environment, resulting in human and financial losses. Water quality would be affected by increased sediment loads. Fish and wildlife habitat, as well as roads and other structures, could be at increased risk. The nature of the landslide response is complicated by factors such as forest harvesting and other land-use changes (Eybergen and Imeson, 1989; IPCC 1996, WG II, Chapter 5; Evans and Clague, 1997).

8.3.2. Ecosystems: Forested

The forests of North America north of Mexico occupy about 732 million hectares, representing about 17% of all global forested lands. Approximately 60% of the North American forests are Canadian (Brooks, 1993). The United States has about 13% of the world's temperate forests and almost half of the world's coastal temperate rainforest (Brooks, 1993). Nearly half of U.S. forests are privately owned, compared to only about 6% in Canada (Brooks, 1993).

Conifers constitute nearly 70% of the world's commercial timber harvest. In North America, conifer species dominate the boreal forests of Canada, Alaska, and the Pacific Northwest and share dominance with hardwoods in the southeastern and northeastern United States. Wood-based manufacturing accounts for about 2% (US$129 billion) of the U.S. gross domestic product (GDP) and about 3% (CAN$23 billion) of the Canadian GDP (Canadian Forest Service, 1996;

International Monetary Fund, 1996; U.S. Department of Commerce, 1996).

Forests provide habitats for wildlife and fish, store and regulate freshwater supplies, are the repository of substantial plant and animal genetic resources, and satisfy aesthetic and spiritual values. Recreation activity associated with forests contributes to income and employment in every forested region of North America. Nontimber commodities gathered in forests are sources of income and recreation.

Forests hold about 62–78% of the world's terrestrial biospheric carbon (Perruchoud and Fischlin, 1995), about 14–17% of which is in the forests of North America; about 86% of that is in the boreal forest (Apps *et al.*, 1993; Heath *et al.*, 1993; Sampson *et al.*, 1993).

Forests play a large role in global water and energy feedbacks (Bonan *et al.*, 1995) and account for most of the world's terrestrial evapotranspiration, which is about 64% of the precipitation (Peixoto and Oort, 1992; Neilson and Marks, 1994). Most of the world's freshwater resources originate in forested regions, where water quality is directly related to forest health.

8.3.2.1. Distribution and Sensitivities

Three broad forest types are recognized in this assessment of North American forests: boreal, temperate evergreen, and temperate mixed forests. The boreal forest (Annex C, Figure C-1) is constrained by cold temperatures to the north that limit tree height and reproduction (Lenihan and Neilson, 1993; Starfield and Chapin, 1996). The southern limits of the boreal forest generally are defined by their juxtaposition with temperate forests or with interior savanna-woodlands and grasslands. Boreal tree species generally are not limited from growing further south. Rather, temperate hardwoods and conifers are limited by cold temperatures from spreading further north; where temperate species can flourish, they outcompete boreal species. Fire and herbivore browsing also are important constraints on forest distribution and species composition (Bergeron and Dansereau, 1993; Landhauser and Wein, 1993; Suffling, 1995; Starfield and Chapin, 1996). Wildfire and insect outbreaks limit forest productivity and can produce considerable mortality: Annual tree mortality losses from insect outbreaks in Canada are about 1.5 times the losses from wildfire and amount to about one-third of the annual harvest volume (Fleming and Volney, 1995). Annual losses from insects and fire in the United States also are about one-third of the annual harvest (Powell *et al.*, 1993). Warming-induced changes in the timing of spring frosts may be important in ending or prolonging outbreaks. Increased drought stress also may enhance insect outbreaks, and changes in climate could extend the ranges of some insects and diseases.

Temperate evergreen forests (Annex C), such as in the Pacific Northwest, tend to occur in areas that are warm enough for photosynthesis during the cool parts of the year but often are

too cold for deciduous species to fix sufficient carbon during the frost-free season (Woodward, 1987). Areas with dry summers also tend to favor conifers or hardwoods with water-conserving leaves (Waring and Schlesinger, 1985; Neilson, 1995). Summer drought and winter chilling for frost hardiness are critical climate factors, rendering these forests sensitive to global warming (Franklin *et al*., 1991). Northwest conifers are long lived and need only successfully reproduce once during their life span for population sustainability (Stage and Ferguson, 1982; Parker, 1986; Savage *et al*., 1996). With global warming, however, establishment periods could become rare in some areas; after harvest, some forests may not be able to regenerate, even if mature trees could still survive the climate. Winter chilling may be required for adequate seed set or to confer frost-hardiness in some species (Burton and Cumming, 1995); because of the well-recognized spatial variation in the genetics of these species, however, such chilling requirements may not hold everywhere. Fire suppression in interior pine forests has left them in a sensitive condition with respect to drought, fire, and pests (Agee, 1990; Sedjo, 1991). Climate change could exacerbate all of these stressors (Williams and Liebhold, 1995). For example, increased drought stress could facilitate insect outbreaks; drought and infestation could lead to more fuel, increasing the risk of catastrophic fire.

Temperate mixed forests (mixed hardwood and conifer) are bound by cold temperatures to the north and subtropical dry regions to the south (the Caribbean coast in North America) and tend to occur in areas that are wet in both winter and summer. Temperate hardwood species also benefit from cold-hardening; with warmer winter conditions and less insulating snow cover, they can be sensitive to spring frost damage, which can kill roots and further sensitize the species to drought stress and widespread mortality (Auclair *et al*., 1996; Kramer *et al*., 1996). Southeastern U.S. pines within this type are among the most important commercial species on the continent. Natural southeastern pine stands historically relied on fire to maintain their composition (Komarek, 1974; Sedjo, 1991) but now are largely controlled by harvest. Compared to northwestern forests, southeastern conifers have a short rotation, which might confer more rapid adaptive capability through establishment of new genotypes.

Elevated CO_2 affects the physiology of trees, possibly increasing productivity, nitrogen-use efficiency and WUE (reduced transpiration per carbon fixed, conferring some drought resistance), and other responses (Bazzaz *et al*., 1996; IPCC 1996, WG II, Section A.2.3). A review of 58 studies indicated an average 32% increase in plant dry mass under a doubling of CO_2 concentration (Wullschleger *et al*., 1995). Norby (1996) documented an average 29% increase in annual growth per unit leaf area in seven broadleaf tree species under $2xCO_2$ scenarios over a wide range of conditions. WUE, examined in another review and indexed by reductions of leaf conductance to water vapor, increased about 30–40% (Eamus, 1991). If such responses were maintained in forests over many decades, they would imply a substantial potential for increased storage of atmospheric carbon, as well as conferring some increased

tolerance to drought. However, some species or ecosystems exhibit acclimation to elevated CO_2 by downregulating photosynthesis (Bazzaz, 1990; Grulke *et al*., 1990; Grulke *et al*., 1993); others do not exhibit acclimation (Bazzaz, 1990; Teskey, 1997). Understanding the sources of large uncertainties in the linkages between forest physiology and site water balance is a research need; no two models simulate these complex processes in the same way.

Most of the early CO_2 research was done on juvenile trees in pots and growth chambers, which may limit the usefulness of some conclusions. New research is beginning to emerge that focuses on larger trees or intact forested ecosystems. Recent reviews of this newer literature (Curtis, 1996; Eamus, 1996a) indicate that acclimation may not be as prevalent when roots are unconstrained; that leaf conductance may not be reduced; and that both responses depend on the experimental conditions, the length of exposure, and the degree of nutrient or water stress. These results imply that forests could produce more leaf area under elevated CO_2 but may not gain a benefit from increased WUE. In fact, with increased leaf area, transpiration should increase on a per-tree basis, and the stand would use more water (Eamus, 1996a). Elevated temperatures would increase transpiration even further, perhaps drying the soil and inducing a drought effect on the ecosystem (Eamus, 1996a).

Nitrogen supply is prominent among the environmental influences that are thought to moderate long-term responses to elevated CO_2 (Kirschbaum *et al*., 1994; McGuire *et al*., 1995; Eamus, 1996b). Unless CO_2 stimulates an increase in nitrogen mineralization (Curtis *et al*., 1995; VEMAP Members, 1995), productivity gains in high CO_2 are likely to be constrained by the system's nitrogen budget (Körner, 1995). Increased leaf area production is a common CO_2 response; however, nitrogen limitations may confine carbon gains to structural tissue rather than leaves (Curtis *et al*., 1995). Thus, in areas receiving large amounts of nitrogen deposition, a direct CO_2 response could result in large increases in leaf area, increasing transpiration and possibly increasing sensitivity to drought via rapid soil-water depletion. Early growth increases may disappear as the system approaches carrying capacity as limited by water or nutrients (Körner, 1995). Shifts in species composition will likely result from different sensitivities to elevated CO_2 (Körner, 1995; Bazzaz *et al*., 1996).

North American forests also are being subjected to numerous other stresses, including deposition of nitrogen and sulfur compounds and tropospheric ozone, primarily in eastern North America (Lovett, 1994). The interactions of these multiple stresses with elevated CO_2 and climate change and with large pest infestations (of, for example, the balsam wooly adelgid, gypsy moth, spruce budworm, and others) are very difficult to predict; however, many efforts are under way to address these questions (Mattson and Haack, 1987; Loehle, 1988; Fajer *et al*., 1989; Taylor *et al*., 1994; Winner, 1994; Williams and Liebhold, 1995). Anthropogenic nitrogen fixation, for example, now far exceeds natural nitrogen fixation (Vitousek, 1994). Atmospheric nitrogen deposition has likely caused considerable accumulation of carbon in the biosphere since the last century

(Vitousek, 1994; Townsend *et al.*, 1996). However, nitrogen saturation in soils also can be deleterious, possibly causing forest dieback in some systems (Foster *et al.*, 1997). Tropospheric ozone also can damage trees, causing improper stomatal function, root death, membrane leakage, and altered susceptibility to diseases (Manning and Tiedemann, 1995). Such ozone-induced changes can render trees more sensitive to warming-induced drought stress (McLaughlin and Downing, 1995). There are many other stress interactions, and researchers think that, in general, multiple stresses will act synergistically, accelerating change due to other stresses (Oppenheimer, 1989).

Assessments of possible consequences of climate change rely on linked atmospheric, ecological, and economic models. Significant uncertainties are associated with each model type, and these uncertainties may amplify as one moves down the line of linked models. The model capabilities of GCMs have improved significantly from the older (IPCC 1990, WG I, Chapter 3) to the newer (IPCC 1996, WG I, Chapter 6) scenarios, resulting in somewhat lower estimates of the potential $2xCO_2$ climate sensitivity and shifting much of the burden of uncertainty to the ecological and economic models. Ecological models still carry large uncertainties in the simulation of site water balance (among many other issues), particularly with respect to the role of elevated CO_2 on plant responses to water stress, competition, and nutrient limitations. Economic models carry uncertainties with respect to future management and technology changes, future per-capita income and available capital, GDP, international trade, and how to couple land-use management with ecological model output, among others. Ecological and economic models are rapidly being enhanced to

narrow these uncertainties; improving the linkages between the many different model types necessary to permit fully time-dependent simulations for integrated regional assessments is an ongoing research need.

8.3.2.2. Key Impacts on Forested Ecosystems of North America

Forest gains as well as forest dieback and decline are projected, with regional differences in the expected response.

Biogeography models—including a direct physiological CO_2 effect under three of the IPCC's First Assessment Report (FAR) $2xCO_2$ equilibrium GCM scenarios (Annex B)—simulate forest area gains of up to 20% over the conterminous United States under the cooler (least warming) or wetter scenarios and forest area losses of as much as 14% under the hottest scenario (VEMAP Members, 1995). The models produced similar forest redistribution patterns, including some conversion of northwest conifers to broadleaf deciduous under potential future equilibrium climates. The models have equal skill in simulating potential natural forest distribution under the present climate; although they diverge to some extent under future climates, they produce similar spatial responses and likely bound the range of forest responses to global warming. Extending these results with the FAR scenarios from the conterminous United States to all of North America using one of the biogeography models indicates that total forest area could increase as much as 32%—but that regions of forest decline or dieback (partial or total loss of trees) could range

Table 8-2: *Potential future forest area (percentage of current) in North America simulated by the MAPSS and BIOME3 biogeography models under three older (IPCC 1990, WG I) equilibrium $2xCO_2$ GCM scenarios and under three newer (IPCC 1996, WG I) transient simulations from which $2xCO_2$ scenarios were extracted (Annex C). The reported ranges include both ecological models under several GCM scenarios. The baseline area estimates are outputs from each model. Because BIOME3 does not differentiate Taiga/Tundra from Boreal Forest, two different aggregations are presented. The Boreal Conifer and Total Forest summaries are MAPSS data only; the "Boreal + Taiga/Tundra" and "Total Forest + Taiga/Tundra" summaries are from both models. Numbers in parentheses are VEMAP results for the conterminous U.S. only, indicating some scenarios with losses in forest area over the U.S., and are based on MAPSS and BIOME2 output (VEMAP Members, 1995).*

	Baseline Area (Mha)		**With CO$_2$ Effect**		**Without CO$_2$ Effect**
Forest Type	MAPSS	BIOME3	FAR Scenarios	SAR Scenarios	SAR Scenarios
Boreal Forest + Taiga/Tundra	594	620	65–105%	64–87%	28–86%
Boreal Conifer Forest	295		87–150%	115–116%	110–112%
Temperate Evergreen Forest	127	110	130–180%	78–182%	82–129%
	(82)	(86)	(58–157%)		
Temperate Mixed Forest	297	383	107–141%	146–198%	129–159%
	(245)	(260)	(88–116%)		
Total Temperate Forest	424	493	114–153%	137–171%	121–142%
Total Forest + Taiga/Tundra	1,019	1,113	102–116%	107–118%	99–105%
Total Forest	719		125–132%	142–144%	121–124%
	(327)	(346)	(86–123%)		

Note: FAR = First Assessment Report (IPCC 1990, WG I); SAR = Second Assessment Report (IPCC 1996, WG I).
Sources: Mitchell and Warrilow, 1987; Schlesinger *et al.*, 1989; IPCC, 1990; Bengtsson *et al.*, 1995; Mitchell *et al.*, 1995; Bengtsson *et al.*, 1996; IPCC, 1996, WG I, Chapters 5 and 6; Johns *et al.*, 1997.

Table 8-3: *Percentage area of current forests that could undergo a loss of leaf area (i.e., biomass decrease) as a consequence of global warming under various older (IPCC 1990, WG I) and newer (IPCC 1996, WG II) GCM scenarios, with or without direct CO_2 effect (see Table 8-2 for details), as simulated by the MAPSS and BIOME3 biogeography models (ranges include both models). Losses in leaf area generally indicate a less favorable water balance (drought).*

Forest Type	With CO_2 Effect		Without CO_2 Effect
	FAR Scenarios	SAR Scenarios	SAR Scenarios
Boreal Forest + Taiga/Tundra	19–40%	0–9%	4–45%
Boreal Conifer Forest	37–80%	14–19%	79–89%
Temperate Evergreen Forest	20–70%	2–14%	41–69%
Temperate Mixed Forest	42–96%	0–7%	12–76%

Sources: Mitchell and Warrilow, 1987; Schlesinger *et al.*, 1989; IPCC, 1990; Bengtsson *et al.*, 1995; Mitchell *et al.*, 1995; Bengtsson *et al.*, 1996; IPCC, 1996, WG I, Chapters 5 and 6; Johns *et al.*, 1997.

from 19–96% of the area of any individual forest type (Tables 8-2 and 8-3). Under hotter scenarios, forests die back from large areas of the conterminous United States (expressing declines in U.S. forest area) but expand into northern Canada and Alaska—so that total North American potential forest area actually increases. These simulated potential forest distributions do not include current or possible future land-use patterns, which will affect actual forest distribution. The models also do not simulate the differential rates of dieback and migration, which could produce near-term losses in total forest area in North America and a large pulse of carbon to the atmosphere.

Using more recent climate change scenarios (IPCC 1996, WG I, Chapter 6; Annex B and Annex C of this report), forest decline and dieback ranged only from 0–19% of the individual forest areas (Table 8-3) when a direct CO_2 effect was included. However, if the direct CO_2 effect is withheld under the newer scenarios, dieback could be quite extensive in all forest types—with a range of 12–89% of the forest area—with large range contractions in all major forest zones. Results without a CO_2 effect under the IPCC's Second Assessment Report (SAR) scenarios are similar in magnitude to results with a CO_2 effect under the FAR scenarios (Annex B). Because the full $2xCO_2$ effect may be less than fully realized, the potential forest response is bounded by simulating forests with and without a CO_2 effect. It is worth noting that by including sulfate aerosols in one SAR scenario, warming over the temperate mixed forest type in eastern North America is reduced, and there is less simulated forest dieback.

The SAR scenarios were produced from GCMs operated in a fully transient mode with gradual increases in greenhouse gases while coupled to a dynamic three-dimensional ocean. The biogeography models can only simulate equilibrium conditions, so average climate statistics were extracted from the simulations for a current-climate period and a period representing the time of $2xCO_2$ forcing. At the time of $2xCO_2$ forcing in the SAR scenarios, however, the GCMs had not equilibrated because of thermal inertia of the oceans and had only attained about 50–80% of their potential equilibrium temperature change. Thus, the SAR scenarios tend to be somewhat cooler than the FAR scenarios, which are run to equilibrium over a mixed-layer ocean. Nevertheless, when allowed to equilibrate to $2xCO_2$ forcing, the SAR scenarios exhibit a global temperature sensitivity that is similar to the FAR scenarios (Annex B). Thus, the less deleterious or even beneficial impacts simulated under the SAR scenarios may simply be precursors to the more severe impacts simulated under the equilibrium FAR scenarios.

Assessments using gap models under the equilibrium FAR GCM scenarios or sensitivity analyses have been completed for eastern North America (Solomon, 1986), the southeastern United States (Urban and Shugart, 1989), British Columbia (Cumming and Burton, 1996), central Canada (Price and Apps, 1996), and the Great Lakes region (Pastor and Post, 1988; Botkin *et al.*, 1989). Gap models differ from equilibrium biogeography models by simulating temporal dynamics of forests at a point; they therefore are able to simulate forest decline, dieback, or enhanced growth, as well as changes in species composition. The different models showed either increases or decreases in biomass depending on the method used for water balance calculations (Bugmann *et al.*, 1996). Slight variations in model structure, small differences in soil texture, or the method for implementing direct CO_2 effects can affect the magnitude and direction of change in simulated productivity and biomass storage (Martin, 1992; Post *et al.*, 1992).

Gap model results using the FAR GCM scenarios indicate the potential for significant forest dieback related to high temperatures, throughout the eastern United States—comparable to the more severe biogeography model simulations (Solomon, 1986; Pastor and Post, 1988; Botkin *et al.*, 1989; Urban and Shugart, 1989). Given cooler SAR climate scenarios and improved gap model technology, however, these older dieback results may be too severe (Fischlin *et al.*, 1995; Bugmann *et al.*, 1996; Loehle and LeBlanc, 1996; Martin, 1996; Oja and Arp, 1996; Pacala *et al.*, 1996; Post and Pastor, 1996; Shugart and Smith, 1996). Moreover, most of the gap model results do not include a direct CO_2 effect.

Studies using a regional forest-growth model suggest that forests in the northeastern United States might grow more (Aber *et al.*, 1995), while forests in the southeastern United

States could experience considerable forest dieback (McNulty *et al.*, 1996). These simulations incorporate a direct CO_2 effect but do not consider vegetation redistribution.

Gap model simulations in the boreal forest indicate increased biomass under cooler scenarios (less warming) but some dieback or shifts to drier types under the warmer scenarios (Price and Apps, 1996). Within the temperate evergreen zone of British Columbia (and throughout North America), gap models indicate that forests could shift upward in elevation and possibly disappear from some zones because of the lack of winter cooling for forest regeneration, increased sensitivity to spring frosts, and drought stress (Cumming and Burton, 1996). Where simulated dieback occurs in any of the forest zones, it tends to occur within a few decades of initial warming—with, for example, a 30% reduction in biomass within 50 years in the Douglas fir zone (Cumming and Burton, 1996).

Thus, two contrasting scenarios of the North American forest future must be considered: one with considerable forest dieback, another with much enhanced forest growth. These contrasting scenarios represent endpoints on a spectrum of possible responses. In general, however, the enhanced-growth scenarios occur under the least amount of simulated global warming, whereas the severe decline or dieback scenarios occur under the greatest projected global warming. With the incorporation of direct CO_2 effects, small temperature increases can produce increased growth, but larger temperature increases still produce declines. Without a direct CO_2 effect, forest decline simulations are far more widespread, even under the least warming scenarios. These results suggest the possibility that early forest responses to global warming could exhibit enhanced growth; later stages could produce widespread decline or dieback. Most combinations of scenarios and CO_2 effects produce intermediate scenarios, with a regional mosaic of forest dieback and enhanced forest growth. When coupled with economic models, these internally consistent but potentially opposite regional responses provide the basis for regional, national, and globally integrated assessments. Also, it is not clear that greenhouse gases will stabilize at the equivalent of $2xCO_2$ forcing; they could increase to $3xCO_2$ or $4xCO_2$ (IPCC 1996, WG I, Section 2.1.3).

Forests cannot move across the land surface as rapidly as the climate can. The faster the rate of climate change, the greater the probability of ecosystem disruption and species extinction.

Were temperature-induced drought dieback to occur, it likely would begin shortly after observable warming; if accompanied by short-term precipitation deficits, it could occur very rapidly (Solomon, 1986; King and Neilson, 1992; Martin, 1992; Smith and Shugart, 1993; Vose *et al.*, 1993; Elliot and Swank, 1994; Auclair *et al.*, 1996; Martin, 1996). That is, dieback could begin within a few decades from the present and might include potential increases in secondary impacts from pests and fire. Alternatively, forest growth might increase in the early stages of global warming, only to revert to widespread and rapid drought-induced forest dieback after higher temperatures have

significantly increased evaporative demand. Vegetation change in areas of enhanced growth, especially previously unforested areas, would be more gradual (decades to hundreds of years), constrained by dispersal, establishment, and competition.

Under global warming the physical and biotic components of most animal habitats will likely change at different rates (Davis, 1986; Dobson *et al.*, 1989; Malcolm and Markham, 1996; Markham, 1996). The faster the rate of change, the greater the disequilibrium between physical and biotic habitat components and the higher the probability of substantial ecosystem disruption and species extinctions (Malcolm and Markham, 1996; Markham, 1996). However, species will respond differently than biomes (Neilson, 1993a,b; Lenihan and Neilson, 1995). The relative mixtures of species in forest communities will change—and under either forest expansion or contraction, some important species could be at risk.

Forest ecosystems are expected to shift northward and upward in altitude, but expansion may be limited by dispersal and poor soils.

All three major forest types within North America expand north and forested areas, with a few exceptions, increase under all scenarios with or without a direct CO_2 effect (biogeography models of potential natural forests under equilibrium conditions). Total forest area increases by as much as 25–32% as projected under the FAR $2xCO_2$ GCM scenarios (including a direct, physiological CO_2 effect)—much less than the 42–44% under the SAR scenarios with a direct physiological CO_2 effect. However, the projected forest-area increases under the SAR scenarios are reduced to 21–24% when a direct physiological CO_2 effect is not included. In the long term, more carbon would be sequestered by forests under these scenarios. Before equilibrium conditions are reached, however, the processes of forest redistribution could cause a temporary reduction in forest area and a carbon pulse to the atmosphere.

Boreal forests displace most of the taiga/tundra region and increase in area under the SAR scenarios but are projected to increase or decrease under the FAR scenarios (Table 8-2). It has been projected that the temperate evergreen forests shift northward into Canada and Alaska and expand under the climate projected by the FAR scenarios (Annex C, Figures C-2 to C-5; Table 8-2). Temperate evergreen forests may expand or contract in area—due in part to conversion from conifers to broadleaf deciduous forests and in part to severe forest dieback under some scenarios (Annex C, Figures C-2 to C-5; Table 8-2; VEMAP Members, 1995). The temperate mixed forest is projected to invade the boreal forest to the north and experience gains in area under all simulations. Smaller gains in area of both temperate forest types occur under more xeric scenarios; forest expansions to the north are balanced by forest dieback in the southern zones. Because dieback in the southern zones might occur more rapidly than northward advances, there could be a short-term reduction in the area of important temperate and boreal forests (King and Neilson, 1992; Smith and Shugart, 1993).

Changes in leaf area can be used to infer changes in forest biomass (Annex C, Figures C-6 to C-9; Tables 8-3 and 8-4). Because taiga/tundra is a low-density, ecotonal region, expansion of forests into that region always produces a dramatic increase in biomass. Under earlier FAR scenarios with a direct CO_2 effect, all three forest types have subregions (ranging from only 3% to slightly over half of the area) that undergo an increase in forest biomass (Table 8-4). Under newer SAR scenarios, however, the area of increased forest biomass is always well over 50%—ranging to as high as 97% in the temperate mixed forest (with a direct CO_2 effect). Without a direct CO_2 effect under the newer scenarios, areas of increased forest biomass range only from 2–49% (usually in the lower end of the range) and are similar to those projected under the earlier scenarios, which included a CO_2 effect.

All studies agree that where forests are limited by cold they will expand beyond current limits, especially to the far north. Whether forests will expand into the drier continental interior or contract away from it, however, depends on hydrological factors and remains uncertain. Vegetation distribution models that incorporate a direct physiological CO_2 effect indicate considerable expansion of all forest types into drier and colder areas and much enhanced growth over most areas—under the newer climate scenarios as well as some of the older studies. Under most of the FAR scenarios with a CO_2 effect and under the SAR scenarios without a CO_2 effect, however, forests would contract away from the continental interior because of increased drought stress.

Longer fire seasons and potentially more frequent and larger fires are likely.

Fire mediates rapid change and could increase in importance for vegetation change. Future climate scenarios could result in longer fire seasons and potentially more frequent and larger fires in all forest zones (even those that currently do not support much fire) because of more severe fire weather, changes in fire-management practices, and possible forest decline or dieback (Fosberg, 1990; Flannigan and Van Wagner, 1991; King and Neilson, 1992; Wotton and Flannigan, 1993; Price and Rind, 1994; Fosberg *et al.*, 1996).

Fire suppression during much of the 20th century has allowed biomass in many interior forests to increase by considerable amounts over historic levels (Agee, 1990). With increased biomass, forests transpire almost all available soil water; they become very sensitive to even small variations in drought stress and are very susceptible to catastrophic fire, even without global warming (Neilson *et al.*, 1992; Stocks, 1993; Stocks *et al.*, 1996). Forests in the interior of North America are experiencing increased frequencies of drought stress; pest infestations; and catastrophic, stand-replacing fires (Agee, 1990). This sequence of events is a reasonable analog for what could happen to forests over much larger areas in the zones projected by biogeography models to undergo a loss of biomass or leaf area as a consequence of temperature-induced transpiration increases and drought stress (Annex C, Figures C-6 to C-9; Table 8-3) (Overpeck *et al.*, 1990; King and Neilson, 1992).

Enhanced fire and drought stress will facilitate changes in species composition and may increase atmospheric carbon contributions from forests.

Given the ownership patterns and remote nature of much of the boreal forest lands, they are generally managed as natural systems. Even highly managed temperate forests are of such large extent that a rapid, large-scale management response would be logistically quite difficult and expensive.

On managed lands, harvesting of dead or dying trees, more rapid harvesting or thinning of drought-sensitive trees, and planting of new species could reduce or eliminate species loss or productivity declines. However, identification of which species to plant (and when) under a rapidly changing climate will be difficult management issues. The more rapid the rate of climate change, the more it may strain the ability to create infrastructure for seeding or planting of trees or support the supply of timber if there is a large amount of salvage. The fast rate of warming may limit some species that have slow dispersal rates or are constrained by human barriers, habitat fragmentation, or lack of suitable habitat—or already are stressed by pollution.

As fire-management agencies operate with increasingly constrained budgets, it is likely that any increases in fire frequency

Table 8-4: *Percentage area of current forests that could undergo a gain of leaf area (i.e., biomass increase) as a consequence of global warming under various older (IPCC 1990, WG I) and newer (IPCC 1996, WG II) GCM scenarios, with or without direct CO_2 effect (see Table 8-2 for details), as simulated by the MAPSS and BIOME3 biogeography models (ranges include both models). Gains in leaf area generally indicate a more favorable water balance.*

Forest Type	With CO_2 Effect		Without CO_2 Effect
	FAR Scenarios	SAR Scenarios	SAR Scenarios
Boreal Forest + Taiga/Tundra	57–70%	74–91%	47–51%
Boreal Conifer Forest	16–42%	53–54%	1–3%
Temperate Evergreen Forest	11–49%	52–79%	7–16%
Temperate Mixed Forest	3–53%	92–97%	2–49%

Sources: Mitchell and Warrilow, 1987; Schlesinger *et al.*, 1989; IPCC, 1990; Bengtsson *et al.*, 1995; Mitchell *et al.*, 1995; Bengtsson *et al.*, 1996; IPCC, 1996, WG I, Chapters 5 and 6; Johns *et al.*, 1997.

or severity will result in a disproportionately large increase in area burned (Stocks, 1993). More and larger boreal fires will result in a reevaluation of protection priorities, with likely increased protection of smaller, high-value areas and reduced protection over large expanses. If forests die back from drought, infestations, or fire in extensive, remote regions, the impacts could include large-scale changes in nutrient cycling and carbon sequestration, as well as loss of value for future timber harvests or as habitat for wildlife and biodiversity. Some adaptive practices—such as harvesting dead or dying trees or thinning—could impact biodiversity, soil erosion, stream quality, and non-market forest products, producing potentially conflicting management options.

Markham and Malcolm (1996) have concluded that ecological resiliency can be increased by conserving biological diversity, reducing fragmentation and degradation of habitat, increasing functional connectivity among habitat fragments, and reducing anthropogenic environmental stresses. They also indicate that adaptation strategies should include redundancy of ecological reserves, reserves with much structural heterogeneity, and the flexibility to spatially relocate habitat protection depending on shifts in future climate (Peters and Darling, 1985; McNeely, 1990). Current habitat fragmentation patterns and human barriers may hinder species migration. Thus, management of the "seminatural matrix" may play an increasing role in fostering species redistribution (Peters and Darling, 1985; Bennett *et al.*, 1991; Franklin *et al.*, 1991; Parsons, 1991; Simberloff *et al.*, 1992).

8.3.3. Hydrology and Water Resources

8.3.3.1. Hydrological Trends and Variability

Several reports of recent trends in precipitation and streamflow have shown generally increasing values throughout much of the United States; in Canada, total precipitation trends indicate an increase, but monthly streamflow analyses show varying seasonal changes. Lettenmaier *et al.* (1994) analyzed data over the period 1948–88 and found generally increasing trends in precipitation during the months of September to December and increasing trends in streamflow during the months of November to April, particularly in the central and north-central portions of the United States. Similarly, Lins and Michaels (1994) report that streamflow has increased throughout much of the conterminous United States since the early 1940s, with the increases occurring primarily in autumn and winter. In Louisiana, precipitation and simulated runoff (streamflow per unit drainage area) have increased significantly over the past 100 years (Keim *et al.*, 1995).

Mekis and Hogg (1997) analyzed annual and seasonal precipitation (total, rain and snow) trends for periods from 1948–96 to 1895–1996 for regions of Canada and noted significant increases in total annual precipitation and snow for most regions. In Ontario, 41 hydrometric stations with a minimum of 30 years of data ending in 1990 were analyzed by Ashfield

et al. (1991). Mean monthly flows increased for the period September to January in more than 50% of the stations; approximately 25% of the stations show a downward trend in flow for the April to September period. Anderson *et al.* (1991) analyzed low-, average-, and maximum-flow time series for 27 stations (unregulated flow) across Canada; the data show a decrease in summer low flows and an increase in winter average and low flows but little trend in seasonal maximum flows. Burn (1994) analyzed the long-term record of 84 unregulated river basins from northwestern Ontario to Alberta for changes in the timing of peak spring runoff. In the sample, the more northerly rivers exhibited a trend to earlier spring snowmelt runoff; the observed impacts on timing were more prevalent in the recent portion of data. These trends generally are consistent with climate models that produce an enhanced hydrological cycle with increasing atmospheric CO_2 and warmer air temperatures, although some of the streamflow trends also may be the result of water-management or land-use changes that reduce surface infiltration and storage.

Recent investigations have shown how natural modes of variability at scales from seasons to years (e.g., ENSO, Pacific Decadal Oscillation) affect hydrological variability in different regions of North America and thereby have underlined the importance of increasing our understanding of the roles these features play in influencing hydrological characteristics. The ENSO phenomenon, a predictable climate signal, affects precipitation and streamflow in the northwestern, north-central, northeastern, and Gulf coast regions of the United States (Kahya and Dracup, 1993; Dracup and Kahya, 1994). For example, La Niña events (the cold phase of the ENSO phenomenon) produce higher than normal precipitation in winter in the northwestern United States, whereas El Niño events (the warm phase of the ENSO phenomenon) cause drier winters in the Northwest on roughly a bidecadal time scale. Precipitation over a large region of southern Canada extending from British Columbia through the prairies and into the Great Lakes shows a distinct pattern of negative precipitation anomalies during the first winter following the onset of El Niño events; positive anomalies occur in this region with La Niña events. On the other hand, the northern prairies and southeastern Northwest Territories show significant positive precipitation anomalies with El Niño events (Shabbar *et al.*, 1997). Variability in ENSO phenomena contributes natural variations in hydrology at decadal and longer time scales that are problematic for CO_2 climate change analysis. Changes in ENSO behavior related to increasing CO_2 are highly uncertain but could produce enhanced variability in precipitation and streamflow for the regions most sensitive to ENSO fluctuations (IPCC 1996, WG I, Section 6.4.4).

Wetlands in North America traditionally have been viewed as wasted land available for conversion to more productive use. This opinion has contributed to the loss of millions of wetland hectares that have been drained or filled for agriculture, highways, housing, and industry. In Canada, where wetlands occupy an estimated 14% of the landscape, 65–80% of Atlantic coastal marshes, southern Ontario wetlands, prairie potholes,

and the Fraser River delta have been lost—largely to agriculture (Environment Canada, 1986, 1988). Figures for the United States indicate that approximately 53% of the original wetland area in the lower 48 states has been lost, mostly (87% of this figure) to agriculture (Maltby, 1986). These losses are accompanied by the loss of ecological, hydrological, and cultural functions wetlands provide, including water purification, groundwater recharge/discharge, stormwater storage/flood control, sediment and pollutant sequestering, carbon storage, cycling of sulfur, and wildlife habitat (Mitsch and Gosselink, 1986; IPCC 1996, WG II, Chapter 6).

Socioeconomically, wetlands provide direct benefits through the harvesting of timber, wild rice, cranberries, and horticultural peat—as well as through recreational activities such as hunting, fishing, and bird watching. The cultures and spiritual values of many First Nation peoples are linked to the health of wetlands.

8.3.3.2.   Impacts, Adaptations, and Vulnerabilities

Important vulnerabilities of water resources to potential climate change scenarios involve changes in runoff and streamflow regimes, reductions in water quality associated with changes in runoff, and human demands for water supplies.

Seasonal and annual runoff may change over large regions as a result of changes in precipitation or evapotranspiration.

Runoff is simply the area-normalized difference between precipitation and evapotranspiration; as such, it is a function of watershed characteristics, the physical structure of the watershed, vegetation, and climate. Although most climate change models show increases in precipitation over much of North America, rates of evaporation and perhaps transpiration also are likely to increase with increasing temperatures. Therefore, regions in which changes in precipitation do not offset increasing rates of evaporation and transpiration may experience declines in runoff and consequently declines in river flows, lake levels, and groundwater recharge and levels (Schindler, 1997). Alternatively, regions that experience substantial increases in precipitation are likely to have substantial increases in runoff and river flows.

Projected changes in annual discharge (summarized in Table 8-5) for some river basins in North America using various climate

Table 8-5: Summary of annual runoff impacts from climate change scenarios

Region/River Basin	Scenario Method	Hydrological Changes (annual)	Reference(s)
East-Central Canada			
St. Lawrence, Ontario and Quebec	GCM: CCC92	-34%	Croley (1992)
Opinaca-Eastmain, Quebec	GCM: GISS84, GFDL80	+20.2%, +6.7%	Singh (1987)
La Grande, Quebec	GCM: GISS84, GFDL80	+15.6%, +16.5%	Singh (1987)
Caniapiscau, Quebec	GCM: GISS84, GFDL80	+13.0%, +15.7%	Singh (1987)
Moise, Quebec	GCM: CCC92	-5%	Morin and Slivitzky (1992)
Grand, Ontario	GCM: GISS87, GFDL87, CCC92	-11%, -21%, -22%	Smith and McBean (1993)
Canadian Prairie			
Saskatchewan	GCM: GISS87[1]	+28%, +35%	Cohen *et al.* (1989); Cohen
	GCM: GFDL87[1]	-27%, -36%	(1991)
	GCM: OSU88[1]	+2%, -4%	
Northwest Canada			
Mackenzie	GCM: CCC92, GFDL-R30	-3 to -7%	Soulis *et al.* (1994)
	analog	+7%	
Mid-Atlantic USA			
Delaware	GCM: GISS, GFDL, OSU	-5 to -38% (soil moisture index)	McCabe and Wolock (1992)
Western USA			
Upper Colorado	GCM: GISS, GFDL, UKMO	-33 to +12%	Nash and Gleick (1993)

[1]Includes low and high irrigation.
Sources: CCC92 (Boer *et al.*, 1992; McFarlane *et al.*, 1992), OSU88 (Schlesinger and Zhao, 1988), GFDL87 (Manabe and Wetherald, 1987), GISS87 (Cohen, 1991), GISS84 (Cohen, 1991), GFDL80 (Cohen, 1991).

change scenarios indicate potential increases as well as declines. (Many of these hydrological impact assessments, however, were developed using older climate change scenarios of somewhat larger increases in global air temperature than the most recent scenarios that include regional aerosol-cooling effects.) Seasonal changes in runoff also could be substantial. Most climate change scenarios suggest increased winter precipitation over much of North America, which could result in increased runoff and river flows in winter and spring. Several climate change scenarios show declines in summer precipitation in some regions (e.g., the southeastern United States; IPCC 1996, WG I, Figure 6.11) or declines in summer soil-moisture levels (e.g., over much of North America; IPCC 1996, WG I, Figure 6.12), which could result in significant declines in summer and autumn runoff in these regions. However, climate change scenarios showing summer declines in precipitation or soil-moisture levels in these regions generally are produced from simulations with doubled CO_2 forcing alone; when aerosol forcing is included, summer precipitation and soil-moisture levels increase only slightly. This pattern highlights the large uncertainty in climate change projections of runoff.

Although large increases in annual runoff will affect flooding and flood management, large reductions may pose more serious threats to uses such as potable drinking water, irrigation, assimilation of wastes, recreation, habitat, and navigation. The greatest impact of declines in supply are projected to be in arid and semi-arid regions and areas with a high ratio of use relative to available renewable supply, as well as in basins with multiple competing uses. For example, reductions in outflow of 23–51% from Lake Ontario from assessments using four GCM scenarios suggest impacts on commercial navigation in the St. Lawrence River and the port of Montreal, as well as hydropower generation (Slivitzky, 1993). Lower flows also may affect the ecosystem of the river by allowing the saltwater wedge to intrude further upstream.

Seasonal patterns in the hydrology of mid- and high-latitude regions could be altered substantially, with runoff and stream-flows generally increasing in winter and declining in summer.

Higher air temperatures could strongly influence the processes of evapotranspiration, precipitation as rain or snow, snow and ice accumulation, and melt—which, in turn, could affect soil moisture and groundwater conditions and the amount and timing of runoff in the mid- and high-latitude regions of North America. Higher winter temperatures in snow-covered regions of North America could shorten the duration of the snow-cover season. For example, one climate change scenario (CCC, Annex B) indicates up to a 40% decrease in the duration of snow cover in the Canadian prairies and a 70% decrease in the Great Plains (Boer *et al.*, 1992; Brown *et al.*, 1994). Warmer winters could lead to less winter precipitation as snowfall and more as rainfall, although increases in winter precipitation also could lead to greater snowfall and snow accumulation, particularly at the higher latitudes. Warmer winter and spring temperatures could lead to earlier and more rapid snowmelt and earlier ice break-up, as well as more rain-on-snow events that pro-

duce severe flooding, such as occurred in 1996–97 (Yarnal *et al.*, 1997).

Damages to structures, hydropower operations, and navigation and flooding caused by late-winter and spring ice-jam events are estimated to cost CAN$60 million annually in Canada and US$100 million in the United States. About 35% of flooding in Canada is caused by ice jams—principally in the Atlantic Provinces, around the Great Lakes, in British Columbia, and in northern regions (Beltaos, 1995). Northern deltas and wetlands, however, depend upon flooding for periodic recharge and ecological sustainability (Prowse, 1997). The $2xCO_2$ GCM simulations (IPCC 1996, WG I, Summary for Policymakers) suggest milder winters in higher latitudes and a general pattern of increased precipitation, with high regional variability. Where warmer winters result in reduced ice thickness, less severe breakups and reduced ice-jam flooding can be expected. However, major changes in precipitation patterns also are predicted. In some regions, there is an increased likelihood of winter or early spring rains. These climatic factors trigger sudden winter thaws and premature breakups that have the greatest potential for damage. Thus, although average conditions may be improved, the severity of extreme events in some regions appears likely to increase. In the more southern latitudes commonly affected by spring ice jams—such as the lower Great Lakes and central Great Plains areas, parts of New England, Nova Scotia, and British Columbia—there may be a reduction in the duration and thickness of the ice cover on rivers, as well as in the severity of ice jamming. In the north, similar effects are expected. In the intermediate latitudes—such as the prairies; much of Ontario and Quebec; and parts of Maine, New Brunswick, Newfoundland, and Labrador—spring jamming may become more common and/or severe. Such events are presently rare or completely unknown in some of these areas (Van Der Vinne *et al.*, 1991; Beltaos, 1995).

In mountainous regions, particularly at mid-elevations, warming could lead to a long-term reduction in peak snow-water equivalent, with the snowpack building later and melting sooner (Cooley, 1990). Glacial meltwater also is a significant source of water for streams and rivers in some mountainous regions, with the highest flows occurring in early or midsummer (depending on latitude). For example, glacial meltwater contributes an average of 85% of the August flow in the Mistaya River near Banff, Alberta (Prowse, 1997). Accelerated glacier melt caused by temperature increases means more runoff in the short term, but loss of glaciers could result in streams without significant summer flow in the future (IPCC 1996, WG II, Sections 7.4.2 and 10.3.7). Late-summer stream discharge could decrease suddenly within only a few years. A steady pattern of glacial retreat is apparent in the southern Rocky Mountains below central British Columbia and Alberta. Water supplies in small communities, irrigation, hydroelectric generation, tourism, and fish habitat could be negatively impacted (IPCC 1996, WG II, Chapter 7; Brugman *et al.*, 1997; Prowse, 1997).

In Arctic regions, permafrost maintains lakes and wetlands above an impermeable frost table and limits subsurface water

storage. As described in Section 8.3.1, discontinuous and continuous permafrost boundaries are expected to move poleward as a result of projected changes in climate. Thawing of permafrost increases active-layer storage capacity and alters peatland hydrology. Although climatic warming could have a large effect on Arctic hydrology, the changes are highly uncertain at this time.

In general, increases in winter and early spring temperatures under a $2\times CO_2$ climate could shift hydrological regimes toward greater flows in winter and early spring and lower flows in summer in the mid- and high-latitude regions of North America (Ng and Marsalek, 1992; Soulis *et al.*, 1994). River and reservoir systems that are fed by snowmelt or rely on glacier melt for spring and summer flow during critical periods of high agricultural and municipal demand and low precipitation may have critical supply-demand mismatches. California and the Great Plains and prairie regions of Canada and the United States could be particularly vulnerable (Cohen *et al.*, 1989; Gleick, 1993).

Altered precipitation and temperature regimes will affect the seasonal pattern and variability of water levels of wetlands, thereby affecting their functioning—including flood protection, carbon storage, water cleansing, and waterfowl/wildlife habitat.

It is difficult to generalize about the sensitivity of wetlands to climate change (IPCC 1996, WG II, Chapter 6). It appears, however, that climate change will have its greatest effect through alterations in hydrological regimes—in terms of the nature and variability of the hydroperiod (the seasonal pattern of water level) and the number and severity of extreme events (Gorham, 1991; Poiani and Johnson, 1993). However, other variables related to changing climate may drive a site-specific response. Such variables include increased temperature and altered evapotranspiration, altered amounts and patterns of suspended sediment loadings, fire, oxidation of organic sediments, and the physical effects of wave energy (Mitsch and Gosselink, 1986; IPCC 1996, WG II, Chapter 6).

There are many highly significant social and economic threats to wetlands, but there is insufficient information on the precise nature of anticipated local changes in climate. This difficulty prevents accurate assessment of risks or opportunities to adapt. The responses of affected wetlands are expected to vary; they might include migration of the wetland area along river edges or the slope of a receding lake and/or altered species composition. More serious effects would include altered physical characteristics; degradation to a simpler, less diverse form; or complete destruction. There also could be a loss of desired attributes, such as their ability to provide suitable habitat for particular species; their ability to act as a feeding or breeding area in support of an adjacent open-water commercial or recreational fishery; or their ability to buffer occasional flooding (Mitsch and Gosselink, 1986; IPCC 1996, WG II, Chapter 6). Altering climate and acid depositions can cause declining levels of dissolved organic carbon (DOC) in wetlands—thus increasing the water volumes, sediment areas, and associated organisms exposed to harmful ultraviolet-B (UV-B) irradiation. Potential effects include changes in aquatic communities and photoinhibition of phytoplankton (Schindler *et al.*, 1996; Yan *et al.*, 1996).

Additional losses of prairie pothole wetlands could reduce migratory waterfowl and wildlife populations.

Occupying depressions in the landscape in dry climates with small watershed areas, prairie pothole wetlands are highly susceptible to a lack of moisture occurring through the effects of decreased snowpack and associated spring recharge, droughts, and increased climatic variability. Already strained by losses of 71% in Canada (Environment Canada 1986, 1988) and 50–60% in the United States (Leitch, 1981), this area yields 50–75% of all the waterfowl produced in any year in North America (Leitch and Danielson, 1979; Weller, 1981). Trends in Canadian duck abundance already reflect the interactions between changing wetness regimes and landscape alterations (Bethke and Nudds, 1995). Any additional stress would be of great concern and could be accommodated only through active programs to protect, enhance, and increase wetland areas in this region.

Increases in the frequency or magnitude of extreme hydrological events could result in water quality deterioration and water management problems.

Hydrological variability (i.e., the frequency and magnitude of extreme events) is an extremely important issue for the management of water resources. Under a warmer climate, the hydrological cycle is projected to become more intense, leading to more heavy rainfall events (IPCC 1996, WG I, Section 6.5.6). Several $2\times CO_2$ GCM simulations have indicated an increase in the magnitude of mean rainfall events, particularly for central and northwest North America, even with small changes in mean annual rainfall (Cubasch *et al.*, 1995; Gregory and Mitchell, 1995; Mearns *et al.*, 1995; IPCC 1996, WG I, Section 6.5.7). In addition, these simulations indicate increases in the length of dry spells (consecutive days without precipitation). However, few model simulation analyses have addressed the issue of variability in daily precipitation and increases in the frequency or severity of extreme hydrological events; as a result, issues surrounding variability and extreme hydrological events remain highly uncertain at this time.

In many regions, projected increases in hydrological variability would result in greater impacts on water resources than changes in mean hydrological conditions (IPCC 1996, WG II, Chapter 10 Executive Summary). Increases in the frequency or magnitude of extreme rainfall events would likely have their greatest impacts on water resources in the winter and spring, when the ground is frozen or soil moisture levels are high; severe flooding may be more likely. More severe or frequent floods could result in increased erosion of the land surface, as well as stream channels and banks; higher sediment loads and increased sedimentation of rivers and reservoirs; and increased loadings of nutrients and contaminants from agricultural and urban areas (IPCC 1996, WG II, Section 10.5.5). Longer dry

spells would likely have their greatest impact in the summer, when streamflows generally are low. Increases in the severity of summer droughts could result in reduced water quality (e.g., lower dissolved oxygen concentrations, reduced dilution of effluents) and impaired biological habitat (e.g., drying of streams, expansion of zones with low dissolved oxygen concentrations, water temperatures exceeding thermal tolerances) (IPCC 1996, WG II, Sections 10.5.3 and 10.5.4).

Projected increases in hydrological variability (e.g., more frequent or larger floods) could lead to increased expenditures for flood management and disaster assistance (IPCC 1996, WG II, Section 14.4.3). Flood-control structures might require modifications to accommodate larger probable maximum-flow events. Alternatives to structural flood-control measures can be instituted to reduce risk at a lower cost to society, but these strategies require significant political will. Even with the high frequency of extreme events that have occurred recently (and their attendant costs), changes to less-costly and more effective nonstructural methods of risk reduction are slow in gaining acceptance. Navigation also might be impaired by changes in hydrological variability, as illustrated by severe restrictions on navigation in the Mississippi River during the drought of 1988 (IPCC 1996, WG II, Section 14.3.4). Hydropower generation could be severely restricted during droughts. It is estimated that hydropower production might decline 20% during the peak-load summer months in northern California as a result of more severe droughts (IPCC 1996, WG II, Section 14.3.3). More severe summer droughts also could increase agricultural irrigation demands (IPCC 1996, WG II, Section 14.3.1) and exacerbate current drinking water supply problems in some large urbanized areas, such as California and Houston, Texas (IPCC 1996, WG II, Section 12.3.5).

Lake water levels could decline in regions such as the Arctic and the Great Lakes where precipitation increases do not compensate for warming-enhanced evaporation rate increases.

Lake levels are sensitive to changes in precipitation and evaporation, which lead to changes in streamflow and groundwater flow. Changes in lake levels will depend on regional changes in temperature and precipitation (the latter of which is highly uncertain). In areas where climate change scenarios suggest that precipitation or soil moisture levels could decline, lake levels are likely to decline or to fluctuate more widely (IPCC 1996, WG II, Section 10.5.2). Decreases in precipitation and/or soil moisture are indicated for the southeastern United States and much of the midcontinental region of North America in several $2xCO_2$ GCM simulations with only CO_2 forcing. Water-level declines would be most severe in lakes and streams in dry evaporative drainage basins and basins with small catchments. Semipermanent prairie sloughs are fed by groundwater in addition to precipitation and spring snowmelt. Severe droughts deplete groundwater storage and cause these sloughs to dry out—resulting in turn in a decline of bird habitats (Poiani and Johnson, 1991, 1993). In the north-central United States, some drainage lakes and seepage lakes are highly responsive to precipitation; lake levels declined substantially during the late-1980s drought (Eilers *et al.*, 1988).

High-latitude lakes also may be particularly vulnerable to changes in precipitation and temperature. For a $2xCO_2$ climate change scenario with temperature increases of 3–5°C and precipitation increases of 10–15%, lake levels in the Mackenzie delta of arctic Canada fluctuate more widely. If precipitation were to decline by 10% with these temperature increases, however, many lakes could disappear within a decade as a consequence of decreased flood frequency (Marsh and Lesack, 1996).

The Great Lakes of North America are a critically important resource, and potential climate change effects are of great concern. Based on $2xCO_2$ scenarios from several GCMs that indicated seasonal temperature increases of 2.6–9.1°C and seasonal precipitation changes of -30% to +40% (generally summer/autumn declines and winter increases), the following lake level declines could occur: Lake Superior -0.2 to -0.5 m, Lakes Michigan and Huron -1.0 to -2.5 m, and Lake Erie -0.9 to -1.9 m; the regulation plan for Lake Ontario cannot meet the minimum downstream flow requirements and maintain lake levels (Croley, 1990; Hartmann, 1990; Mortsch and Quinn, 1996). Using the Canadian Climate Centre (CCC) GCM II scenario (which generally has drier summer and autumn conditions than other GCMs for this region), the surface area of Lake St. Clair decreases by 15%; its volume is reduced by 37%; the water level declines 1.6 m; and the shoreline may be displaced 1–6 km lakeward, exposing lake bottom (Lee *et al.*, 1996). These Great Lakes water-level changes are based on climate change scenarios from models that produced global temperature increases that are at least twice as large and precipitation changes that generally are greater than the most recent climate change simulations with aerosols included. Nonetheless, although highly uncertain at this time, the potential declines in lake water levels shown in these analyses could have large effects on wetlands, fish spawning, recreational boating, commercial navigation, and municipal water supplies in the Great Lakes area. Also of concern is the exposure of toxic sediments and their remediation with declines in lake levels (Rhodes and Wiley, 1993).

Responses to adapt to these large changes in lake levels in developed areas could be costly. Changnon (1993) estimated the costs for dredging, changing slips and docks, relocating beach facilities, and extending and modifying water intake and sewage outfalls for a 110-km section of the Lake Michigan shoreline including Chicago to range from $298–401 million for a 1.3-m decline and $605–827 million (1988 dollars) for a 2.5-m decline.

Water quality could deteriorate during summer low flows in regions experiencing reduced summer runoff.

Changes in water quality as well as changes in hydrological regimes could occur as a result of climate warming. Increases in water temperature in streams and rivers reduce oxygen solubilities and increase biological respiration rates and thus may result in lower dissolved oxygen concentrations, particularly in summer low-flow periods in low- and mid-latitude areas (IPCC 1996, WG II, Section 10.5.4). Although temperature increases

also may stimulate photosynthesis via increased nutrient cycling and thus prevent dissolved oxygen declines during the day, sharp nighttime declines could occur. Summer dissolved oxygen concentrations in the hypolimnion of lakes, particularly more eutrophic lakes, also may decline, and areas of anoxia may increase because of increased respiration rates in a warmer climate (IPCC 1996, WG II, Section 10.5.4). However, reduction in the length of winter ice cover may reduce the incidence of winter anoxia in more northerly lakes and rivers. Increases in water temperature also will impact industrial uses of water, primarily in the low and mid-latitudes, by reducing the efficiency of once-through cooling systems (IPCC 1996, WG II, Section 14.3.3). Increases in water temperature will have a positive impact on navigation in the mid- and high latitudes, especially in the Great Lakes, by increasing the length of the ice-free season (IPCC 1996, WG II, Section 14.3.4)—perhaps compensating for reduced cargo capacity due to low water levels.

Changes in the seasonality of runoff also may affect water quality. In the middle and high latitudes, the shift in the high-runoff period from late spring and summer to winter and early spring might reduce water quality in summer under low flows. Extended droughts in boreal regions have been shown to result in acidification of streams due to oxidation of organic sulfur pools in soils (Schindler, 1997). However, acidic episodes associated with spring snowmelt in streams and lakes in the northeastern United States and eastern Canada might be reduced under a warmer climate with lower snow accumulation and lower discharges during the spring melt (IPCC 1996, WG II, Section 10.5.3; Moore *et al.*, 1997). In general, water-quality problems (particularly low dissolved oxygen levels and high contaminant concentrations) associated with human impacts on water resources (e.g., wastewater effluents) will be exacerbated more by reductions in annual runoff than by other changes in hydrological regimes (IPCC 1996, WG II, Section 14.2.4).

Increases in competition for limited water under a warmer climate could lead to supply shortfalls and water-quality problems, particularly in regions experiencing declines in runoff.

Under a warmer climate, more intensive water resource management will be required because population growth, economic development, and altered precipitation patterns will lead to more intense competition for available supplies (IPCC 1996, WG II, Sections 12.3.5 and 14.4). Managing increased and diversified water demands will be particularly problematic in regions that currently have the lowest water availability (e.g., western-central North America) and those that will experience declines in runoff with climate change.

National water summaries by the U.S. Geological Survey provide comprehensive data on water availability and demand. Agriculture and steam electric generation account for approximately 75% of total water withdrawals in the United States; agricultural uses are most dominant west of the 100th meridian, where evaporation generally exceeds precipitation. When seasonal and interannual variability of regional climates are

considered, the most inadequate water supplies within the United States (70% depletion of available supplies by off-stream uses) are in the southwest—including the lower Colorado River basin, the southern half of California's Central Valley, and the Great Plains river basins south of the Platte River.

A warmer climate will likely increase the demand for irrigation water by agriculture (IPCC 1996, WG II, Section 14.3.1) and for industrial cooling water at the same time that urban growth will be increasing the demand for municipal water supplies. In addition, higher water temperatures will reduce the efficiency of cooling systems (Dobrowolski *et al.*, 1995), and might make it increasingly difficult to meet regulatory constraints defining acceptable downstream water temperatures, particularly during extremely warm periods (IPCC 1996, WG II, Section 14.3.3). Furthermore, growing instream flow requirements to protect aquatic ecosystems also will reduce effective water supplies. However, improved management of water infrastructure, pricing policies, and demand-side management of supply have the potential to mitigate some of the impacts of increasing water demand (Frederick and Gleick, 1989; IPCC 1996, WG II, Section 12.5.5).

8.3.4. *Food and Fiber: Agriculture*

8.3.4.1. *Description of the Resource*

Agricultural land represents about 12% of the land area of North America. Approximately 3% of the population and 1.7% of the annual growth in gross national product (GNP) are related to agriculture. Agricultural land use comprises a total of approximately 233 million ha. Irrigated farmland represents 21 million ha in the United States, with much of this along the Mississippi River, the central Great Plains, and the western states. North America is characterized by an abundance of fertile soils and a highly productive agricultural sector that leads the world in the production of small grains. Within the United States, there are 10 farm production regions, with 6 corresponding regions in Canada (Adams *et al.*, 1995b; Brklacich *et al.*, 1997a).

Agriculture in North America has a long history of sensitivity to climate variability (e.g., the timing and magnitude of droughts and floods, extremes in heat and cold) and is subject to a wide array of other factors that can limit potential productivity (e.g., tropospheric ozone, pests, diseases, and weeds). Agriculture has an equally long history of developing strategies to cope with the many factors capable of limiting production. Climate change is an additional factor that could enhance or reduce the sensitivity of the agricultural sector to these current stress factors. As world population grows, the demand for North American agricultural products is expected to increase, with possible increases in agricultural commodity prices (IPCC 1996, WG II, Section 13.6.8). Should increased demand lead to further intensification of agriculture in North America, increased emphasis on sustainable agriculture is likely (Matson *et al.*, 1997).

8.3.4.2.   Potential Impacts of Climate Change
            on Agriculture

Potential impacts of climate change on agriculture will be reflected most directly through the response of crops, livestock, soils, weeds, and insects and diseases to the elements of climate to which they are most sensitive. Soil moisture and temperature are the climate factors likely to be most sensitive to change across large agricultural areas of North America. The differential response of species to elevated CO_2 concentrations is expected to show a generally positive but variable increase in productivity and WUE for annual crops; limited evidence suggests less of a growth response for perennial crop species. Many weed species are expected to benefit from CO_2 "fertilization" and increased WUE, and increased temperatures may facilitate the expansion of warm-season weed species to more northerly latitudes (IPCC 1996, WG II, Section 13.2). Insect pests and fungal and bacterial pathogens of importance to agricultural production are sensitive to climate change through the direct effects of changes of temperature and moisture on the pest or pathogen, on host susceptibility, and on the host-parasite interrelation (IPCC 1996, WG II, Section 13.4). Livestock is sensitive to climate through impacts on feed and forage crops, through the direct effects of weather and extreme events on animal health, and through changes in livestock diseases (IPCC 1996, WG II, Section 13.5).

Long-term crop management strategies that increase soil organic matter will benefit agricultural lands by increasing soil nutrient status and water-holding capacity while increasing soil carbon storage (Matson *et al.*, 1997).

8.3.4.3.   Climate Variability and Extreme Events

Changes in mean temperature and precipitation will likely affect agricultural crop and livestock production. Climate modifications that lead to changes in daily and interannual variability in temperatures and, in particular, precipitation also will impact crop yields.

Mearns *et al.* (1996) used the Clouds and Earth's Radiant Energy System (CERES)-Wheat model to demonstrate the impact of daily temperature variability on simulated wheat yields at two sites in Kansas. A doubling of daily temperature variability contributed to increased crop failures and lower yields as a consequence of cold damage and winter kill. Simulated wheat yields also decreased as variability in precipitation increased, although absolute reductions in yield were dependent on soil type and associated moisture-holding capacity. Although these simulations illustrate the potential sensitivity of wheat production to increased variability in temperature and precipitation, they do not incorporate the beneficial role that elevated CO_2 may play in modifying these responses, nor are extreme events considered in these analyses. Extreme events like drought, flooding, hail, hurricanes, and tornadoes also will impact agriculture, but reliable forecasts of such occurrences are not yet regionally available.

8.3.4.4.   Direct and Indirect Effects

The results of a large number of experiments designed to examine the effects of elevated CO_2 concentrations on crops have generally confirmed high confidence in a net beneficial effect of CO_2 fertilization, up to some level. Sustained plant response under field conditions to concentrations beyond $2xCO_2$ would likely be dependent on species as well as water and nutrient status and is highly uncertain.

A mean value yield response of C_3 crops (most crops except maize, sugar cane, millet, and sorghum) to doubled CO_2 is reported to be approximately +30% (range -10% to +80%). There is reason to expect, however, that this value represents an upper estimate unlikely to be achieved under field conditions. Factors known to affect the magnitude of CO_2 response in crops include the availability of plant nutrients, the crop species, temperature, precipitation, and other environmental factors, such as air pollution, soil quality, weeds, insect pests, and diseases (IPCC 1996, WG II, Section 13.2.1). Increased WUE is a result of elevated CO_2 as well, though in many regions of North America, higher temperatures associated with elevated CO_2 can be expected to increase evaporative demand and transpiration, resulting in minimal benefit from the increase in WUE (Brklacich *et al.*, 1997b).

Changes in soils (e.g., loss of soil organic matter, leaching of soil nutrients, salinization, and erosion) are likely consequences of climate change for some soils in some climatic zones. Cropping practices such as crop rotation, conservation tillage, and improved nutrient management are technically effective in combating or reversing such deleterious effects (IPCC 1996, WG II, Section 13.3; Matson *et al.*, 1997).

Livestock production could be affected by changes in grain prices, changes in the prevalence and distribution of livestock pests, and changes in grazing and pasture productivity. Livestock are sensitive to stress from warmer, drier conditions, as well as reduced range forage quality and water availability. Warmer winter temperatures may enhance winter survival of range livestock. Taking action to improve forage quality or water supply could benefit livestock. Analyses indicate that intensively managed livestock systems such as those in North America have more potential for adaptation than crop systems because of their mobility in terms of access to food and water (IPCC 1996, WG II, Section 13.5).

The risk of losses due to weeds, insects, and diseases is sensitive to temperature and moisture (including rainfall, humidity, and dew); the risk is likely to increase in subregions where these factors become more favorable for specific disease organisms but may decrease under drier conditions. Increased climate variability may provide additional challenges for pest-management adaptation to climate change.

Elevated CO_2 levels may enhance the growth of C_3 weeds, based on the results of controlled exposure experiments. Evidence also exists, however, that other factors determining plant productivity

may be more important in controlling plant response in the field (e.g., water- and nutrient-use efficiency) than the differential CO_2 response (Bazzaz and McConnaughay, 1992). There currently is little experimental evidence to directly evaluate the effects of elevated CO_2 on weed infestation, insect pests, or plant diseases under field conditions. Less severe winters may increase the range and severity of insect and disease infestations. Temperature and moisture are critical to the spread and development of many plant diseases (IPCC 1996, WG II, Section 13.4.3). Successful disease development requires convergence of a susceptible host, a virulent pathogen, and suitable environmental conditions. Increased variability of precipitation, for example, could affect the host-parasite interaction positively or negatively, leading to more or less disease development (Shriner, 1980). Increased climate variability also could render less effective disease-forecasting models currently used to manage some diseases and require increased reliance on pesticides. North American agriculture will need to address these concerns in the context of increasing pressure on agriculture to reduce chemical inputs.

8.3.4.5. Yield and Production Changes by North American Subregion

Previous studies that have simulated the impact of climate change on the North American agriculture sector have taken a variety of approaches. Tables 13-11 and 13-12 in the SAR (IPCC 1996, WG II) outline the range and variability of yield impacts that have been suggested across a number of studies looking at climate change impacts for the United States and Canada. For these studies (IPCC 1996, WG II, Section 13.6.8), when biophysical and economic impacts were combined, market adjustments were found to lessen the impacts of negative yield changes. More recent projections of increases in global mean surface temperatures in the future are lower than past estimates. These lower estimates are derived from new, transient GCM scenarios that take into account the interactions between the atmosphere and oceans and the cooling effects of sulfate and other aerosols in the troposphere (Darwin, 1997). Most of the impact studies currently available for review have not utilized the projections from these more recent climate model simulations as a background; as a result, they may overestimate the magnitude of expected temperature impacts.

The outcome of the net economic impact summarized in the SAR (IPCC 1996, WG II, Section 13.6.8) was sensitive to assumptions about population, income, trade barriers, and institutions and ranged from negative to positive. For Canada, the vulnerability of the agricultural sector derives from the importance of agriculture to subregional (e.g., the prairies) and rural economies, the location of agriculture in a marginal climate with regard to temperature and precipitation, and limitations to
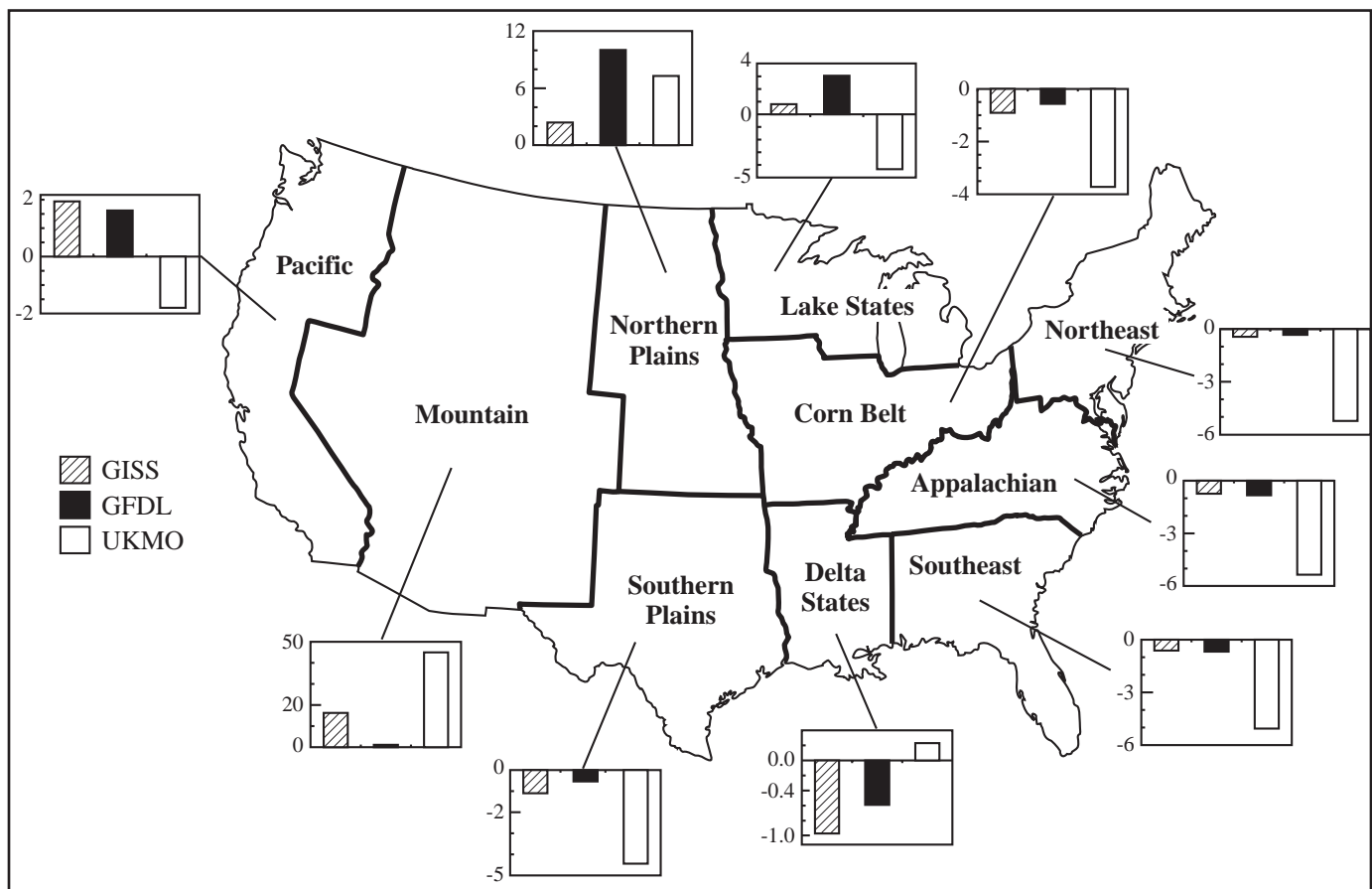
Figure 8-8: Effects of climate change on regional economic welfare (percentage change in total welfare from base, assuming 555 ppm CO_2 and changes in export demand) (adapted from Adams, 1995b). See page 287 for details of the climate scenarios used.

northward shifting of cropping by poor soil quality (Cohen *et al*., 1992).

Economic welfare may improve for more northerly farm production regions—with potential benefits indicated for the lake states, the northern Plains, the mountain region, and the Pacific region.

Evaluation of the direct and indirect effects of climate on yield at the farm, regional, or higher level of aggregation requires integrated models that consider system interactions. Changes in crop production, crop water demand, and regional water resources will arise as a consequence of climate change, although the impacts of these changes on agriculture will be modified by trends in world food production and commodity exports. These interactions can be modeled to estimate the economic consequences of climate change for regions of the United States. Adams *et al*. (1995a,b) used three GCM scenarios to evaluate the economic consequences to crop production and regional welfare if climate changes of similar magnitude were to occur. Figure 8-8 illustrates the subregional variability in economic welfare suggested by climate change, including a CO_2 fertilization effect (and accounting for changes in export demand). Based on these analyses, eastern, southeastern, and corn belt regions yielded estimates of negative impacts, while positive effects were projected for northern plains and western regions.

Subregional shifts in economic welfare with climate change will likely arise as a consequence of impacts on crops with specific temperature requirements for growth.

Citrus production, for example, may shift slightly northward as temperatures rise in southern states. Yields are predicted to decline in southern Florida and Texas as a consequence of higher-than-favorable temperatures during the winter (Rosenzweig *et al*., 1996). Warmer temperatures experienced at slightly more northern locations may lessen the chance of freeze damage, but the overall risk of early- and late-season frost will remain a major factor in crop loss. It is worth noting that as a woody perennial, citrus offers little possibility of short-term adaptation to climate change through management because the timing of phenological events in citrus is not under the control of the orchard manager. Other simulation studies show that corn and soybean yields may decrease across much of the U.S. corn belt with a 2°C rise in temperature (Phillips *et al*., 1996) and that potato yields may decrease on average by 22% across sites from Maine to Washington as temperatures increase 1.5–5°C (Rosenzweig *et al*., 1996).

Experimental results in combination with knowledge of physical and biological processes, along with modeling of these basic physiological processes, provide information on potential changes in yield, which can in turn provide input to an agricultural sector model capable of simulating sector-level impacts of alternative climate change scenarios (Adams *et al*., 1995a,b).

Recent work has extended previous studies regarding the economic effects of climate change on agriculture to address some of the limitations in earlier studies. This new work (Adams *et al*., 1995b) looks at U.S. agriculture sector impacts by incorporating other crops such as fruits and vegetables into the regional crop alternatives for the southeastern region and other southerly locations; considering the impacts of farmer adaptations to climate change; allowing for crop migration into regions where those crops are not currently being grown; incorporating changes in forage production and livestock performance; and assessing the potential for technological change, as manifested in present and future yields, to offset climate change.

The analyses by Adams *et al*. (1995b) used estimates from uniform incremental climate change scenarios and from two GCM-based analyses to assess a wide range of potential temperature and precipitation changes, as well as alternative levels for atmospheric CO_2 concentrations. The scenarios included 16 combinations of alternative temperature and precipitation changes (0°C, 1.5°C, 2.5°C, and 5°C for temperature and -10%, 0%, +7%, and +15% for precipitation). In addition, the analysis considered four alternative levels for atmospheric CO_2 concentrations (355, 440, 530, and 600 ppm). This scheme produced a total of 64 incremental scenarios, which were evaluated for 1990 and 2060 conditions. These scenarios represented the data set for estimation of a climate change response function for 1990 and 2060 conditions of technological development and agricultural demand. In addition to these uniform scenarios, the two GCM-based analyses used climate forecasts from the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL)-R30 GCMs (see Table 1-2). These analyses provided points of comparison with previous studies, as well as tests of the reasonableness of the economic effect response functions developed from the 64 uniform scenarios.

Estimation of the economic consequences of these scenarios required predictions of the impacts of climate change on yield levels for crops and forage, animal grazing requirements and performance, crop migration potentials, technology-based changes in yields, and changes in water resource availability. These predicted changes were then used in an economic model of U.S. agriculture. The economic model provided estimates of changes in social welfare, crop prices and quantities, resource use, and other measures of economic performance arising from the climate scenarios (Adams *et al.*, 1995b).

Under the majority of the climate change scenarios evaluated in the study, net welfare increased; only 34 of the 128 scenarios showed welfare losses. In general, increases in precipitation and CO_2 increase welfare. Slight-to-moderate increases in temperature also could increase welfare. The response function analysis also showed that increases in CO_2 and precipitation could offset the potentially negative effects of large temperature increases (Adams *et al.*, 1995b).

The magnitude of welfare changes showed modest gains for an optimistic case and modest loss to modest gain from an adverse case for present and future technology and economic growth cases, respectively.

The values represented very small percentage changes in total agriculture value (< 3% of the value of the base model solution). As a result, in the aggregate, Adams *et al.* (1995b) concluded that climate appears to be a relatively small stress to agriculture in the United States. Welfare losses from adverse climate change also tended to be smaller than previous estimates, whereas gains from favorable climate change tend to be larger because of the more comprehensive treatment of adjustment possibilities such as the inclusion of new crops and migration possibilities that were used in the analysis. This study concludes, as others have, that climate change of the type evaluated does not appear to be a food security issue for the United States (Adams *et al.*, 1995b). On the other hand, this study did not incorporate the costs of adaptations or the consequences of changes in subregional agricultural production for the economies of those subregions; it only addressed the consequences of change in mean climate, without increased climate variability; and it did not evaluate the possible consequences of potential secondary effects on pests, pathogens, or soils that might result from climate change. These shortcomings represent important research needs with regard to integrated modeling of climate change impacts for the agricultural sector.

Sensitivity analyses performed in conjunction with the Adams *et al.* (1995b) analyses indicated that potential farmer adaptations to climate change can play a major role in mitigating adverse effects of climate change, suggesting the importance of technology and related assumptions in future analyses. Sensitivity analyses of export assumptions reinforced the importance of world trade (exports) on the welfare of the U.S. agricultural sector. Global climate change is likely to increase the demand for U.S. commodities, with possible increases in welfare. Because of the importance of North American agriculture to world food production, trade issues are an important interregional consideration.

When the GCM-based analyses were considered, climate changes according to the GISS forecasts led to net welfare increases of $12 billion for the 1990 base—approximately 20% larger than previous analyses of GISS climate change using the Agriculture Sector Model (Adams *et al.*, 1995b). The increase was related primarily to changes in the model allowing other mitigation activities that permit the agricultural sector to exploit more fully new climate conditions. The GFDL-R30 analysis revealed losses of more than $14 billion (measured against the 1990 base). These losses arise from harsher climate conditions under the GCM. Results from the GCM cases did not compare well with estimates generated by response functions resulting from the uniform change scenarios, indicating the importance of regional differences in climate as determinants of estimates of national economic consequences.

Several global climate change scenarios imply modest improvements in the agroclimatic potential for high-latitude agriculture in North America.

Recent studies (Mills, 1994; Brklacich *et al.*, 1996, 1997a) have investigated the extent to which global climate change might shift the frontier for Canadian agriculture northward. About 1.2 million ha in the Peace River region of northern Alberta and British Columbia currently are devoted to spring-seeded cereals, forages, and pasture crops. Soils capable of supporting agricultural production north of the Peace River region (i.e., above 58°N latitude) are abundant, but these regions currently are too cool and too remote from markets.

Climate change scenarios derived from the GFDL and CCC $2xCO_2$ models were estimated to relax current constraints imposed by short, cool, frost-free seasons. However, it also was estimated that these benefits would be offset somewhat by declines in summer precipitation, with concomitant increases in crop moisture deficits (most notably under the CCC scenario).

The CERES-Wheat model was used to estimate the combined effects of increasing CO_2 levels to 555 ppm and the GFDL and CCC climatic change scenarios on spring wheat yields. Under the GFDL scenario, modest increases in spring-seeded wheat yields were estimated. Increases in crop moisture stress under the CCC scenario were estimated to offset the benefits of elevated CO_2 levels and longer, warmer, frost-free seasons; overall, modest declines in spring wheat yields were estimated.

Winter temperature increases were estimated at 3–4°C and 4°C under the GFDL and CCC scenarios, respectively. Assessments using CERES-Wheat indicated that these temperature increases would be sufficient to support winter wheat production at several locations within the Peace River region. It was also estimated that, for lands north of the Peace River region (i.e., north of the current climatic frontier for commercial agriculture), these temperature increases would not be sufficient to remove the risk of winter crop damage. In these northern prairie regions, soil capability to sustainably support agriculture may become more limiting than temperature.

Development of the capability to simulate the agricultural impacts of multiple transient climate scenarios is a research need that must be met to deal credibly with the cost of adaptation, about which there is significant uncertainty. Socioeconomic adjustment must be modeled to treat key dynamic processes—such as how the expectations of farmers change; whether farmers can easily detect climate change against a background of high natural variability; and how current investments in equipment, education, and training will affect the costs of adjustment.

8.3.4.6.   *Adaptation*

Historically, farming systems have adapted to changing economic conditions, technology, and resource availability and have kept pace with a growing population (CAST, 1992; Rosenberg, 1992). Evidence exists that agricultural innovation responds to economic incentives such as factor prices and can relocate geographically (Hayami and Ruttan, 1985; CAST, 1992). A number of studies indicate that adaptation and adjustment at all levels—but especially at the farm level—will be

important to limit losses or to take advantage of improving climatic conditions (IPCC 1996, WG II, Section 13.9). Examples of technological options for adaptation by agriculture include seasonal changes in sowing dates; different crop varieties or species; new crop varieties; water supply and irrigation systems; management adjustments with fertilizer, tillage, and so forth; and improved short-term climate prediction (IPCC 1996, WG II, Section 13.9.1; Darwin *et al.*, 1995). Socioeconomic options for adaptation include improved training and general education of populations dependent on agriculture; assessment of currently successful strategies for responding to climate variability; improved agricultural research to increase the robustness of new farming strategies; interactive communication to bring research results to farmers and farmers' problems to researchers; improved preservation and maintenance of genetic material critical to adaptation; and food programs to buffer against local supply changes. Transportation, distribution, and market integration provide additional flexibility for regions to respond to climate variability, and changes in policies could increase the adaptive capacity of agriculture (IPCC 1996, WG II, Section 13.9.2).

Recent analyses of issues of long-run sustainability associated with agricultural adaptation to climate change from arbitrary doubling of equivalent CO_2 concentrations have concluded that there is considerably more sectoral flexibility and adaptation potential than was found in earlier analyses.

Schimmelpfenning *et al.* (1996) concluded that the costs and benefits of climate change cannot be adequately evaluated independent of behavioral, economic, and institutional adjustments required by changing climate. Smit *et al.* (1996) and Brklacich *et al.* (1997b), in their research into agricultural adaptation to climatic variability and change in Ontario, reached a similar conclusion and urged that future research into agriculture and climatic change be reframed to explicitly consider agricultural decision making and adaptation processes. Although scientific controversy remains over the nature and rate of climate change and the importance of climate variability, most scenarios suggest gradual changes in mean temperature and precipitation over decades, providing opportunities for farms and other parts of the sector to adapt. In addition, the time scale of 80–100 years makes other profound social changes inevitable. Income and population growth and technological innovation will accelerate or decelerate, depending on global location, at the same time that adaptation to climate is taking place. Social and cultural factors may influence the rate at which adaptation measures are implemented within some subregions of North America. There may be time lags between decisions to follow an adaptive strategy and subsequent adjustments in the agricultural system. The costs and time required for such adjustments in infrastructure will need to be considered in planning adaptation options. Although none of these factors can be considered in isolation, recent research shows that the negative effects of climate change on agriculture probably are overestimated by studies that do not account for economic adjustments or consider the broader economic and environmental implications of such changes. However, uncertainties

remain about the implications of changes in climate variability, as well as crop responses to increases beyond a doubling of equivalent atmospheric CO_2 concentrations.

8.3.4.7. Vulnerabilities

Vulnerability to climate change-induced hunger or severe economic distress for the overall economy of North America as a result of climate change impacts on the agricultural sector is relatively low.

The United States and Canada have high GNP per capita; the agricultural population is a small share of the total population; and agriculture is, in general, a small share of the economy. These areas are important for world food production. Midcontinental areas of the United States and Canada are prone to drought, which would be exacerbated if climate change reduced moisture availability or increased the demand for water (as occurs in several GCM scenarios). Economic dislocation is likely to be limited to the agricultural sector or to subregions highly dependent on agriculture (IPCC 1996, WG II, Section 13.7). Evidence suggests that yields of crops grown at the margin of their climatic range or in climates where temperature or precipitation could easily exceed threshold values during critical crop growth periods are more vulnerable (Matthews *et al.*, 1994a,b; IPCC 1996, WG II, Section 13.7). A regional economy that offers only limited employment alternatives for workers dislocated by the changing profitability of farming is relatively more vulnerable than those that are economically diverse. As an example, the Great Plains area of North America is most dependent on agriculture and thus might be the most economically vulnerable to climate change (Rosenberg, 1993).

8.3.5. Food and Fiber: Production Forestry

Timber is one of the most valuable agricultural crops produced in North America. The forest products sector in the United States employs some 1.5 million people (1990) nationwide and adds approximately $80 billion to the GDP. Forest products are especially important to the economies of the Pacific Northwest and the southern United States. Two-thirds of U.S. forestlands (195 million ha) are considered productive enough to potentially support timber management and accessible to harvest. Less than one-third of U.S. timberlands are publically owned; approximately 15% is owned by the timber industry, and 57% is held by other private landowners. Timberland ownership differs greatly by region, with western forests largely on public lands and eastern forests largely in private ownership (OTA, 1993).

In Canada, direct employment in 1996 for the forest sector was 363,000; the sector contributed $16.177 billion to Canada's GDP. In terms of contribution to GDP, the sector is important to British Columbia, Quebec, and New Brunswick. Thirty-five percent of Canadian forestland is considered productive and accessible enough for harvest, though there may be some constraints

on harvesting. Ownership is 71% provincial, 23% federal (including territorial land), and 6% private.

See section 8.3.2 for a detailed discussion of the impacts of climate change on forest ecosystems.

Consumers and producers could gain or lose, and the long-term stability of the forest-products market could be jeopardized.

Enhanced forest growth scenarios and extensive forest dieback scenarios have been analyzed with respect to market processes. Under the most severe ecological scenarios—where forest dieback occurs relatively early and there are long-term reductions in timber inventories and harvest—consumer prices would increase; producers would benefit from higher prices, but overall benefits to society would decrease. Under scenarios of more moderate dieback or forest expansion, consumers could benefit from lower prices; producers might benefit or lose, depending on local forest responses to dieback, local demand, and access to national and international markets. Alternative management practices must be carefully considered if benefits are to be gained under moderate forest dieback scenarios. However, the long-term sustainability of forests and any benefits could vary considerably under different scenarios.

Analyses of the economic consequences of climate change have been based on a number of quite different ecological assessments and a variety of economic models, but all are based on the equilibrium FAR scenarios or on sensitivity analyses. One study coupled the FASOM forest sector model—incorporating flexible pricing and forest management—to output from forest gap models over the conterminous United States (Callaway *et al.*, 1995; Adams *et al.*, 1996). The results, with severe forest dieback, indicated consumer price increases of 100–250%, with economic losses of 4–20% of the net value of commercial forests.

A study by Van Kooten and Arthur (1989) concluded that forest productivity could tend to increase in Canada but could increase or decrease in the United States. Consumer prices could decrease (largely as a consequence of increases in Canadian forest growth and harvest). Producers could sustain economic losses, but with exports from Canada to the United States, net changes (consumers plus producers) could be negative for Canadians and positive for the U.S. market.

Timber growth in the conterminous United States in one study generally increased over a 50-year projection period, pushing prices down by 6–35% (Joyce *et al.*, 1995). A study using a global trade model produced similar results, with general increases in global forest productivity (Perez-Garcia *et al.*, 1997).

A study using a different forest-sector model in the United States incorporated management strategies that optimized pre- and post-dieback forest management practices (Sohngen and Mendelsohn, 1997). The value of the market (consumer plus producer surpluses) could increase by 1–11% under scenarios of either enhanced forest growth or moderate forest dieback. The increased flow of green or salvage trees into the market depressed prices, but overall losses to producers were minimized by shifting biomes or altered yield functions. Economically optimal management strategies (such as thinning, salvage logging, and species transplanting), however, might be restricted by social and ecological constraints.

The most intensively managed industry and private forestlands may be least at risk of long-term decline resulting from the impacts of climate change because the relatively high value of these resources is likely to encourage adaptive management strategies (OTA, 1993).

Private forest managers have the financial incentive and the latitude to protect against extensive loss from climate-related impacts. They can use several available techniques: short rotations to reduce the length of time a tree is influenced by unfavorable climate conditions; planting of improved varieties developed through selection, breeding, or genetic engineering to reduce vulnerability; and thinning, weeding, managing pests, irrigating, improving drainage, and fertilizing to improve general vigor. Such actions would reduce the risk from moisture stress and secondary risks from fire, insects, and disease. Thinning, for example, reduces competition for moisture and can effectively increase tolerance to drought; it also may speed development of a climate-adapted forest by removing trees that are growing poorly (OTA, 1993). However, some adaptive measures such as thinning or harvesting dead or dying trees could impact biodiversity, soil erosion, stream quality, and nonmarket forest products, generating potentially conflicting management options.

Binkley and van Kooten (1994) found that overall impacts on the Canadian forest sector would not be significant. This finding was attributed to the ability of the production forest sector to adapt to whatever species prevail during and after climate change; to salvage-cut dying stands; to plant cut areas with species that are better adapted to the projected climate; and to move to locations where resources are more plentiful. Long-run sustainable yield levels, however, may be reduced as a result of increased losses to fire and insect outbreaks. For example, in the Mackenzie Basin Impact Study, a general decline in forest production has been suggested for the basin because of a combination of factors—including increased area burned, increased susceptibility to pests, and drought-related die offs (Cohen, 1997a).

A healthy mixed-species, mixed-age forest probably is less susceptible to insect infestation than extensive areas of even-aged forest stands.

Planting single-species forests might seem to pose increased threats of loss from insect pests or disease because of limited genetic diversity (Perry and Maghembe, 1989). However, commercial tree species show a great deal of genetic diversity among individuals—even among trees from the same parents (Kitzmiller, 1993). This inherent diversity could make trees

less likely to succumb to a single pest or disease than most agricultural crops (Kellison and Weir, 1987). Forest managers should attempt to ensure diversity in the seedlings they use to establish their forest stands even if they are planting single-species forests (OTA, 1993).

Once a decline in forest health begins, less intensively managed forests may face greater fire and pest damage. At particular risk will be forests already subject to moisture stress and fire hazard.

Less-managed forests may not be at any greater inherent risk than actively managed forests, however. Once they are subjected to stress, wilderness forests and National Parks may be at elevated risk of substantial decline because of policy restrictions imposed on silvicultural and pest-management activities. Similarly, because management currently is limited on most National Forest lands and less-productive nonindustrial private lands, those forests could be at risk of unchecked loss. If the general health of these forests declines, their vulnerability to large-scale mortality could increase (OTA, 1993).

Forests maintained for the production of wood products and fiber would benefit from any near-term or long-term increase in productivity. Reduced growth or increased mortality would have a damaging effect. Managers of industry forests and other private timberlands can be expected to respond with adaptive measures if and when they perceive changes in climate and market conditions.

Although no timber company is altering forest practices today, some are actively preparing for the types of risks posed by climate change. Weyerhaeuser, for example, is conducting experimental silvicultural programs to examine the effects of thinning practices in ameliorating the effects of droughts (OTA, 1993). It also is sponsoring research on the genetics, physiology, and biotechnology of heat- and drought-tolerant seedlings. Such technological development should help protect the timber industry and future wood supplies (OTA, 1993).

Despite the possibility of some adaptive management responses, climate change could be very costly to the timber industry.

In the southern United States, declining timber volumes could lead to $300 million in lost annual revenues, whereas the increased management measures needed to compensate for poorer conditions could add $100 million to the annual costs of production (Regens *et al.*, 1989; Hodges *et al.*, 1992). A sea-level rise could force the movement of coastal pulp and paper mills, further increasing the costs of climate change. Some of these mills would cost as much as $1 billion to replace. For the Pacific Northwest, an expanded upslope range of Douglas fir forests might add 5% to the regional timber harvest (Hodges *et al.*, 1992). However, the increased costs of logging at higher elevations could offset much of this potential gain.

A report by the Office of Technology Assessment of the U.S. Congress (OTA, 1993) identified a number of adaptation strategies that should be considered to maintain and enhance commercial forest productivity under climate change. These strategies are largely measures that have value to the forest industry even without climate change but would serve to ameliorate the impacts of climate change as well:

- Establish an expanded forest seed-bank program to ensure maintenance of genetic diversity.
- Prepare to respond to major forest declines through improved forest health maintenance and measures to minimize risk of fire and pest and disease outbreaks.
- Develop new management strategies focused on adaptation to climate change.
- Improve incentives for maintaining and protecting private forestland.

8.3.6. Food and Fiber: Fisheries and Aquatic Systems

Although there is considerable uncertainty about the physical changes and response of the various freshwater and marine species, it is possible to suggest how certain species may respond to projected climate changes over the next 50–100 years. The uncertainties highlight the importance of research to separate the impacts of changing climate from natural population fluctuations and fishing effects. Many commercial finfish populations already are under pressure (e.g., overexploited), and global change may be of minor concern compared with the impacts of ongoing and future commercial fishing and human use or impacts on the coastal zone. Further, changes in the variability of climate may have more serious consequences on the abundance and distribution of fisheries than changes in mean conditions alone (Katz and Brown, 1992), and changes in future climate variability are poorly understood at this time.

Fish, including shellfish, respond directly to climate fluctuations, as well as to changes in their biological environment (predators, prey, species interactions, disease) and fishing pressures. Although this multiforcing sometimes makes it difficult to establish unequivocal linkages between changes in the physical environment and the responses of fish or shellfish stocks, some effects are clear (see reviews by Cushing and Dickson, 1976; Bakun *et al.*, 1982; Cushing, 1982; Sheppard *et al.*, 1984; Sissenwine, 1984; and Sharp, 1987). These effects include changes in the growth and reproduction of individual fish, as well as the distribution and abundance of fish populations. In terms of abundance, the influence occurs principally through effects on recruitment (how many young survive long enough to potentially enter the fishery) but in some cases may be related to direct mortality of adult fish.

Fish carrying capacity in aquatic ecosystems is a function of the biology of a particular species and its interrelationship with its environment and associated species. Specific factors that regulate the carrying capacity are poorly known for virtually all species, but some general statements can be made with some

confidence. Fish are affected by their environment through four main processes (Sheppard *et al*., 1984):

- *Direct physiological effects, including metabolic processes influenced by temperature, salinity, and oxygen levels*—Fish often seek optimal temperature or salinity regimes or avoid suboptimal conditions. Thus, ocean and freshwater changes as a result of projected climate changes can lead to distributional changes. In suboptimal conditions, performance is reduced, leading to starvation or increased predation.
- *Diseases*—Certain environmental conditions are more conducive to diseases than others (e.g., warm waters can trigger disease outbreaks; likewise, cold temperatures can limit them).
- *Food*—The environment affects feeding rates and competition, as well as abundance, quality, size, timing, spatial distribution, and concentration of food.
- *Predators*—The environment affects predation through influences on the abundance and distribution of predators.

Fish are influenced not only by temperature and salinity conditions but also by mixing and transport processes (e.g., mixing can affect primary production by promoting nutrient replenishment of the surface layers; it also can influence the encounter rate between larvae and prey organisms). Ichthyoplankton (fish eggs and larvae) can be dispersed by the currents, which may carry them into or away from areas of good food production, or into or out of optimal temperature or salinity conditions—and perhaps, ultimately determine whether they are lost to the original population.

Climate is only one of several factors that regulate fish abundance. Managers attempt to model abundance trends in relation to fishing effects in order to sustain fisheries. In theory, a successful model could account for global warming impacts along with other impacts without understanding them. For many species of fish, the natural mortality rate is an inverse function of age: Longer-lived fish will be affected by natural changes differently than shorter-lived fish. If the atmosphere-freshwater-ocean regime is stable for a particular time, it is possible to estimate the age-specific mortality rates for a species of interest. However, at least some parts of the atmosphere-freshwater-ocean system are prone to oscillations on a decadal scale, which may not be cyclical. These natural changes occur globally; thus, they will have impacts on the freshwater and marine ecosystems that support North American fish populations. Under natural conditions, it may be expected that the different life histories of these fish will result in different times of adjustment to a new set of environmental conditions.

Any effects of climate change on fisheries are expected to be most pronounced in sectors that already are characterized by full utilization, large overcapacities of harvesting and processing, and sharp conflicts among users and competing uses of aquatic ecosystems. Climate change impacts, including changes in natural climate variability on seasonal to interannual time scales, are likely to exacerbate existing stresses on fish stocks. The effectiveness of actions to reduce the decline of fisheries depends on our ability to distinguish among these stresses and other causes of change and on our ability to effectively deal with those over which we have control or for which we have adaptation options. This ability is insufficient at present; although the effects of environmental variability are increasingly recognized, the contribution of climate change to such variability is not yet clear.

Recreational fishing is a highly valued activity that could incur losses in some regions as a result of climate-induced changes in fisheries.

Recreational fishing is a highly valued activity within North America. In the United States, for example, 45 million anglers participate annually; they contribute to the economy through spending on fishing and related activities (US$24 billion in 1991). The net economic effect of changes in recreational fishing opportunities as a result of climate-induced changes in fisheries is dependent on whether projected gains in cool- and warm-water fisheries offset losses in cold-water fisheries. Work by Stefan *et al*. (1993) suggests mixed results for the United States, ranging from annual losses of US$85–320 million to benefits of about US$80 million under a number of GCM projections. A sensitivity analysis (U.S. EPA, 1995) was conducted to test the assumption of costless transitions across these fisheries. This analysis assumed that best-use cold-water fishery losses caused by thermal changes were effectively lost recreational services. Under this assumption, all scenarios resulted in damages, with losses of US$619–1,129 million annually.

8.3.6.1. Freshwater Ecosystem Impacts, Adaptations, and Vulnerabilities

Commercial and recreational freshwater fisheries are important to the economy of many regions, as well as the well-being of native populations. In many aquatic ecosystems, freshwater fish also are important in maintaining a balance in other aquatic populations lower in the food web (via predatory and other effects). In broader terms, aquatic ecosystems are important as recreational areas, as sources of water for domestic and industrial use, and as habitat for a rich assemblage of species, including some that are threatened or endangered.

Several studies have indicated that projected climate change will have important impacts on North American freshwater fisheries and aquatic ecosystems. It must be noted, however, that most studies to date have used results from earlier climate model simulations that gave air temperature increases under a $2xCO_2$ climate that were as much as twice as large for the same time period as more recent estimates that include aerosol forcing—thus overestimating the effects of temperature increases, particularly in the summer.

Changes in survival, reproductive capacity, and growth of freshwater fish and the organisms and habitats on which they

depend result from changes in water temperature, mixing regimes, and water quality.

In North America, freshwater fish have been grouped into three broad thermal groups (cold-water, cool-water, and warm-water guilds) based on differences in the temperature optima of physiological and behavioral processes. In simulations of deep, thermally stratified lakes in the mid- and high latitudes, including the Laurentian Great Lakes, winter survival, growth rates, and thermal habitat generally increase for fish in all three thermal guilds under the $2xCO_2$ climate (DeStasio *et al.*, 1996; IPCC 1996, WG II, Sections 10.6.1.2 and 10.6.3.2; Magnuson and DeStasio, 1996). However, in smaller mid-latitude lakes, particularly those that do not stratify or are more eutrophic, warming may reduce habitat for many cool-water and cold-water fish because deep-water thermal refuges are not present or become unavailable as a consequence of declines in dissolved oxygen concentrations (IPCC 1996, WG II, Section 10.5.4). For example, Stefan *et al.* (1996) examined the effect of temperature and dissolved oxygen changes in lakes in Minnesota; they projected that under a $2xCO_2$ climate (from a GISS GCM that projected a 3.8°C air temperature increase in northern Minnesota), cold-water fish species would be eliminated from lakes in southern Minnesota, and cold-water habitat would decline by 40% in lakes in northern Minnesota.

Changes in the productivity and species composition of food resources also may accompany climatic warming and, in turn, influence fish productivity. Production rates of plankton and benthic invertebrates increase logarithmically with temperature; rates increase generally by a factor of 2–4 with each 10°C increase in water temperature, up to 30°C or more for many organisms (Regier *et al.*, 1990; Benke, 1993; IPCC 1996, WG II, Section 10.6.1.1). Although this effect generally should increase fish productivity, shifts in species composition of fish prey with warming might prevent or reduce productivity gains. Biogeographic distributions of aquatic insects are centered around species thermal optima, and climate warming may alter species composition by shifting these thermal optima northward by about 160 km per 1°C increase in temperature (Sweeney *et al.*, 1992; IPCC 1996, WG II, Section 10.6.3.1). If species range shifts lag changes in thermal regimes because of poor dispersal abilities or a lack of north-south migration routes (e.g., rivers draining northward or southward) or if species adaptation is hindered by limited genetic variability, climatic warming might result initially in reductions in the preferred prey organisms of some fish (IPCC 1996, WG II, Section 10.6.3.3).

Climatic warming may result in substantial changes in the thermal regimes and mixing properties of many mid- and high-latitude lakes. In the mid-latitudes, some lakes that presently are dimictic (mixing in spring and autumn) may no longer develop winter ice cover and may become monomictic (mixing during fall, winter, and spring), with a longer summer stratification period. At high latitudes, some lakes that presently are monomictic and mix during summer may stratify in summer and mix twice a year, in autumn and spring (IPCC

1996, WG II, Section 10.5.4). Changes in lake mixing properties may have large effects on hypolimnetic dissolved oxygen concentrations (affecting available fish habitat) and on epilimnetic primary productivity, although these effects are likely to depend greatly on the morphometric characteristics of individual lakes and are difficult to predict (IPCC 1996, WG II, Section 10.5.4). For example, longer summer stratification and higher water temperature result in more severe hypolimnetic oxygen depletion in lakes in Minnesota under a $2xCO_2$ climate simulation (Stefan *et al.*, 1993). In other lakes, reduction in the duration or lack of winter ice cover might reduce the likelihood of winter anoxia (IPCC 1996, WG II, Section 10.6.1.4). At high latitudes, development of summer stratification under a warmer climate might increase lake primary productivity by maintaining algae for longer periods within the euphotic zone. Climate changes that result in decline in runoff also may have substantial effects on the mixing properties of smaller lakes that are heavily influenced by fluxes of chemicals from their catchments. For example, the surface mixed layer of boreal lakes at the Experimental Lakes Area in northwest Ontario has deepened over the past 20 years as a result of a long-term drought that reduced inputs of DOC from the catchment and thus increased water clarity (IPCC 1996, WG II, Section 10.5.3 and Box 10-2; Schindler *et al.*, 1996).

Long-term research and monitoring of key physical, chemical, and ecological properties (particularly water temperature and mixing properties; concentrations of nutrients, carbon, and major ions; acid/base status; populations of key organisms; primary production; and organic-matter decomposition) remain key research needs to reduce uncertainties in projections of freshwater fisheries' responses to climate change.

Climate warming may result in general shifts in freshwater species' distributions northward, with widespread/subregional species extinction at the lower latitudes and expansion at the higher latitudes of species' ranges.

Climatic warming may produce a general shift in species distribution northward. Species extinction and extirpations are likely to occur at the lower latitude boundaries of species distributions, and range expansion likely will occur at the higher latitude boundaries of species distributions (IPCC 1996, WG II, Section 10.6.3). For example, a 3.8°C increase in mean annual air temperature is projected to eliminate more than 50% of the habitat for brook trout and result in severe fragmentation of its distribution in the southern Appalachian Mountains in the southeastern United States (Meisner, 1990). In contrast, a 4°C increase in mean air temperature is projected to expand the ranges of smallmouth bass and yellow perch northward across Canada by about 500 km (Shuter and Post, 1990).

In streams and rivers, particularly at low and mid-latitudes, the distributions of many fish species may contract because of limitations on availability of thermal refuges and migratory routes during periods of high temperatures and lower streamflow in the summer (IPCC 1996, WG II, Section 10.6.3.2). Eaton and Scheller (1996) project that the suitable habitat for cold-, cool-,

and even many warm-water fish species would be reduced by about 50% in streams of the lower 48 states in the United States by summer mean air temperature increases of 2–6°C (derived from a CCC GCM under a $2xCO_2$ climate). In the North Platte River drainage of Wyoming, Rahel *et al*. (1996) project losses from the present geographic range of cold-water fish species of from 7–16% for a 1°C increase to 64–79% for a 5°C increase in summer air temperatures, with considerable fragmentation of remaining populations. In a national study of climate-induced temperature effects on fish habitat, complete elimination of cold-water habitat is projected for sites modeled in 5 to 10 states and severe reductions in 11 to 15 states, depending on the GCM climate projection used (U.S. EPA, 1995). It must be noted, however, that most studies of warming effects on stream fish populations have used mean temperature increases that generally are greater than those produced by current models for the same time period; these later models include aerosol forcing and show minimal summer daytime changes and more cloud cover in summer for many regions.

Whole ecosystem experiments that alter the thermal, hydrological, or mixing regimes in small lakes and streams or in large-scale mesocosms (e.g., lake enclosures or artificial streams) are needed to determine the responses of organisms, processes, and habitats to global change. Additional work also is needed in the area of comparative studies of populations or ecological processes across latitudinal and hydrological gradients and ecosystem types to enable us to better understand climate-induced temperature effects in the context of natural seasonal and interannual variability.

In addition, qualitative projections of the consequences of climate change on the fish resources of North America will require good regional atmospheric and oceanic models of the response of the ocean to climate change; improved knowledge of the life histories of the most vulnerable species for which projections are required; and a further understanding of the roles that the environment, species interactions, and fishing play in determining the variability of growth, reproduction, and abundance of fish stocks.

If climate changes result in lower water levels, reduced runoffs, and increased hydrological variability, the productivity of some freshwater species may decline.

In areas of North America that experience significant reductions in runoff, lower water levels in some lakes may eliminate or reduce the productivity of fish species dependent on shallow near-shore zones or adjacent wetlands as spawning or nursery areas (IPCC 1996, WG II, Section 10.6.2.2). Some shallow lakes with relatively short water residence times may disappear entirely with reduced annual runoff. For example, Marsh and Lesack (1996) project with a hydrological model that under a $2xCO_2$ climate, many lakes in the Mackenzie delta in the Canadian arctic could disappear in several decades as a result of decreased precipitation and flooding frequency. In some lake districts, connectivity among lakes would be decreased by the cessation of flow in connecting streams—possibly eliminating species such as northern pike from some shallow-water lakes because they no longer have connections to deep-water lakes for winter habitat (IPCC 1996, WG II, Section 10.6.2.2).

In many areas, increases in flow variability are likely to produce larger effects on biota than changes in mean flows (IPCC 1996, WG II, Section 10.6.2.1), which could result in some changes in ecosystem productivity and organism abundance (including positive and negative effects). In arid-land streams, more intense storms and longer periods of drought may produce severe streambank erosion, lower biomass and productivity, and a decline in biological interactions (IPCC 1996, WG II, Box 10-3). In humid regions, more intense or clustered storms could reduce the abundance of many stream organisms via scouring of streambeds, although greater frequency of flood-plain flooding also might increase the productivity of many river and stream organisms. Longer periods of drought in humid regions, particularly in summer, could increase the probability that streams will cease flowing and become dry; reductions in annual runoff also could increase the probability that streams will dry. In a regional analysis of U.S. streams, Poff (1992) projected that nearly one-half of perennial runoff streams in the eastern United States may become intermittent with only a 10% decline in annual runoff. Even if streams do not become intermittent, longer droughts and lower summer baseflows could result in more severe water quality deterioration (low dissolved oxygen concentrations, high concentrations of contaminants), which will reduce available habitat and eliminate intolerant species from streams (IPCC 1996, WG II, Section 10.5.4).

8.3.6.2. Oceans

An early review (Wright *et al*., 1986, summarized by Mann, 1993) projected that for the northern Atlantic, some of the consequences of global warming could include:

- A rise in the average sea surface temperature, causing an increase in evaporation and a more vigorous hydrological cycle of precipitation, runoff, and so forth
- The greatest increase in evaporation in mid-latitudes, leading to increased precipitation in northern regions, increased river runoff, increased stability of the water column, and increased strength of buoyancy-driven currents such as the Labrador current
- An increase in the north-south gradient in salinity
- A decrease in the thickness and extent of ice cover
- A reduction of the north-south temperature gradient and possibly a reduction in average wind stress over the whole of the north Atlantic, which could lead to a decrease in the strength of wind-driven currents such as the Gulf Stream.

In their summary of the Symposium on Climate Change and Northern Fish Populations, Sinclair and Frank (1995) described the variability of the northern Pacific in circulation and mixing and linked that variability in part to shifts in atmos-

pheric circulation—specifically, the changes in the location and level of the Aleutian low-pressure system. Existing models have not been able to shed light on the most probable responses of the northern Pacific to a doubling of atmospheric CO_2.

Mann (1993) briefly considered various sources of data for the wind-driven coastal upwelling system off California. He suggested that available data could be used to support the hypothesis that coastal upwelling increases during global cooling but decreases during global warming.

8.3.6.3.   Impacts, Adaptations, and Vulnerabilities of Ocean Fisheries Resources

Overall, there likely will be relatively small economic and food supply consequences at the regional/national level; however, impacts are expected to be more pronounced at the subregional level.

Natural climate variability—for example, changes in ocean temperatures and circulation patterns associated with the El Niño phenomenon and with the northern Pacific gyre—affects the distribution and composition of fisheries. Because interannual and decadal-scale natural variability is so great relative to global change and the time horizon on capital replacement (ships and plants) is so short, impacts on fisheries can be easily overstated; there likely will be relatively small economic and food supply consequences in the United States and Canada at the national level. At the state or regional level, impacts (positive and negative) will be more pronounced, particularly when a center of production shifts sufficiently to make one fishing port closer to a resource while a traditional port becomes more distant. Over time, fishing vessels and their support structure will relocate, followed by processors and eventually families as well. Community impacts can be significant.

Changes in primary production levels in the ocean as a result of climate change may affect fish stock productivity. As a first step in assessing the role of changes in primary production on fish productivity, global primary production in the ocean has been estimated by Longhurst *et al*. (1995) using satellite measurements of near-surface chlorophyll fields. Annual global primary production was estimated at 45–50 Gt carbon (C)/year. This annual global primary production is the sum of the annual primary production in 57 biogeochemical provinces covering the world ocean. More than 10 such provinces border North America. For example, the total primary production is estimated at 0.37 Gt C/year in the "California Upwelling Coastal" province and 1.08 Gt C/year in the "Northwest Atlantic Continental Shelf" province.

Exactly how climate-induced changes in primary production would affect the next trophic link, zooplankton, remains a matter of debate (e.g., Banse, 1995). However, changes in zooplankton biomass are known to affect fish stock productivity. Brodeur and Ware (1995) identified a twofold increase in salmonid biomass in the eastern subarctic Pacific since the 1950s, coincident with a large-scale doubling of the summer zooplankton biomass in the same region. Beamish and Bouillon (1995) examined trends in marine fish production off the Pacific coast of Canada and the United States. They concluded that the carrying capacity for fish in the northern North Pacific Ocean and the Bering Sea fluctuates in response to long-term trends in climate.

Projected changes in water temperatures, salinity, and currents can affect the growth, survival, reproduction, and spatial distribution of marine fish species and of the prey, competitors, and predators that influence the dynamics of these species.

Environmental conditions have a marked effect on the growth of many fish species. For example, mean bottom temperatures account for 90% of the observed (10-fold) difference in growth rates between different Atlantic cod (*Gadus morhua*) stocks in the north Atlantic (Brander, 1994, 1995). Warmer temperatures lead to faster growth rates. Regional studies have shown similar results (Fleming, 1960; Shackell *et al*., 1995). In the northwest Atlantic, the largest cod typically are found on Georges Bank—where a 4-year-old fish, on average, is five times bigger than one off Labrador and Newfoundland. Temperature accounts not only for differences in growth rates between cod stocks but also year-to-year changes in growth within a stock.

In addition to growth, the environment affects the reproductive cycle of fish and shellfish. For example, the age of sexual maturity of certain fish species is determined by ambient temperature. Atlantic cod off Labrador and the northern Grand Banks mature at age 7 and in the northern Gulf of St. Lawrence and the eastern Scotian Shelf at age 6; in the warmer waters off southwest Nova Scotia and on Georges Bank, they mature at 3.5 years and 2 years, respectively (Myers *et al*., 1996).

Spawning times also are influenced by temperature. Generally, cold temperatures result in delayed spawning (Hutchinson and Myers, 1994a), whereas warm temperatures result in earlier spawning. Marak and Livingstone (1970) found that a 1.5–2°C temperature change produced a difference in the spawning time of haddock on Georges Bank by a month, with earlier spawning and a longer duration in warmer years.

Temperature is one of the primary factors, along with food availability and suitable spawning grounds, that determine the large-scale distribution patterns of fish and shellfish. Because most fish species or stocks tend to prefer a specific temperature range (Coutant, 1977), long-term changes in temperature can lead to expansion or contraction of the distribution range of certain species. These shifts generally are most evident near their northern or southern boundaries; warming results in a distributional shift northward, and cooling draws species southward.

Changes in distribution also were observed during a warming trend in the 1940s in the Gulf of Maine—which produced a northward shift in the abundance and distribution of Atlantic mackerel, American lobster, yellowtail flounder, Atlantic men-

haden, and whiting, as well as the range extension of more southern species such as the green crab (Taylor *et al.*, 1957).

Frank *et al.* (1990) projected a northward shift of the southern extensions of important fisheries such as Atlantic cod, Atlantic halibut, American plaice, and redfish out of the Gulf of Maine and into Canadian waters. Also projected is the northern extension of more southern fish species such as Atlantic menhaden, butterfish, and redhake further northward into the Gulf of Maine. Coutant (1990) suggests a northward shift of summer stocks of striped bass, with losses occurring for Virgina, Delaware, and New York and gains projected for Massachusetts, New Hampshire, Maine, and New Brunswick.

Understanding recruitment variability has been the number one issue in fisheries science in this century. Since the advent of intensive fishing, it has become increasingly difficult to sort out the relative importance of fishing versus environment as the cause of recruitment variability. Still, recruitment levels frequently have been associated with variations in temperature during the first years of life of the fish (Drinkwater and Myers, 1987). American lobster landings increased steadily during the 1980s and into the 1990s, to all-time historic highs. However, the temperature/landing relationships for lobster are not consistent with an expected positive linear relationship—suggesting that more than one variable can control the relationship, and a different variable may be the dominant one at any given time.

Climate also can affect the fishery through its influence on availability (fish available to be caught) and catchability (difficulty to catch), both of which depend not only on the abundance of fish but on when and how they are distributed. If cod traps are located in waters that are too cold, catches are low. Only when the temperature is warm enough do catches increase. In the case of lobster catchability, when temperatures are low, lobster are known to move slowly, reducing the potential for encountering lobster traps and hence reducing catchability (McLeese and Wilder, 1958).

Climate change can be expected to result in distributional shifts in species, with the most obvious changes occurring near the northern or southern boundaries of species' ranges. Migration patterns will shift, causing changes in arrival times along the migration route. Growth rates are expected to vary (with the amplitude and direction species-dependent). Recruitment success could be affected by changes in time of spawning, fecundity rates, survival rate of larvae, and food availability. Another possibility associated with climate change is a change in stratification (as a result of differences in heating, freshwater, and vertical mixing rates), which may lead to changes in the ratio of pelagic to groundfish abundance (Frank *et al.*, 1990). If stratification were to increase, more production would be expected to be recycled within the upper layers of the oceans, and less would reach the bottom.

Evidence of environmental control on the distribution of marine fish is abundant. For example, Welch *et al.* (1995) have identified critical temperatures defining the southern bound-

aries of salmonid species. The authors suggest that future temperature changes in the northern Pacific therefore could have a direct impact on the production dynamics of Pacific salmon. Impacts of global warming in the ocean, however, will be difficult to separate from natural shifts in ocean carrying capacity. A general warming of the ocean will have an impact on predators and prey distributions. In the Strait of Georgia, there was an abrupt decline in marine survival after the 1976–77 regime shift, but the mechanisms responsible remain unknown. On the west coast, warm periods after the 1989–90 climate change resulted in an influx of predators that caused large increases in juvenile mortalities. It is impossible to forecast the actual changes in the marine ecosystems; thus, the degree to which chinook marine survival may be affected is unknown. The abruptness of change in the Strait of Georgia and the west coast is of concern because it indicates that signals of change need to be detected quickly and managed effectively (Beamish *et al.*, 1997).

Because salmonid species (and other anadromous species such as striped bass) rely on marine and freshwater aquatic systems at different points in their life cycles, projected changes in marine and freshwater water temperatures, ocean currents, and freshwater flows are more likely to impact growth, survival, reproduction, and spatial distribution of these species than of other fish species.

Because of their anadromous life history, pink salmon are affected by changes in freshwater and changes in the ocean—and the impacts in each of these habitats are equally important. Recent research has shown that trends in pink salmon productivity shift in response to climate-driven changes in the ocean. Because the mortality of young pink salmon is so high (95–98%) shortly after they first enter the ocean, small changes in marine survival can result in large changes in adult returns.

Warmer freshwater and oceans and changes in the pattern of Fraser River flows probably will reduce the abundance of pink salmon, although individual size may increase because of improved growth in the warmer water. Warmer temperatures will reduce incubation time, and the longer period in fresh water will improve growth. In the smaller rivers, where flows are a function of winter precipitation, increased precipitation may increase water flows—resulting in higher egg and alevin mortality. Dracup *et al.* (1992) examined the effect of climate change in altering the timing of streamflow regimes; they suggest that these changes may increase mortality and reduce fish population in the Sacramento-San Juaquin chinook salmon fishery.

Marine effects obviously are relevant to hatchery-reared fish. Reduced coastal productivity resulting from reduced upwelling may reduce the total carrying capacity for pink salmon, and it may not be possible to build stocks to historic levels in a poor-productivity regime by producing more fry.

In recent years, research has shown that chum salmon productivity follows trends that shift in relation to climate-related changes in the ocean. Thus, changes in upwelling and the

intensity of winds may reduce the carrying capacity for chum in the ocean to levels below what might occur during natural changes.

Increases in temperature in freshwater rearing areas and increased winter flows may increase freshwater chum mortalities for stocks in the Fraser River and other southern rivers. Chum are a very adaptable species, however, and spawning tends to be in the lower portion of rivers and streams; thus, the changes in saltwater may be more influential than changes in fresh water. It is possible that earlier and larger spring flows in rivers may improve survival in the ocean, if the initiation of the spring bloom occurs at a more favorable time. In recent years, relatively large numbers of age-0 ocean chum salmon have remained in the Strait of Georgia until late in the year, even though the surface temperatures have increased over the past 20 years. This pattern may indicate that the timing of plankton production is more favorable as a result of larger flows in April (Beamish *et al*., 1997).

In the south, warmer river water and reduced flows in late summer may increase mortalities and reduce spawning success. Warmer waters in the winter will accelerate incubation and hatching and cause alevins to enter lakes earlier. Henderson *et al*. (1992) concluded that warming of sockeye rearing lakes would lower plankton production and reduce the size of smolts going to sea. These smaller smolts also may encounter reduced food when they enter the ocean, and the resulting slower growth may expose juveniles to predation longer and increase mortality in the early marine period. Welch *et al*. (1995) proposed that global warming would increase winter temperatures sufficiently that sockeye juveniles would migrate out of the northern Pacific into the Bering Sea, effectively reducing the winter feeding area. It is known that there are large interannual fluctuations in survival (Burgner, 1991) and large, natural, decadal shifts in marine survival (Hare and Francis, 1995; Adkison *et al*., 1996; Beamish *et al*., 1997). The mechanisms involved are not understood, but the shifts in abundance clearly show that changes in the ocean environment have profound impacts on the productivity of the stocks.

It is possible that changes affecting the northern stocks may not have a major impact on the stocks in the next 50 years. This speculation is based on the cumulative effects of freshwater and marine events in the early 1990s that have produced historic high returns to some of the northern sockeye stocks in Canada and Alaska.

Projected changes in climate can affect the timing of the return of anadromous species to fresh water to spawn in some of the smaller streams. Changes in the timing of spawning can change the behavior (e.g., select for later-spawning fish); however, it is not anticipated that large numbers of stocks would be adversely affected in the next 50 years. Warmer rivers will shorten the incubation time, which may result in a longer growing season in fresh water. Although fish may feed longer and grow to larger sizes, they also may enter the ocean earlier. This shift may change the percentage of life history types that survive more

than overall survival because there already is an extended period of entry into saltwater for the various rearing types.

Aquaculture potential will be affected by projected changes in climate and climate variability and could take advantage of extended favorable conditions in currently marginal areas.

Most of the recent growth in total fisheries production is from aquaculture, which has grown rapidly during the past few decades and accounts for about 10% of total world fish production—mostly of higher-valued products. Aquaculture contributes to the resiliency of the fisheries industry, tending to stabilize supply and prices. Advancements are unevenly distributed across regions, farming systems, and communities. Growth in the United States is about 5% annually. The marine component is growing rapidly, but freshwater aquaculture is still dominant. Aquaculture will not rapidly solve the scarcity of natural fish, and current industry growth will fulfill the demand only for certain commodities, regions, and consumer groups.

Genetic engineering holds great promise to increase the production and efficiency of fish farming (Fischetti, 1991). However, fishers and resource managers are very concerned about accidental or intentional release of altered and introduced species that might harm natural stocks and gene pools. Around Scandinavia, escapees and nonindigenous reproduction may have reached or exceeded the recruitment of salmon wild stocks (Ackefors *et al*., 1991). Other concerns associated with aquaculture are the discharge of excess nutrients into surrounding waters that can add to eutrophication; the heavy use of antibiotics and contamination with pesticides, potentially leading to disease outbreaks; and the introduction of pathogenic organisms and antibiotic-resistant pathogens.

Ranching (in which young fish are released to feed and mature at sea) and fish farming, like their equivalents on land, have self-generated and imposed impediments to success. The activities can compete for coastal space with other uses, and continued expansion can jeopardize the quality and quantity of fish habitat (e.g., through loss of mangroves and wetlands, competition for food with wild stocks, or other factors) (NCC, 1989).

Climate variability is important to aquaculture. Decreasing temperatures may cause low minimum temperatures through the year—possibly causing mass mortalities, especially along the east coast. Long-term temperature trends will affect what species of fish or shellfish are suitable, as well as the expansion or contraction of suitable aquaculture sites. General warming may allow aquaculture sites to expand into regions previously unavailable because water temperatures were too cold or there was a presence of sea ice. Growth rates of fish or shellfish and their food requirements are temperature dependent. Aquaculturists also are interested in projections of wind mixing, which contributes to flushing (i.e., the exchange of water between the aquaculture site and surrounding waters). Low flushing can lead to decreased oxygen; greater potential for the spread of diseases; and, in the case of filter feeders such as mussels, reduced food availability.
The survival, health, migration, and distribution of many North

American marine mammals and sea turtles are expected to be impacted by projected changes in the climate through impacts on their food supply, sea-ice extent, and breeding habitats.

In North American waters, approximately 125 extant species of marine mammals (e.g., whales, dolphins, seals, sea lions, polar bears, and marine otters) are known to occur at least some time during the year. Although reliable abundance estimates for these mammals in North America are limited, there are endangered or threatened species among these mammals (e.g., 28 species are listed as either endangered or threatened under the U.S. Endangered Species Act or depleted under the U.S. Marine Mammal Protection Act); many are recovering from commercial harvesting and overexploitation.

Many marine mammals (e.g., the great whales) are able to locate and follow seasonal centers of food production, which frequently change from year to year depending on local oceanographic conditions. Similarly, their migrations may change to accommodate interannual differences in environmental conditions. However, some marine mammals (e.g., seals and sea lions) have life histories that tie them to specific geographic features (e.g., pupping beaches or icefields). Although there is some flexibility in their need for specific habitats, some marine mammals may be more severely affected than others by changes in the availability of necessary habitats and prey species that result from climate change.

Seasonal sea-ice extent, at least in some areas of the Northern Hemisphere, is retreating. This information, coupled with projections of warming, suggests that current barriers to gene flow among marine mammal stocks in the Arctic may change dramatically in the next 50 years. Although this shift may not result in a reduction in abundance at the species level, it could very well change the population structure of many species of Arctic whales and seals, which will greatly affect their management.

Coastal wetlands and beaches may be eliminated in some areas by rising sea level. As a result, marine mammal calving and pupping beaches may disappear from areas where there are no alternatives. Affected marine mammals could include, for example, all of the temperate and tropical seals and sea lions, coastal whales and dolphins, and manatees in estuarine habitats.

Six species of sea turtles (all of which are listed as endangered or threatened under the U.S. Endangered Species Act) regularly spend all or part of their lives off North American coasts and in U.S. territorial waters of the Caribbean Sea and Pacific Ocean. The loss of nesting beaches that would result from combination of coastal development and projected sea-level rise is a threat to all marine turtle species.

8.3.7.   Coastal Systems

Rising sea level is gradually inundating wetlands and lowlands; eroding beaches; exacerbating coastal flooding; threatening coastal structures; raising water tables; and increasing the salinity of rivers, bays, and aquifers (Barth and Titus, 1984). The areas most vulnerable to rising seas are found along the Gulf of Mexico and the Atlantic Ocean south of Cape Cod. Although there also are large low areas around San Francisco Bay and the Fraser delta (British Columbia), most of the Pacific coast is less vulnerable than the Atlantic and Gulf coasts. Because of a combination of rocky shores, lower rates of sea-level rise, higher elevations, and less shorefront development, most of the Canadian coast is much less vulnerable to the direct effects of rising sea level (Shaw *et al.*, 1994) than the low, sandy and muddy shores of the United States.

This section focuses primarily on the impacts of sea-level rise, which is the most thoroughly studied effect of global warming on coastal zones. Nevertheless, global climate change also is expected to alter coastal hydrology, the frequency and severity of severe storms, and sea-ice cover. Moreover, the impacts of regional climate change on inland areas also will affect coastal zones—particularly the estuaries into which most of the continent drains.

8.3.7.1.   Physical Effects and Their Implications

The implications of rising sea level are well understood, in part because sea level has been rising relative to the land along most of the coast of North America (and falling in a few areas) for thousands of years. For the most part, the relative rise and fall of sea level has been caused by adjustments of the earth's crust to the glacial mass that was removed from the land surfaces after the end of the last ice age (Grant, 1975). Change in the volume of water in oceans was also of importance. Water locked up in ice caps during ice ages lowered the volume of water in oceans, thus lowering sea level. The changes discussed here have occurred over geologic time (Holocene Epoch—last 10,000 years). The land is rising (i.e., relative sea level is falling) in the northern areas that had been covered by the ice sheet; land is subsiding in nearby areas that were not covered by the glaciers, such as the Canadian maritime provinces and U.S. middle Atlantic states.

A 50-cm rise in sea level would inundate approximately 50% of North American coastal wetlands in the next century; many beaches would be squeezed between advancing seas and engineering structures, particularly along estuarine shores.

Coastal marshes and swamps generally are found between the highest tide of the year and mean sea level. Coastal wetlands provide important habitat and nourishment for a large number of birds and fish found in coastal areas. Wetlands generally have been able to keep pace with the historic rate of sea-level rise (Kaye and Barghoorn, 1964). As a result, the area of dry land just above wetlands is less than the area of wetlands. If sea level rises more rapidly than wetlands can accrete, however, there will be a substantial net loss of wetlands (Titus, 1986; Park *et al.*, 1989). Because the current rate of sea-level rise is greater than the rate that prevailed over the past several thousand years (IPCC 1996, WG I), some areas—such as Blackwater National

Wildlife Refuge (NWR) along the Chesapeake Bay—are already experiencing large losses of coastal wetlands (Kearney and Stevenson, 1985). Blackwater NWR is also a victim of herbivory by an introduced rodent, which makes interpretation of the role of sea-level rise difficult.

Coastal development is likely to increase the vulnerability of wetlands to rising sea level. In many areas, development will prevent the wetland creation that otherwise would result from the gradual inundation of areas that are barely above today's high-water level (Titus, 1986, 1988). In Louisiana, flood control levees, navigation infrastructure, and other human activities have disabled the natural processes by which the Mississippi delta otherwise could keep pace with rising relative sea level; as a result, Louisiana currently is losing about 90 km^2 (35 mi^2) of wetlands per year (Gagliano *et al.*, 1981; Penland *et al.*, 1997).

Louisiana is expected to experience the greatest wetland loss from rising sea level, although most of these losses are predicted to occur even with the current rate of relative sea-level rise. The mid-Atlantic, south Atlantic, and Gulf coasts also are likely to lose large areas of wetlands if sea-level rise accelerates. A 50-cm rise in sea level would cause a net loss of 17–43% of the wetlands, even if no additional bulkheads or dikes are erected to prevent new wetland creation. Table 8-6 presents estimated losses in U.S. wetlands by region. Similar comprehensive assessments are unavailable for Canada. Nevertheless, regional studies suggest that the most vulnerable area is likely to be the salt marsh coast of the Bay of Fundy. Because 85% of these wetlands are enclosed by a system of dikes, the risk is not so much the direct submergence by higher water levels but rather the possibility that unless the dikes are fortified, an increased storm surge could overtop and breach the dikes. Many of the wetlands around San Francisco are similarly vulnerable.

In estuaries, sandy beaches may be even more vulnerable than vegetated wetlands to being squeezed between rising sea level and development. A 1-cm rise in sea level generally erodes beaches about 1 m (Bruun, 1962). Thus, because estuarine beaches usually are less than 5 m wide (Nordstrum, 1992), even a 5-cm rise in sea level can eliminate these systems in areas where adjacent land is protected with structures. Moreover, the environmental regulations that protect wetlands generally have not been applied to protect estuarine beaches (Titus, 1997), which are important for recreation, navigation,

Table 8-6: *Regional and national wetland losses in the U.S. for the trend and 1-m global sea-level rise scenarios (% loss of current area).*

Region	Current Wetland Area (mi^2)	Trend	1-m Shore Protection Policy		
			Total[a]	Developed[a]	None[a]
Northeast	600	7	16	10	1[d]
Mid-Atlantic	746	-5	70	46	38
South Atlantic	3,814	-2	64	44	40
South/Gulf Coast of Florida	1,869	-8	44	8[d]	7[d]
Louisiana[b]	4,835	52	85	85	85
Florida panhandle, Alabama, Mississippi, and Texas	1,218	22	85	77	75
West[c]	64	-111	56	-688	-809
United States	13,145	17	66	49	50
Confidence Intervals					
95% Low	—	9	50	29	26
95% High	—	25	82	69	66

[a] The "total" protection scenario implies that all shorelines are protected with structures; hence, as existing wetlands are inundated, no new wetlands are formed. "Developed" implies that only areas that are currently developed will be protected; "no protection" assumes that no structures will be built to hold back the sea.

[b] Evaluation of management options currently contemplated for Louisiana (e.g., restoring natural deltaic processes) was outside the scope of this study.

[c] This anomalous result is from small sample size. The impact on nationwide results is small.

[d] Results are not statistically significant; sampling error exceeds estimate of wetlands lost.

Source: Titus *et al.*, 1991.

Table 8-7: *Loss of dry land from sea-level rise (95% confidence interval, mi^2).*

	Baseline	Rise in Sea Level (cm)		
		50	100	200
If no shores are protected	NR	3,300–7,300	5,100–10,300	9,200–15,400
If developed areas are protected	1,500–4,700	2,200–6,100	4,100–9,200	6,400–13,500

NR = not reported.
Source: Titus *et al.*, 1991.

and habitat for several endangered species (Nordstrum, 1992).

A 50-cm rise in sea level could inundate 8,500–19,000 km^2 of dry land, even if currently developed areas are protected.

The dry land within 1 m above high tide includes forests, farms, low parts of some port cities, communities that sank after they were built and that now are protected with levees, parts of deltas, and the bay sides of barrier islands. The low forests and farms generally are in the Mid-Atlantic and Southeast. Major port cities with low areas include Boston, New York, Charleston, Miami, and New Orleans. New Orleans' average elevation is about 2 m below sea level; parts of Texas City, San Jose, and Long Beach, California, are about 1 m below sea level. In the United States, 8,500–19,000 km^2 (3,300–7,300 mi^2) of dry land are within 50 cm of high tide—5,700–16,000 km^2 (2,200–6,100 mi^2) of which currently are undeveloped (Table 8-7) (Titus *et al.*, 1991). Approximately 100 km^2 of land in the Fraser delta (British Columbia) also is within 1 m of sea level.

Many islands are at risk. The low bay sides of developed barrier islands could be inundated while their relatively high ocean sides erode. Undeveloped barrier islands will tend to migrate landward through the overwash process.

The most economically important vulnerable areas are recreational resorts on the coastal barriers—generally long and narrow islands or spits (peninsulas) with the ocean on one side and a bay on the other—of the Atlantic and Gulf coasts. Typically, the oceanfront block is 2–5 m above high tide; the bay sides often are <0.5 m above high water.

Erosion threatens the high ocean sides of these densely developed islands; this oceanfront erosion generally is viewed as a more immediate problem than inundation of the islands' low bay sides. Shores currently are eroding at a rate of 0.25–0.5 m/yr in many areas. Studies using the "Bruun (1962) rule" have estimated that a 1-cm rise in sea level will cause beaches to erode 0.5–1 m from New England to Maryland, 2 m along the Carolinas, 1–10 m along the Florida coast, and 2–4 m along the California coast (Bruun, 1962; Kana *et al.*, 1984; Everts, 1985; Kyper and Sorensen, 1985; Wilcoxen, 1986). Because many U.S. recreational beaches are less than 30 m wide at high tide, even a 30-cm rise would threaten homes in these areas. Canada's longest barrier coast is in New Brunswick along the

Gulf of St. Lawrence; the narrow barrier islands and spits generally are undeveloped. Rising sea level tends to cause narrow islands to migrate landward through the overwash process (Leatherman, 1979). Although the barriers themselves are undeveloped, there are important recreational areas along the mainland coast behind the barriers, as well as environmentally sensitive freshwater bogs and woodlands.

Other types of islands also may be vulnerable to sea-level rise. In the Chesapeake Bay, several islands populated by a traditional subculture of fishermen are likely to be entirely submerged (Toll *et al.*, 1997). The coast of Prince Edward Island, except for some parts along the Northumberland Strait, is highly erodible because of its bedrock cliffs, sandy barriers, coastal dunes, salt marshes, and intertidal flats. The heart of the island's tourist industry, along the Gulf of St. Lawrence, is likely to experience increased beach erosion, which would threaten shorefront buildings.

Rising sea level would increase flooding and storm damage. Regional climate change could offset or amplify these effects, depending on whether river flows and storm severity increase or decrease.

Changing climate generally is increasing the vulnerability of coastal areas to flooding both because higher sea level raises the flood level from a storm of a given severity and because rainstorms are becoming more severe in many areas. It also is possible that hurricanes could become more intense, thus producing greater storm surges; IPCC (1996) concluded, however, that the science currently is inadequate to state whether or not this is likely. Existing assessments in coastal areas generally focus on the impact of rising sea level.

Because higher sea level provides a higher base for storm surges, a 1-m rise in sea level (for example) would enable a 15-year storm to flood many areas that today are flooded only by a 100-year storm (Kana *et al.*, 1984; Leatherman, 1984). Many coastal areas currently are protected with levees and seawalls. Because these structures have been designed for current sea level, however, higher storm surges might overtop seawalls, and erosion could undermine them from below (National Research Council, 1987). In areas that are drained artificially, such as New Orleans, the increased need for pumping could exceed current pumping capacity (Titus *et al.*,

1987).

The U.S. Federal Emergency Management Agency (FEMA, 1991) has examined the nationwide implications of rising sea level for the National Flood Insurance Program. The study estimated that rises in sea level of 30 cm and 90 cm would increase the size of the 100-year floodplain in the United States from 51,000 km^2 (19,500 mi^2) in 1990 to 60,000 km^2 and 70,000 km^2 (23,000 mi^2 and 27,000 mi^2), respectively. Assuming that current development trends continue, flood damages incurred by a representative property subject to sea-level rise are projected to increase by 36–58% for a 30-cm rise and 102–200% for a 90-cm rise.

Because of its higher elevations, the Canadian coastal zone is less vulnerable to flooding than the U.S. coast. Nevertheless, flooding appears to be a more serious risk to Canada than the loss of land from erosion or inundation. Some communities (e.g., Placentia, Newfoundland) already are vulnerable to flooding during high astronomical tides and storm surges, sometimes exacerbated by high runoff. In Charlottetown, Prince Edward Island, some of the highest-value property in the downtown core and significant parts of the sewage system would experience increased flooding with a 50- to 100-cm rise in sea level. According to Clague (1989), a rise of a few tens of cm would result in flooding of some waterfront homes and port facilities during severe storms in British Columbia, forcing additional expenditures on pumping.

Coastal flooding also is exacerbated by increasing rainfall intensity. Along tidal rivers and in extremely flat areas, floods can be caused by storm surges from the sea or by river surges. Washington, D.C., and nearby Alexandria, Virginia, were flooded twice by Hurricane Fran in 1996: first by a storm surge in the Chesapeake Bay and lower Potomac River, then three days later by the river surge associated with intense precipitation over the upper Potomac River's watershed. Higher sea level and more intense precipitation could combine synergistically to increase flood levels by more than the rise in sea level alone in much of coastal Louisiana and Florida, as well as in inland port cities along major rivers (such as Portland and Philadelphia). The direct effect of higher sea level also could be exacerbated throughout the coastal zone if hurricanes or northeasters become more severe—a possibility that has been suggested but not established (IPCC 1996, WG I).

Rising sea level would increase salinities of estuaries and aquifers, which could impair water supplies, ecosystems, and coastal farmland. As with flooding, regional climate change could offset or amplify these effects, depending on whether river flows increase or decrease.

Rising sea level also enables saltwater to penetrate farther inland and upstream in rivers, bays, wetlands, and aquifers; saltwater intrusion would harm some aquatic plants and animals and threaten human uses of water. Increased drought severity, where it occurs, would further elevate salinity. Increased salinity already has been cited as a factor contribut-

ing to reduced oyster harvests in Delaware Bay (Gunter, 1974) and the Chesapeake Bay and as a reason that cypress swamps in Louisiana are becoming open lakes (Louisiana Wetland Protection Panel, 1987).

Higher salinity can impair both surface and groundwater supplies. New York, Philadelphia, and much of California's Central Valley get their water from portions of rivers that are slightly upstream from the point at which the water is salty during droughts. If saltwater is able to reach farther upstream in the future, the existing intakes would draw salty water during droughts.

The aquifers that are most vulnerable to rising sea level are those that are recharged in areas that currently are fresh but could become salty in the future. Residents of Camden and farmers in central New Jersey rely on the Potomac-Raritan-Magothy aquifer, which is recharged by a portion of the Delaware River that is rarely salty even during severe droughts today but would be salty more frequently if sea level were to rise 50–100 cm or droughts were to become more severe (Hull and Titus, 1986). Miami's Biscayne aquifer is similarly vulnerable; the South Florida Water Management District already spends millions of dollars each year to prevent the aquifer from becoming salty (Miller *et al.*, 1992).

A second class of vulnerable aquifers consists of those in barrier islands and other low areas with water tables close to the surface, which could lose their freshwater lens entirely (see IPCC 1990, WG II, Figure 6.3; also Chapter 9 in this report).

Finally, rising sea level tends to make some agricultural lands too saline for cultivation. In areas where shorefront lands are cultivated, the seaward boundary for cultivation often is the point where saltwater from ground and surface waters penetrates inland far enough to prevent crops from growing. As sea level rises, this boundary penetrates inland—often rendering farmland too salty for cultivation long before inundation converts the land to coastal marsh (see, e.g., Toll, 1997).

Coastal areas in the Arctic and extreme north Atlantic and Pacific are less vulnerable, except where sea ice and/or permafrost currently is present at the shoreline.

Sea-level rise and storm surges along the tundra coastline of Alaska and Canada are likely to cause erosion, flooding, and inundation through mechanisms similar to those for other parts of the North American coast. Several additional factors, notably sea-ice effects and coastal permafrost degradation, also will come into play. Projected changes in sea ice include a 35% decrease in winter ice thickness, along with significant retreat of the southern limit of sea ice and complete absence of summer sea ice among the Arctic Islands (Maxwell and Barrie, 1989). These decreases in the period and extent of sea-ice cover will result in larger ocean fetches and greater wave attack on the coastal zone (Lewis, 1974), with attendant erosion. Subsequent modeling suggested that the wave energy during the open-water season may increase wave heights by 16–40%

(McGillivray *et al*., 1993).

Rates of erosion of permafrost also can be expected to increase. The Alaska and Yukon coasts already experience significant erosion during the annual thaw. According to Lewellen (1970), erosion rates in the mid-1960s and early 1970s ranged from a few decimeters to as much as 10 m per year. Maximum erosion occurred in areas where permafrost contained considerable pore, wedge, or massive ice (Lewis, 1974) or where the permafrost shoreline was exposed to the sea (Lewellen, 1970).

8.3.7.2.   Adapting to Sea-Level Rise

Adaptive responses focus on protection of shores or allowing them to retreat, with subsequent loss of existing shoreline systems and structures.

Several U.S. government agencies have started to prepare for rising sea level. The U.S. Coastal Zone Management Act requires state coastal programs to address rising sea level, and a few states have modified coastal land-use policies to address rising sea level. The U.S. Army Corps of Engineers is required to consider alternative scenarios of future sea-level rise in its feasibility studies. These anticipatory measures have been implemented in part because assessments have identified measures whose costs are less than the benefits of preparation—even when future benefits are discounted by an economic rate of return.

8.3.7.2.1.   Erecting walls to hold back the sea

Most assessments of North American response strategies to future sea-level rise have concluded that coastal cities will merit protection with bulkheads, dikes, and pumping systems (National Research Council, 1987; Titus *et al*., 1991). Bulkheads, seawalls, and rock revetments already are being used to halt erosion to protect land that is well above sea level. Dikes and pumping systems are used to protect urban areas such as New Orleans that are below sea level, and other areas that are below flood levels.

Although structural measures can protect property from rising water levels, the resulting loss of natural shorelines may have adverse environmental, recreational, and aesthetic effects. Wetland and shallow-water habitats already are being lost because protective structures prevent those systems from migrating inland. In other areas, sandy and muddy beaches are being eliminated—impairing the ability of some amphibious species to move between the water and the land and directly removing the habitat of species that inhabit these beaches. The elimination of natural beaches may harm recreational and fishing navigation by removing locations from which small craft can be launched or beached in an emergency; the loss of beaches also impairs the ability of the public to move along the shore for fishing, recreation, and other uses. In the past 15 years, the state of Maryland alone has lost the use of 500 km (300 mi) of

shorelines through the issuance of permits for bulkheads and revetments (Tidal Waters Division, 1978–93).

8.3.7.2.2.   Elevating land surfaces and beaches

The effects of rising sea level can be offset by elevating beaches, land surfaces, and structures as sea level rises. A key benefit of this approach is that the character of the shore is not altered. Rapidly subsiding communities such as Galveston, Texas, have used fill to raise land elevations; some authors have suggested that it will be necessary to elevate Miami because the soils are too permeable for effective pumping (e.g., Walker *et al*., 1989). Regulations along San Francisco Bay require projects along the shore or on newly reclaimed land to be either protected by a dike or elevated enough to accommodate accelerated sea-level rise.[1]

The practice of elevating land surfaces is most applicable to recreational barrier islands, where environmental and aesthetic factors (such as natural beaches and waterfront views) can be as important as property values and shore-protection costs (Gibbs, 1984; Howard *et al*., 1985; Titus, 1990). Figure 8-9 illustrates possible responses to sea-level rise for barrier islands: building a dike, elevating the land surface, engineering a landward retreat, and no protection. A case study of Long Beach Island, New Jersey, concluded that any of the three protection options would be less costly than the current value of the threatened land (Titus, 1990). Although dikes have a lower direct cost than elevating land and structures, the latter approach is least disruptive to existing land uses and can be implemented gradually over time.

8.3.7.2.3.   Protecting natural shorelines by allowing shores to retreat

Several planning measures have been proposed to enable some shorelines to remain in roughly their natural state as sea level rises, rather than be replaced with structures. For the most part, these measures apply to areas that are not yet developed. They broadly fall into two categories: setbacks, which are regulations that prevent development of areas likely to be inundated, and rolling easements—which allow development today, but only with the explicit condition that the property will not be protected from rising water levels (Titus, 1997).

Setbacks currently are used to ensure that homes are safe from current flood risks. Several U.S. states currently require an additional erosion-based setback, in which new houses are set back an additional 20 to 60 times the annual erosion rate (Klarin and Hershman, 1990; Marine Law Institute *et al*., 1995). Eventually, however, the shore will erode to any setback line. Moreover, it is economically inefficient, and sometimes

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[1]San Francisco Bay Conservation and Development Commission. Resolution 88-15. Adoption of Bay Plan Amendment No. 3-88 Concerning Sea Level Rise Findings and Policies.

unconstitutional, to prevent the use of property now solely to avoid an adverse impact in the future (Titus, 1991).

Many of these problems are avoided with rolling easements—a planning measure in which coastal development is allowed in return for the property owner agreeing not to build structures or otherwise artificially stop the natural inland migration of wetlands and beaches. This option requires neither a specific estimate of future sea-level rise nor large public land purchases, and it is economically efficient because it does not prevent owners from using their land unless or until the sea rises enough to inundate it. The ability of the government to prevent property owners from eliminating the shore is grounded in the "public trust doctrine," under which the public has always owned tidal waters and either owned or had an access right along all intertidal beaches (Slade, 1990). If this approach were implemented in the next decade, ensuring the continued survival of natural wetland and beach shores in U.S. areas that are still undeveloped would cost approximately $400–1,200 million (Titus, 1997).

Texas common law recognizes rolling easements along its Gulf coast beaches. Maine and Rhode Island have issued regulations that prohibit structures that block the inland migration of wetlands. South Carolina's Beachfront Management Act, passed in response to the risks of a 1-ft rise in sea level, originally required setbacks along the coast, but in the aftermath of a trial court ruling that was eventually upheld by the U.S. Supreme Court (*Lucas* v. *South Carolina Coastal Council*), the statute was modified to require rolling easements in some locations[2] (South Carolina Beachfront Management Act, 1988). Because Canada inherited the same common law from England as the United States, all of these approaches could be applicable to Canada if its coastal zone becomes densely developed in the next century.

8.3.7.2.4. National assessments of adaptive responses

Several nationwide assessments have been conducted in the United States, mostly focusing on the potential loss of wet and dry land and the cost of holding back the sea. These studies have recognized that the impact of sea-level rise ultimately depends on whether—and how—people hold back the sea; they generally estimate impacts assuming alternative policies for protecting coastal land. A rise of 50 cm would inundate 8,600–19,000 km^2 (3,300–7,300 mi^2) of dry land if no shores are protected and 5,700–16,000 km^2 (2,200–6,100 mi^2) if currently developed areas are protected (Table 8-7). The loss of coastal wetlands would be 17–43% if no shores are protected and 20–45% if currently developed areas are protected—but 38–61% if all shores were protected. These results suggest that efforts to mitigate wetland loss from
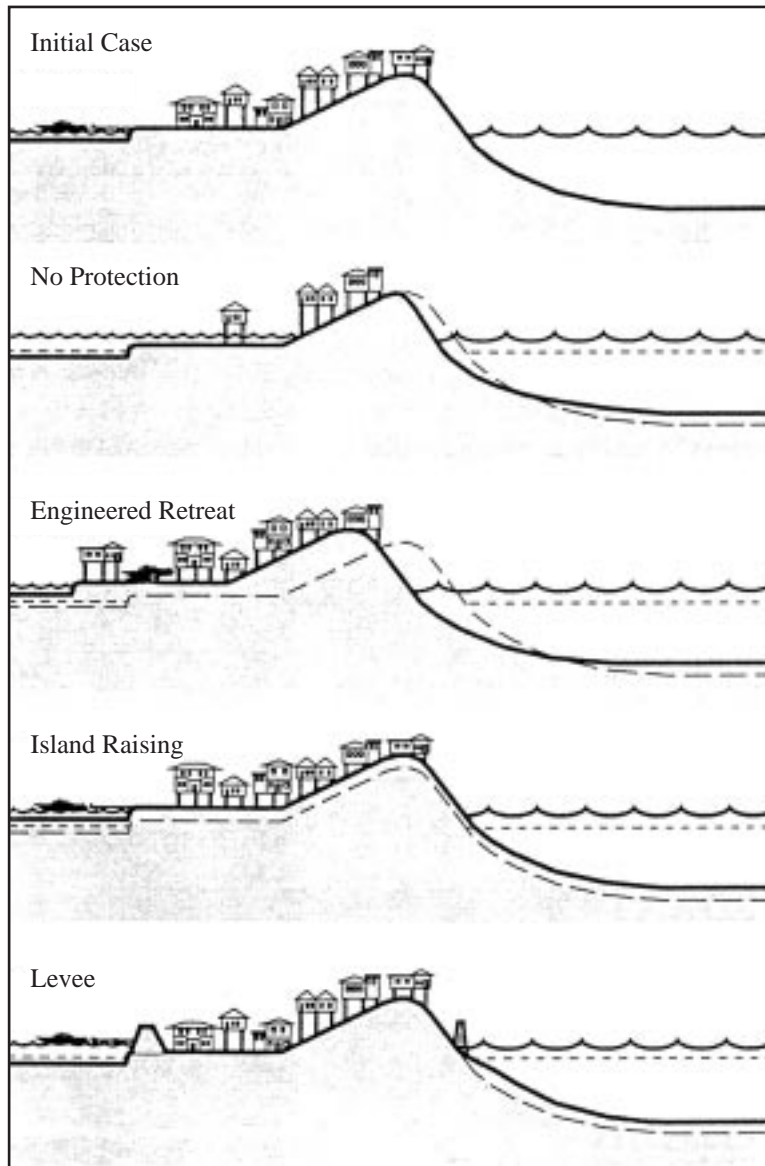
Figure 8-9: Responses to sea-level rise on developed barrier islands. Lightly developed islands may have no practical choice other than the "no protection" option, which would result in ocean-side erosion and in some cases bayside inundation. Under the "engineered retreat" option, a community might tolerate ocean-side erosion but move threatened structures to newly created bayside lands, imitating the natural overwash process that occurs with narrow undeveloped islands. A more common response is likely to be to raise entire islands as well as their beaches; although the sand costs are much higher than with an engineered retreat, existing land uses can be preserved. Finally, wide urbanized islands may choose to erect seawalls and levees (dikes); the loss of beach access and waterfront views, however, make this option less feasible for recreational barrier island resorts.

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[2]The rolling easements are called "special permits." SC Code 48-39-290 (D)(1).

sea-level rise could exempt existing development and focus on areas that are still undeveloped (Titus *et al.*, 1991).

Studies generally estimate that the cumulative cost of a 50-cm rise in sea level through the year 2100 would be $20–200 billion; the cost of a 1-m rise would be approximately twice that amount. Titus *et al.* (1991) estimated that for a 50-cm rise, barrier islands could be protected by placing sand on eroding beaches and the low bay sides, at a cost of $15–81 billion; elevating houses and roads, at a cost of $29–36 billion; and protecting mainland areas with dikes and bulkheads, at a cost of $5–13 billion—for a total cost of $55–123 billion.

Yohe (1990) estimated that if shores were not protected, a 50-cm rise would inundate land and structures worth $78–188 billion; Yohe *et al.* (1996) estimated that the cost would only be $20 billion. Their lower estimate appears to have resulted from two differences in their study: First, rather than assuming that all developed areas would be protected, Yohe *et al.* assessed the value of land and structures and assumed that only areas that could be economically protected would be protected. Second, the two studies appear to make different assumptions regarding the area of developed barrier islands in the United States. The Yohe *et al.* (1996) analysis was based on a sample of the entire coast, which included five densely developed ocean beach resorts; Titus *et al.* (1991) based their estimates on an assessment by Leatherman (1989)—who examined every beach community between New Jersey and the Mexican border, as well as in California, along with one site in each of the other states.

8.3.8.   Human Settlements and Industry

Housing, industry, commerce, and the major components of infrastructure that support settlements—energy, water supply, transportation, waste disposal, and so forth—have varying degrees of vulnerability to climate change. They can be affected directly through projected changes in climate (temperature, precipitation, etc.) and indirectly through projected impacts on the environment, natural resources, and agriculture. Indirect pathways to impacts include expected changes in the availability of natural resources, geographic shifts in climate-sensitive resource industries, effects on environmental quality and health from changes in ecosystems, and other effects resulting from changes in environmental service functions. Furthermore, these effects on human settlements in theory could lead to tertiary impacts—such as altering land use and redistributing population and activities to other regions—resulting in further changes in natural resources and other activities. Such effects, however, are largely speculative at the current state of knowledge.

Climate directly affects the quality of life; alters patterns of settlement and human activities; subjects humans to risks to their health, safety, and property (e.g., due to extreme events); and, therefore, has costs and benefits for individuals and for the private and public sectors. As such, changes in climate are expected to have positive and negative impacts.
Climate change will have direct impacts on economic activity

in the industry, energy, and transportation sectors; impacts on markets for goods and services; and impacts on natural resources on which economic activity depends. Activities directly sensitive to climate include construction, transportation, offshore oil and gas production, manufacturing dependent on water, tourism and recreation, and industry that is located in coastal zones and permafrost regions. Activities with markets sensitive to climate include electricity and fossil fuel production for space heating and air conditioning, construction activity associated with coastal defenses, and transportation. Activities dependent on climate-sensitive resources include agro-industries (food/drink, forestry-related activity, and textiles), biomass production, and other renewable energy production.

Impacts occurring in the distant future are difficult to predict in detail because the context of human settlement patterns and technologies cannot be forecast accurately. Concomitantly, there are substantial opportunities for adaptation to changed climates in conjunction with the development of future housing and infrastructure facilities, depending in part on our capability to forecast climate changes. Many types of impacts on human facilities have the potential to be partially or completely reduced or eliminated through adaptation, though this usually will increase their costs.

8.3.8.1.   Impacts on Transportation

Projected changes in climate will have both negative and positive impacts on the operation and maintenance costs of transportation systems.

Studies in temperate and northern climates generally have indicated that higher temperatures will result in lower maintenance costs, especially with fewer freeze-thaw cycles and less snow (e.g., Walker *et al.*, 1989; Daniels *et al.*, 1992). Black (1990) points out, however, that increased pavement buckling caused by longer periods of intense heat is a possibility. Lewis (1988) and Hirsch (1988) cite such cases from the great North American summer heat wave of 1988.

In moderate climates, water transport would be affected by changes in river navigability. Reductions in rainfall, which are possible during the summer in mid-latitudes in North America, could adversely affect waterborne transportation. During the 1988 drought, industries that relied on bulk transportation of raw materials and finished products by barge on the Mississippi River found that low water kept more than 800 barges tied up for several months. In 1993, by contrast, floods in the upper Mississippi valley also disrupted the barge transportation system, and in 1997 increased siltation associated with floods prevented ships from reaching the port of New Orleans for several days. To the extent that industry is moving toward just-in-time production systems, it will become more vulnerable to interruptions for these and other reasons.
In colder regions, the most significant direct impact of warm-

ing is likely to be on inland and coastal water transportation. A longer season for Arctic shipping is likely for locations like Prudhoe Bay, Alaska, which depends on the short ice-free season to barge in modular loads too large to go by truck. Increased wave activity and increased frequency of extreme weather events might have a more significant effect on coastal transportation operations, but little research has been conducted on this topic. A survey of the potential impacts on Canadian shipping suggested net benefits to Arctic and ocean shipping as a consequence of deeper drafts in ports and longer navigational seasons (IBI Group, 1990).

Winter roads on ice constitute an important part of the transportation network in parts of Canada's north. For example, about 10–15% of the total annual flow of goods in the Mackenzie Valley moves over winter roads, some of which cross major rivers. As the name implies, winter roads (or ice roads) are functional in the winter only; they are made of snow, ice, or a mixture of soil and snow/ice and can be created on the frozen surface of lakes and rivers. Lonergan *et al*. (1993) found a substantial reduction in the length of the "ice road" season based on climate change projections.

Further south, there would be a greater number of ice-free days for inland waterways such as the Great Lakes and St. Lawrence Seaway (IBI Group, 1990). Inland waterways, however, may suffer loss of depth from greater periods of seasonal drought, reducing their usefulness for commercial shipping even if the ice-free season is lengthened (Black, 1990). A similar study showed that reduced ice cover compensated for lower water levels in two of three climate change scenarios but that dredging costs generally increased in the six Great Lakes ports examined (Keith *et al.*, 1989). Other climate impacts could arise from changes in snowfall or melting of the permafrost (IBI Group, 1990).

Changes in the location and nature of agricultural activities, as well as other climate-dependent industries, could have a large impact on the freight transport system.

Existing assessments of transportation impacts have recognized the potential significance of changes in geographical patterns of economic activity on the transportation network. Black (1990) notes that even gradual, long-term global warming could cause a major disruption of the movement of goods and people in North America. The IBI Group (1990) suggests that there probably would be a northward spreading of agricultural, forestry, and mining activities—resulting in increased population and intensified settlement patterns in Canada's mid-north and even in Arctic areas. Marine, road, rail, and air links would have to be expanded accordingly.

8.3.8.2.   Recreation and Tourism

Climate creates opportunities and limitations for outdoor recreation. It is a major influence on the economic viability of some recreation enterprises. Several studies have projected shorter North American skiing seasons as a result of climate change. In a study of the implications of an effective CO_2 doubling on tourism and recreation in Ontario, Canada, Wall (1988) projected that the downhill ski season in the South Georgian Bay region could be eliminated. This outcome assumed a temperature rise of 3.5–5.7°C and a 9% increase in annual precipitation levels. Some of these losses would be offset by an extended summer recreational season. Lamothe and Périard (1988) examined the implications of a 4–5°C temperature rise throughout the downhill skiing season in Quebec. They projected a 50–70% decrease in the number of ski days in southern Quebec; ski resorts equipped with snowmaking devices probably would experience a 40–50% reduction in the number of ski days. This change in winter recreational traffic would have direct implications for road traffic (down) and requirements for snow-removal and road repair (also probably down). On the other hand, Masterton *et al*. (1976) have noted that low temperatures are a limiting factor on recreation activity in the northern part of the prairie provinces. The summer recreation season in many areas may be extended (Masterton *et al*., 1976; Staple and Wall, 1994). Warmer temperatures may offset some of the costs of sea-level rise for recreational barrier islands.

8.3.8.3.   Extreme Weather Events

Human settlements and infrastructure are especially vulnerable to several types of extreme weather events, including droughts, intense precipitation, extreme temperature episodes, high winds, and severe storms. Hence, there could be impacts should the frequency or intensity of these extreme events increase or decrease with climate warming.

Weather-related natural disasters (wildfires, hurricanes, severe storms, ice, snow, flooding, drought, tornadoes, and other extreme weather events) are estimated to have caused damages in the United States averaging about $39 billion per year during the years 1992–96 (FEMA, 1997). Those losses included damages to structures (buildings, bridges, roads, etc.) and losses of income, property, and other indirect consequences.

As indicated in Section 8.2.3 and IPCC (1996, WG I, Section 6.5), the ability to predict changes in the frequency or intensity of extreme weather events using global and regional models has been limited by their lack of small-scale spatial and temporal resolution and uncertainties about representation of some processes.[3] Historical changes in frequencies of extreme events also provide some insights on possible changes, but there is

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[3]Most hydrological studies of flooding and water resources now use scenarios based on GCM simulations, but there are important uncertainties in this use: "Weaknesses of models in coupling the land surface and atmospheric hydrologic cycles and in GCM simulations of regional climate and extremes, particularly with regard to precipitation. Weaknesses in using GCM simulations to define climate-change scenarios at the spatial and temporal resolution required by hydrological models. The spatial resolution of current GCMs is too coarse for their output to be fed directly into hydrological models." (IPCC 1996, WG II, Section 10.2.2).

debate about which changes are significant and which are unambiguously attributable to climate warming. However, some indications of directions of change have been inferred from observations and model simulations for North America, particularly regarding increased variability of precipitation. Beyond those inferences, a number of vulnerabilities of resources to extreme events have been identified should such events increase in frequency or magnitude. Conversely, decreases in extreme events could reduce levels of damages currently experienced. Additional research is needed to better understand the sensitivity and vulnerabilities of North American human settlements and infrastructure to extreme events, including factors beyond climate that are changing those vulnerabilities.

Flooding may be a very important impact because of the large amount of property and human life potentially at risk in North America, as is evident from historical disasters. There have been relatively few studies addressing the change in risk directly because of the lack of credible climate change scenarios at the level of detail necessary to predict flooding.

The evidence for an increasing trend in warm-period rainfall intensities in the United States (discussed in Section 8.2.2) suggests the potential for a shift in the periodicity of the flood regime in North America. More frequent or more extreme flooding could cause considerable disruption of transportation and water supply systems.

Increases in heavy rainfall events (e.g., suggested changes in frequency of intense subtropical cyclones) (Lambert, 1995) and interactions with changes in snowmelt-generated runoff could increase the potential for flooding of human settlements in many water basins. Changes in snowmelt runoff may add to or subtract from rainfall events, depending on basin characteristics and climate changes for a basin. Extreme rainfall events can have widespread impacts on roads, railways, and other transportation links. As long as rainfall does not become more intense, impacts on urban roads and railways in temperate, tropical, and subtropical zones are likely to be modest.

Some areas in North America may experience changed risks of wildfire, land slippage, and severe weather events in a changed climate regime. Although this increase in risk is predicated on changes in the frequency or intensity of extreme weather events—about which there is controversy—considering these risks in the design of long-lived infrastructure may prove cost-effective in some circumstances. Human settlement infrastructure has increasingly concentrated in areas vulnerable to wildfire, such as the chaparral hillsides in California. Settlements in forested regions in many areas are vulnerable to seasonal wildfires. Areas of potentially increased fire danger include broad regions of Canada (Street, 1989; Forestry Canada, 1991) and seasonally dry Mediterranean climates like the state of California in the United States. It is possible that fuel buildup under drought conditions would decrease, decreasing fire intensities. Although generally less destructive of life than in many developing world locations, landslides triggered by peri-

odic heavy rainfall events threaten property and infrastructure in steep lands of the western United States and Canada. Relict landslides occur in much of northern Europe and North America (Johnson and Vaughan, 1989). Although stable under present natural conditions, these landslides are reactivated by urban construction activities and are triggered by heavy rains (Caine, 1980). Lands denuded of vegetation by wildfire or urban development also are vulnerable.

Although there has been an apparent downward trend in Atlantic hurricanes in recent years (e.g., Landsea *et al.*, 1996), not all authors agree (Karl *et al.*, 1995b). What is certain is that the amount of property and the number of people in areas known to be vulnerable to hurricanes is large and increasing in low-lying coastal areas in much of the United States Atlantic and Gulf coasts. For example, although data on the amount or proportion of national physical assets exposed to climate hazards are not readily available, it is known that in the United States about $2 trillion in insured property value lies within 30 km of coasts exposed to Atlantic hurricanes (IRC, 1995).

Most authors have found increases in seasonal minimum temperatures in North America, but not in seasonal maximums (IPCC 1996, WG I, Chapter 3). These results would suggest reduced incidence of cold-related problems without a concomitant increase in heat-related problems. However, increases in regional cold outbreaks occurred from the late 1970s to the mid-1980s. There has been little evidence of an increase in danger from tornadoes in the region (Grazulis, 1993; Ostby, 1993).

Offshore oil and gas exploration and production would be influenced by change in extreme events. In the south, an increase in extreme storm events in the Gulf of Mexico may mean increasing fixed and floating platform engineering standards (i.e., more expensive platforms) and more frequent and longer storm interruptions. In terms of interruptions, weather-related production shutdowns result in losses to production companies in the range of $1 million dollars per day—$10,000–50,000 per facility where evacuation is necessary. The industry defers millions of dollars annually in royalties (approximately $7 million each day for offshore Gulf of Mexico facilities) paid for hydrocarbon produced from fields owned by the public.

8.3.8.4. *Energy Supply Systems*

The energy sector is diverse, but a few generalizations can be made. Many components of conventional energy supply systems that involve fossil and nuclear energy—including onshore extraction (with exceptions), land transportation of fuels, conversion, and end-use (except for space conditioning)—are largely independent of climate. However, exploration and well servicing offshore and in tundra and boreal regions, particularly in wet springs in boggy areas, are dependent on the climate regime; if climate conditions change (wetter or drier), the duration of the servicing/exploration season could change, with economic

impacts in those sectors. Water transportation, activities in the arctic and mountainous areas, cooling systems for thermal power generation, and energy demand for space conditioning also may be affected to some degree by changes in climate, positively or negatively. Many renewable energy sources—such as hydropower, solar, wind, and biomass—are strongly affected by climate in positive or negative ways. Only large-scale hydropower and some biomass currently make a large contribution to the North American energy supply. However, this sector may become more dependent on renewable energy in the future, and hence more vulnerable to climate change, especially if greenhouse gas controls constrain the use of fossil fuels and current barriers to nuclear growth continue.

Thermal electric generating plants and nuclear energy plants are susceptible to hydrological and water resource constraints that affect their cooling water supply. Power plant output may be restricted because of reduced water availability or thermal pollution of rivers with a reduced flow of water. Events such as these have occurred during droughts in several parts of the world, including the United States (Energy Economist, 1988). Under more extreme temperature conditions, some nuclear plants might shut down to comply with safety regulations (Miller *et al.*, 1992). Future power plants are less likely to depend on once-through cooling and may be designed to deal with anticipated shortages of cooling water supplies.

Hydroelectricity, which provides 20% of the region's electricity (and is the primary energy source in some areas of North America, such as the Pacific Northwest and Quebec), depends on the quantity and seasonal distribution of precipitation. Greater annual precipitation overall in the North American region is projected, with the greatest increases in winter and spring. For the north, this likely will mean greater snowfall to be added to the spring runoff, which would put greater demand on reservoirs to even out electricity supply. For southern hydroelectric facilities, climate projections suggest greater seasonal variation—unfortunately not coincidental with anticipated increased demand for summer air conditioning. Some areas (particularly the southwest of the continent) may experience lower rainfalls in the summer and fall, which, along with increased demand for air-conditioning, would exacerbate peak power requirements. However, GCMs are less reliable in simulating regional precipitation than temperature, and these predictions currently are not sufficiently reliable as a basis for hydroelectric and water resource planning.

Local energy distribution will not be affected, but long-distance transmission lines and pipelines may be subject to land disturbances, particularly in the western mountains where increased precipitation may induce slope instability. In the north, the permafrost, which normally provides a solid base for construction and transportation, is expected to degrade or thaw faster in some areas, producing stress on structures that may have been designed for a permafrost regime. Projected changes include not only melting but also decreases in the strength properties of the permafrost and increases in frost heaving. The vulnerability of pipelines as a result of projected changes in

underlying permafrost (Nixon *et al.*, 1990) are expected to be particularly acute in discontinuous permafrost areas and in the southern reaches of continuous permafrost. As a result, modifications or repairs to pipelines may be necessary, and some concerns have been raised regarding the potential of increased risk of environmental contamination.

Small-hydropower—usually located in nondammed streams—may provide more power in periods of peak runoff. Solar energy is highly dependent on cloud cover, which may increase with the expected intensification of the hydrological cycle; the exception might be the south-central area of North America, where increased insolation is expected (and where it would coincide with increased electricity demand for space cooling). The wind—not yet a significant contributor to North America's energy supply—is a highly variable source. Biofuels, currently primarily wood waste and grains, provide about 4% of the region's primary energy supply; changes in the availability of these fuels are possible as a result of projected changes to forest growth and productivity (see Section 8.3.2) and projected changes in the availability (absolutely and regionally) of grains, mainly corn for ethanol (see Section 8.3.4.1). However, future growth in biofuels is likely to involve dedicated energy farms utilizing short-rotation, highly managed crops.

8.3.8.5. Energy Demand

Climate warming would result in increased demand for cooling and decreased demand for heating energy, with the overall net effect varying with geographic region; however, changes in energy demand for comfort are expected to result in a net saving overall for North America.

Space heating and cooling are the most climate-sensitive uses of energy; they account for about 14% of energy use in North America, based on U.S. estimates extended to include Canada (see Table 8-8). The demand for summer cooling is likely to increase with projected warming. On the other hand, winter heating demand will be reduced. Rosenthal *et al.* (1995) concluded that a 1.8°C global warming would reduce total U.S. energy use associated with space heating and air conditioning by 1 exajoule (EJ)—11% of demand—in the year 2010; costs would be reduced by $5.5 billion (1991 dollars). Belzer *et al.* (1996) found that a 4°C warming would decrease total site energy use for commercial sector heating and cooling by 0.5–0.8 EJ (13–17%) and associated primary energy by 0.1–0.4 EJ (2–7%), depending on the degree to which advanced building designs penetrate the market. (This analysis was based on projected buildings in the year 2030, though the assumed temperature increase is much greater than Intergovernmental Panel on Climate Change (IPCC) projections for that period.)

The seasonal occurrence of peak demand for electricity is an important factor. If peak demand occurs in winter, maximum demand is likely to fall, whereas if there is a summer peak, maximum demand will rise. The precise effects are strongly

Table 8-8: *Use of energy in buildings in U.S., 1989–90.[1]*

Energy Source/Use	Residential	Commercial[2]	Total
Electricity			
– Air conditioning	1.5	0.9	
– Space heating	0.9	0.3	
– Ventilation	—	0.8	
Natural Gas			
– Space heating	3.4	1.3	
Fuel Oil	1.0	0.4	
LPG	0.3	—	
District Heat	—	0.6	
Total	7.1	4.3	11.4

[1]All values based on *Buildings and Energy in the 1980s*, Energy Information Administration, DOE/EIA-0555(95)/1, June 1995.
[2]Commercial values are from 1989.
Note: Total energy resource consumption within the U.S. in 1990 was 80 quads, so space conditioning accounted for about 14% of total.

dependent on the climate zone (Linder and Inglis, 1989). Climate change may cause some areas to switch from a winter peaking regime to approach a summer peaking regime (Scott *et al.*, 1994). Fewer studies have estimated the possible impact of climate change on investment requirements in electricity supply. An exception is the "infrastructure" component (Linder and Inglis, 1989) of the U.S. national climate effects study (Smith and Tirpak, 1989), which estimated that with a 1.1°C warming, peak demand would increase by 29 gigawatts (GW), or 4% of the baseline level for that year. Decreases in investment for heating supply fuels have not been estimated.

Although usually smaller in total magnitude of energy demand, the use of electricity and fuels for irrigation pumping and the use of fuels for drying of agricultural crops also can be significant weather-sensitive demands in some regions (Darmstadter, 1993; Scott *et al.*, 1993). Pumping would tend to increase in regions suffering a decrease in natural soil moisture—for example, Goos (1989) found a 20% increase in energy demand for irrigation in the province of Alberta—whereas drying energy would decrease where humidity decreases. Automobile fuel efficiency may decrease slightly as a result of greater use of air-conditioning. With a 4°C warming, autos would consume an additional 47 liters of fuel per 10,000 km driven, for a total cost of $1–3 billion per year at current energy prices (Titus, 1992).

The technological capacity to adapt to climate change is likely to be readily available in North America. However, its application will be realized only if the necessary information is available, the institutional and financial capacity to manage change exists, and the benefits of adaptive measures are considered to be worth their costs. Therefore, to increase the potential for adaptation and to reduce costs, it is essential that information about the nature of climate change is available sufficiently far in advance in relation to the planning horizons and lifetimes of investments.

Some adaptation will occur if better information concerning the risks posed by climate change is available and the appropriate signals are available from the marketplace. Over periods of half a century or more, many sectors will change significantly, and new products, markets, and technologies will emerge. In the transportation industry, for example, nominal replacement cycles are 10–20 years for transit vehicles and 35–70 years for most infrastructure (National Council on Public Works Improvement, 1988). Turnover of capital stock provides the opportunity to adapt easily if information is available. Given uncertainties, however, autonomous adaptation signaled by the marketplace cannot be relied upon entirely for long-lived public transportation and other infrastructure. Governments may have to set a suitable policy framework, disseminate information about climate change, and act directly in relation to vulnerable infrastructures. For example, effective land-use regulation (zoning and building codes) can help reduce vulnerabilities by directing population shifts away from vulnerable locations such as floodplains, steep hillsides, and low-lying coastlines. Research is needed to better understand the factors that affect effective adaptive capacity and how those factors vary within North America.

Some forms of adaptation, such as those in the areas of fire prevention and water supply-and-demand balancing, will likely be advantageous regardless of climate regime. Examples would include major adaptive responses in fire-control systems in rural areas—such as controlled burns to limit fuel, fire breaks, aerial fire retardant delivery, and rural fire departments and "smoke jumpers"—and short-term activity controls during high fire-danger weather, such as prohibitions on open burning, commercial activities such as logging, and recreation activities such as hiking, hunting, or use of off-road vehicles. If the frequency or intensity of fire danger warrants, other potential adaptive responses involve improved spatial planning of communities and some longer-term land-use controls. These strategies would provide better isolation of fires and could limit damage to human settlements even under current conditions.

In the energy supply sector, anticipation of possible regional climate changes will be important in the design of and site selection for solar and wind energy systems, as well as energy transportation systems. For example, possible thawing of permafrost in Arctic regions may require changes in the design of oil pipelines to avoid slumping, breaks, and leaks (Brown, 1989; Anderson *et al.*, 1994). Systems with long lifetimes, such as large hydroelectric impoundment systems, will have difficulty adjusting in the absence of long-term predictions. Future biomass energy farms, however, are likely to be intensively managed and have short crop rotation; therefore, they would be

better able to adapt to changing conditions through choices of crops and management techniques.

For energy demand, building design can assist adaptation. Increased building-shell efficiency and changes to building design that reduce air-conditioning load show promise (Scott *et al.*, 1994). Though effective, however, adaptive strategies are not implemented without costs (Loveland and Brown, 1990). Reducing the size of space-heating capacity in response to warmer climate would be a logical adaptive response in more temperate and polar countries and may free up investment funds for other purposes, even within the energy sector. Community design to reduce heat islands (through judicious use of vegetation and light-colored surfaces) (Akbari *et al.*, 1992), reducing motor transportation, and taking advantage of solar resources also may be viable and would have sustainability benefits.

8.3.9. Human Health

Climate change is likely to have wide-ranging and mostly adverse impacts on human health. These impacts would arise by direct pathways (e.g., exposure to thermal stress and extreme weather events) and indirect pathways (increases in some air pollutants, pollens, and mold spores; malnutrition; increases in the potential transmission of vector-borne and waterborne diseases; and general public health infrastructural damage) (IPCC 1996, WG II Sections 18.2 and 18.3, and Figure 18-1). Climate change also could jeopardize access to traditional foods garnered from land and water (such as game, wild birds, fish, and berries), leading to diet-related problems such as obesity, cardiovascular disorders, and diabetes among northern populations of indigenous peoples as they make new food choices (Government of Canada, 1996).

8.3.9.1. Thermal Extremes

Temperate regions such as North America are expected to warm disproportionately more than tropical and subtropical zones (IPCC 1996, WG I). The frequency of very hot days in temperate climates is expected to approximately double for an increase of 2–3°C in the average summer temperature (CDC, 1989; Climate Change Impacts Review Group, 1991). Heat waves cause excess deaths (Kilbourne, 1992), many of which are caused by increased demand on the cardiovascular system required for physiological cooling. Heat also aggravates existing medical problems in vulnerable populations—particularly the elderly, the young, and the chronically ill (CDC, 1995; Canadian Global Change Program, 1995). For example, mortality during oppressively hot weather is associated predominantly with preexisting cardiovascular, cerebrovascular, and respiratory disorders, as well as accidents (Haines, 1993; IPCC 1996, WG II, Section 18.2.1). In addition to mortality, morbidity such as heat exhaustion, heat cramps, heat syncope or fainting, and heat rash also result from heat waves. People living in hot regions, such as the

southern United States, cope with excessive heat through adaptations in lifestyle, physiological acclimatization, and adoption of a particular mental approach (Ellis, 1972; Rotton, 1983). In temperate regions, however, periods of excessive heat occur less frequently, and populations accordingly are less prepared with responsive adaptive options (WHO, 1996).

Data in cities in the United States and Canada show that overall death rates increase during heat waves (Kalkstein and Smoyer, 1993), particularly when the temperature rises above the local population's temperature threshold. In addition to the 1980 heat wave that resulted in 1,700 heat-related deaths, heat waves in 1983 and 1988 in the United States killed 566 and 454 people, respectively (CDC, 1995). More recently, in July 1995, a heat wave caused as many as 765 heat-related deaths in the Chicago area alone (Phelps, 1996). Tavares (1996) examined the relationship between weather and heat-related morbidity for Toronto for the years 1979–89 and found that 14% of the variability for all morbidity in persons 0–65 years of age was related to weather conditions.

Death rates in temperate and subtropical zones appear to be higher in winter than in summer (Kilbourne, 1992). Comparative analyses of the causes of differences between summer versus winter weather-related mortalities are lacking, however. The United States averaged 367 deaths per year due to cold in the period 1979–94 (Parrish, 1997), whereas the annual average number of Canadians dying of excessive cold is 110 (Phillips, 1990). It has been suggested that winter mortality rates, which appear to be more related to infectious diseases than to extremely cold temperatures, will be little impacted by climate change. Any global warming-induced increases in heat-related mortality, therefore, are unlikely to be of similar magnitude to decreases in winter mortality (Kalkstein and Smoyer, 1993).

Mortality from extreme heat is increased by concomitant conditions of low wind, high humidity, and intense solar radiation (Kilbourne, 1992). In Ontario, the number of days annually with temperatures above 30°C could increase fivefold (from 10 to 50 days per year) under doubled CO_2 scenarios (Environment Canada *et al.*, 1995).

Several studies (e.g., WHO, 1996) have found that future heat-related mortality rates would significantly increase under climate change. Table 8-9 shows projected changes in heat-related deaths for selected cities in North America under two climate change scenarios. Acclimatization of populations, however, may reduce the predicted heat-related morbidity and mortality. Kalkstein *et al.* (1993) found that people in Montreal and Toronto might acclimatize somewhat to global warming conditions. People in Ottawa, on the other hand, showed no signs of potential acclimatization. It is important to note that acclimatization to increasing temperatures occurs gradually, particularly among the elderly, and may be slower than the rate of ambient temperature change.

Air conditioning and adequate warning systems also may

Table 8-9: *Total summer heat-related deaths in selected North American cities: current mortality and estimates of future mortality under two different climate change scenarios with global mean temperature increases of ~0.53°C or ~1.16°C.[1]*

City	Present Mortality[2]	GFDL89 Climate Change Scenario				UKTR Climate Change Scenario			
		~0.53°C		~1.16°C		~0.53°C		~1.16°C	
		no acc	acc	no acc	acc	no acc	acc	no acc	acc
United States									
Atlanta	78	191	96	293	147	247	124	436	218
Dallas	19	35	28	782	618	1364	1077	1360	1074
Detroit	118	264	131	419	209	923	460	1099	547
Los Angeles	84	205	102	350	174	571	284	728	363
New York	320	356	190	879	494	1098	683	1754	971
Philadelphia	145	190	142	474	354	586	437	884	659
San Francisco	27	19	40	104	85	57	47	76	62
Canada									
Montreal	69	121	61	245	124	460	233	725	368
Toronto	19	36	0	86	1	289	3	563	7

[1]Figures represent average summer-season heat-related deaths for each city under each climate change scenario. Figures assume no change in population size and age distribution in the future.
[2]Raw mortality data.
Source: Modified from Kalkstein *et al*. (1997) in WHO (1996), p. 57.

reduce heat-related morbidity and mortality in a warmer North America. It has been suggested that air conditioning could reduce heat-related deaths by 25% (Phelps, 1996). A warning system such as the Philadelphia Hot Weather-Health Watch/Warning System (PWWS) that alerts the public when oppressive air masses (e.g., extended periods of extreme high temperatures, high humidity, moderate to strong southwesterly winds, and high pressure) may occur might further reduce heat-related mortality (Kalkstein and Smoyer, 1993). The PWWS is a three-tiered system that produces a health watch, health alert, or health warning and then accordingly initiates a series of interventions, including media announcements, promotion of a "buddy system," home visits, nursing and personal care intervention, increased emergency medical service staffing, and provision of air-conditioned facilities (Kalkstein *et al*., 1995).

8.3.9.2.   Air Quality and Ground-Level Ozone

Projected climate changes could lead to exacerbation of respiratory disorders associated with reduced air quality in urban and rural areas and effects on the seasonality of certain allergic respiratory disorders.

It is well established that exposure to single or combined air pollutants has serious public health consequences. For example, ozone at ground level has been identified as causing damage to lung tissue, particularly among the elderly and children—reducing pulmonary function and sensitizing airways to other irritants and allergens (Beckett, 1991; Schwartz, 1994; U.S. EPA, 1996). Ground-level ozone affects not only those with impaired respiratory function, such as persons with asthma and chronic obstructive lung disease, but also healthy individu-

als. Even at relatively low exposure levels, healthy individuals can experience chest pain, coughing, nausea, and pulmonary congestion as a result of exposure to ground-level ozone.

Researchers also recognize that concurrent hot weather and air pollution can have synergistic impacts on health (Katsouyanni *et al*., 1993). For example, warmer temperatures can accelerate production and increase concentrations of photochemical oxidants in urban and rural areas and thus exacerbate respiratory disorders (Shumway *et al*., 1988; Schwartz and Dockery, 1992; Dockery *et al*., 1993; Katsouyanni *et al*., 1993; Pope *et al*., 1995; Phelps, 1996).

Few large-scale studies have been performed to assess the implications of climate change on air quality or population exposures to high concentrations of ground-level ozone. This limitation is related to difficulty in devising a defensible scenario of future climate change for a specific location, the previous focus on acute short-term effects rather than long-term effects, and the expense involved in modeling atmospheric chemistry. There is a limited number of studies, however, that shed some light on possible impacts of climate change on air quality and associated health implications.

Emberlin (1994), for example, has suggested that global warming may affect the seasonality of certain allergic respiratory disorders by altering the production of plant aero-allergens. Asthma and hay fever can be triggered by aero-allergens that cause high seasonal morbidity. The severity of allergies may be intensified by projected changes in heat and humidity, thereby contributing to breathing difficulties (Environment Canada *et al*., 1995; Maarouf, 1995).

Ozone concentrations at ground level continue to be the most per-

vasive air pollution problem in North America. The U.S. population exposed to unhealthy levels of ozone has fluctuated over the past 10–20 years—reaching a peak in 1988, when 112 million people lived in areas with higher than acceptable concentrations. In addition, recent studies (U.S. EPA, 1996) provide evidence of a positive correlation between ground-level ozone and respiratory-related hospital admissions in several cities in the United States. Such hospital admissions in the province of Ontario strongly relate to ambient levels of sulfur dioxide and ozone and to temperature (Canadian Public Health Association, 1992).

Research has shown that ground-level ozone formation is affected by weather and climate. Many studies have focused on the relationship between temperature and ozone concentrations (Wolff and Lioy, 1978; Atwater, 1984; Kuntasal and Chang, 1987; Wackter and Bayly, 1988; Wakim, 1989). For example, the large increase in ozone concentrations at ground level in 1988 in the United States and in parts of southern Canada can be attributed, in part, to meteorological conditions; 1988 was the third-hottest summer in the past 100 years. In general, the aforementioned studies suggest a nonlinear relationship between temperature and ozone concentrations at ground level: Below temperatures of 22–26°C (70–80°F), there is no relationship between ozone concentrations and temperature; above 32°C (90°F), there is a strong positive relationship. Regression analyses have revealed that high temperatures are a

necessary condition for high ozone concentrations at ground level; other meteorological variables often need to be considered, however. Weather variables that have been included in regression equations include temperature, wind speed, relative humidity, and sky cover (Wakim, 1990; Korsog and Wolff, 1991); however, other variables that could be included are wind direction, dew-point temperature, sea-level pressure, and precipitation.

Studies of ground-level ozone concentrations in which emissions and other weather factors are held constant (Smith and Tirpak, 1989) suggest the following impacts on ground-level ozone as a result of a 4°C warming:

- In the San Francisco Bay area, maximum ozone concentration could increase by about 20% and could approximately double the area that would be out of compliance with the National Ambient Air Quality Standard (NAAQS).
- In New York, ground-level ozone concentrations could increase by 4%.
- In the Midwest and Southeast, changes in ground-level ozone levels could range from a decrease of 2.4% to an increase of 8%, and the area in exceedance of the ozone standard could exhibit nearly a threefold increase.

In Canada, a projected fivefold rise in the frequency of hot days
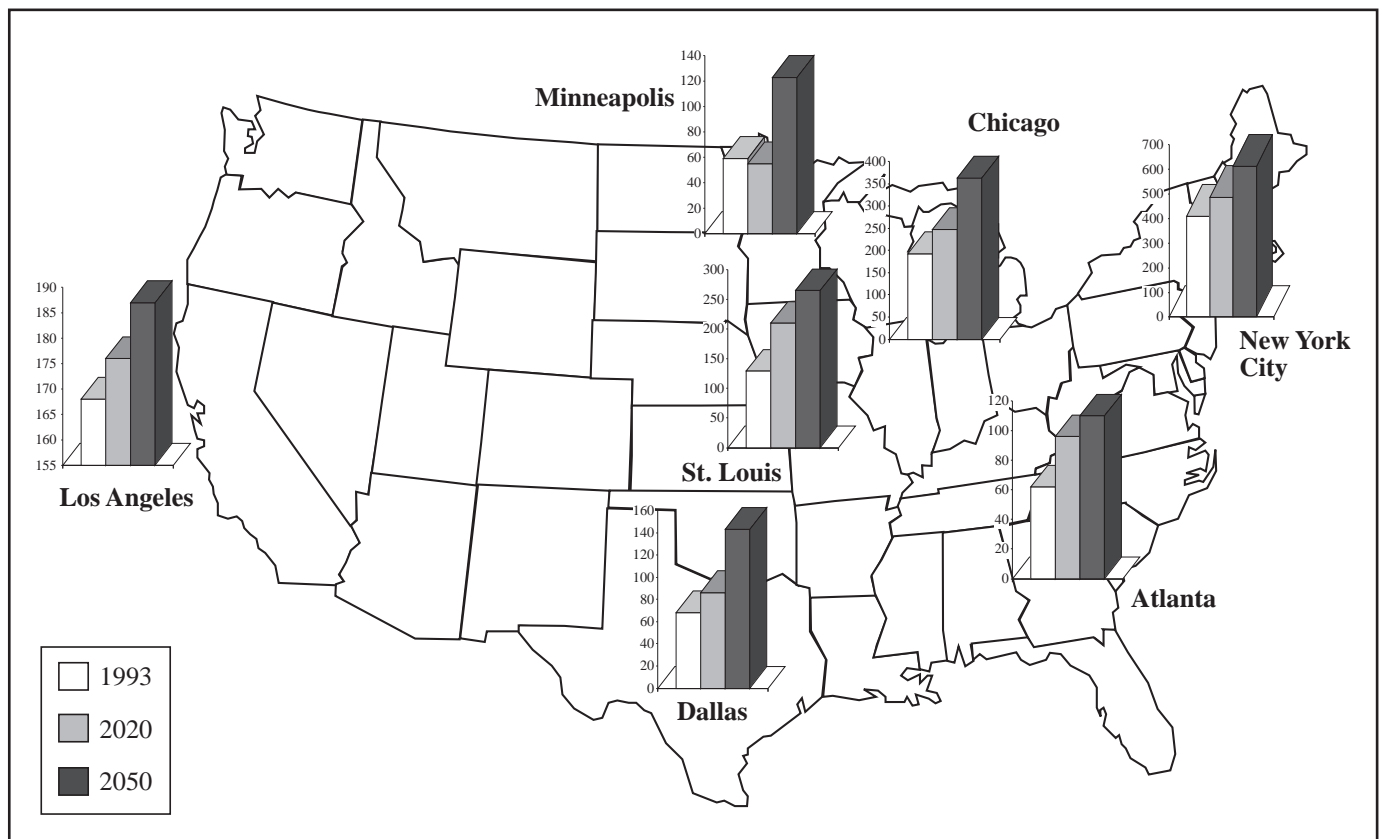
Figure 8-10: Average annual weather-related mortality for 1993, 2020, and 2050 climate (Kalkstein and Greene, 1997), based on 1980 population and the GFDL89 climate change scenario. Annual estimates were obtained by adding summer and winter mortality. The projections do not account for population growth, nor do they fully account for air-conditioning use; however, they do assume acclimation to changed climate.

(i.e., those with temperatures >30°C) could lead to a greater number of days with levels of ground-level ozone considered to be a health risk for sensitive individuals in the population (Environment Canada *et al.*, 1995).

8.3.9.3.   Extreme Weather Events

In the United States, 145 natural disasters resulted in 14,536 deaths from 1945 to 1989. Of these events, 136 were weather disasters; these extreme weather events caused 95% of all disaster-related deaths. Floods are the most frequent type of disaster.

More frequent extreme weather events are predicted to accompany global warming (see Figure 8-10), in part as a consequence of projected increases in convective activity. More intense rainfall events accompanying global warming would be expected to increase the occurrence of floods, and warmer sea-surface temperatures could strengthen tropical cyclones (IPCC 1996, WG I).

Climate models are unable to predict extreme events because they lack spatial and temporal resolution. In addition, there is no clear evidence that sustained or worldwide changes in extreme events have occurred in the past few decades. Nonetheless, such events cause loss of life and endanger health by increasing injuries, infectious diseases, stress-related disorders, and adverse health effects associated with social and environmental disruptions and environmentally enforced migration. Because each extreme weather event is unique in scale and location, and population vulnerability varies considerably, it is not possible to quantify the health impacts that would be associated with potential changes in extreme weather events.

Recent floods in the United States (e.g., Mississippi River flooding in 1993) were caused primarily by unusually high precipitation combined with soil saturation from earlier precipitation (Kunkel *et al.*, 1994). In the United States, flash floods currently are the leading cause of weather-related mortality. In addition to causing deaths by drowning, flooding can lead to widespread destruction of food supplies and outbreaks of disease as a result of breakdowns in sanitation services. Flooding also may result in the release of dangerous chemicals from storage sites and waste disposal sites into floodwaters. Increased runoff from agricultural lands during periods of heavy precipitation also can threaten water supplies. The 1993 Mississippi River flooding, for example, caused wide dispersal of microorganisms and chemicals from agricultural lands and industrial sites (Changnon, 1996).

8.3.9.4.   Biological Agents: Vector- and Waterborne Diseases

8.3.9.4.1.   Vector-borne diseases

Changing climate conditions may lead to the northward spread of vector-borne infectious diseases and potentially enhanced transmission dynamics as a result of warmer ambient temperatures. Vector-borne diseases (primarily carried by arthropod or small mammal "vectors") and waterborne diarrheal diseases represent a large proportion of infectious diseases, which are the world's leading cause of fatalities. Projected changes in climate almost certainly would make conditions less suitable for the transmission of several vector-borne diseases (e.g., plague and some forms of encephalomyelitis) in much of their current North American range. Other diseases (e.g., Saint Louis encephalitis and western equine encephalomyelitis) might extend their range northward or exhibit more frequent outbreaks. The crucial factor is the availability of appropriate habitats for vectors and (in the case of zoonotic diseases) vertebrate "maintenance" hosts. Although projected changes in climate might provide opportunities for diseases to extend their range, the North American health infrastructure may prevent a large increase in disease cases; providing this protection, however, could increase the demands on and costs of the current public health system.

The transmission of many infectious diseases is affected by climatic factors. Infective agents and their vector organisms are sensitive to factors such as temperature, surface water, humidity, wind, soil moisture, and changes in forest distribution (IPCC 1996, WG II, Chapter 18).

Malaria: Climatic factors, which increase the inoculation rate of *Plasmodium* pathogens and the breeding activity of *Anopheles* mosquitoes, are considered the most important factors contributing to epidemic outbreaks of malaria in nonendemic areas. A temperature relationship for sporadic autochthonous malaria transmission in the temperate United States has been observed in New York and New Jersey during the 1990s (Layton *et al.*, 1995; Zucker, 1996). Common to these two outbreaks was exceptionally hot and humid weather, which reduced the development time of malaria sporozoites enough to render these northern anopheline mosquitoes infectious. Such temperature sensitivity of parasite development also has been observed in the laboratory (Noden *et al.*, 1995).

Martens *et al.* (1995) estimated that an increase in global mean temperature of several degrees by the year 2100 would increase the vectorial capacity of mosquito populations 100-fold in temperate countries. In these countries, however, continued and increased application of control measures—such as disease surveillance and prompt treatment of cases—probably would counteract any increase in vectorial capacity. Similarly, Duncan (1996) showed that projected increases in mean daily temperatures may allow for the development of malaria in Toronto. It was not suggested, however, that climate alone would permit the spread of malaria because many other factors must be considered.

Malaria once prevailed throughout the American colonies and southern Canada (Russell, 1968; Bruce-Chwatt, 1988). By the middle of the 19th century, malaria extended as far north as 50°N latitude. In Canada, malaria disappeared at the end of the 19th century (Bruce-Chwatt, 1988; Haworth, 1988). Serious malaria control measures were first undertaken in the southern United States in 1912 (Bruce-Chwatt, 1988). By

1930, malaria had disappeared from the northern and western United States and generally caused fewer than 25 deaths per 100,000 people in the South (Meade *et al.*, 1988). In 1970, the World Health Organization Expert Advisory Panel on Malaria recommended that the United States be included in the WHO official register of areas where malaria had been eradicated. The history of malaria in North America reinforces the suggestion that although increased temperatures may lead to conditions suitable for the reintroduction of malaria to North America, socioeconomic factors such as public health facilities will play a large role in determining the existence or extent of such infections.

Arboviruses: Dengue fever and dengue hemorrhagic fever (DHF) periodically have occurred in Texas, following outbreaks in Mexico, during the past two decades (Gubler and Trent, 1994; PAHO, 1994). Because of the sensitivity of dengue to climate, especially ambient temperature, it has been suggested that this disease may increase in the United States if a sustained warming trend occurs. However, due to high living standards, this disease is not likely to increase in incidence or geographic distribution in the United States, even if there is a sustained warming trend. Dengue viruses occur predominantly in the tropics, between 30°N and 20°S latitude (Trent *et al.*, 1983); freezing kills the eggs, larvae, and adults of *Aedis aegypte*, the most important vector (Chandler, 1945; Shope, 1991). It should be noted, however, that the eggs of *Ac. Alhopictus*, also a vector, are not killed by freezing.

Jetten and Focks (1997) analyzed the impact of a 2°C and a 4°C temperature rise on the epidemic potential for dengue, including the impacts for cities in temperate areas (Figure 8-11). Their analysis shows that areas adjacent in latitude or elevation to current endemic zones may become more receptive to viral introductions and enhanced transmission. Furthermore, their study shows that the proportion of the year when transmission can occur in North America could significantly increase under warming scenarios.

Encephalitides: Of reported encephalitis cases in North America, many are mosquito related, including Saint Louis encephalitis, which has occurred as far north as Windsor, Ontario (1975); LaCrosse encephalitis; and western, eastern, and Venezuelan equine encephalomyelitis (Shope, 1980). The elderly are at highest risk for Saint Louis encephalitis, and children under 16 years are at greatest risk of LaCrosse encephalitis.

Although mosquito longevity diminishes as temperatures rise, viral transmission rates (similar to dengue) rise sharply at higher temperatures (see Figure 8-11) (Hardy, 1988; Reisen *et al.*, 1993). From field studies in California (Reeves *et al.*, 1994), researchers have suggested that a 3–5°C temperature increase could cause a northern shift in western equine and Saint Louis encephalitis outbreaks, with the disappearance of western equine encephalitis in southern endemic regions. Also to be considered in these types of impact assessments is the impact of projected climate change on mosquito habitat (e.g., freshwater

hardwood swamps for the eastern equine encephalomyelitis vector *Culiseta melanura*—which may well be eliminated from the southeast United States).

Outbreaks of Saint Louis encephalitis are correlated with periods of several consecutive days in which temperature exceeds 30ºC (Monath and Tsai, 1987). For example, the 1984 California epidemic followed a period of extremely high temperatures. In addition, eastern equine encephalitis has been associated with warm, wet summers along the east coast of the United States (Freier, 1993). Computer analysis of monthly climate data has demonstrated that excessive rainfall in January and February, combined with drought in July, most often precedes outbreaks of eastern equine encephalitis (Bowen and Francy, 1980). Such a pattern of warm, wet winters followed by hot, dry summers resembles many of the GCM projections for climate change over much of the United States.

Tickborne diseases: Ticks transmit Lyme disease—the most common vector-borne disease in the United States, with more than 10,000 cases reported in 1994—along with Rocky Mountain spotted fever (RMSF), and Ehrlichiosis. Involved tick and mammal host populations are influenced by land use and land cover, soil type, and elevation, as well as the timing, duration, and rate of change of temperature and moisture regimes (Mount *et al.*, 1993; Glass *et al.*, 1994). The relationships between vector life-stage parameters and climatic conditions have been verified experimentally in field and laboratory studies (Goddard, 1992; Mount *et al.*, 1993). *Ixodes scapularis*—an important hard-backed tick vector in North America—will not deposit eggs at temperatures below 8°C, and larvae will not emerge from eggs at temperatures below 12°C; the nymphal molt requires approximately 35 days at 25°C, and the adult molt requires 45 days at 25°C. Temperature also affects the activity of ticks; a minimum threshold for activity is 4°C. Ticks also are highly dependent on a humid environment. Climate change, therefore, could be expected to alter the distribution of these diseases in both the United States and Canada (Grant, 1991; Canadian Global Change Program, 1995; Environment Canada *et al.*, 1995; Hancock, 1997). For example, any tendency toward drying would suggest a reduction in the incidence of these diseases.

8.3.9.4.2. Waterborne diseases

Freshwater: Diarrheal diseases in North America can be caused by a large variety of bacteria (e.g., *salmonella*, *shigella,* and *campylobacter*), viruses (e.g., rotavirus), and protozoa (e.g., *giardia lamblia*, *toxoplasma*, and *cryptosporidium*). Climatic effects on the distribution and quality of surface water, including increases in flooding or water shortages, can impede personal hygiene and impair local sewage systems. For example, extreme precipitation contributed to an outbreak of toxoplasmosis in British Columbia in 1995 when excessive runoff contaminated a reservoir with oocysts from domestic and wild cats (British Columbia CDC, writ. comm. 1995).
Cryptosporidiosis, which causes severe diarrhea in children and

can be fatal to immunocompromised individuals, is the most prevalent waterborne disease in the United States (Moore *et al.*, 1995). Natural events (e.g., floods, storms, heavy rainfall, and snowmelt) often can wash material of fecal origin, primarily from agricultural nonpoint sources, into potable water. The Milwaukee cryptosporidiosis outbreak in 1993 resulted in 403,000 reported cases; it coincided with unusually heavy spring rains and runoff from melting snow (MacKenzie *et al.*, 1994).

Factors enhancing waterborne cryptosporidiosis will depend on hydrological responses to climate change and the degree of flooding in water catchment areas. Flushing from heavy rains

may be more important than actual flooding, especially for private wells influenced by surface water. Land-use patterns also determine contamination sources (e.g., agricultural activities) and therefore must be considered.

In addition, intensification of heavy rainfall events (as suggested by some scenarios) could lead to more rapid leaching from hazardous-waste landfills, as well as contamination from agricultural activities and septic tanks. This leaching or contamination represents a potential health hazard—particularly at times of extensive flooding, which can lead to toxic contamination of groundwater or surface drinking water. Improvements in water
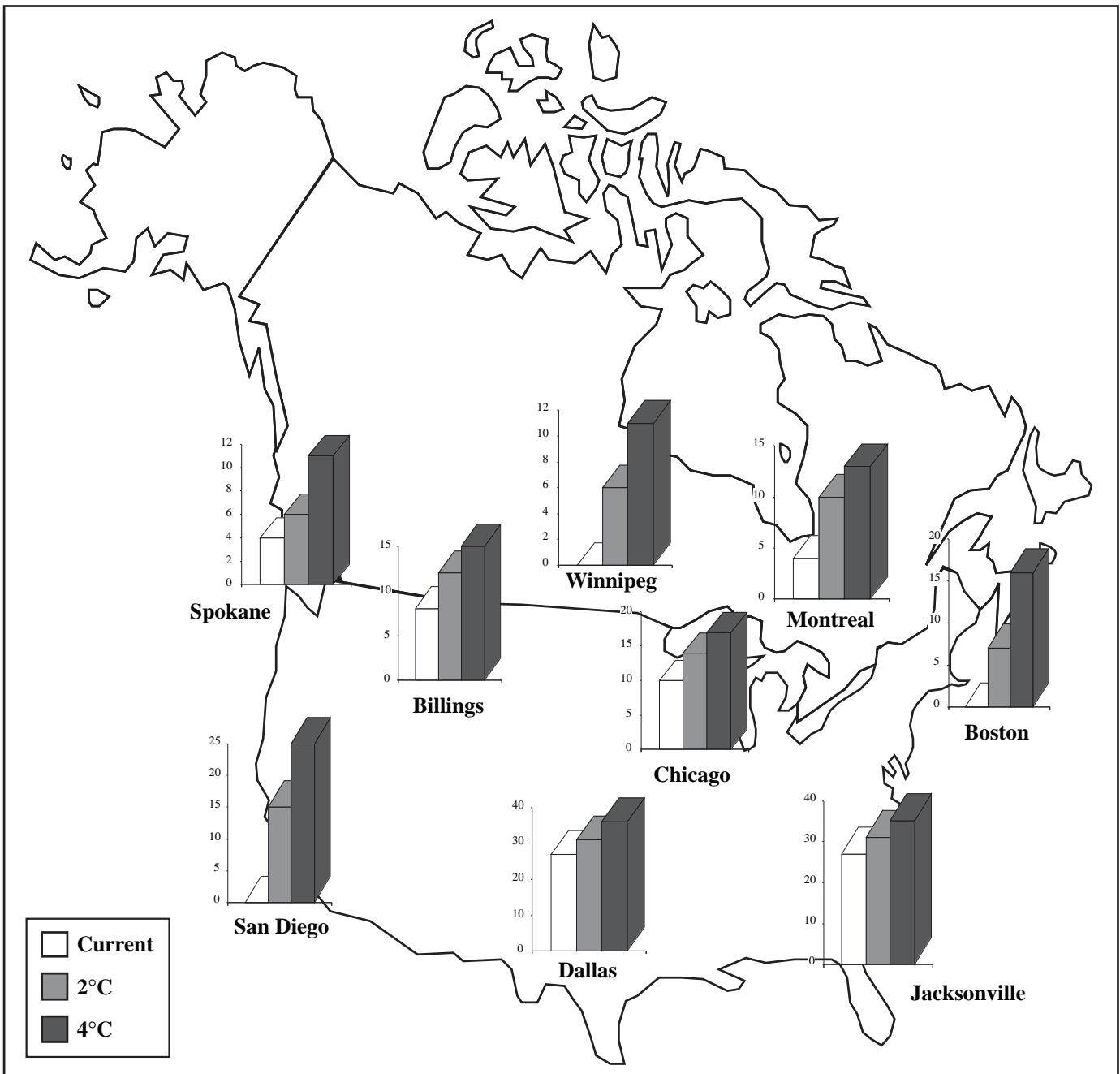
Figure 8-11: Weeks of potential dengue transmission under current temperature and 2°C and 4°C warming (adapted from Focks *et al.*, 1995; Jetten and Focks, 1997). Presence of dengue virus, mosquito vector, and exposed human populations are required for disease transmission.

treatment facilities and technologies could help ameliorate this situation.

<u>Marine</u>: Warm water favors the growth of toxic organisms such as red tides, which cause paralytic shellfish poisoning, diarrheic shellfish poisoning, and amnesic shellfish poisoning. For example, one species of toxic algae previously confined to the Gulf of Mexico (*Gymnodinium breve)* extended northward in 1987 after a "parcel of warm Gulf Stream water" reached far up the east coast, resulting in human neurologic shellfish poisonings and substantial fish kills (Tester, 1991). Domoic acid, a toxin produced by *Nitzchia pungens* diatom that causes amnesic shellfish poisioning, appeared on Prince Edward Island for the first time in 1987. The outbreak coincided with an El Niño year, when warm eddies of the Gulf Stream neared the shore and heavy rains increased nutrient-rich runoff (Hallegraeff, 1993).

Zooplankton, which feed on algae, can serve as reservoirs for *Vibrio cholerae* and other enteric pathogens, particularly gram-negative rods. Quiescent forms of *V. cholerae* have been found to persist within algae; these quiescent forms can revert to a culturable (and likely infectious) state when nutrients, pH, and temperature permit (Huq *et al.*, 1990). *V. cholerae* occur in the Gulf of Mexico and along the east coast of North America. With warmer sea surface temperatures, coastal algal blooms therefore could facilitate cholera proliferation and transmission.

8.4.   Integrative Issues

This chapter has discussed the impacts of climate change on the North American region largely in the context of sector-by-sector assessments of plausible impacts. Several common characteristics among sectors can be identified, however. Also, viewed collectively, interactions between sectors and subregions can be assessed, and insights about the integrated nature of the effects of climate change can emerge.

8.4.1.   Limitations of Climate Scenarios
for Regional Analyses

Most impact studies have assessed how systems would respond to climate change resulting from an arbitrary doubling of equivalent CO_2 concentrations. These so-called $2xCO_2$ scenarios are limited for regional-scale analyses to the extent that they inadequately correspond to the spatial scales of variability in North American natural and human systems. They also do not permit an examination of the effects of climate variability on physical, biological, and socioeconomic systems. Very few studies have considered dynamic responses to steadily increasing concentrations of greenhouse gases. Consequently, important insights about the ability of systems to respond to changing climate over time are lost. This lack of information is of particular concern because the ability of natural ecological systems to migrate often may be much slower than the predicted rate of climate change. Even fewer studies have examined the consequences of increases beyond a doubling of equivalent

atmospheric concentrations.

8.4.2.   Regional Texture of Impacts

All of the potential impacts of climate change exhibit a regional texture. Variations in the regional distribution of impacts need to be clearly articulated for policymakers. Failure to do so can lead to misleading impressions about the potential changes in social welfare as a result of climate change and alternative policy responses. A simple look at aggregate impacts on U.S. agriculture, for example, might suggest that climate change is not likely to harm agriculture enough to significantly affect the overall U.S. economy; policymakers might be left with the erroneous impression that no policy-relevant problems exist. Distributional differences emerge, however, upon examination of the regional texture of agricultural impacts.

Different adaptation strategies and options will be necessary to deal with these regional and sectoral differences. In areas where production significantly increases—such as the northern edge of agricultural production in North America—additional adaptation may be necessary in the development of infrastructure to support expanded population and transportation requirements associated with growth. The texture of the distribution of sectors and their biological, physical, and social components across the North American landscape cannot adequately be captured at a fine enough scale to be relevant to long-range planning at the present time; these are essential elements of future assessment needs.

It is also recognized—but poorly understood because of limited research—that climate change may have some benefits (e.g., it may reduce stress or provide opportunities) for certain areas or sectors within North America (e.g., expanded agriculture, reduced heating costs) or have a neutral effect on climate-insensitive sectors. If one examines any one particular climate impact, it is likely that there will be "winners" and "losers" either across subregions or within a subregion (e.g., across demographic groups). Nevertheless, the weight of evidence suggests that when all potential impacts are considered collectively, every subregion will incur some negative impacts of climate change.

8.4.3.   The Role of Adaptation

Some future climate change is inevitable. Strategies for technological and behavioral adaptation offer an opportunity to reduce the vulnerability of sensitive systems to the effects of climate change and variability. Some adaptive strategies can be undertaken in anticipation of future climate change; others are reactive and can be undertaken as the effects of climate change are realized.

Four points must be kept in mind when considering the extent to which adaptive strategies should be relied upon. First, adaptation is not without cost. Scarce natural and financial resources must be diverted away from other productive activities into adaptive prac-

tices. These costs must be carefully weighed when considering the tradeoffs among adapting to the change, reducing the cause of the change, and living with the residual impacts. Second, the economic and social costs of adaptation will increase the more rapidly climate change occurs. Third, although many opportunities exist for technological and behavioral adaptation, uncertainties exist about potential barriers and limitations to their implementation. Fourth, uncertainties exist about the efficacy and possible secondary effects of particular adaptive strategies.

8.4.4.   *Water as a Common Resource Across Sectors and Subregions*

Water is a linchpin that integrates many subregions and sectors. Available water supplies will be directly affected by climate change, but they also are affected by changes in demand from the many sectors that rely upon the water. Water is a scarce resource used in the agriculture, forest, and energy sectors. It is used in urban areas and in recreational activities. It also is essential for the survival of wetlands, nonforest ecosystems, wildlife, and other ecological systems.

Assessments of the potential impacts of climate change and variability on any of these systems and sectors must account for the inherent competition for water supplies and the need for water of varying qualities in various activities. For example, in an assessment of the potential impacts of climate change on agriculture, an assumption that farmers will be able to adapt to changing climatic conditions through a reliance on irrigation is valid only to the extent that water is available under future climate scenarios. In many cases, the scarcity of available water supplies will increase because of the direct effects of climate change on water, as well as increased demands for available water supplies.

8.4.5.   *Systemic Nature of the Problem*

In evaluating the implications of climate change impacts on North America, one must consider that although there are regional differences in response by sector and by subregion, the scale of anticipated changes is such that there may be adjustments taking place in every sector and subregion simultaneously. Any one of the impacts (whether beneficial or detrimental) that has been discussed for North America may appear well within the capability of existing structures and policies to adapt. However, the fact that they are occurring simultaneously may pose a significant challenge to resource managers and policymakers. The systemic nature of impacts and issues raises important questions about society's ability to manage the aggregate/cumulative risks posed by climate change.

This systemic problem also must be placed into the larger context of the multiple stressors that are and will be acting on North American resources. Many stressors (environmental, social, and economic) influence natural and human systems and pose significant challenges for decisionmakers and policymakers. The challenge of coping with the cumulative risks of climate change

adds to the complexity. What must be kept in mind is that changing climate is not the only—nor necessarily the most important—factor that will influence these systems and that it cannot be isolated from the combination of other factors determining their future welfare.

8.4.6.   *Integrated Nature of the Problem*

A complete assessment of the effects of climate change on North America must include a consideration of the potential interactions and feedbacks between sectors and subregions. Changes in the climate system can affect natural and human systems in a chain of consequences (see Figure 8-12). Some of these consequences are the results of direct effects of climate change and variability on physical, biological, and socioeconomic systems; some result from indirect links between climate-sensitive systems and related social and economic activities; some result from feedbacks between human activities that affect the climate system, which in turn can lead to further impacts (e.g., human activities affecting the climate system—which, in turn, can lead to further impacts on human health, the environment, and socioeconomic systems).

Most existing studies of potential impacts have focused on the more narrow direct pathway between climate change and climate-sensitive systems and sectors. These effects include direct climate impacts on human health (e.g., heat stress), environmental processes (e.g., impacts of runoff and streamflow on the hydrological cycle, coastal damages caused by sea-level rise, changes in biodiversity), market activities that are linked to the environment (e.g., agriculture, commercial timber, waterborne transport), and human behavior (e.g., changes in air conditioning use as a result of changes in the frequency of very hot days).

Fewer studies have captured the more indirect effects of climate change, which may take many different forms. Many of the primary determinants of human health (adequate food,
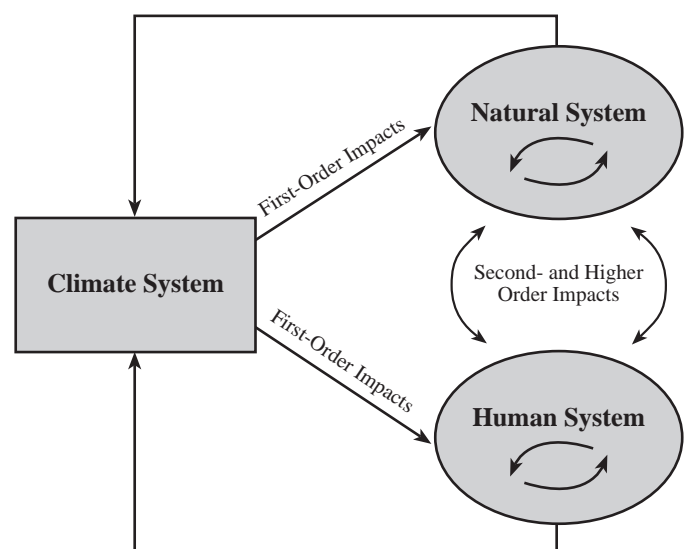
Figure 8-12: Chain of consequences.

clean water, secure shelter) are related to outputs from sectors such as agriculture, water resources, and fisheries. The potential spread of infectious diseases is indirectly related to climate change through changes in ecosystems and the hydrological cycle. Therefore, it is important to integrate these relevant systems into a human health assessment.

Other indirect effects include secondary impacts on market activities that are dependent upon sectors directly affected by climate change. For example, climate change will directly affect crop yields and hence agricultural production and prices.

These effects, in turn, will influence the prices of goods and services that use agricultural commodities in their production, which will feed back to the agricultural sector and agricultural prices. Shifts in agricultural production could have a large impact on freight transport patterns and may require adjustments in the transportation network—with marine, road, rail, and air links potentially needing expansion into areas not currently serviced. One study of the U.S. economy suggests that the direct effects of climate change on U.S. agriculture, energy use, and coastal protection activities could lead to price increases for all economic sectors, causing a reallocation of

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Box 8-3. Mackenzie Basin Impact Study

The Mackenzie Basin Impact Study (MBIS) was a 6-year climate change impact assessment focusing on northwestern Canada (supported by Environment Canada and other sponsors) to assess the potential impacts of climate change scenarios on the Mackenzie Basin region, its lands, its waters, and the communities that depend on them (Cohen, 1997a). The MBIS was designed to be a scientist-stakeholder collaborative effort, with 30 research activities on various topics—ranging from permafrost and water levels to forest economics and community response to floods.

The MBIS integration framework included several integration modeling exercises—such as resource accounting, multiregional input-output modeling and community surveys of the nonwage economy of an aboriginal community, a multiobjective model focusing on scenarios of changing land utilization, and a land assessment framework (ILAF) with goal programming and an analytic hierarchy process. MBIS researchers identified six main policy issues related to climate change as another form of "vertical integration": interjurisdictional water management, sustainability of native lifestyles, economic development opportunities, buildings, transportation and infrastructure, and sustainability of ecosystems (Cohen, 1997a). Integration also was attempted through information exchange (scenarios and data) while study components were in progress and a series of workshops that provided opportunities for scientists and stakeholders to express their views on how climate change might affect the region and to react to research results (Cohen, 1997a,b).

The main result of the integrated assessment was that most participating stakeholders saw climate impacts scenarios as a new and different vision of the future for their region, and that adaptation measures alone might not be enough to protect the region from adverse impacts.
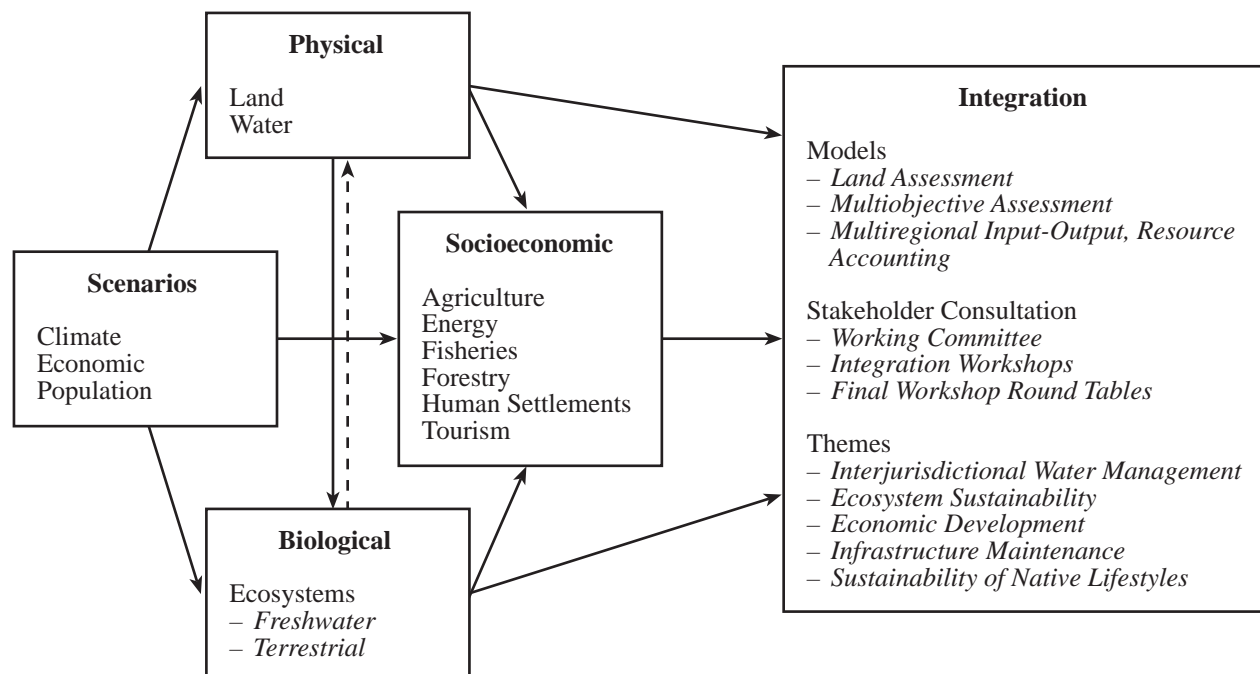
Integration research framework for the Mackenzie Basin Impact Study (Cohen, 1997a).

Box 8-4. Great Lakes-St. Lawrence Basin Project

The Great Lakes-St. Lawrence Basin (GLSLB) Project on "adapting to the impacts of climate change and variability" is a binational project initiated in 1992 by Environment Canada to improve our understanding of the complex interactions among climate, environment, and society so that regional adaptation strategies could be developed in response to potential climate change and variability (Mortsch and Mills, 1996). The GLSLB Project identified four climate-sensitive theme areas upon which to focus the research: water use and management, land use and management, ecosystem health, and human health. Another prime focus of the GLSLB Project is adaptation, which provides the conceptual framework for integrating research efforts. GLSLB Project studies contain common components that will facilitate the integration of research findings, including study objectives; policy issue foci; a multidisciplinary approach; scenarios tested; impact and adaptation assessment methods; the concept of adaptation; and scales of time, space, and human activity (Mortsch and Mills, 1996). A number of more pragmatic integration concepts also have been incorporated into the GLSLB Project, including the use of "end-to-end studies" assessing biophysical and socioeconomic impacts and developing and evaluating potential adaptation strategies, economic modeling (LINK model), the use of Geographic Information Systems (GIS), and common communication goals (Mortsch and Mills, 1996).

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spending and the sectoral composition of output.

Other indirect effects include changes in nonmarket activities as a result of projected impacts of climate change on ecosystems (e.g., changes in recreational fishing as a result of projected impacts of climate change on aquatic ecosystems). For example, the loss of fishing opportunities could be severe in some parts of the region, especially at the southern boundaries of fish species' habitat regions. The loss of fishing opportunities may result in economic losses for the fishing industry. In turn, related industries such as the food, transportation, and lodging industries will be affected. All of these examples illustrate how each sector that is directly or indirectly affected by climate change can adversely affect others.

As this chain of consequences illustrates, the task of assessing various impacts and the feedbacks among them is enormously complex and requires a number of simplifying assumptions. Although there are complex macroeconomic models to assess the costs and consequences of various mitigation policies, the state of the art in impact work at present limits the insights that can be gained from this kind of "top-down" modeling. The dominant approach has been "bottom-up"—aggregating direct and indirect impacts into a single overall estimate, without much attention to feedbacks among various sectors. Nevertheless, the complex, integrated nature of the climate change problem suggests the need for integrated assessments that incorporate many aspects of the region. Sectoral assessments alone would not be sufficient.

Examples of broad, integrated approaches to climate impact assessment are two regional studies in North America: the Mackenzie Basin Impact Study and the Great Lakes-St. Lawrence Basin Project.

These two efforts have tried to account for some of the synergies and interactions among sectors that make each region unique. Each represents a learning experience that ultimately will lead to improvements in how regional assessments and integration are done.

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