Confronting Climate Change in the Great Lakes Region

Impacts on Our Communities and Ecosystems

A REPORT OF

The Union of Concerned Scientists and
The Ecological Society of America

Confronting Climate Change in the Great Lakes Region

Impacts on Our Communities and Ecosystems

PREPARED BY

George W. Kling
Katharine Hayhoe
Lucinda B. Johnson
John J. Magnuson
Stephen Polasky
Scott K. Robinson
Brian J. Shuter
Michelle M. Wander
Donald J. Wuebbles
Donald R. Zak

WITH CONTRIBUTIONS FROM

Richard L. Lindroth
Susanne C. Moser
Mark L. Wilson

April 2003

A REPORT OF
The Union of Concerned Scientists and
The Ecological Society of America

Citation: Kling, G.W., K. Hayhoe, L.B. Johnson, J.J. Magnuson, S. Polasky, S.K. Robinson, B.J. Shuter, M.M. Wander, D.J. Wuebbles, D.R. Zak, R.L. Lindroth, S.C. Moser, and M.L. Wilson (2003). *Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems.* Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C.

Designed by
DG Communications, Acton, Massachusetts
(www.nonprofitdesign.com)

Printed on recycled paper.

Copies of this report are available from
UCS Publications, Two Brattle Square, Cambridge, MA 02238–9105
Tel. 617–547–5552

In Canada, copies of the report are available from the
David Suzuki Foundation
1-800-453-1533 or orders@davidsuzuki.org

The report and additional technical background information are also available at
www.ucsusa.org/greatlakes

Cover Photo Credits (clockwise from top right)
Killarney Provincial Park, *Ontario*, photograph by Claude Grondin; *Niagara Falls*, Center for Great Lakes and Aquatic Sciences, courtesy of Minn. Sea Grant; *Sleeping Bear Dunes National Lakeshore*, Michigan, photograph by Robert DeJonge, courtesy of Mich. Travel Bureau and Minn. Sea Grant; *Chicago, Illinois*, photograph by John J. Magnuson; *Farmscape near Chippewa Falls, Wis.*, photograph by Ron Nichols, courtesy of USDA; *North Star Lake, Minn.*, photograph by Richard Faulkner, courtesy of Edge of the Wilderness National Scenic Byway.

Table of Contents

Figures

Boxes

Tables

Acknowledgements

The authors thank the steering committee of this project, and especially Louis Pitelka, for conceptual guidance and review of the report. Mary Barber, past her call of duty at ESA, and Peter Frumhoff from UCS provided leadership from the two sponsoring organizations. In addition, we appreciate the more than two-dozen individuals who provided scientific peer review of all or portions of earlier versions of this report. Our sincere thanks for ensuring scientific accuracy go to David Allan, Bennet Brabson, Alex Boston, Scott Bridgham, Quentin Chiotti, Peter Curtis, Evan Delucia, Kieran Donaghy, Laurie Drinkwater, Gabe Filippelli, Ann N. Fisher, Pierre Gosselin, Dave Grigal, Glenn Guntenspergen, Danny Harvey, Bob Hecky, Joan Klaassen, Tim Kratz, Uriel D. Kitron, A. Carl Leopold, Sarah Marchildon, Pam Matson, Patrick J. Mulholland, LeRoy Poff, Terry Root, Ian Rutherford, Gerry Scott, Kristin Shrader-Frechette, Brent Sohngen, and Scott Swinton. Any remaining errors are ours, of course.

Many individuals also supplied data, technical information and copies of published or forthcoming research papers. Thank you to Richard Adams, Victor B. Caballero, Steve Clemmer, Jeff Deyette, Glenn Guntenspergen, Kshama Harpankar, Tom Hollenhorst, Tim Johnson, Michelle Manion, Alan Nogee, John Pastor, Jeff Price, Aaron Rappaport, Harold Rennie, Phil Ryan, Paul Strode, Nori Tarui, and Michael Ward. In addition, Kenneth Kunkel supplied historical climate data and contributed to the climate chapter, David Viner provided access to HadCM3 model results, and Michael Wehner and Jerry Meehl provided access to PCM model results.

Help in identifying, producing, and supplying graphics and photographs came from Alex Boston, Taryn Clark, Tim Daniel, Robert Darmody, Claude Grondin, Svenja Hansen, Dave Hanson, James M. Haynes, Tom Hollenhorst, Linda Holthaus, Dave Hvizdak, Lucinda Johnson, Tim Johnson, Denise Karns, George Kling, Marty Kroell, Robert McLeese, John J. Magnuson, Sarah Marchildon, Ron Moen, John Pastor, Julia Petipas, Marie Reynolds, Larry Ricker, Keith Stewart, Paul Strode, David Taylor, Scott A. Thom, Michael Ward, Mike Williams, Heather Webb, and Minnesota Sea Grant. Vanessa Parker-Geisman helped tremendously with finding and choosing between graphics and kept track of them all.

The production of this report was made possible through the generous support of The Henry Luce Foundation, Inc. with additional foundation support from the John D. and Catherine T. MacArthur Foundation, Marbrook Foundation, Oak Foundation, the V. Kann Rasmussen Foundation, and Wallace Global Fund. The University of Illinois Office of the Vice Chancellor for Research and the Illinois-Indiana Sea Grant Program Office financially supported the climate modeling work. The David Suzuki Foundation (Vancouver, British Columbia) generously provided funding for some work related to the Canadian portion of the project. The report will be released under the auspices of the DSF in Ontario.

Finally, we could not have completed this project without Rhonda Kranz of the Ecological Society of America and Susanne Moser of the Union of Concerned Scientists, who persistently and patiently managed the project through its different phases.

Executive Summary

The Great Lakes region of the United States and Canada is a land of striking glacial legacies: spectacular lakes, vast wetlands, fertile southern soils, and rugged northern terrain forested in spruce and fir. It is also home to 60 million people whose actions can profoundly affect the region's ecological bounty and the life-sustaining benefits it provides. Now that the world is entering a period of unusually rapid climate change, driven largely by human activities that release heat-trapping greenhouse gases into the atmosphere, the responsibility for safeguarding our natural heritage is becoming urgent.

Growing evidence suggests that the climate of the Great Lakes region is already changing:

- Winters are getting shorter.
- Annual average temperatures are growing warmer.
- The duration of lake ice cover is decreasing as air and water temperatures rise.
- Heavy rainstorms are becoming more common.

This report examines these trends in detail and discusses the likelihood that they will continue into the future. The consequences of these climatic changes will magnify the impacts of ongoing human disturbances that fragment or transform landscapes, pollute air and water, and disrupt natural ecosystems and the vital goods and services they provide. *Confronting Climate Change in the Great Lakes Region* explores the potential consequences of climate change, good and bad, for the character, economy, and environment of the Great Lakes region during the coming century. It also examines actions that can be taken now to help forestall many of the most severe consequences of climate change for North America's heartland.

What is the likely climate future for the Great Lakes region?

In general, the climate of the Great Lakes region will grow warmer and probably drier during the twenty-first century. Climate models predict that by the end of the century, temperature in the region will warm by 5 to 12°F (3 to 7°C) in winter, and by 5 to 20°F (3 to 11°C) in summer. Nighttime temperatures are likely to warm more than daytime temperatures, and extreme heat will be more common. Annual average precipitation levels are unlikely to change, but the seasonal distribution is likely to vary greatly, increasing in winter and decreasing in summer. Overall, the region may grow drier because any increases in rain or snow are unlikely to compensate for the drying effects of increased evaporation and transpiration in a warmer climate. This drying will affect surface and groundwater levels, and soil moisture is projected to decrease by 30 percent in summer. In addition, the frequency of 24-hour and multiday downpours, and thus flooding, may continue to increase.

These changes in temperature and precipitation will strongly alter how the climate feels to us. Within three decades, for example, a summer in Illinois may feel like a summer in Oklahoma does today. By the end of the century, an Illinois summer may well feel like one in east Texas today, while a Michigan summer will probably feel like an Arkansas summer does today. Residents in Toronto could experience a shift from a southern Ontario summer to one that by 2030 may feel more like one in upstate New York, and by the end of the century more like one in northern Virginia today.

What might these changes mean for Great Lakes ecosystems and the goods and services they provide?

Lakes

- Lake levels have been highly variable in the 1900s, but declines in both the inland lakes and the Great Lakes are anticipated in the future.
- Declines in the duration of winter ice are expected to continue.
- Loss of winter ice may be a mixed blessing for fish, reducing winterkill in shallow lakes but also jeopardizing reproduction of whitefish in the Great Lakes bays, where ice cover protects the eggs from winter storm disturbance.
- The distributions of many fish and other organisms in lakes and streams will change. Coldwater species such as lake trout, brook trout, and whitefish and cool-water species such as northern pike and walleye are likely to decline in the southern parts of the region, while warm-water species such as smallmouth bass and bluegill are likely to expand northward.
- Invasions by native species currently found just to the south of the region and invasions of warm-water nonnative species such as common carp will be more likely, increasing the stress on native plant and animal populations in the region.
- In all lakes, the duration of summer stratification will increase, adding to the risk of oxygen depletion and formation of deep-water "dead zones" for fish and other organisms.

- Lower water levels coupled with warmer water temperatures may accelerate the accumulation of mercury and other contaminants in the aquatic food chain and ultimately in fish.

- Many fish species should grow faster in warmer waters, but to do so they must increase their feeding rates. It remains uncertain whether prey species and the food web resources on which they depend will increase to meet these new demands.

Streams and Wetlands

- Earlier ice breakup and earlier peaks in spring runoff will change the timing of stream flows, and increases in heavy rainstorms may cause more frequent flooding.

- Changes in the timing and severity of flood pulses are likely to reduce safe breeding sites, especially for amphibians, migratory shorebirds, and waterfowl, and may cause many northern migratory species such as Canada geese to winter further north.

- Reduced summer water levels are likely to diminish the recharge of groundwater supplies, cause small streams to dry up, and reduce the area of wetlands, resulting in poorer water quality and less habitat for wildlife.

- Drought and lower water levels may ultimately increase ultraviolet radiation damage to frogs and other aquatic organisms, especially in clear, shallow water bodies.

- River flooding may become more common and extreme because of the interaction of more frequent rainstorms with urbanization and other land management practices that increase pavement and other impervious surfaces and degrade the natural flood-absorbing capacities of wetlands and floodplains. The result could be increased erosion, additional water pollution from nutrients, pesticides, and other contaminants, and potential delays in recovery from acid rain.

> The risk of oxygen depletion and deep-water "dead zones" will increase in all lakes.

- Land use change and habitat fragmentation combined with climate change-induced shrinking of streams and wetlands will also decrease the number and type of refugia available to aquatic organisms, especially those with limited dispersal capabilities such as amphibians and mollusks, as streams and wetlands shrink.

Forests

- The distribution of forests is likely to change as warmer temperatures cause the extent of boreal forests to shrink and many forest species to move northward. The new forest composition will depend on the ability of individual species to colonize new sites and the presence of both geographic and human barriers to migration.

- Increasing atmospheric CO_2 concentration is likely to spur forest growth in the short term, but the long-term response is not clear at present. Increasing ground-level ozone concentrations, for example, will probably damage forest trees, potentially offsetting the positive effect of CO_2.

- Continued deposition of nitrogen from the atmosphere may spur growth in forests, but the long-term consequences include increased nitrate pollution of waterways, groundwater, and drinking water supplies.

- Long-distance migratory birds such as scarlet tanagers, warblers, thrushes, and flycatchers depend on trees and caterpillars for food. Especially for those migrants who time their migration by day length rather than by weather, food sources may be severely reduced when they arrive in the Great Lakes region.

- Resident birds such as northern cardinals, chickadees, and titmice might be able to begin breeding earlier and raise more broods each season. However, increasing populations of resident species could further reduce the food available for migratory songbirds that breed in the Great Lakes, ultimately reducing forest bird diversity in the region.

- The geographic range of forest pest species such as the gypsy moth is likely to expand as temperatures warm and the distribution of food plants changes.
- Changes in leaf chemistry due to CO_2 fertilization are possible, reducing food quality for some organisms. This could cause some leaf-eating pests to eat more and could ultimately alter aquatic and terrestrial food webs.

Agriculture

- Earlier studies predicted that climate change would benefit or only marginally disrupt Great Lakes agricultural productivity over the next 100 years, with warming and increased CO_2 fertilization boosting yields in the northern parts of the region. Newer climate projections used in this report, however, suggest a less favorable impact on agriculture, largely because of changes in the distribution of rain: Wetter periods are expected during times that could delay harvest or planting, and dry spells are projected during times when crops need water. As optimal agricultural climates move northward and eastward, crop yields may be limited by soil quality and be more vulnerable to weather extremes such as floods and droughts.

Lower summer water levels are likely to diminish the recharge of groundwater, cause small streams to dry up, and reduce the area of wetlands.

- The length of the growing season will continue to increase so that by the end of the century it may be four to nine weeks longer than over the period 1961–1990.
- Crop losses may increase as new pests and diseases become established in the region and as warmer, longer growing seasons facilitate the buildup of larger pest populations. Already the range of the bean leaf beetle, a pest of soybeans, appears to be shifting northward.
- Ozone concentrations already reach levels that damage soybeans and horticultural crops, and increasing concentrations may counteract the increased production expected from CO_2 fertilization.
- Warmer temperatures may impair livestock health in southern parts of the region, and a drier summer climate may reduce the productivity of pasture grasses.
- Overall, the influence of climate change on both crop and livestock sectors will be greatly moderated by technological advances and trends in markets. However, increasing variability in the climate is likely to increase economic risks for smaller farms.

Economic, Social, and Health Impacts

- As lake levels drop, costs to shipping in the Great Lakes are likely to increase, along with costs of dredging harbors and channels and of adjusting docks, water intake pipes, and other infrastructure. On the other hand, a longer ice-free season will increase the shipping season.
- Shorter, warmer winters will result in losses in winter recreation such as skiing, ice fishing, and snowmobiling, but may lengthen the season for warm-weather recreation. Changes in recreational fishing, hunting, and wildlife viewing may occur as the distribution of species shifts across the region.
- Climate warming may lower heating costs in winter, but that may be offset by higher costs for air conditioning in summer.
- Water withdrawals from the Great Lakes are already the subject of contentious debate, and pressures for more water for irrigation, drinking, and other human uses may intensify the conflicts as water shortages develop.
- Decreased water levels could reduce hydropower generation in the region.
- More days with high heat may exacerbate the formation of dangerous levels of ozone. Ozone and other air pollutants generated by coal-fired power plants in the region are likely to exacerbate asthma and other respiratory diseases.
- Health risks associated with extreme heat are likely to increase, while cold-related illnesses are likely to decrease.

How can residents of the Great Lakes region address the challenge of a changing climate?

There are prudent and responsible actions that citizens and policymakers can take now to reduce the vulnerability of ecosystems and safeguard the economy of the region in the face of a changing climate. These actions represent three complementary approaches:

- Reducing the region's contribution to the global problem of heat-trapping greenhouse gas emissions: Although some warming is inevitable as a result of historical emissions of CO_2, many of the most damaging impacts can be avoided if the pace and eventual severity of climate change are moderated. Strategies for reducing emissions include increasing energy efficiency and conservation in industries and homes, boosting the use of renewable energy sources such as wind power, improving vehicle fuel efficiency, reducing the number of miles driven, avoiding waste, and recycling.
- Minimizing human pressures on the global and local environment to reduce the vulnerability of ecosystems and vital ecological services to climate change: Prudent actions include reducing air pollution, protecting the quality of water supplies as well as aquatic habitats, reducing urban sprawl and attendant habitat destruction and fragmentation, restoring critical habitats, and preventing the spread of invasive nonnative species.
- Anticipating and planning for the impacts of change to reduce future damage: This may include a wide range of adaptations, from shifts in fisheries management and farming activities to changes in building codes and public health management plans to prepare for extreme weather events.

> There are prudent and responsible actions that citizens and policymakers can take now to reduce the vulnerability of ecosystems and safeguard the economy of the region.

Climate change is already making an impact on the environment of the Great Lakes region. Waiting to begin reducing emissions or to plan for managing the effects of climate change only increases the eventual expense and the potential for irreversible losses. Fortunately, many of the actions that can be taken now to prevent the most damaging impacts of climate change can also provide immediate collateral benefits such as cost savings, cleaner air and water, improved habitat and recreational opportunities, and enhanced quality of life in communities throughout the region.

CHAPTER
One

Great Lakes Ecosystems and People: Mutual Influence and Dependence

The unique waters and landforms of the Great Lakes region are a striking legacy of climates past. For two and a half million years, massive ice sheets advanced and retreated across the land, scouring the bedrock, gouging out spectacular lake basins, and depositing the geological forerunners of the soils that now nurture forests, farms, and gardens. The ecosystems and human economies of the region, like the landscape itself, have been profoundly shaped by this climatic legacy. Now the world is entering another period of climate change, this time unusually rapid and driven largely by human activities that release heat-trapping greenhouse gases into the atmosphere. The impacts of this climate change, in concert with other human pressures on our lands and waters, promise to alter the character, economy, and environment of the Great Lakes region during the twenty-first century. Examining the potential impacts of future climate on the region is the purpose of this report.

The vast majority of scientists are now certain that the world's climate is changing.

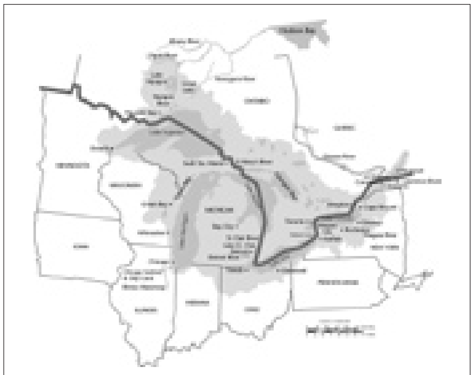
The vast majority of scientists are now certain that the world's climate is changing. Average global temperatures are warming, and the current rate exceeds the normal range of temperature swings experienced for at least the last thousand years. Temperatures in the northern hemisphere have increased by more than 1°F (0.5°C), growing seasons have lengthened, and precipitation has increased by 5 to 10 percent since 1900. Other indicators that the climate is warming include documented losses in the extent of alpine glaciers, sea ice, and seasonal snow cover.

Evidence strongly suggests that current climate change is being driven by increasing atmospheric concentrations of greenhouse gases, mainly carbon dioxide (CO_2) but also methane (CH_4) and nitrous oxide (N_2O). The main reason for the buildup of these gases is the burning of fossil fuels, the clearing of forests, and other activities of a burgeoning human population. Without major shifts in global policies or energy technologies, these changes in the atmosphere will continue. Even if human emissions were to be reduced drastically, CO_2 already in the atmosphere would take decades to decay, ensuring continuing impacts on the climate for several generations. Life on earth has rarely experienced shifts in climate as rapid as those now in progress, and it is unclear whether the plants, animals, and ecosystems on which humans depend can adapt quickly enough. These factors lend added urgency to the need to address both the causes and the impacts of climate change.

Regional Landscapes

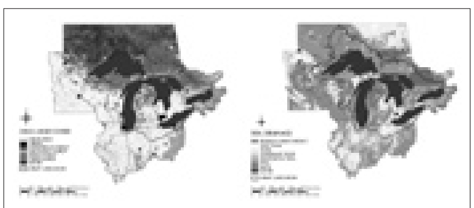
The Great Lakes basin encompasses more than 308,000 square miles of the North American heartland and contains the largest single concentration of liquid fresh water on the planet. The five Great Lakes themselves cover more than 95,000 square miles and hold about 20 percent of the world's supply of fresh water. The region hosts not only the largest lake in the world (Lake Superior) and the four other Great Lakes (Erie, Huron, Michigan, and Ontario), but also hundreds of thousands of smaller lakes, streams, and wetlands — the greatest concentration of small water bodies in the world in an area of this size (Figure 1).

FIGURE 1
The Great Lakes Region



See page 33
for full-size color image of this figure

FIGURE 2
Satellite-Derived Maps Showing Land Cover and Soil Drainage



See page 33
for full-size color image of this figure

This report focuses on the six Great Lakes states (Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin), the southern half of the province of Ontario, and portions of New York and Pennsylvania within the boundaries of the Great Lakes Basin (Figure 1). Because of the way economic and social statistics are collected, this report will sometimes talk about the six Great Lakes states plus Ontario.

The glacial history of the region constrains and influences most aspects of the environment. The repeated glaciations that began 2.4 million years ago ended with the last ice age, which covered the entire region as far south as the Ohio River from 18,000 to 21,000 years ago. The ice finally receded completely about 9,000 years ago, leaving the mark of its passing on the current landscape. Current patterns of land cover and land use in the region (Figure 2) mirror the distribution of soils and sediments left by the glaciers. In the northern upland region located on the Canadian Shield, thin coarse-textured soils support extensive spruce and fir forests. The cold climate and relatively poor soils have discouraged development of large population centers, and the economy depends largely on tourism, timber, and mining. In the lowland areas to the south and east, deep and fertile soils, combined with a warmer climate, support a large proportion of the agricultural production for both Canada and the United States, along with remnant oak and hickory forests and prairie habitat.

Human Geography and Economy

More than 60 million people live in the Great Lakes states and Ontario, half of them within the Great Lakes drainage basin itself, and the population continues to grow. Population grew by 8.7 percent in the Great Lakes states over the past decade[1] (Figure 3) and 12.2 percent over the same period in Ontario.[2] Many major cities are situated on the shores of the Great Lakes, including Buffalo, Chicago, Cleveland, Detroit, Hamilton, Milwaukee, Toronto, and Windsor.

The economy of the region is large and diversified and includes strong manufacturing, services (including tourism and recreation), agriculture, forestry, and government sectors (Figure 4). Regional production in 2000 totaled nearly $2 trillion (US), an amount that exceeds the gross domestic production of any nation except the United States and Japan.

The Great Lakes region forms the industrial heartland of North America. In 2000, over 50 percent of the value of manufacturing shipments in Canada came from Ontario,[3] and the six Great Lakes states contribute more than 25 percent of total value added[*]

[*] The term generally means the enhanced value of a commodity when processed into a secondary, more valuable product or service.

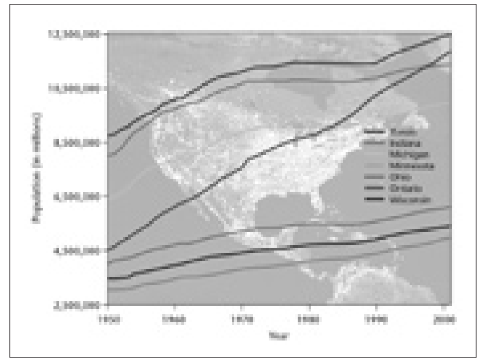
in US manufacturing.[4] Early industry relied upon raw materials mined or harvested in the region and low-cost shipping on the lakes. Iron ore from northern Minnesota, for instance, was shipped down the lakes to feed the giant steel mills of Gary and Pittsburgh. In recent years, the economy has become more diversified and no longer relies to such a large degree on steel, automobile manufacturing, and other heavy industry. The region remains a major shipping center, however, and freighters ply the lakes and seaway corridors to the Atlantic Ocean carrying grain, soybeans, coal, iron ore, and other goods and commodities worth billions of dollars from the Midwest and Canada to markets worldwide. This traffic generates $3 billion (US) in yearly business revenue and 60,000 jobs.[5]

The region also forms part of the agricultural heartland of the continent, and more than 25 percent of the total value of US agricultural products is grown in the Great Lakes states.[6] That includes more than 50 percent of the nation's corn and 40 percent of its soybeans. Agricultural harvests on the Canadian side of the basin represent nearly 25 percent of that nation's output, and total farm cash receipts in Ontario exceed those from all other provinces in Canada except Alberta.[7]

Although forestry contributes less to the regional economy than industry or agriculture, locally important forestry sectors remain. For example, the forest products industry in Ontario employed more than 90,000 people and generated receipts of more than $15 billion (Cdn) in the late 1990s.[8] In Wisconsin in 2000, pulp, paper, wood products manufacturing, and other forest products industries employed 74,000 workers and generated more than $18 billion (US) in shipments.[9]

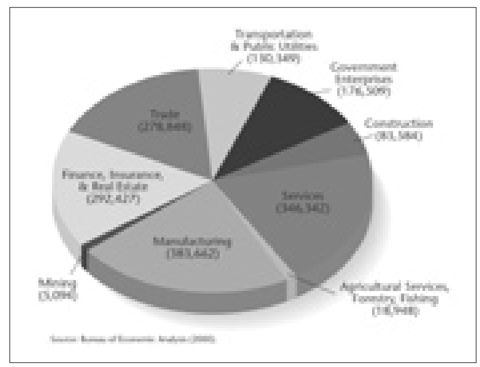
The services sector, which includes many tourism, recreation, and environment-related enterprises, has grown increasingly important and is now one of the largest economic sectors in the region. The Great Lakes themselves represent the major recreation and tourism attraction in middle America.[10] Indiana Dunes National Lakeshore and Sleeping Bear Dunes National Lakeshore in Michigan each hosted more than one million visitors in 1999.[11] In 2001, Ontario parks from Point Pelee to Lake Superior drew more than 11 million visitors altogether.[12] In addition, crowds of summer vacationers flock to the many small inland lakes of Northern Michigan, Minnesota, Ontario, and Wisconsin. In winter, too, large numbers of visitors arrive to take advantage of opportunities for downhill and cross-country skiing and snowmobiling. More than 15 million people in the Great Lakes states participate in fishing, hunting, or wildlife watching (Figure 5), activities that bring $18.5 billion (US) in sales annually.[13] In Ontario, travel and tourism brought in more than $20 billion (Cdn) in 2000.[14]

FIGURE 3
Population Change in the Great Lakes Region (1950–2001)



See page 34
for full-size color image of this figure

FIGURE 4
The World's Third-Largest Economy (in Millions of US Dollars)



See page 34
for full-size color image of this figure

Human Pressures on Ecosystem Health and Services

The well-being of people in the Great Lakes region depends on the healthy functioning of ecosystems and the services they provide. Some of these services are easily valued because they are bought, sold, or traded. Clearly, agriculture, forestry, tourism, and outdoor recreation rely directly on the vitality of both natural and managed ecosystems and the plant and animal communities they harbor. Other ecological processes have not been assigned any direct economic value, yet they supply vital support services such as air and water purification, flood protection, pest control, soil renewal, habitat, aesthetic values, and support of cultural traditions, especially for Native Americans and First Nations groups. Forest birds and amphibians, for example, serve humans by devouring insects that would otherwise harm people, forests, and crops. Amphibians may be especially important as consumers of mosquitoes in small, ephemeral wetlands that lack fish.

FIGURE 5
The Changing Character of the Region

See page 34
for full-size color image of this figure

These and other ecological services and the ecosystems and species that supply them face increasing pressure, not only from human-induced climate changes but from many direct human disturbances as well. These include land development and land-use change, discharges of pollutants into the air and water, timber harvesting, mining, intensive agriculture, tourism, and even shipping, an activity responsible for introducing the zebra mussel and other damaging non-native invasive species into the Great Lakes. As the population of the region grows, these direct stresses will increase; so too will the region's contribution to changes in the atmosphere and, indirectly, climate.

The six Great Lakes states use an estimated 16.5 quadrillion BTUs (17,000 PJ) of energy each year. Of this total, more than 90 percent comes from burning fossil fuels: 36 percent from petroleum, 32 percent from coal, and 25 percent from natural gas. Electricity production in this part of the United States depends heavily on burning coal, which emits the most carbon per BTU. More than 60 percent of electricity in the six states is generated by coal-fired power plants.[15] In contrast to the US states in the region, Ontario electricity production is highly diversified, with 27 percent from coal and natural gas. For its total energy needs, Ontario currently uses 3,000 PJ (2.8 quadrillion BTUs) per year, including 40 percent from petroleum products, 32 percent from natural gas and 3.5 percent from coal.[16]

> Ecological services and the ecosystems and species that supply them face increasing pressure from climate change and other human disturbances.

The pace of land-use change is likely to continue to outstrip population growth in the region thanks to urban sprawl and vacation home development. From 1970 to 1990, the population of northeastern Illinois grew by only 4.1 percent while residential land consumption increased by nearly 46 percent. In Michigan, the population is projected to grow 12 percent between 1990 and 2020, but urbanized land may increase 63 to 87 percent during that period. In Ontario, the greater Toronto area is expected to expand its urbanized area by 60 percent by the year 2021.[17] Much of the land not taken up by urban sprawl is given to agriculture, and almost half of the land in the Great Lakes states has been converted to crop fields, pastures, and dairy farms.

Converting land from forest or grassland to farms, houses, shopping malls, or factories not only results in outright loss of habitat for plant and animal species, but also fragments the landscape, leaving islands of natural habitat isolated in a sea of human development. These habitat remnants may be too small and degraded to sustain healthy plant and animal populations, especially when roads, fences, and other human structures create barriers to migration between them.[18] Landscape fragmentation also makes it more difficult for species to migrate to suitable new habitats as the climate shifts.

Urban development greatly modifies local hydrology as well by increasing the extent of impervious surfaces such as roofs and pavement and destroying natural wetlands and floodplains that would otherwise absorb storm runoff and recharge ground waters.[19] Increasing impervious surfaces in a watershed by 10 to 20 percent causes a 35 to 50 percent increase in surface runoff.[20] Paved surfaces also behave as heat sinks, raising air and stream water temperatures. Removing streambank trees exacerbates this heating.[21] Overall, the impacts of climate change on the environment and on human well-being in the Great Lakes region will be strongly modified by changes in population, urbanization, land use, and policy and management decisions.[22]

CHAPTER
Two

Scenarios of Change: Past, Current, and Future Climate

Two major factors that shape the region's climate are its location in the middle of the North American land mass and the presence of the Great Lakes. The midcontinent, midlatitudes location far from the oceans contributes to large seasonal swings in air temperature between warm summers and cold winters. In the winter, bitterly cold Arctic air masses occasionally move southward into the region, and the polar jet stream is often located near or over the region. The result is frequent storm systems that bring cloudy, windy conditions and rain or snow. In the summer, a semipermanent high-pressure system in the subtropical Atlantic pumps warm, humid air into the region, particularly the southern portions of the Great Lakes basin.

The Great Lakes themselves have a substantial impact on the climate. Because large bodies of water gain and lose heat more slowly than the surrounding land, surface water temperatures in the lakes tend to be warmer than the land during the late fall and early winter. Conversely, lake water remains much colder than the surrounding land in the late spring and summer. This phenomenon moderates air temperatures near the shores of the lakes. The influence of the lakes is most evident on the downwind sides, where it helps to create microclimates such as the wine-growing regions of southwestern Michigan and Ontario. Perhaps the best-known aspect of the Great Lakes' influence downwind, however, is "lake-effect" snowfall. During the late fall and winter, cold air masses sweep across the warmer lakes, picking up heat and moisture and generating extreme snowstorms on the lee sides of the lakes. A lake-effect snowstorm in 2002 dumped seven feet of snow in Buffalo over several days.

> The Great Lakes themselves help create unique climatic features, such as lake-effect snowfalls and microclimates beneficial for wine growing.

Climate Trends and Variability in the Great Lakes Region

Natural variations in climate are driven by many factors, including changes in solar radiation reaching the Earth, the direction and intensity of ocean currents that generate El Niño and La Niña events, natural fluctuations in greenhouse gases such as water vapor, CO_2, and ozone, and chaotic interactions within the earth-climate system. The state of the science on currently observed climate

The International Consensus on Climate Change

The Intergovernmental Panel on Climate Change (IPCC), jointly established by the World Meteorological Organization and the United Nations Environment Programme, periodically assembles hundreds of the world's leading natural and social scientists to assess the state of the global climate and how it is changing. In its 2001 assessment, the IPCC concluded: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities," and "most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations." The IPCC conclusions have been reinforced by recent assessments in the United States, including a 2001 report from the National Academy of Sciences and a 2002 US Climate Action Report published by the Department of State.

Within the scientific community, climate change discussions have now moved beyond the questions "Is the climate changing?" and "Are humans contributing?" to "How large will the changes be in coming decades?" and "What impacts will we experience from the changing climate?" The IPCC concluded that there is a high probability of significant global climate change, including warming in most places, during coming decades. Similarly, the National Academy of Sciences study concluded that, "human-induced warming and associated sea-level rises are expected to continue through the twenty-first century." Unless policy actions are taken now, globally averaged temperatures could increase from 2 to 11°F over the coming century, and the warming in the United States and southern Canada could be as much as 50 percent more than this average.

This report builds upon and echoes many conclusions from recent reports on climate change impacts in the Great Lakes region[23] and introduces new analyses and projections based on the most recent climate change models.

changes and their causes is described in the box above.

Locally or regionally, natural climate variability can be quite large, generating year-to-year differences of several degrees in annual temperature or swings from very wet years to droughts. Current climate trends in the Great Lakes region may still reflect some natural variability (see box, p.13), although evidence strongly indicates that human-driven changes in the atmosphere are the primary cause for the climate shifts now being observed worldwide.

Climate in the Great Lakes region is generally highly variable on time scales of one to several years, a fact that makes it more difficult to detect long-term trends. However, careful analyses of data from the National Climate Data Center (1895–2001) and the Midwest Climate Center (1900–2000) reveal some significant shifts in temperature, total precipitation, and extreme events in recent decades:[24]

- Temperatures over the past three decades have ranged from near average to somewhat warmer than average. In the past four years, however, annual average temperatures have ranged 2 to 4°F (1 to 2°C) warmer than the long-term average and up to 7°F (4°C) above average in winter. This recent warming is comparable in magnitude to warm periods during the 1930s and 1950s (Figure 6a).
- The past two decades have seen the hottest months in recorded history, although extended heat waves (seven days or longer) have been relatively infrequent since the 1950s. A few episodes of extreme cold occurred in the 1990s, but most years saw a lessening of cold waves.
- The last spring freeze has been occurring progressively earlier, and current dates are approximately one week earlier than at the beginning of the

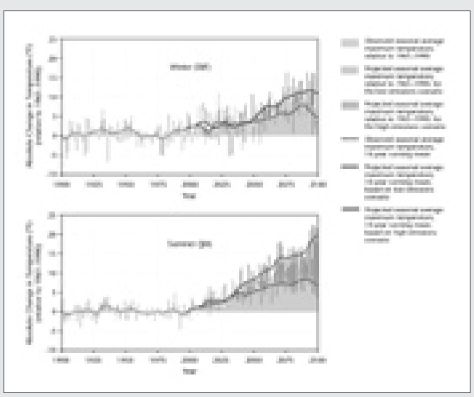
Natural Variability, Long-Term Changes, and the Challenge of Prediction

Climate can be highly variable. For a given year, the annual temperature can vary by 5°F (3°C) from the long-term mean (Figure 6a). Precipitation varies even more significantly from year to year (Figure 6b).

Natural variations in climate are clearly substantial, but one critical comparison is between short-term variability and the long-term changes that have occurred since the last ice age. During the past 20,000 years, the climate of the Great Lakes area has changed enough to alter the regional distribution of forests, prairies, and other vegetation types dramatically, and this change was driven by a 9 to 11°F (5 to 6°C) change in temperature. Put in these terms, the current projections for a 5 to 20°F (3 to 11°C) warming in the region in less than 100 years should ring bells of alarm.

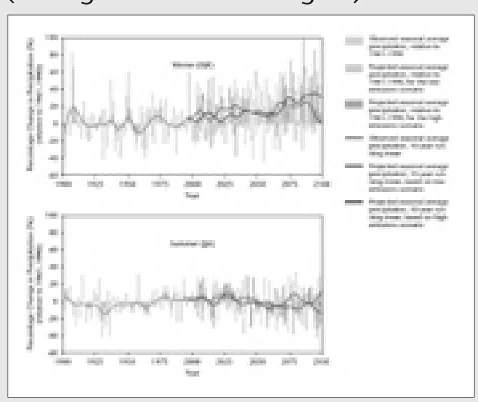
The challenge in climate change prediction is to determine whether there will be longer-term trends in temperature or precipitation, and whether those trends will be accompanied by a change in variability. Scientists now believe with high confidence that both changes will occur: Average daily temperatures are expected to rise sharply over the next century (Figure 6a), and although precipitation is currently quite variable, the frequency of extreme events such as rainstorms and droughts is likely to increase.

FIGURE 6A
Observed and Projected Change in Average Daily Temperature
(Averaged Over Entire Region)



See page 36
for full-size color image of this figure

FIGURE 6B
Observed and Projected Change in Average Daily Precipitation
(Averaged Over Entire Region)



See page 37
for full-size color image of this figure

1900s. Growing seasons have also begun to lengthen in the past two decades.

- Both summer and winter precipitation has generally been above average for the past three decades, making this the wettest period of the twentieth century (Figure 6b). However, water levels in the Great Lakes were higher during the mid- to latter-nineteenth century, indicating even wetter conditions then.
- Over the past five decades, the frequency of 24-hour and 7-day intense rainfall events, which result in flooding of streams and rivers, has been fairly high relative to the long-term average (Figure 7).

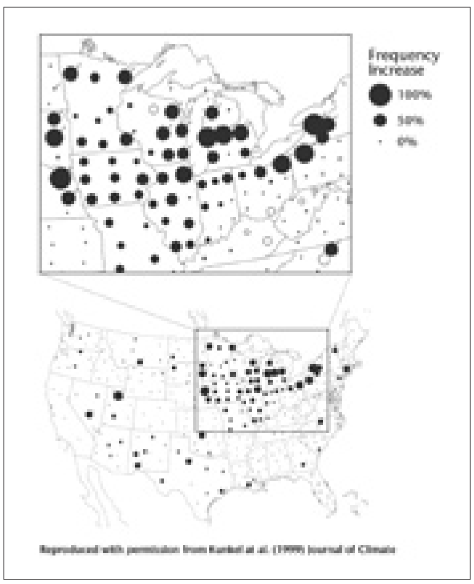
Historical Records of Change: Lake Temperature, Ice Cover, and Water Levels

Because the Great Lakes are critically important to the regional economy, excellent records have been kept of variations in their water temperature, ice cover, and water levels. These long-term records help in identifying trends that may extend into or be amplified in the future.

Water Temperatures

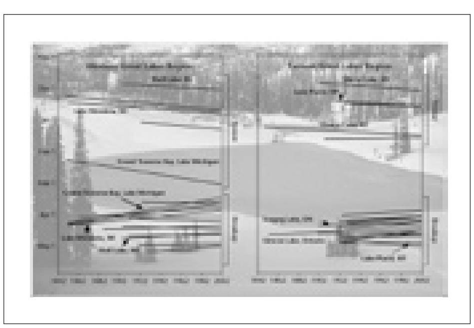
The key trends observed from water temperature records of the Great Lakes and other inland lakes include:

FIGURE 7
Historical Trends in Extreme Rainfall Events (1931–1996)



See page 35 for full-size color image of this figure

FIGURE 8
Change in Timing of Lake Freezes and Thaws



See page 35 for full-size color image of this figure

- Increases in near-shore water temperatures at five of seven sites in the eastern Great Lakes area have lengthened the period of summer stratification of the lakes by one to six days per decade.[25] (Stratification is the layering and separation of warmer surface waters from cooler bottom waters, a phenomenon that prevents turnover and oxygenation of bottom waters.)
- Increasingly warmer water temperatures have been observed in spring and fall over the last 80 years, and summer water temperatures have also increased, though less dramatically.[26]
- Local trends in water temperature correlate with trends in global mean air temperature, suggesting that climate changes in the Great Lakes may track changes in global temperature.[27]

Duration and Extent of Lake Ice

Shifts in the duration and extent of ice cover on lakes and streams are highly sensitive indicators of climate variability and change. Thus, they can provide early signs of ecosystem responses to climate change.[28] Consistent historical changes in ice cover have been observed in the inland lakes and in the bays of the Great Lakes themselves:

- Freeze-up has been occurring later in fall and ice-out (the loss of ice cover in spring) earlier in spring for the past century (Figure 8), and the rates of change have been greater in the past 20 years than over the preceding 80 years. Recently, the fall freeze has been moving later by 1.5 days per decade and spring breakup earlier by 2 days per decade.
- Records over the past 100 to 150 years consistently show shorter periods of ice cover (see box, p.15).
- Changes in ice cover for the inland lakes are greatest in Michigan, Minnesota, and Wisconsin (Figure 8). In New York and Ontario, lake-effect snowfall can delay ice breakup,[29] although it does not influence the fall freeze date. In the Great Lakes themselves, the extent of ice cover has been highly variable from 1963 to the present with no long-term trend; however, in recent years the Great Lakes have had little ice cover.
- Occurrences of unusually extensive ice cover have declined in recent years, while periods of greatly reduced or no ice cover have become more frequent.[30] In the winter of 2001–2002, for example, a number of inland New York lakes with a history of ice cover did not freeze.
- Year-to-year variations in ice cover are associated in part with large-scale climate drivers such as El Niño, the North Atlantic Oscillation, and the strength of the Aleutian low. These drivers can in turn be influenced by the buildup of heat-trapping

On Thin Ice in Madison

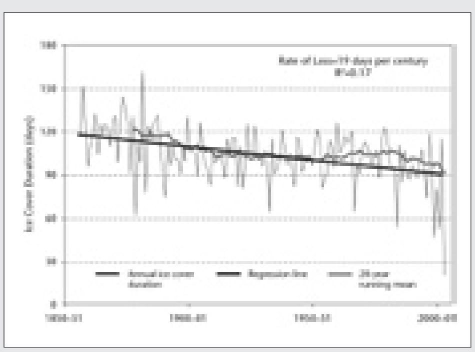
Thousands of visitors to Madison, Wisconsin, strolled on the snow-covered ice of Lake Monona in early February 2002, enjoying giant kites shaped like penguins, lobsters, stars, and even cathedral windows. It was the international Kites on Ice festival, a winter highlight in Madison and a magnet for serious kite fliers from around the world. That year, however, the kites were not flying above their usual site on the frozen lake in front of Monona Terrace near the state capitol. The ice there remained dangerously thin, with open water showing near the shore. Instead the festival had to be moved several miles around the lake to an area with safer ice.

Ice fishermen, ice boaters, and other winter recreationists on Madison's four lakes were not so lucky that winter. The iceboat regatta had to be moved off Lake Monona completely. On Lake Mendota, the largest of the four lakes, where ice fishermen in the 1980s were logging 70,000 to 100,000 hours each winter, ice fishing was virtually eliminated. Snowmobiling, iceboating, and skiing were similarly curtailed.

The winter of 2001–2002 provides a glimpse of the future for residents of the Great Lakes region, where the duration and extent of ice cover have been declining for more than a century. On Lake Mendota, for example, the average duration of ice cover has decreased from about four months in the mid-1800s to about three months by the late 1990s.[31] The extreme came in 2001–2002, when Lake Mendota had the shortest ice duration observed since 1853: ice cover lasted only 21 days (Figure 9a). On Lake Monona, too, the mean duration of ice cover has declined from 114 days in the 1870s to 82 days in the 1990s.

The continuing decline in winter ice cover portends a severe cultural shift for the region, where winter fun on ice has long been an integral part of residents' sense of place (Figure 9b). While the unfrozen lakes are accessible mostly to boaters, the frozen lakes become a playground for all, from families walking dogs or skating and children flopping into the snow to make "angel" imprints to hobbyists with extravagant kites and ice yachts. In cities such as Madison, where even iceless winters would remain wet and cold, lost ice activities will not be easily replaced by other outdoor fun.

FIGURE 9A
Ice Cover Duration on Lake Mendota, Wisconsin



See page 38
for full-size color image of this figure

FIGURE 9B
Kites on Ice Winter Festival 2002 on Lake Monona, Wisconsin

See page 39
for full-size color image of this figure

greenhouse gases. Recent analyses suggest that El Niños are becoming stronger,[32] and the influence of El Niños on earlier ice breakup has increased in recent years.[33]

Shifts in ice cover not only signal a response to climate change but also drive further ecological, social, and climate impacts. Reduced ice cover leads to greater evaporation from open water in winter, which contributes to lower water levels, loss of winter recreation on lakes, and perhaps an increase in lake-effect snows (depending on air temperature and wind direction).

Lake Water Levels and Stream Flows

Historically, water levels in the Great Lakes have been highly variable, and there has been no clear trend toward lower water levels from 1860 to the present.[34] Even though water levels in the Great Lakes were very low in 2000, for instance, levels in several inland lakes in Wisconsin rose dramatically from 1967 to 1998, largely because of increasing snowfall, rising groundwater levels, and presumed increases in groundwater contributions.[35] Indeed, until the late 1990s, the Great Lakes themselves had experienced three decades of extremely high water levels.[36]

Water levels usually rise in the spring as snowmelt enters the lakes and drop in late summer and fall as surface water evaporates and the weather turns drier. Despite a lack of overall trends in water level, there have been trends in the seasonal timing of changing water levels from the 1960s to 1998.[37] In both Lakes Ontario and Erie over this period, the seasonal rises and falls of water level are occurring one month earlier than before, while in Lake Superior, the maximum water level is occurring slightly earlier in the year. These trends apparently result from earlier snowmelt and earlier tapering off of summer runoff.

The frequency of heavy summer rainstorms has increased over the past 25 years in the Great Lakes region[38] (Figure 7, p.14), and flooding from these downpours, which saturate soils and cause rapid runoff, may be increasing.[39] The trend toward more frequent heavy rainstorms appears to have increased flooding in small- and medium-sized streams in the central United States from 1921 to 1985.[40] Even if the climate turns drier in the future, increased flooding of streams and erosion of lake shores is likely if a greater proportion of the rain falls in extreme storm events.[41] Flooding is also exacerbated by construction of roads, buildings, and other impervious surfaces that prevent water from infiltrating the soil.

Projections of Future Climate in the Great Lakes Region

For most people, the critical impacts of climate change will be those that occur at local and regional scales. Sophisticated general circulation models (GCMs) of the Earth's climate system are the best tools for global climate projections. While most of these models agree on future climate changes for the Earth as a whole, regional predictions are difficult because the extrapolation from large to local scales is not precise. Also, the model-simulated variability and uncertainty in climate increase as the area under consideration grows smaller. For this reason, the climate change projections presented in this report rely on multiple approaches. Analyses of regional temperature and precipitation projections from several of the most up-to-date GCMs have been combined with 100 years of historical data from the Midwest Climate Center to serve as a guide to possible future changes.

This report uses results from two of the latest generation of GCMs: the Parallel Climate Model (PCM) developed for the US Department of Energy at the US National Center for Atmospheric Research, and the HadCM3 model developed at the UK Meteorological Office's Hadley Centre for Climate Modeling.* Model simulations of human-induced climate change must rely on some plausible scenarios about how much CO_2 the world will be emitting in the future. These emission scenarios are, in turn,

* For additional technical background on the models and scenarios used in this report, as well as additional modeling results, see www.ucsusa.org/greatlakes.

based on assumptions about such factors as world population growth, economic development, technological change, and continued reliance on fossil fuels. The climate analyses in this report are based on model runs using scenarios that span the range of business-as-usual projections made by an IPCC special report on emission scenarios.[42] The high-emission scenario projects rapid economic growth and continued dependence on fossil fuels, while the low-emission scenario foresees a move toward clean, efficient technologies and sustainable economies.

Climate models often differ considerably in their sensitivity, that is, in the degree of warming they project in response to increases in atmospheric greenhouse gases. When compared with the full range of climate models, the HadCM3's sensitivity lies in the middle of the range, while the PCM's sensitivity is low, indicating that the climate projections presented in this report capture much of the range of plausible climate futures for this region.

Temperature

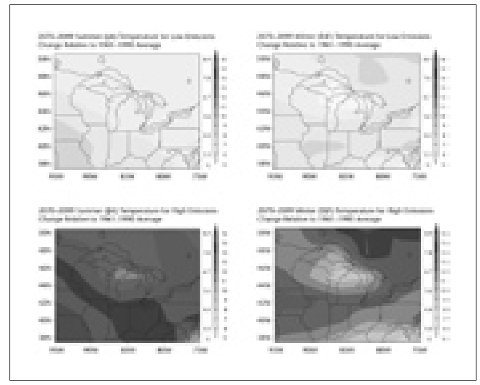
Temperature is expected to increase throughout the next century and to vary substantially by season. By 2025–2035, both models project that spring and summer temperatures in the Great Lakes region are likely to be 3 to 4°F (1.5 to 2°C) above current averages. Projections of fall and winter temperature change over the next few decades are ambiguous, with warming not evident until the middle of the century. By the end of the century, however, substantial temperature increases are expected in all seasons (Figure 10). The HadCM3 model projects that winter temperature increases averaged over the period 2070–2099 will range from 6 to 9°F (3 to 5°C) if the low-emission scenario prevails, and 8 to 14°F (5 to 8°C) for the high-emission scenario. Summer temperatures are projected to increase even more for the high-emission scenario (11 to 16°F, 6 to 9°C), but slightly less for the low scenario (5 to 7°F, 3 to 4°C).

Warming is expected to vary across the region. Temperature increases centered over the Great Lakes will be 2 to 5°F (1 to 3°C) lower than temperature increases over the southwestern and northern areas of the region (Michigan, northern Minnesota, Wisconsin, and Ontario) (Figure 10). In winter, the greatest warming is expected to occur at higher latitudes. This will be reversed for summer, with the greatest changes occurring over the southern and western parts of the region (Illinois, Indiana, Minnesota, and Ohio). The seasonal cycle of temperature over the region is also projected to shift, with summer and to a lesser extent winter warming more than spring and fall.

These projected changes in temperature patterns are consistent with recent trends in growing season length and dates of first and last frost. Historical data show that the longest growing seasons occurred in the 1990s (Figure 11). Compared with the turn of the century, the growing seasons today are about one week longer, primarily because the last spring frost has been occurring earlier. Model projections suggest that the length of the growing season will continue to increase, and by the end of the century, it may be 4 to 9 weeks longer than the 1961–1990 average (Figure 11). The date of

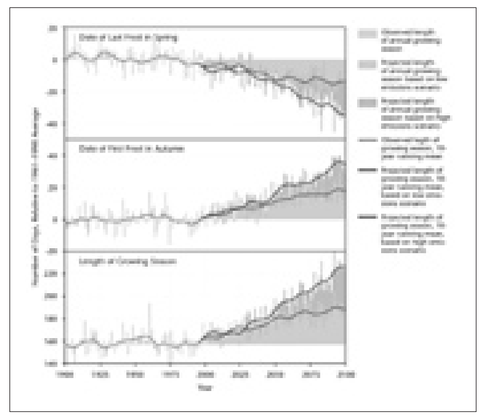
In less then three decades, spring and summer temperatures in the Great Lakes region are likely to be 3 to 4°F (1.5 to 2°C) above current averages.

FIGURE 10
Projected Changes in Temperature During Summer and Winter by 2070–2099 (Relative to 1961–1990, Average for Low- and High-Emission Scenarios)



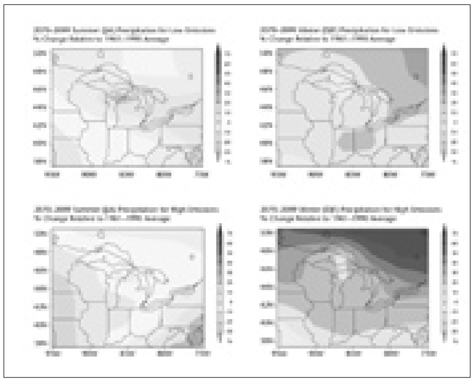
See page 38
for full-size color image of this figure

FIGURE 11
Growing Season in the Great Lakes Region (1900–2100)



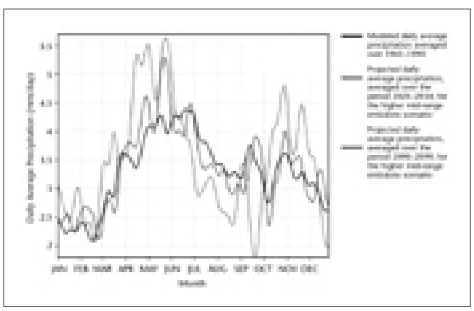
See page 39
for full-size color image of this figure

FIGURE 12
Projected Changes in Precipitation During Summer and Winter by 2070–2099 (Relative to 1961–1990, Average for Low- and High-Emission Scenarios)



See page 40
for full-size color image of this figure

FIGURE 13
Seasonal Precipitation Cycle (Historical Baseline and Projected Changes, 10-Day Running Mean)



See page 41
for full-size color image of this figure

last spring frost is projected to be earlier by as much as 15 to 35 days, and the date of first autumn frost is projected to be later by up to 35 days.

Precipitation, Extreme Events, and Runoff

Both the low- and high-emission scenarios project that average annual precipitation may be slightly above average, rising 10 to 20 percent by the end of the century (Figure 6b, p.13). Changes in the seasonal precipitation cycle are likely to be higher, with winter and spring rain increasing and summer rain decreasing by up to 50 percent. The largest precipitation increases during winter months are expected at higher latitudes and under the higher-emission scenario (Figure 12). Although this may result in more snowfall, warming temperatures are expected to cause a decrease in the average depth of snow cover during the winter. In summer, the largest decreases are expected over the southern and western parts of the region, where most agriculture is concentrated. Precipitation is also projected to increase downwind of the Great Lakes, probably because of the influence of the lakes on local conditions under warmer temperatures. Toward the end of the century, spring and fall may be wetter and winter and summer drier on average across the region relative to today's seasonal patterns (Figure 13).

The frequency of heavy rainstorms, both 24-hour and multiday, will almost certainly continue to increase during the next century and may double by 2100 (Figures 14 and 15). The intensity of these events may increase, though this is accorded a lower confidence level, and would be likely to increase the risk of flooding.[40]

Perhaps most important to the welfare of the region will be the impacts of climate change on water distribution and resources. As climate warms, evapotranspiration is expected to increase year-round, with the largest relative increases in winter and spring.[43] Evapotranspiration is shorthand for the processes of evaporation from soils and surface waters and transpiration of moisture from plants, both of which return water to the atmosphere. The difference between precipitation and evapotranspiration gives an indication of how much water is available for runoff into streams and lakes or for recharging groundwater supplies. On average over the entire region by the end of the century, the amount of water available for runoff is expected to remain the same or perhaps increase for all seasons except summer. In summer, less runoff is predicted and changes are expected to be highly variable across the region. Large areas where runoff is reduced may occur across the Midwest during winter and summer and in the central Great Lakes region during autumn. In contrast, runoff is projected to increase over the entire region during spring and over the southern Great Lakes region during fall.

The frequency of heavy rainstorms, both 24-hour and multiday, will almost certainly continue to increase during the next century and may double by 2100.

Changes in the amount of water available for runoff will also affect soil moisture, which is a key factor in plant growth and soil processes. Thus, soil moisture is projected to increase as much as 80 percent during winter in some locales, but decrease regionally by up to 30 percent in summer and fall relative to the 1961–1990 average. This shift will favor crops and ecosystems that rely on recharge of water levels during the winter months; however, crops requiring a certain level of summer rainfall and soil moisture may come under substantial stress, and some wetland ecosystems may dry up entirely during summers.

Migrating Climates

A dramatic way of visualizing the effects of these climate projections is to estimate where Ontario and selected Great Lakes states will have "moved" climatically over the next century. Such analyses are limited, of course, to average conditions and do not consider the extremes or variability in projected climate changes. They also do not take into account differences in major topographical features from state to state such as the Appalachians, the Ozarks, or the Great Lakes. That said, here are a few comparisons based on projections of seasonal average temperature and precipitation (Figure 16):

- By 2095, a typical winter climate in the state of Illinois can be expected to feel hotter and drier, much like current-day Oklahoma or Arkansas.
- By 2095, today's Michigan winter climate is likely to be replaced by a climate similar to that in Ohio today.
- Summer changes will appear more quickly. By 2030, Illinois summers may resemble those of Oklahoma or Arkansas in terms of average temperature and rainfall. However, by the end of the century, the Illinois summer climate will generally resemble that of current east Texas.
- Michigan summer weather could be similar to that of Ohio in a few decades, while by the end of the century, Michigan summers are likely to resemble those of northern Arkansas today.

> By century's end, summers in Illinois will generally resemble those of east Texas today, while Michigan summers are likely to resemble those Arkansas now experiences.

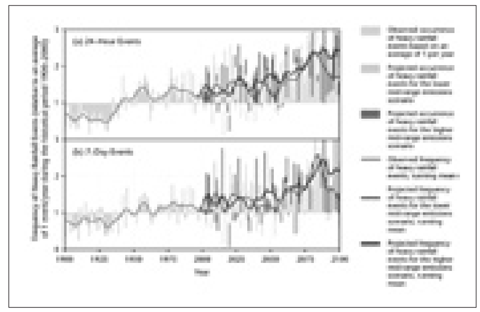
- By 2030, southern Ontario summers may feel more like those in upstate New York and, by the end of the century, similar to those in northern Virginia today.

The Potential for Surprise

In addition to the gradual long-term trends in climate just discussed, it is possible that very abrupt and strong short-term changes in climate could occur as well. An abrupt change is one that takes place so rapidly and unexpectedly within years to decades that human or natural systems have difficulty adapting.[44] Abrupt changes in past climate are well documented by records preserved in fossils, ice cores, and lake sediments. Patterns of abrupt change from glacial to interglacial periods were common, for example, with sudden changes in the North Atlantic rapidly affecting the entire Northern Hemisphere, including the Great Lakes region.[45] Temperatures shot up by as much as 29°F (16°C) and rainfall doubled in a matter of decades in some regions in response to the warming of North Atlantic surface waters after the ice sheets melted.[46]

In the past, abrupt changes occurred most often when the climate system was being forced to change rapidly by

FIGURE 14
Increased Frequency of Heavy Rainfall Events in the Great Lakes Region



See page 41
for full-size color image of this figure

FIGURE 15
Precipitation Shifts Signal Trouble for Farmers

See page 42
for full-size color image of this figure

FIGURE 16
Migrating Climate: Changing Winters and Summers in Illinois and Michigan

See page 42
for full-size color image of this figure

natural forces such as meteor impacts or major volcanic eruptions. Now it is again forced to change rapidly, but by a combination of natural and human forces. A recent report on abrupt climate change concluded, "greenhouse warming and other human alterations of the earth system may increase the possibility of large, abrupt, and unwelcome regional or global climatic events."[44] Abrupt changes in climate could obviously have dramatic impacts on the Great Lakes region, leaving even less time for society, the economy, and natural ecosystems to adapt or mitigate the damage.

CHAPTER
Three

Ecological Vulnerability to Climate Change: Aquatic Ecosystems

The Great Lakes region is distinguished by its abundant lakes, streams, and wetlands. All of these aquatic ecosystems will be affected in some way by the direct human stresses and human-driven climate changes explored in Chapters 1 and 2.

Lake Ecosystems

Lakes in the region differ widely in size, depth, transparency, and nutrient availability, characteristics that fundamentally determine how each lake will be affected by climate change (Figure 17). A wide variety of studies have focused on the inland waters and Great Lakes, providing strong evidence of how the waters have changed and are likely to change in the future.

Higher Lake Temperatures

Warmer air temperatures are likely to lead to increasing water temperatures and changes in summer stratification in the Great Lakes[47] and in the inland lakes and streams of the region.[48] Earlier model studies project that summer surface water temperatures in inland lakes will increase by 2 to 12°F (1 to 7°C). Projections for deep water range from a 14°F warming to a counterintuitive 11°F cooling. The response in deep waters varies because warming air temperatures can cause a small, deep lake to stratify sooner in spring, at a cooler temperature. Projected changes in water temperature would be even greater using the more recent climate scenarios on which this report is based, especially by 2090. Overall, changes in temperature and stratification will affect the fundamental physical, chemical, and biological processes in lakes (see box, p.22). Higher water temperatures, for example, result in lower oxygen levels.

Lower oxygen and warmer temperatures also promote greater microbial decomposition and subsequent release of nutrients and contaminants from bottom sediments. Phosphorus release would be enhanced[49] and mercury release and uptake by biota would also be likely to increase.[50] Other contaminants, particularly some heavy metals, would be likely to respond in a similar fashion.[51] (Heavy metals such as mercury become more soluble in the absence of oxygen. Oxygen binds with these elements to form insoluble compounds that sink to the bottom.)

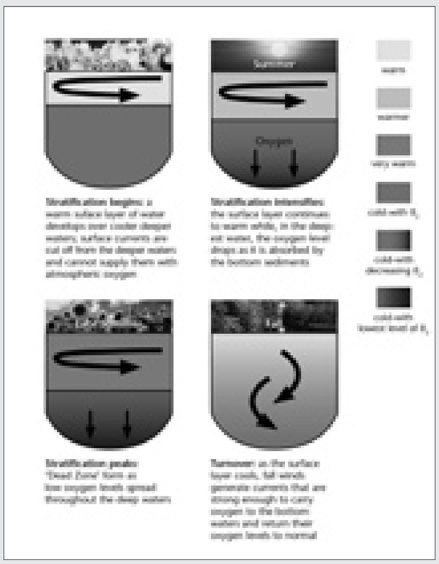
FIGURE 17
Impacts on Lake Ecosystems

See page 42
for full-size color image of this figure

Climate Change and "Dead Zones" in Lake Erie

The fall of 2001 brought startling and discouraging news to residents around Lake Erie. Testing stations in the lake's central basin reported the most rapid oxygen depletion in nearly 20 years. "It's like going back to the bad old days when Lake Erie was dead," one aquatic biologist told the Toledo Blade. The bad old days were the 1960s when Lake Erie had been all but choked to death: massive phosphorus pollution had fertilized algal blooms and their decay was using up the dissolved oxygen needed to support fish and other aquatic life. Then, in 1972, implementation of the Great Lakes Water Quality Agreement led to billions of dollars in new sewage treatment plants, bans on phosphate laundry detergent, new farming practices that reduced fertilizer runoff, and other measures that drastically cut phosphorus input to Lake Erie. As phosphorous loading dropped, so did the extent and duration of the summer "dead zones."

FIGURE 18A
Lake Stratification and the Development of "Dead Zones"



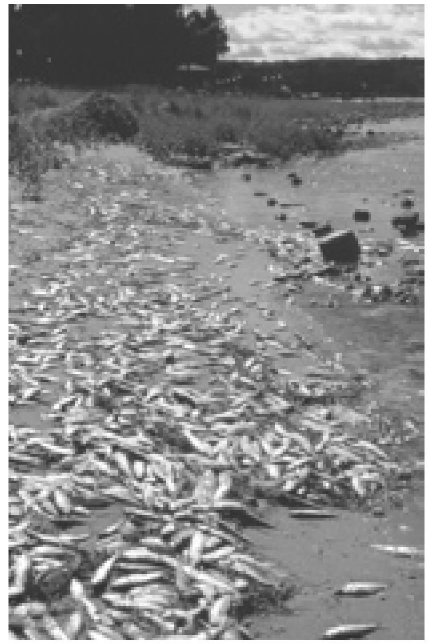
See page 43
for full-size color image of this figure

Was the massive dead zone of 2001 an anomaly or a trend, scientists and policymakers wondered? And what had caused it this time? A committee of US congressmen traveled to the lake to investigate, and researchers in the United States and Canada launched a $2 million effort to find answers. The suspected culprits ranged from ozone depletion, which allows ultraviolet light to reach deeper into the waters, to the invading zebra mussels that now line the lake bottom down to 100 feet (30 meters). Missing from most discussions, however, was the recognition that a warming climate will mean more frequent and larger dead zones in the future.

A dead zone is an area of water—in a lake or even in a part of the ocean such as the Gulf of Mexico off the mouth of the Mississippi River—that contains no oxygen to support life. Dead zones form when oxygen in the water is consumed by organisms, but these zones can only persist when the water is isolated from the atmosphere and thus from a source of new oxygen. This isolation occurs when water is stratified—that is, layered and separated with warmer surface waters acting as a lid on top of the cooler bottom waters, isolating them from the air (Figure 18a).

When winter ends in the Great Lakes region and surface waters become free of ice, lakes usually mix from top to bottom and the entire lake becomes saturated with oxygen. Soon after this spring mixing, however, the sun warms the surface waters and stratification sets in. Once the lake is stratified, oxygen begins to decrease (hypoxia) in bottom waters, and the race is on to see whether all the oxygen will be depleted (anoxia) and a dead zone created before the lake again mixes fully in the late fall or early winter. The more rotting biomass such as dead algae in the water, the more oxygen is consumed. In recent years, oxygen consumption has had the advantage in this race because shorter winters have led to earlier spring stratification in many lakes, meaning that the lake bottom runs out of oxygen even sooner in the summer. For example, winters on Lake Erie have been growing shorter since the 1960s. Also, recent increases in the near-shore water temperatures for four of the five Great Lakes indicate that their summer stratification periods have increased by one to six days per decade.[25]

FIGURE 18B
Lake Michigan Fish Kill



See page 43
for full-size color image of this figure

In a warming climate, the duration of summer stratification will increase in all the lakes in the region. Warming could also lead to a partial disappearance of the fall and spring periods of complete mixing that are typical of all the Great Lakes. This mixing resupplies oxygen and nutrients throughout the water column. In the fall, the formerly warm and buoyant surface waters cool and then sink, driving mixing. This occurs only if the surface waters cool to the temperature of maximum water density (39°F or 4°C).[52] Lake Ontario is particularly sensitive to this effect. Under some climate warming scenarios,[53] it would experience only a single, short period of complete mixing in late winter, then deep water temperatures would increase throughout the year. The deeper Great Lakes (Huron, Michigan, and Superior) would experience a similar suppression of mixing in some years, along with a significant warming of deep waters.[54] No suppression of mixing will occur in shallower bodies of water such as Lake St. Clair and the western basin of Lake Erie, because there will always be sufficient wind to stir the entire water column from top to bottom.

In the end, longer stratification periods and warmer bottom temperatures will increase oxygen depletion in the deep waters of the Great Lakes[55] and will lead to complete loss of oxygen during the ice-free period in many inland lakes of at least moderate depth.[56] Anoxia or hypoxia in deep waters will have negative impacts on most of the organisms in the lakes. Persistent dead zones can result in massive fish kills, damage to fisheries, toxic algal blooms, and foul-smelling, musty-tasting drinking water (Figure 18b).

Reduced Ice Cover

Extrapolations from 80 to 150 years of records strongly suggest that ice cover will decline in the future. Hydrologic model simulations also predict drastic reductions in ice cover on the Great Lakes[57] and on inland waters in the future (Table 1). Changes in ice cover create large ecological and economic impacts. Shorter ice cover periods, for example, can be a mixed blessing for fish. Reduced ice will lessen the severity of winter oxygen depletion in many small inland lakes,[56] thus significantly reducing winterkill in many fish populations. However, small species uniquely adapted to live in winterkill lakes go extinct locally when predatory fishes are able to invade and persist in lakes that previously experienced winterkill.[58] Reduced ice cover also allows greater storm disturbance, which increases egg mortality of the commercially valuable lake whitefish, whose eggs incubate over winter on the bottom of Great Lakes bays.[59] Increases in the ice-free period extend the shipping season on the Great Lakes but reduce ice fishing, ice boating, skiing, snowmobiling, and winter festivals such as Wisconsin's "Kites on Ice" (see box, p.15).

Changes in Lake Water Levels

Climate scenarios and lake models have consistently predicted less runoff, more evaporation, and lower water levels in both large and small lakes in the region.[60] The most recent hydrologic models continue to project lower lake and groundwater levels in the future (Table 2), despite a lack of clear trends in the historic record. Predictions based on one of the climate models used in this report (HadCM3) suggest even greater declines in late summer water levels because this model projects higher temperatures and lower summer rainfall in the region than the models used in previous studies. However, the absence of long-term trends in the historic Great Lakes water levels record[34] and increases in water in some inland areas of Wisconsin[35] suggest that lake water levels may not yet show the decline expected from long-term climate change.

Changes in Lake Productivity

The growth of algae in the water and on lake bottoms is called primary production because these planktonic plants form the base of the food web that nourishes animals from zooplankton to fish. Primary production is controlled by a combination of temperature, light (or the portion of the ice-free year when light is available), and nutrients. Excessive nutrients can

TABLE 1 **Ice Cover Expected to Decrease in the Great Lakes Region**

Lake	Current Situation	Future Scenarios By 2030	Future Scenarios By 2090
Lakes Superior and Erie (6 basins)[a]	77 to 111 days of ice cover	Decrease ice cover from 11–58 days	Decrease ice cover from 33–88 days
Lake Superior (3 basins)[a]	No ice-free winters	Increase ice-free winters from 0–4%	Increase ice-free winters from 4–45%
Lake Erie (3 basins)[a]	2% of winters are ice free	0–61% of winters are ice-free	4–96% of winters are ice-free
Small inland lakes[b]	~90–100 days of ice cover	Decrease ice cover by 45–60 days with a doubling of atmospheric CO_2	

Source: See note 61.

TABLE 2 **Water Levels Likely to Decrease in the Future** (as shown here for the Great Lakes, Crystal Lake, Wisconsin, and groundwater near East Lansing, Michigan)

Lake or Site	2 × CO_2 (range of 3-4 simulations)	2030 (range of 2 simulations)	2090 (range of 2 simulations)
Lake Superior	–0.23 m to –0.47 m	–0.01 m to –0.22 m	+0.11 m to – 0.42 m
Lake Huron/Michigan	–0.99 m to –2.48 m	+0.05 m to –0.72 m	+0.35 m to – 1.38 m
Crystal Lake, Wisconsin	–1.0 m to –1.9 m (2 simulations)		
Groundwater near Lansing, Michigan		–0.6 to +0.1 m	

Source: See note 62. Additional data on lake level declines can be found in the technical appendices: http://www.ucsusa.org/greatlakes/glchallengetechbac.html

TABLE 3 **Expected Effects of Warmer and Drier Summer Climate on Lakes and Subsequent Impacts on Algal Productivity**

Climate-Driven Change	Impact on Production	Most Sensitive Lake Type
Increases in both ice-free period and maximum summer water temperature	Increase in production	Moderate in area, depth, and nutrient concentration
Increase in duration of summer stratification and loss of fall top-to-bottom mixing period	Decrease in production caused by decrease in nutrient regeneration rates	Deep and oligotrophic (nutrient-poor; e.g., Lake Ontario)
Drought-induced decrease in lake water volume	Initial increase in production, followed by progressive decrease as the lake level declines	Small and shallow
Drought-induced decrease in annual input of nutrients (phosphorus) and dissolved organic carbon	Decrease in production resulting from nutrient limitation	Small and oligotrophic

lead to eutrophication, causing increased algal growth, including noxious algal blooms and degraded water quality. On the other hand, drops in primary production can ultimately reduce fish production in a lake.

Research indicates that the longer ice-free periods and higher surface water temperatures expected in the future will spur greater algal growth.[63] Other aspects of climate change, however, may offset these productivity gains. Cloudy days can lower productivity by making less light available for algal photosynthesis.[64] Cloud cover has increased in the Great Lakes region recently, but future trends in cloudiness are not clear. Increased primary productivity could also be limited or even reversed by a decline in availability of nutrients, primarily nitrogen and phosphorus, necessary for plant growth. Predicted reductions in runoff and a general drying of watersheds during summer are likely to reduce the amounts of phosphorus and other dissolved materials that streams carry into lakes.[65] Finally, prolonged or stronger stratification can also lead to lower primary production in lakes by preventing the mixing that brings nutrients from bottom waters and sediments up into surface waters.[66]

Changes in the species composition of algae and in seasonal patterns of blooms are also likely consequences of climate change. Earlier ice-out (thaw of lake ice) and spring runoff will shift the timing of the spring algal bloom,[67] and earlier and longer periods of summer stratification tend to shift dominance in the algal community during the growing season from diatoms to inedible blue-green algae. If climate change causes inedible nuisance species to dominate algal productivity, or if the timing of algal production is out of synch with the food demands of fish, then all upper levels of the food chain, particularly fish, will suffer (see box, p.22).

The impacts of climate change on aquatic productivity will differ among lakes. Table 3 summarizes the likely outcomes.

River and Stream Ecosystems

The aspects of climate change that will have the greatest impact on streams are warming air temperatures and general drying of watersheds, especially during summer and autumn. This drying will result from warmer temperatures and higher rates of evaporation during a longer ice-free period. This future scenario is consistent with past trends toward longer ice-free periods, earlier spring stream flows, and more frequent midwinter breakups and ice jams.[68] Despite a general drying,

TABLE 4 **Impacts of Climate Change on Stream Ecosystems**

Climate-Driven Change	Likely Impacts on Physical and Chemical Properties	Likely Impacts on Ecosystem Properties	Intensifying or Confounding Factors
Earlier ice-out and snow melt	Peak flows occur earlier. Ephemeral streams dry earlier in the season. Backwater pools experience anoxia earlier.	The timing of fish and insect life cycles could be disrupted.	Snowmelt occurs earlier and faster in urban areas and where coniferous forest harvest has occurred.
Lower summer water levels	More headwater streams dry; more perennial streams become intermittent. Concentrations of dissolved organic carbon decrease, thereby reducing ultraviolet-B attenuation. Groundwater recharge is reduced.	Habitat decreases in extent. Hydrologic connections to the riparian zone are reduced. Groundwater recharge is reduced. Species with resting life stages or rapid colonizers dominate communities.	Impervious surfaces and impervious soils exacerbate stream drying due to reduction in infiltration and groundwater recharge.
More precipitation in winter and spring and increased water levels	Spring floods reach greater heights. Surface runoff increases. Nutrient and sediment retention decrease. Groundwater recharge potential increases.	Floodplain habitat for fish and invertebrates grows. Hydrologic connections with wetlands increase.	Precipitation occurring when soils are frozen results in higher runoff and increases flood height.
Warmer temperatures	Stream and groundwater temperatures increase.	The rates of decomposition and respiration increase. Insects emerge earlier. Primary and secondary production per unit of biomass increases when nutrients are not limited; however, total production could decrease if aquatic habitat shrinks under drought conditions.	Impervious surfaces and both natural and human-made retention basins increase water temperatures. Woody riparian vegetation can buffer stream temperatures. In areas with porous soils and active groundwater connections, temperature extremes are smaller.
More frequent heavy rainfall events	Larger floods occur more frequently. Erosion and pollutant inputs from upland sources increase. Runoff increases relative to infiltration.	Fish and invertebrate production decreases. Fish and insect life histories and food webs are disrupted by changes in the intensity, duration, and frequency of flooding.	Impervious surfaces increase runoff and stream flow. Channelized streams increase peak flow.
Elevated atmospheric CO_2		Possible changes in leaf litter quality could impact aquatic food webs.	

model predictions for the region also suggest that over the next 100 years precipitation will increase during winter and spring. This could increase the magnitude of spring floods, especially if the floods coincide with snowmelt when soils are still frozen. Stream responses to these climate-driven changes will vary greatly across the region (Table 4), mainly because of differences in the relative contribution of groundwater versus surface water to their flow patterns.[69] Direct human disturbances such as removing streamside vegetation, paving or developing land, channelizing streams, depositing nitrogen and acid from acid rain, diverting water, and introducing invasive species will undoubtedly alter the way stream ecosystems respond to climate change.

Impacts of Changes in Hydrology

Heavy rainfall events and flooding are increasing in the Great Lakes region[38] (see Figure 7, p.14), and projected increases in the frequency of these events may amplify the range of conditions that make flooding more likely in the future, such as stream channeling and land-use changes that increase the amount of impervious surfaces. The likelihood of flooding will also increase with changes in land use. Streams in the agricultural areas on fine-textured soils and flat topography at the eastern end of Lake Erie, for instance, rise quickly in response to rain and are likely to be especially vulnerable to intense summer storms.

Floods exert their greatest physical influence by reshaping river channels, inundating floodplains, and moving large woody debris and sediments. Flooding can degrade water quality when untreated human, commercial, or agricultural wastes overflow from treatment facilities or when soils are eroded from agricultural fields treated with pesticides and fertilizers.[70] High water flow also diminishes the capacity of a stream to recycle nutrients and sequester suspended or dissolved organic matter.[71] Channelized urban and agricultural streams have little capacity to retain water, and the anticipated increases in spring runoff by the end of the century will result in increased height of spring floods and lower nutrient and sediment retention in these streams.

Not all impacts of flooding are negative, of course. Aquifer recharge is one benefit. Floods also transport fine sediments downstream, increasing the quality and quantity of habitat for some fish and invertebrates. In addition, several important fish species move upstream into the Great Lakes tributaries to reproduce during spring (sturgeon, walleye, and white sucker) or fall (steelhead, Chinook salmon, and brook trout), cued by either increased flow or day length. Although changes in the frequency and severity of disturbances such as floods can disrupt some aquatic communities, many fish and invertebrate species coevolved with seasonal flood pulses to take advantage of the expanded habitat for spawning and nursery sites.[72] In the Great Lakes region, these species include bass, crappie, sunfish, and catfish.[73]

FIGURE 19
Impacts on Stream Ecosystems

See page 44
for full-size color image of this figure

Apart from extreme events, summer rainfall is expected to decline in the future, especially in the southern and western portions of the region (see Figure 13, p.18). Drier conditions will translate into lower summer stream flow and less stream habitat.[74] Headwater streams, which often make up more than 75 percent of the river miles in a watershed, are probably the most vulnerable of all aquatic ecosystems under warmer and drier conditions (Figure 19).[75] Drought effects can lead to warmer water temperatures, depleted oxygen, higher concentrations of contaminants as water volume declines,[76] reduced transport of nutrients and organic matter,[77] and disruption of food webs.[78] Regions with intensive agricultural production on fine soils and flat topography, such as those found at the eastern end of Lake Erie,[69] will be most vulnerable to extreme events and reduced summer rainfall, since their hydrology is controlled largely by surface water. In small streams where flow comes primarily from surface runoff, one study predicts that 50 percent of the streams will stop flowing if annual runoff decreases by 10 percent.[79]

One consequence of periodic droughts is that sulfates and acidity are mobilized during post-drought rains and can deliver a strong acid pulse to streams and lakes in the watershed. Because of this phenomenon, climate warming may slow or even halt the recovery of many acid-stressed aquatic ecosystems.[80] Streams most susceptible to acid rain include those on the Canadian shield of Ontario, along the higher-gradient reaches of New York, and in northern Michigan, Minnesota, and Wisconsin.

Impacts of Higher Water Temperature

Across the watershed, stream temperatures will closely mirror increasing air temperatures, although the warming may be modified by shade from riparian forests and other vegetation and by water storage in wetlands.[81] Locally, cool groundwater seeps will provide some buffering for streams against warming air temperatures. Warmer water will affect stream organisms from plankton to insects and fish (fish are discussed below). In response to warmer waters, some insect species increase growth rates, emerge earlier, are smaller at maturity, alter their sex ratios, or reduce fecundity.[82] Plankton productivity tends to increase with warmer temperatures and longer growing seasons,[83] but reductions in water volume, coupled

TABLE 5 **Impacts of Climate Change on Wetland Ecosystems**

Climate-Driven Change	Likely Impacts on Physical Properties	Likely Impacts on Ecosystems	Intensifying or Confounding Variables
Earlier ice-out and snow melt	Wet periods are shorter, especially in ephemeral wetlands.	Fast-developing insect and amphibian species are favored, as are species with resting stages. The timing of amphibian and insect life cycles could be disrupted.	Snowmelt occurs earlier and faster in urban areas and where coniferous forest harvest has occurred.
Lower summer water levels	Isolation and fragmentation within wetland complexes increase. Fens store less carbon. Reductions in dissolved organic carbon result in less attenuation of ultraviolet-B radiation.	Habitat and migration corridors are reduced, as are hydrologic connections to riparian zones and groundwater recharge. Emergent vegetation and shrubs dominate plant communities. Amphibian and fish reproduction fails more often in dry years. Organisms with poor dispersal abilities become extinct.	Agricultural and urban development exacerbate fragmentation effects.
Warmer temperatures	Evaporative losses increase. Fens and bogs store less carbon.	The rates of decomposition and respiration increase. Insects emerge earlier. Primary and secondary production per unit of biomass increase when nutrients are not limited. Species at the southern extent of the range become extinct.	Impervious surfaces increase water temperature. More competition from invasive species may accelerate extinctions.
More frequent heavy rainfall events	Wetlands increase in extent.	Habitat area increases. Ground-nesting birds may be lost during floods.	Wetland losses from development reduce flood storage capacity.
Elevated atmospheric CO_2		Possible changes in leaf litter quality could impact aquatic food webs.	

with possibly intermittent flow in smaller streams, should lead to reductions in overall aquatic production.

The effects of increasing water temperature would be compounded by forest harvest (especially of conifers), which opens up the canopy and promotes earlier snowmelt.[84] Northern Michigan, Minnesota, Wisconsin, and western Ontario will be most vulnerable to this phenomenon. Urban areas also experience earlier and faster snowmelt than do rural areas.

Warmer temperatures should enhance decomposition and nutrient cycling in streams, allowing microbes to break down human and agricultural wastes into nutrients that fuel greater primary productivity. However, other impacts of climate change, such as prolonged low flows combined with higher temperatures, may lead to oxygen depletion, which will slow decomposition and waste-processing functions.[85]

Impacts on Biodiversity and Food Webs

A warmer climate will combine with land-use change and the introduction of invasive species to pose great threats to aquatic biodiversity in the coming century. Native plant and animal species will differ widely in their responses to changing stream temperature and hydrology. Some will respond by adapting to warmer temperatures, or expanding their ranges northward, or seeking refuge in areas where temperatures and flow patterns remain suitable. Others will decline to extinction.[86] Insects and plants that have resistant or mobile life history stages (larvae, cysts, seeds) will survive better than other organisms during reduced water flows.[87] Fish species presumed to be at higher risk of extinction are those that have small geographic ranges, require steady water flows or slack water habitats, reproduce at an older age, or require specific foods. Of 146 fish species in Wisconsin, 43 percent have two or more of the above traits, indicating potential sensitivity to global warming. Darters and sea lampreys are among the species that are especially sensitive.[86]

FIGURE 20
Impacts on Wetland Ecosystems

See page 44
for full-size color image of this figure

Another potential impact on stream food webs and the biodiversity they support comes directly from increasing atmospheric CO_2 levels. Some studies indicate that plant leaves grown under elevated CO_2 have lower food value.[88] If these changes in leaf chemistry turn out to be significant, they could slow microbial decomposition of plant material that falls into streams—a major source of energy and nutrients in many aquatic ecosystems—and also reduce growth and survival in some stream insects that feed on the leaves.[89] Any such impacts would be magnified up the food chain.

Wetland Ecosystems

Because of low topography or the presence of impervious soils, the Great Lakes region historically harbored extensive expanses of wetlands, particularly in the prairie regions of Minnesota and Illinois, the boreal regions of northern Minnesota and Ontario, and the low-lying fringes of Lake Michigan (Figure 20) and Lake Erie, including the Great Black Swamp in western Ohio. For more than a century, however, these wetlands have been extensively modified or drained for urban development and agricultural production, resulting in 40 to 90 percent losses in wetland area in the Great Lakes states and Ontario.[90] These losses are especially apparent in the southern portion of the region.

Wetlands near the Great Lakes occur as three distinct types: fringing coastal marshes that are directly impacted by lake levels and wave action, riverine wetlands that are partially influenced by both lake and river, and protected lagoons or barrier beach systems that are hydrologically connected to the lake only via groundwater.[91] Where they have not disappeared, coastal marshes in the southern part of the basin, particularly on Lake Erie and southern Lake Ontario, have been extensively diked to protect them from water level fluctuations. Coastal wetlands such as those in Saginaw Bay and large estuaries such as Green Bay are hot spots of primary productivity because nutrients and sediments from throughout the

Climate and Bird Diversity on Michigan's Upper Peninsula

One of the most popular bird-watching destinations in the Midwest is Michigan's Upper Peninsula, a densely forested neck of land that stretches 384 miles east from the northern Wisconsin border into the heart of the Great Lakes. Although parts of the peninsula lie farther north than Montreal, the climate is moderated by Lakes Superior, Michigan, and Huron, which create a continuous 1,700-mile shoreline around the Upper Peninsula. This shoreline and the peninsula's 16,500 square miles of largely unfragmented forest contain a rich diversity of terrestrial and aquatic habitats that provide refuge for more than 300 bird species. About 25 to 30 percent are year-round residents; the rest are migratory species that arrive in the Upper Peninsula each spring to breed or each fall to winter. A warming climate will drive complex changes in habitat, quality, and timing of food resources, and other factors that are likely to diminish bird diversity on the Upper Peninsula in the future. Hardest hit will be the migratory and wintering species.

FIGURE 21A
Songbird Declines Expected

See page 45
for full-size color image of this figure

Habitat changes, particularly the expected northward shift of boreal forest species such as spruce and fir, will have profound impacts on bird communities. Spruce, fir, and hemlock are vital to a number of species such as crossbills, siskins, grosbeaks, and breeding warblers (Figure 21a). The nature of a peninsula will also make it more difficult for plant communities to respond quickly to changes since the land is isolated from sources of new colonists. Human land-use changes such as second-home development and logging will interact with climate to exacerbate habitat loss or degradation.

A number of resident bird species might, however, benefit from warming, including mockingbirds, chickadees, woodpeckers, titmice, and northern cardinals. For example, northern cardinals, chickadees, and titmice might be able to start breeding earlier and raise more broods within a season than they do now.[92] More important, reduced winter-related mortality might increase populations of these year-round residents. It may also enable some cold-intolerant species such as the Carolina wren and sharp-shinned hawks to expand their range northward.[93]

The prospects are less rosy for songbirds that migrate to the Upper Peninsula from the tropical forests of Central and South America to breed. Food may be scarce along the route if trees leaf out and insects hatch earlier than normal in response to warming. More vital in the Upper Peninsula may be any change in the spring emergence of aquatic insects along the shoreline and in the wetlands, since this flush of insects serves as the primary food supply for arriving migrants.

Another concern arises from the fact that different parts of North America are warming and will probably continue to warm at different rates. Spring temperatures immediately to the south of the

Great Lakes region are warming less than spring temperatures observed in the region itself. If these areas to the south continue to be cooler relative to areas further north, migratory birds may face a dilemma: They need to arrive earlier on their northern breeding grounds, but may be unable to migrate because food resources such as caterpillars are not yet adequate to allow them to fatten up for the flight from their more southern staging areas. Already some warblers such as the yellow-rumped warbler seem to be arriving earlier on their breeding grounds, as expected if they are responding to earlier springs, whereas other species such as the chipping sparrow are arriving later, perhaps in response to colder springs immediately to the south of the region.[94]

FIGURE 21B
Climate Change Impacts on Waterfowl

See page 45
for full-size color image of this figure

If some year-round resident birds do thrive and expand in a warming climate, their success may further reduce the food available to populations of migratory songbirds breeding in the region, especially if the "pulse" of midsummer insects is also reduced. Forest bird diversity in the Great Lakes is highest in northern areas such as the Upper Peninsula largely because of the increased diversity of migratory species. Warming therefore may reduce forest bird diversity if fewer resources are available to migratory songbirds. One study projects that the Great Lakes region could lose more than half its tropical migrants, although new bird species colonizing from outside the region could cut the net loss in bird diversity to 29 percent. Waterfowl are also expected to decline. Studies based on earlier and milder warming forecasts than those used in this report project 19 to 39 percent declines in duck numbers by the 2030s in response to lost breeding and migratory habitats as well as declines in the aquatic plants on which ducks feed.[95]

Loss of bird diversity will have economic as well as ecological consequences. Wildlife watching—principally bird watching—is a $3.5 billion (US) a year industry in northern Michigan, Minnesota, and Wisconsin. In addition, hunting—including waterfowl hunting—is a $3.8 billion (US) industry in these three states (Figure 21b). Besides these potential economic losses, a decline in birds will mean a loss in ecological services such as seed dispersal and insect control.

watershed are deposited there, and these systems support rich plant, bird, and fish communities.[96]

Inland wetlands are even more diverse and range from entirely rain-driven systems such as bogs to riparian wetlands fed by contributions from both surface and ground water. Bogs and fens cover extensive areas in the northern Great Lakes region and contain a wide variety of acid-loving plants, including the widely known pitcher plant.

Impacts of Changes in Hydrology

All wetland types are sensitive to alterations in hydrology that are likely to accompany climate change (summarized in Table 5, p.28).[97] A warmer and drier climate will threaten both inland and coastal wetlands, although higher precipitation during winter and spring and intense storm events may at times offset the generally decreased water levels.[98] The largest impact should be on rainfall-dependent wetlands, since systems that are largely recharged by ground water are more resistant to climate-driven changes.[99] Projected declines in summer rainfall in the southern and western portions of the region (Figure 12, p.18) will also cause drying of prairie potholes and similar depressional wetlands.

Some impacts will be positive. Although dropping water levels will cause wetlands to shrink, new vegetation may colonize formerly open-water habitats on some exposed shorelines, creating new types of habitat.[100] In wetlands fringing the Great Lakes, shoreline damage and erosion are likely to decrease as water levels drop.[101]

The impacts of climate change will often exacerbate continuing direct human disturbances such as dredging and filling, water diversion, and pollution.[102] As demands for public drinking water supplies and irrigation water increase, for example, groundwater pumping may pose the greatest threat to ephemeral wetlands. Also, the spread of invasive species such as phragmites, purple loosestrife, and Eurasian water milfoil poses an added threat to many wetland communities, especially when habitat or ecological processes are disrupted.[103]

> Climate change will exacerbate human disturbances such as dredging and filling, water diversion, and pollution.

Ecosystem Functioning

Wetlands serve as the main interface for moving nutrients, pollutants, and sediments from land to water. Decreased runoff from the land, particularly in summer, will decrease the deposition of material from uplands into wetlands. The material that does enter wetlands will be retained longer, however, before high-water pulses flush it downstream into lakes and rivers. Although decomposition rates will increase with warmer temperatures, fluctuating water levels combined with warmer temperatures are likely to reduce the capacity of wetlands to assimilate nutrients and human and agricultural wastes.

Fluctuations in water levels and soil moisture also influence the release of nutrients and heavy metals.[104] Lower water levels expose more organic wetland soils to oxygen, which may reduce exports of mercury (mercury binds with oxygen and is immobilized), but also may reduce the breakdown of nitrate by denitrifying bacteria in wetland soils. Increased oxygen concentrations in exposed soils, especially when accompanied by acid precipitation, may release other metals such as cadmium, copper, lead, and zinc,[51] and wetlands downstream of industrial effluents could face increased risk of heavy metal contamination during periods of low water.

Carbon stored in wetland soils may also be lost to the atmosphere in a warmer climate. Northern peatlands such as those found in Minnesota and Ontario form when cold temperatures and waterlogged soils limit the rate of decomposition of carbon-rich plant organic matter.[105] Warmer temperatures are likely to increase the rate of organic matter decomposition and accelerate carbon release to the atmosphere in the form of CO_2. Carbon release from wetlands in the form of methane, which is 25 times more potent than CO_2 as a greenhouse gas, will be enhanced by warmer temperatures and higher water levels.[106]

Reduced stream flow in summer will also decrease the amount of dissolved organic carbon washed from land into surface waters. Less dissolved organic carbon results in clearer water, which allows higher doses of ultraviolet-B radiation to penetrate further through the water column.[107] Organisms such as frogs living in shallow waters will be at greatest risk because UVB penetration is generally restricted to the top two to eight inches of the surface water.[108] In deeper waters, organisms can find refuge from the harmful radiation.[109]

Impacts on Biodiversity

Wetland plant and animal communities are continually adapting to changing water levels, although extreme events such as drought or flooding can result in persistent disturbance to community structure and functions such as decomposition rates and productivity.[110] Climate warming is likely to cause some wetland species to shift their ranges to accommodate their heat tolerances. Because of differences in breeding habits, age to maturity, or dispersal rates, some species are more vulnerable than others to disturbance and change.[111] Earlier spring or summer drying of

Color Figures

FIGURE 1
The Great Lakes Region
from page 8

The Great Lakes basin encompasses more than 308,000 square miles of the North American heartland and contains the largest single concentration of liquid fresh water on the planet. It is a land of spectacular lakes, vast wetlands, fertile southern soils, and rugged northern terrain forested in spruce and fir. The 60 million people who live here are heavily concentrated in the south, and their actions profoundly affect the region's ecological bounty and the life-sustaining benefits it provides.

Credit: Amanda Wait/ DG Communications

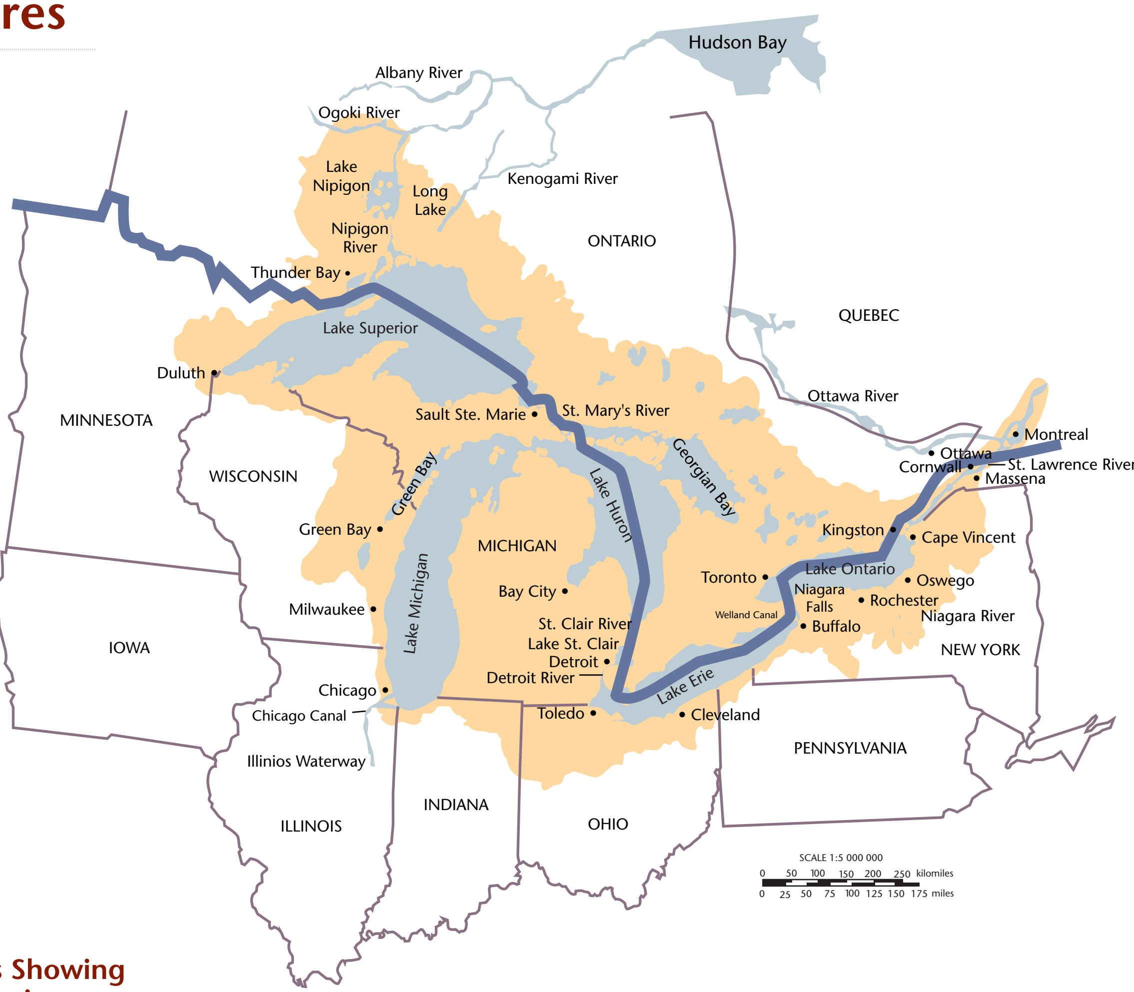
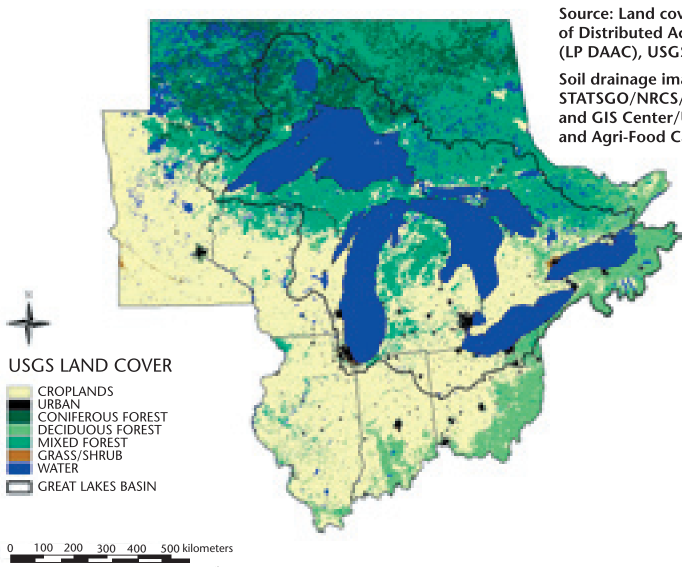


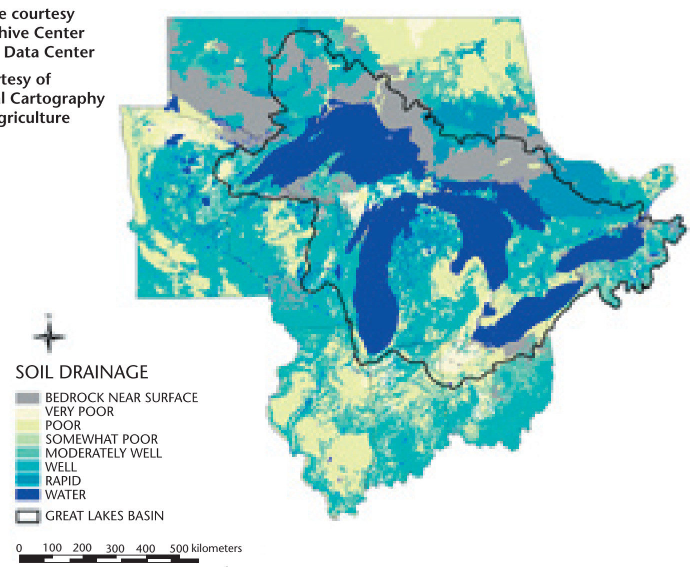
FIGURE 2
Satellite-Derived Maps Showing Land Cover and Soil Drainage
from page 8

Current patterns of regional land cover mirror the distribution of soils and sediments left by repeated glaciation. The colder climate and thin, coarse-textured soils of the Canadian Shield support extensive boreal forests, while the warmer climate and deep, fertile soils in the region's lowland areas support much of the agricultural production for both Canada and the United States.



Source: Land cover image courtesy of Distributed Active Archive Center (LP DAAC), USGS's EROS Data Center

Soil drainage image courtesy of STATSGO/NRCS/National Cartography and GIS Center/USDA/Agriculture and Agri-Food Canada



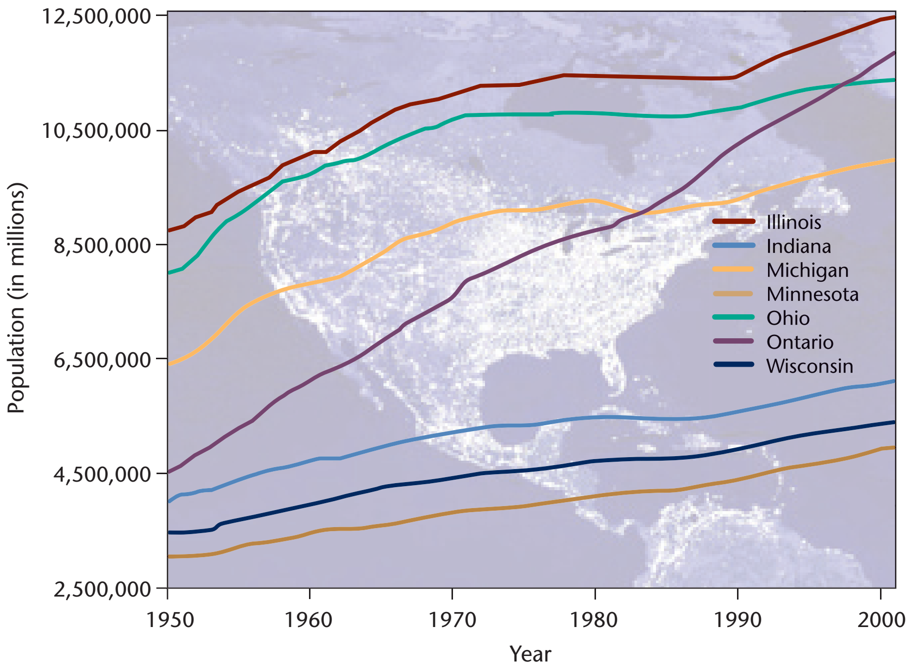


FIGURE 3

Population Change in the Great Lakes Region (1950–2001)

from page 9

Over the past decade, population grew by an average of 8.7 percent in the Great Lakes states and 12.2 percent in Ontario. The region's ecosystems and species already face increasing pressure from land development and urban sprawl, air and water pollution, and natural resource extraction. The activities of this growing population will increase heat-trapping emissions, which, in turn, will exacerbate existing environmental stresses.

Photo Credit: Defense Meteorological Satellite Program (DMSP) and NOAA Satellite and Information Services

Source: US data from Bureau of Economic Analysis (BEA); Canadian data from Ontario Ministry of Finance

FIGURE 4

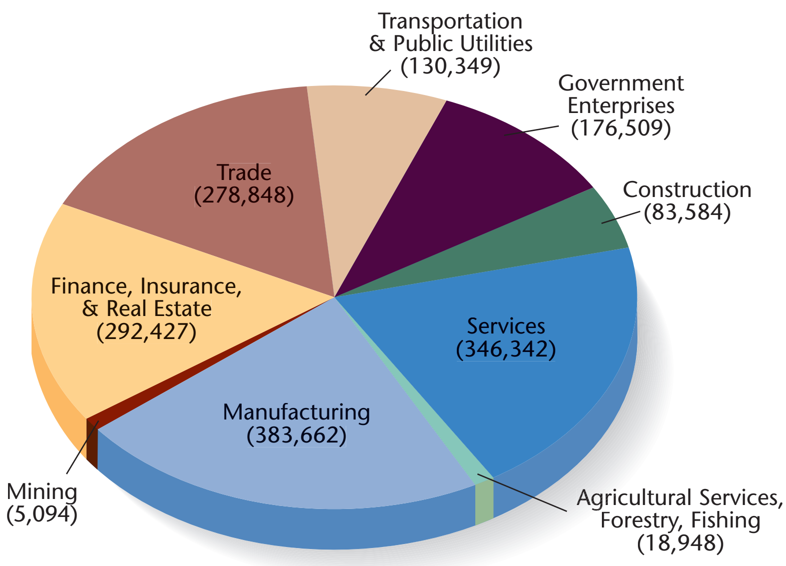
The World's Third-Largest Economy

(in Millions of US Dollars)

from page 9

The region's economy is large and diversified, with regional production in 2000 totaling nearly $2 trillion (US)—an amount that exceeds the gross domestic production of any nation except the United States and Japan. The services sector, including tourism and recreational activities such as birdwatching, hunting, boating, and skiing, has grown increasingly important and is now one of the largest economic sectors in the region.

Source: Bureau of Economic Analysis (2000)



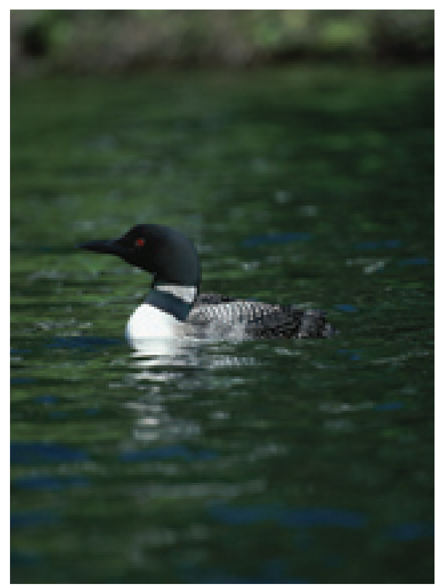


FIGURE 5

The Changing Character of the Region

from page 10

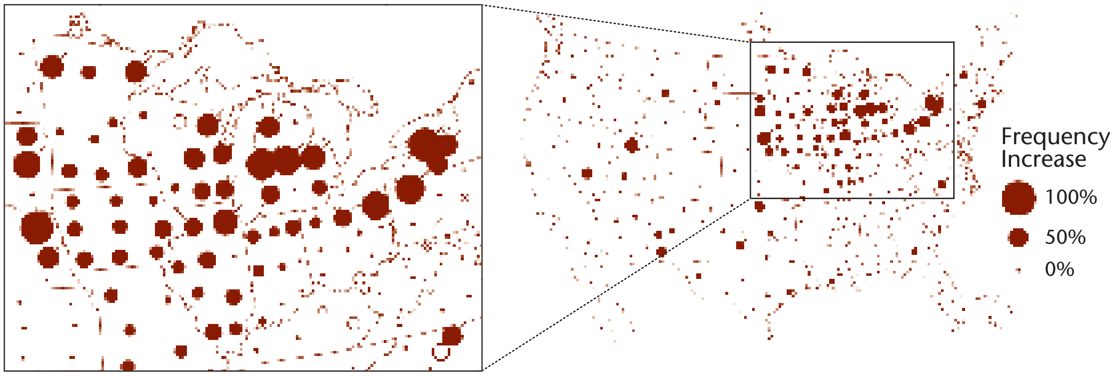
Climate change will transform the character of the Great Lakes region. Many beloved places, prized species, special activities, and defining characteristics will be lost or altered. The magnificent forests and pristine lakes of Michigan, Minnesota, New York, and Ontario—all home to the common loon—will be altered as temperatures rise and precipitation patterns change.

Photo Credit: EyeWire

FIGURE 7

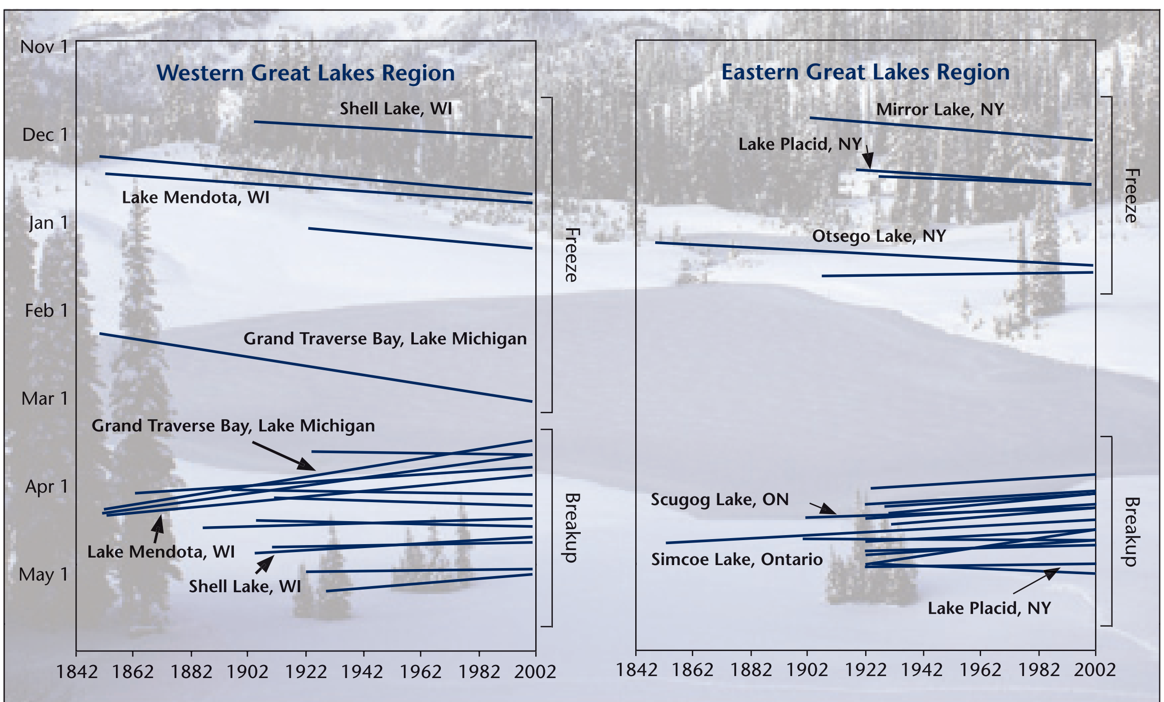
Historical Trends in Extreme Rainfall Events (1931–1996)

from page 14



The past 30 years were the region's wettest in the 20th century. Over this period, heavy summer downpours have also become more frequent, contributing to increases in flooding in small- and medium-sized streams. Extreme rainstorms can swamp municipalities' sewage and stormwater capacities, increasing the risks of water pollution and waterborne infectious diseases. In 1993, for example, extended rainfalls and runoff overwhelmed Milwaukee's municipal drinking water purification system and led to a *cryptosporidium* outbreak, causing 403,000 cases of intestinal illness and 54 deaths.

Credit: Reproduced with permission from Kunkel et al. (1999), Journal of Climate



	Freeze		Breakup	
	Western Great Lakes	Eastern Great Lakes	Western Great Lakes	Eastern Great Lakes
Long-term data (80 or more years)	mean=1.2 range=0.7 to 2.5 lake sample=5	mean=0.3 range=-0.1 to 0.6 lake sample=5	mean=0.7 range=-0.3 to 2.9 lake sample=13	mean=0.5 range=0 to 1.5 lake sample=13
Last 2 decades	mean=3.4 range=-2.7 to 13.5 lake sample=24	mean=0.3 range=-5.4 to 5.4 lake sample=25	mean=2.8 range=-1.1 to 15.2 lake sample=38	mean=0.1 range=-3.8 to 8.4 lake sample=34

Freeze and breakup change in days per decade. Positive change indicates a later freeze date and an earlier breakup date. Negative change indicates an earlier freeze date and later breakup date.

FIGURE 8

Change in Timing of Lake Freezes and Thaws

from page 14

Records over the past 80 years consistently show durations of ice cover on inland lakes shortening, as fall freezes occur later and spring thaws earlier. Reduced ice cover leads to greater evaporation from open water in winter, contributing to lower water levels. Changes in inland lake ice cover are greatest in Michigan, Minnesota, and Wisconsin.

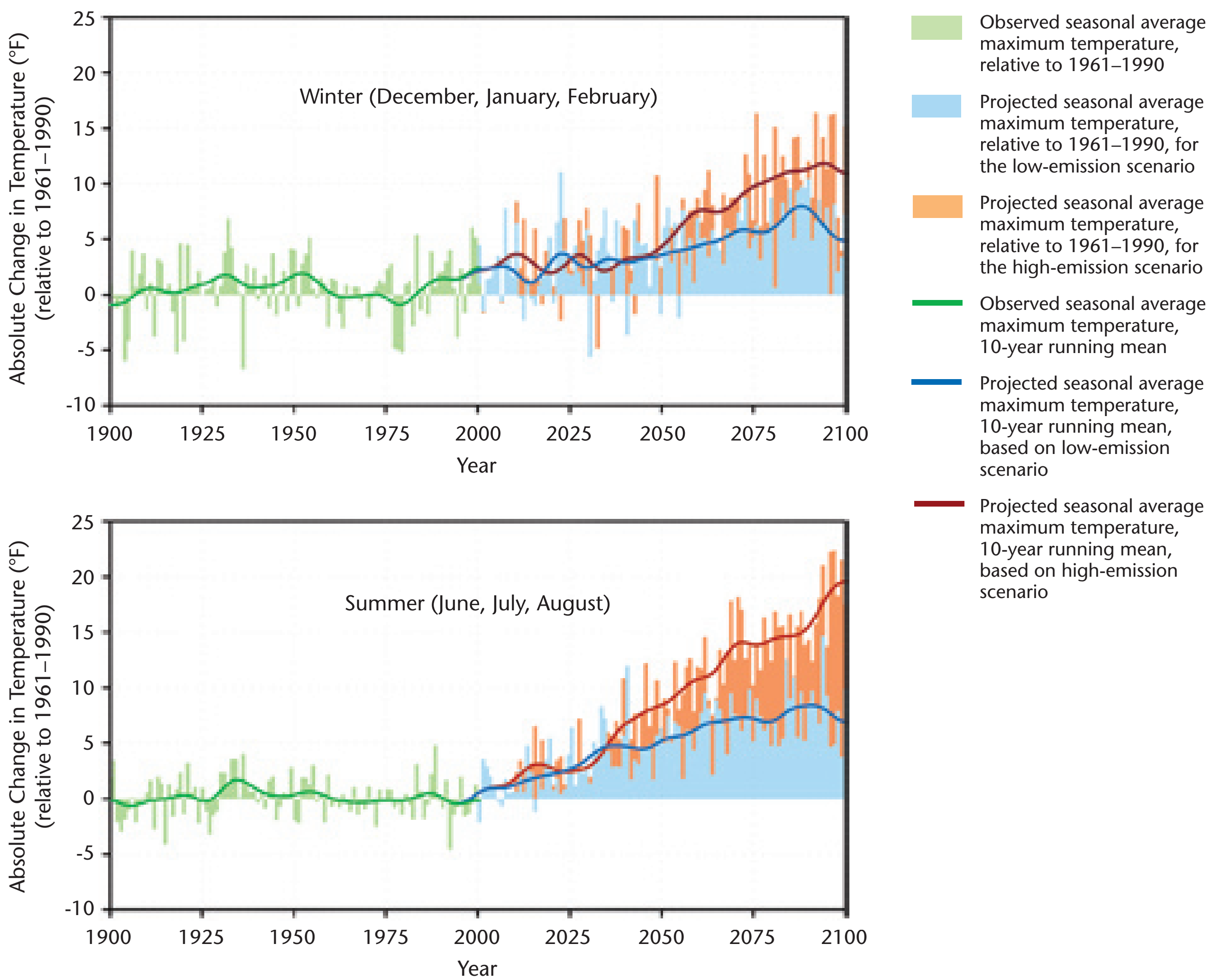
Source: Data courtesy of T. B. Clark, and J. J. Magnuson, R. A. Assel, V. Card, M. Futter, P. A. Soranno, and K. M. Stewart

FIGURE 6A

Observed and Projected Change in Average Daily Temperature

(Averaged Over Entire Region)

from page 13



Although the region's climate is highly variable, analyses of historical data reveal a recent and significant shift in temperature (left) and precipitation (right), consistent with our growing understanding of a changing climate. By the end of the 21st century, average summer temperatures are projected to increase by 5 to 20°F (3 to 9°C). This large temperature range reflects the difference between a low- and a high-emission scenario. Humans can reduce heat-trapping gas emissions, which would help keep the temperature increase at the lower end of the range. In both scenarios, average annual precipitation and variability between wet and dry years are projected to increase slightly.

Source: Hayhoe and Wuebbles

FIGURE 6B

Observed and Projected Change in Average Daily Precipitation

(Averaged Over Entire Region)

from page 13

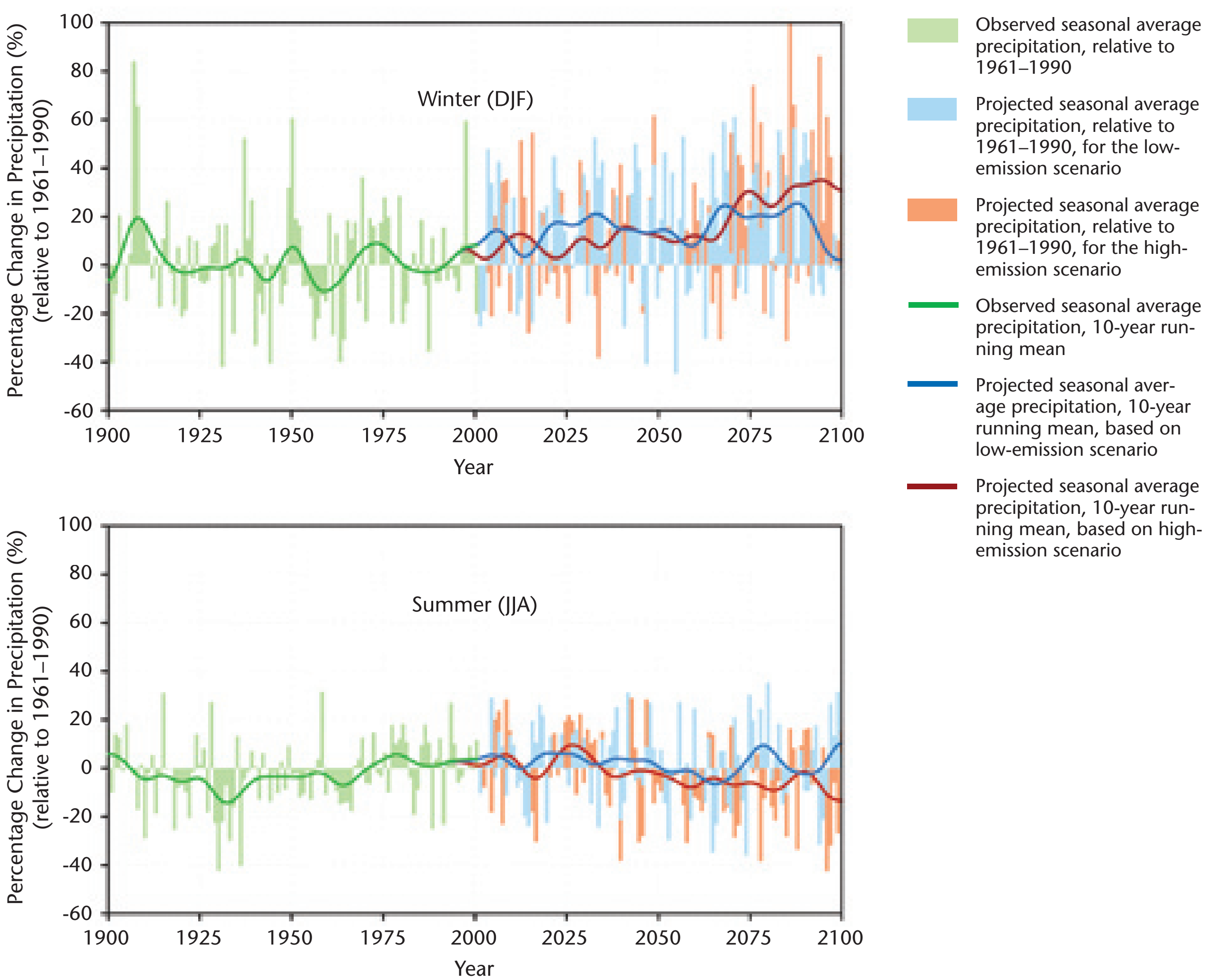


FIGURE 9A

Ice Cover Duration on Lake Mendota, Wisconsin

from page 15

Hydrologic models predict drastic reductions in ice cover on both the Great Lakes and inland waters. Freeze-up has been coming later in the fall and ice-out earlier in the spring for the past century and a half. While ice cover duration has declined over the past 80 years, the last 20 years has seen the most rapid reduction. Lake Mendota, near Madison, Wisconsin, illustrates this trend.

Source: John J. Magnuson, data from North Temperate Lakes LTER database, Center for Limnology, University of Wisconsin-Madison

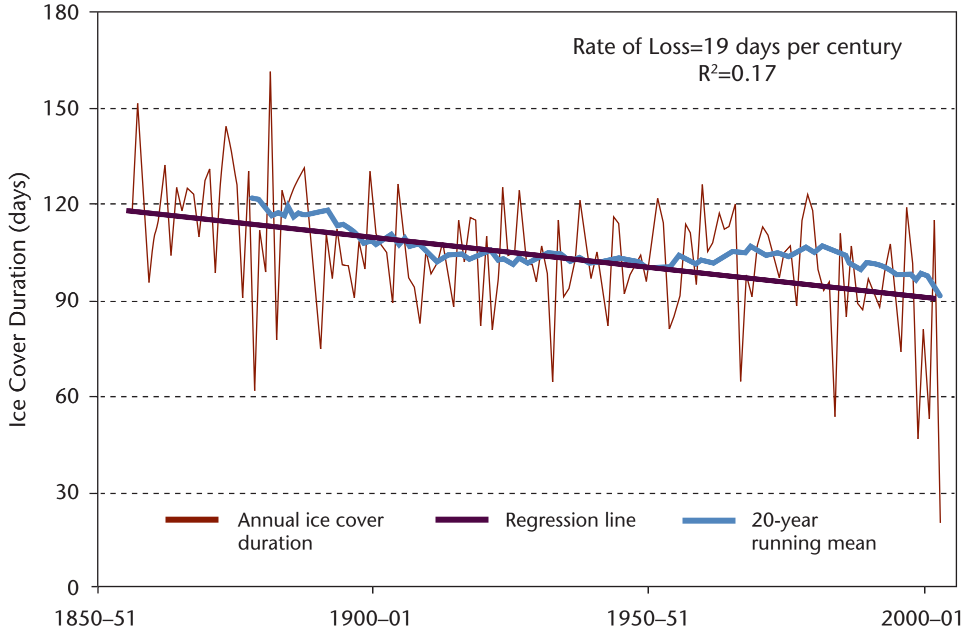
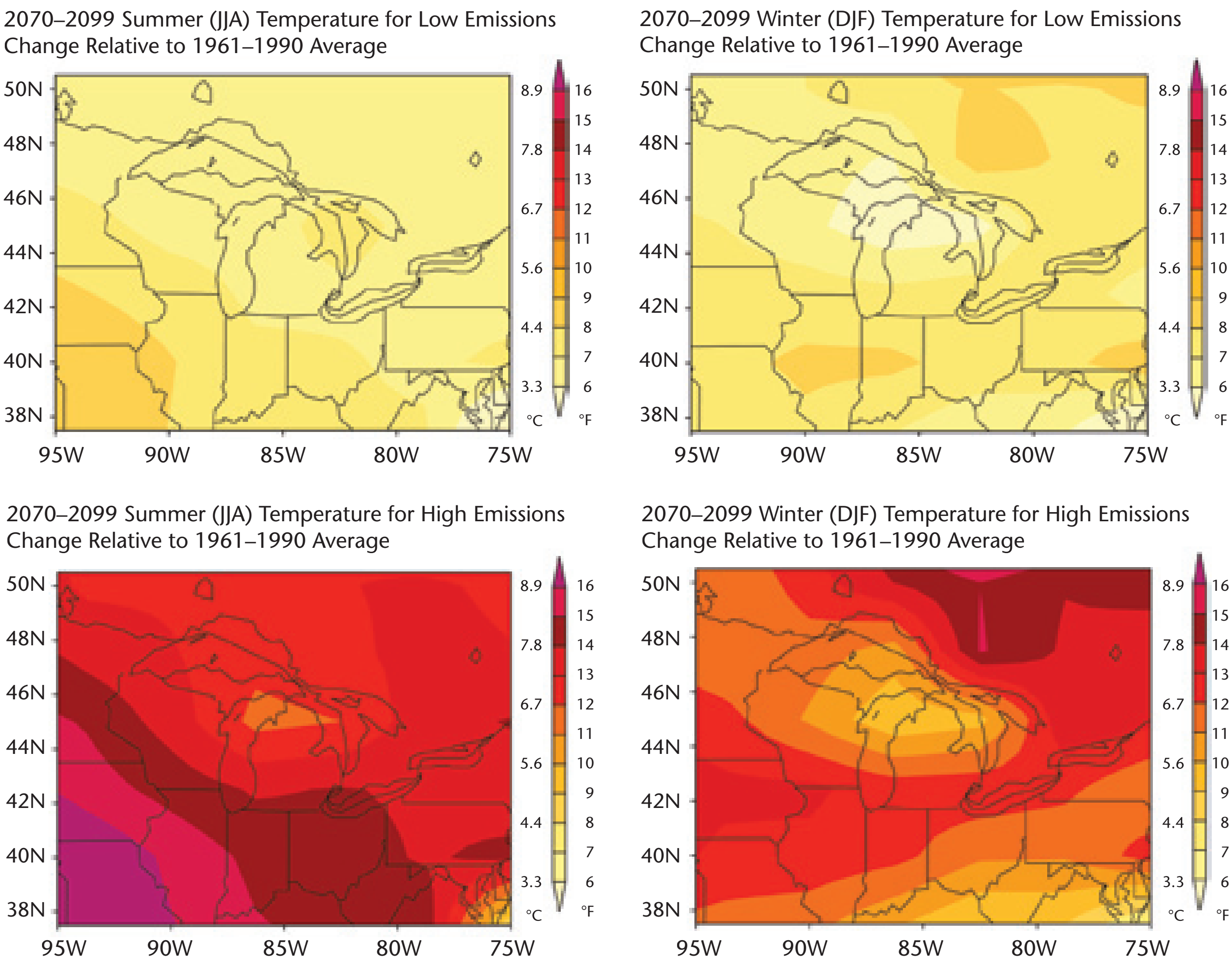


FIGURE 10

Projected Changes in Temperature During Summer and Winter by 2070–2099

(Relative to 1961–1990, Average for Low- and High-Emission Scenarios)

from page 17



Temperatures are expected to rise sharply throughout the next century and to vary substantially by season and across the region. In winter, for example, the greatest warming is expected at higher latitudes, while in summer, the greatest changes will occur over the southern and western parts of the region. The seasonal cycle of temperature over the region is also projected to shift, with summer, and to a lesser extent winter, warming more than spring and fall. By the last three decades of the century, temperatures are likely to increase substantially in all seasons.

Source: Hayhoe and Wuebbles

FIGURE 9B

Kites on Ice Winter Festival 2002 on Lake Monona, Wisconsin

from page 15

Longer ice-free periods may extend the shipping season on the Great Lakes but will reduce ice fishing, ice boating, skiing, snow-mobiling, and other winter activities, such as the "Kites on Ice" winter festival in Madison. The continuing decline in winter ice cover thus presages a severe cultural shift for the region, where winter fun on ice has long been an integral part of residents' sense of place. Communities dependent on revenues from cold-weather activities could be hard hit by warm winter temperatures and less snow.

Photo Credit: John J. Magnuson

FIGURE 11

Growing Season in the Great Lakes Region

(Observed and Projected Changes, 1900–2100)

from page 17

Compared with the beginning of the 20th century, the growing season today is about one week longer, primarily because the last spring frosts have come earlier. The length of the growing season will continue to increase so that by the end of this century, it may be four to nine weeks longer than over the period 1961–1990. While a warmer, longer growing season may improve agricultural productivity, such conditions may also facilitate the buildup of large pest populations.

Source: Hayhoe & Wuebbles

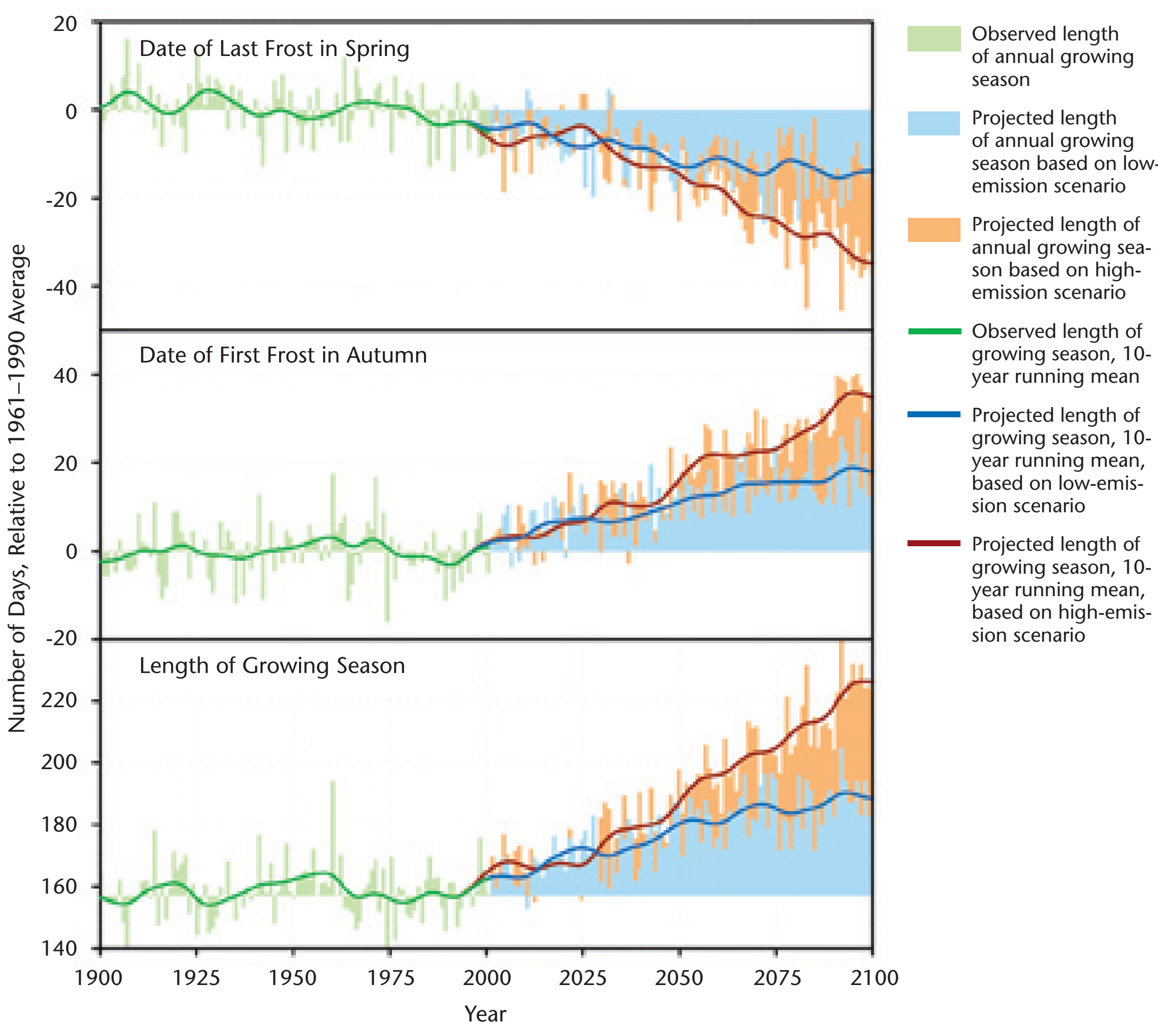


FIGURE 12

Projected Changes in Precipitation During Summer and Winter by 2070–2099

(Relative to 1961–1990, Average for Low- and High-Emission Scenarios)

from page 18

Average annual precipitation may increase slightly by the end of the century, but the regional climate may actually become drier overall because any increases in rain or snow are unlikely to compensate for the drying effects of increased evaporation (from soils and surface waters) and transpiration (release of moisture from plants). Seasonal precipitation cycles are likely to be more extreme, with winter and spring rain increasing and summer rain decreasing by up to 50 percent. The largest summer decreases are expected over the southern and western parts of the region, where most agriculture is concentrated.

Source: Hayhoe and Wuebbles

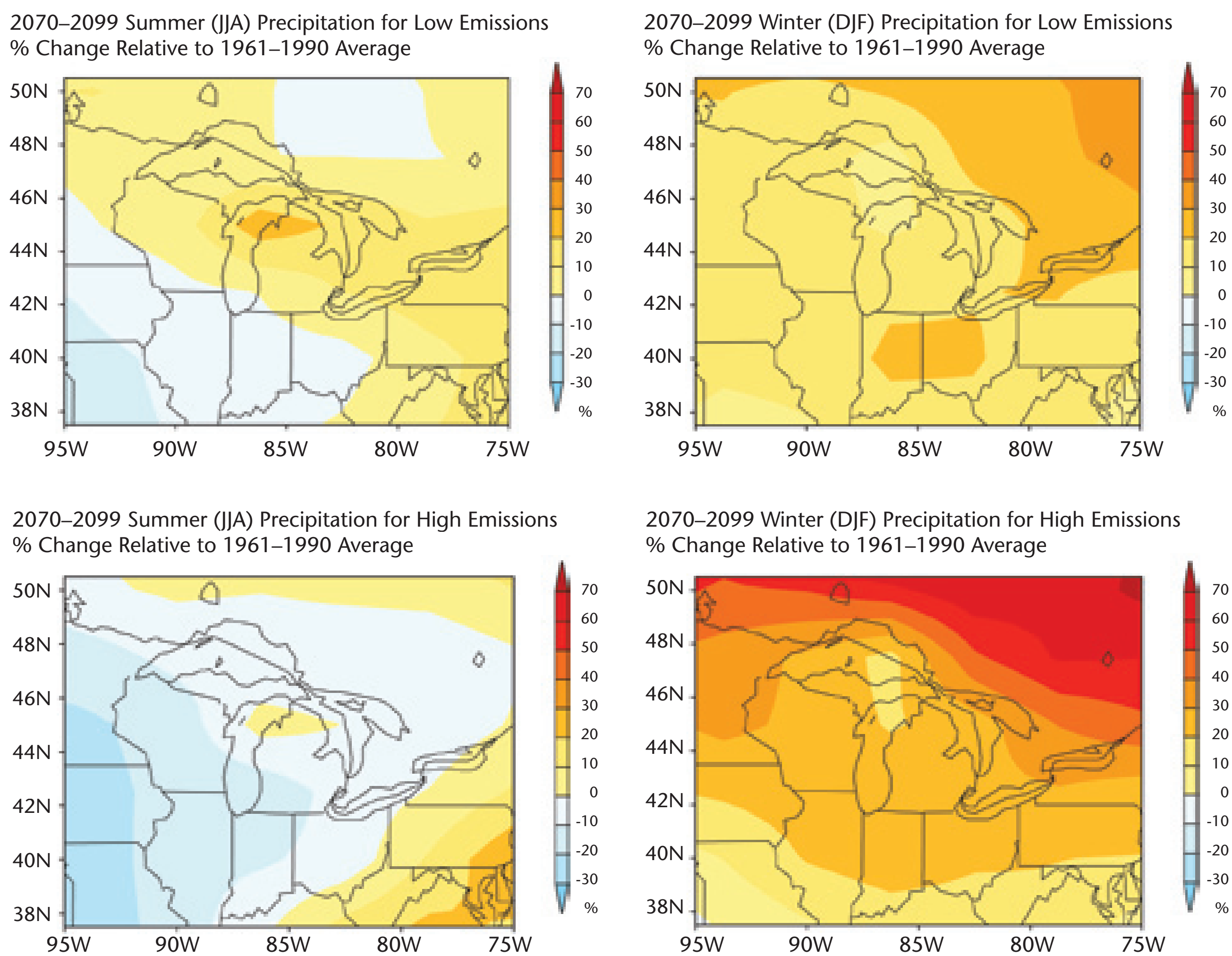


FIGURE 13

Seasonal Precipitation Cycle

(Historical Baseline and Projected Changes, 10-Day Running Mean)

from page 18

The projected seasonal precipitation shifts, with winter and spring precipitation increasing and summer rain decreasing, translate into a climate of more extremes. Heavy downpours, floods, heat waves, droughts, and tornadoes are expected to be more frequent in a warmer world, increasing burdens on emergency management, public works, and health care services and exacting a growing financial toll on homeowners, governments, and businesses. Illinois has experienced a stark preview of this future scenario during the past 15 years with a severe drought in 1988, two Mississippi River floods, a severe rainstorm in Chicago in 1996, two deadly heat waves, a 1999 wind-storm in Bloomington, and numerous tornadoes.

Source: Hayhoe and Wuebbles

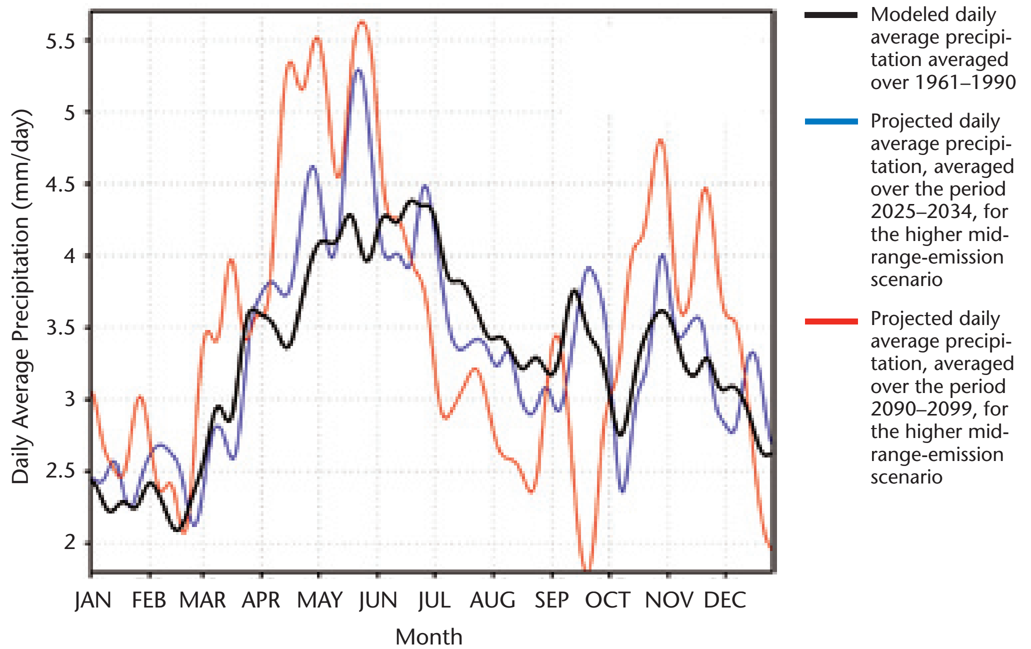


FIGURE 14

Increased Frequency of Heavy Rainfall Events in the Great Lakes Region

from page 19

The next several decades will almost certainly see continued increases in heavy rainfall—perhaps doubling by 2100—with longer dry spells in between. The intensity of extreme rainfall events may also increase. Upgrading water control infrastructure based on historical frequencies of extreme events will thus be inadequate in a warming world, especially as more frequent downpours interact with more impervious surfaces.

Source: Hayhoe and Wuebbles

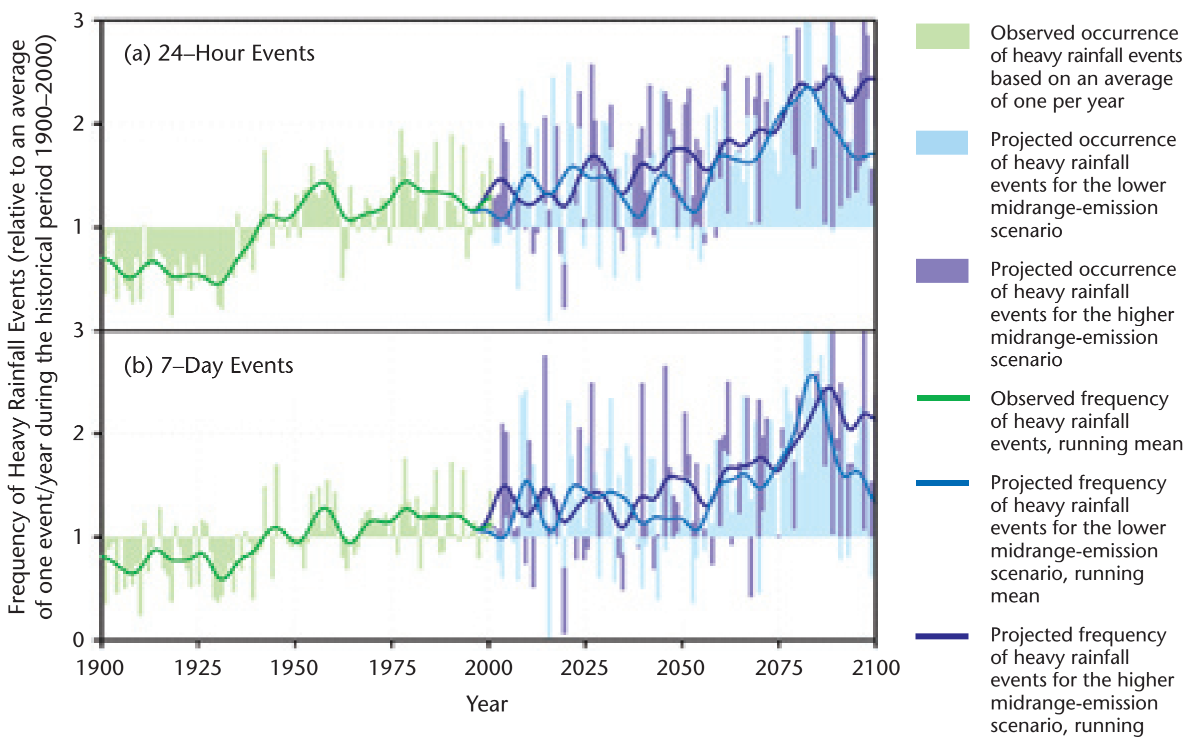
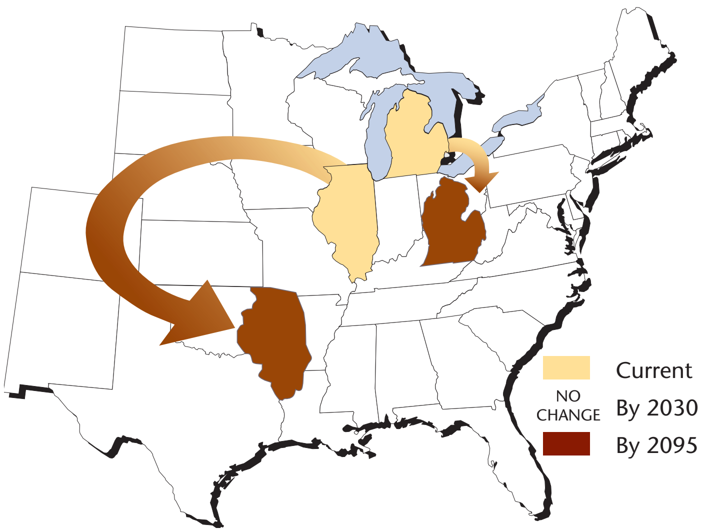
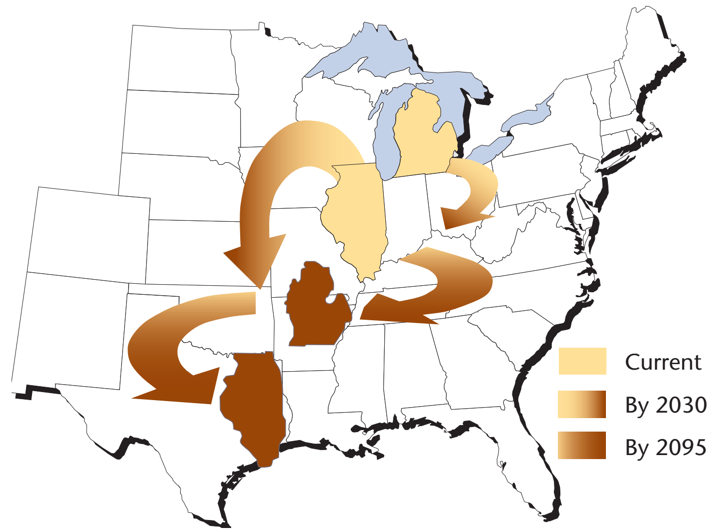


FIGURE 16
Migrating Climate: Changing Winters and Summers in Illinois and Michigan
from page 19



Changing Winters (DJF average) in Illinois and Michigan



Changing Summers (JJA average) in Illinois and Michigan

The changes in temperature and precipitation described in this report will strongly alter how the climate feels to Great Lakes residents. Within three decades, for example, a summer in Illinois may feel like a summer in Oklahoma does today (right panel). By the end of the century, an Illinois summer may well feel like one in east Texas today, while a Michigan summer will probably feel like an Arkansas summer. Average winter climates will similarly shift (left panel), and other states and provinces in the region will experience comparable changes.

Source: Hayhoe and Wuebbles

FIGURE 15
Precipitation Shifts Signal Trouble for Farmers
from page 19

Projected increases in rainfall and runoff in the spring, followed by a drier growing season and more rainfall during harvest times, will create a challenging climate change scenario for Great Lakes farmers. Shifts in the timing of planting and harvest, increases in irrigation, and other adjustments may be required as the climate changes.

Photo Credit: Courtesy of the University of Minnesota

FIGURE 17
Impacts on Lake Ecosystems
from page 21

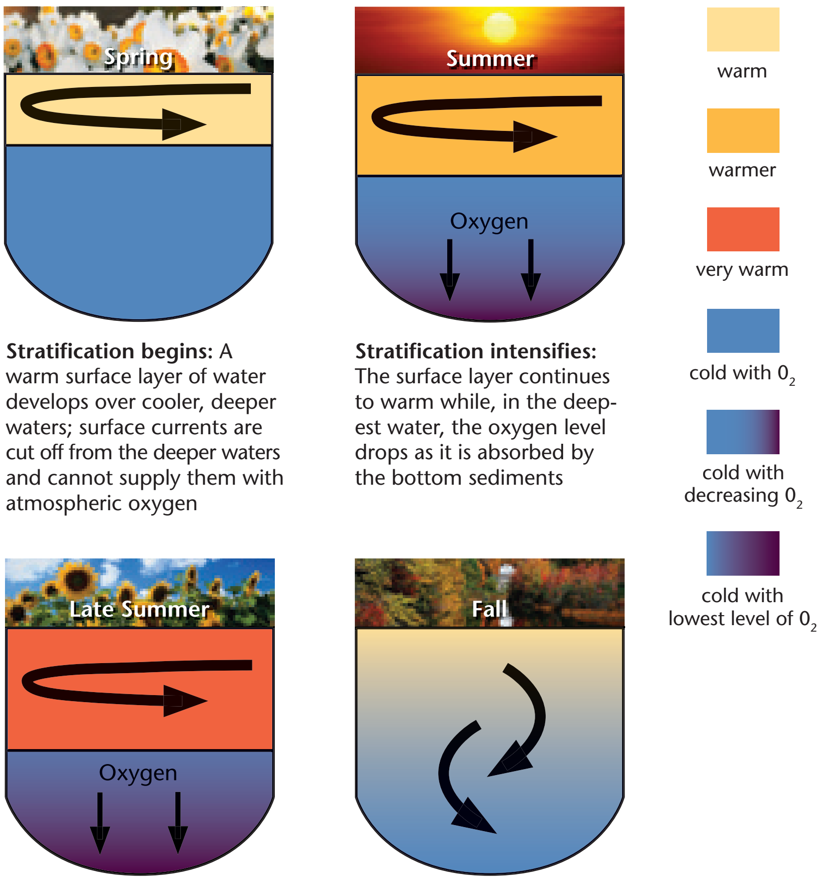
Northern Minnesota's Pine Lake is one of many that dot the Land of 10,000 Lakes. Throughout the region these lakes differ widely; each lake's unique characteristics will determine how it will be affected by climate change. In general, however, warmer air temperatures are likely to lead to increasing water temperatures, which, in turn, can lower water level and oxygen content. These conditions may accelerate the accumulation of mercury and other contaminants in the aquatic food chain and, ultimately, in fish.

Photo Credit: Larry Ricker, LHR Images

FIGURE 18A

Lake Stratification and the Development of "Dead Zones"

from page 22



Stratification begins: A warm surface layer of water develops over cooler, deeper waters; surface currents are cut off from the deeper waters and cannot supply them with atmospheric oxygen

Stratification intensifies: The surface layer continues to warm while, in the deepest water, the oxygen level drops as it is absorbed by the bottom sediments

Stratification peaks: 'Dead zone' forms as low oxygen levels spread throughout the deep waters

Turnover: As the surface layer cools, fall winds generate currents that are strong enough to carry oxygen to the bottom waters and return their oxygen levels to normal

Source: Based on information provided by Brian Shuter
Credit: Amanda Wait/DG Communications

FIGURE 18B

Lake Michigan Fish Kill

from page 23

Photo Credit: John J. Magnuson

A warming climate increases the duration of summer separation of upper and lower water levels (known as stratification) in the deep lakes. This, in turn, makes frequent and larger "dead zones"—areas of water depleted of oxygen and unable to support life—more likely. Persistent dead zones can result in toxic algal blooms, foul-smelling, musty-tasting drinking water, damage to fisheries, and massive fish kills—such as seen here on the shores of Green Bay, Wisconsin in 2001. Lake Erie recently experienced a large and unexpected dead zone episode in 2001.

FIGURE 19

Impacts on Stream Ecosystems

from page 27

Warmer air temperatures and drier conditions will translate into lower summer stream flow and less stream habitat. Headwater streams, such as the Little Miami River in Ohio, comprise approximately 75 percent of the river miles in a watershed and are probably the most vulnerable of all aquatic ecosystems under these conditions. Warmer water temperatures, higher concentrations of contaminants as water volume declines, and reduced transport of nutrients and organic matter combine to cause disruptions of aquatic food webs.

Photo Credit: Mike Williams, Ohio Department of Natural Resources

FIGURE 20

Impacts on Wetland Ecosystems

from page 29

Earlier ice breakup and spring runoff, more intense flooding, and lower summer water levels mean trouble for wetlands and the species that depend on them. Poorer water quality and less habitat for wildlife threaten Horicon Marsh in Wisconsin, a large inland cattail marsh that has been designated a “globally important bird area” and is home to ducks, cranes, herons, and other shorebirds. Large, productive coastal wetlands such as Saginaw Bay, Michigan are not exempt from risk, but the smaller, isolated, rainfall-dependent inland wetlands are probably most threatened by the projected climate changes.

Photo Credit: Ryan Hagerty, US Fish & Wildlife Service

FIGURE 22

Leopard Frog in Wisconsin Wetland

from page 53

Dredging and filling for development, water diversion, and pollution already threaten the region’s wetlands. Climate change will exacerbate these threats. As overall water quality and quantity diminishes ephemeral wetlands, the reproductive success of frogs and many salamanders will be threatened. The leopard frog hiding in this photo may be luckier than some; although the wetlands home of this declining species may dry up, the leopard frog has some “backup” habitat along lakeshores.

Photo Credit: John J. Magnuson

FIGURE 21A

Songbird Declines Expected

from page 30

Migratory songbirds such as the evening grosbeak, pictured, are likely to decline in the northern forests as the climate changes. Although some resident bird species may benefit and new species may enter the region, a 29 percent net loss in forest bird diversity is projected. Such a decline also means a loss in ecological services such as seed dispersal and insect control, and a potentially significant loss to the economies of northern Michigan, Minnesota, and Wisconsin, where bird watching is a multibillion-dollar industry.

Photo Credit: Dave Menke, US Fish & Wildlife Service

FIGURE 21B

Climate Change Impacts on Waterfowl

from page 31

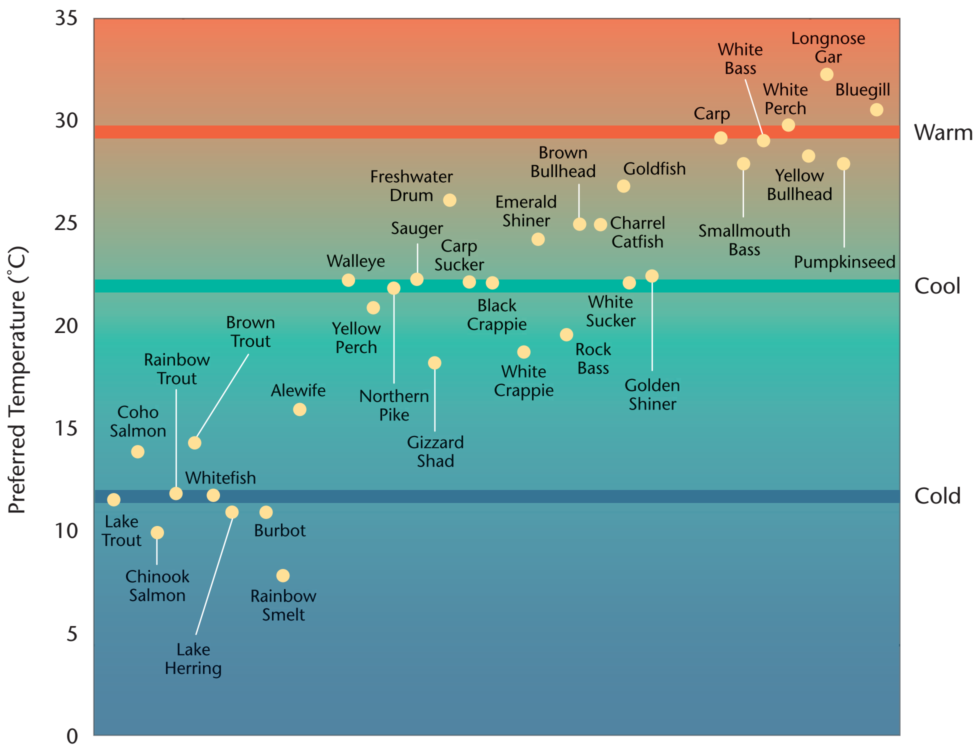
Waterfowl are also expected to decline with a changing climate. Conservative estimates project a 19 to 39 percent decline in duck numbers by the 2030s in response to lost breeding and migratory habitats, as well as declines in the aquatic plants on which ducks feed. Hunting is a $3.8 billion (US) industry in Michigan, Minnesota, and Wisconsin, and is a popular outdoor activity throughout the region.

Photo Credit: Tim Daniel, Ohio Department of Natural Resources

FIGURE 23

Temperature Groupings of Common Great Lakes Fish

from page 53



Source: Based on information provided by Brian Shuter
Credit: Amanda Wait/DG Communications

Common fish species of the Great Lakes region can be grouped together by their temperature preferences, called "thermal guilds." In the schematic left, the colored bars identify the median value of the preferred temperatures for the species listed in each guild. In the graph below, this simulation for Minnesota inland lakes (with a CO_2 doubling) shows that cold-water species such as lake and brook trout may decline dramatically in the region. Cool-water species such as the muskie and walleye as well as warm-water species such as bluegill and smallmouth bass will vie to take their place. Changes in the distribution and productivity of fish species will affect the nearly 10 million anglers who fish these waters.

FIGURE 24

Water Temperature and Fish Distribution Changes

from page 55

Source: Data from Stefan et al. (1995)

Photo Credits: Bluegill (warm water), Doug Stamm; Muskie (cool water), John J. Magnuson; Brook Trout (cold water), Gerald C. Bucher

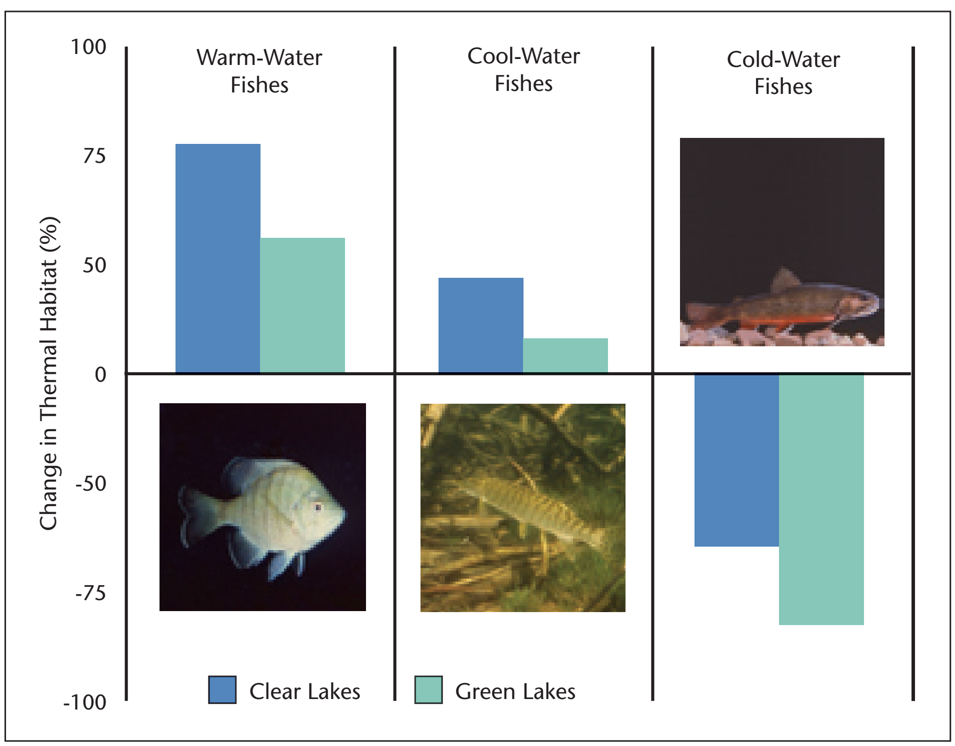


FIGURE 25

Water Changes Affect Hydropower

from page 56

Hydropower accounts for almost 25 percent of the electricity generated in Ontario, and the Moses Niagara Plant in New York is also a significant generator. Decreased water levels could reduce regional hydropower generation by a conservative estimate of 15 percent by 2050. Projected drier summers suggest that the pressure to increase water extraction for irrigation, drinking, and other human uses will grow within the basin, amplifying the already contentious debate over water withdrawals from the Great Lakes.

Photo Credit: Courtesy of the Center for Great Lakes and Aquatic Sciences

FIGURE 27A

Forest Pests in a Changing Climate

from page 59

Cold winter temperatures determine the northern extent of some damaging forest pests. Gypsy moths—pictured here as larva feeding on an aspen leaf and as adults—defoliate more hardwood forests than any other insect in North America. As winters warm, these insects will almost certainly become more widely established throughout the region. The fate of other insects and pathogens is harder to predict due to complicated interactions between the insects, plants, and climate changes.

Photo Credit: John H. Ghent, USDA Forest Service, courtesy of Forestry Images

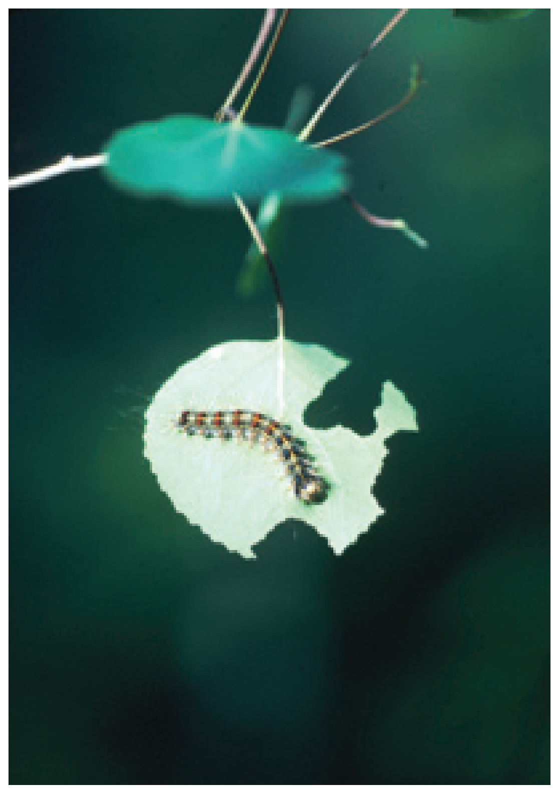


FIGURE 27B

Gypsy Moth Larva Feeding on Aspen Leaf

Photo Credit: Rick Lindroth

FIGURE 26
The Northern Forests
from page 57

Ontario and the northern parts of Michigan, Minnesota, and Wisconsin are still dominated by forests of spruce, hemlock, and fir. Warmer temperatures will likely cause the extent of boreal forests to shrink and other forest species to move northward unless hindered by lakes, unsuitable soils, or development. Increasing atmospheric concentrations of CO_2 and nitrogen are likely to spur forest growth in the short term, but increasing ground-level ozone and higher risk of forest fires could diminish long-term forest health and productivity.

Photo Credit: John Pastor

FIGURE 28
Range Shifts of the Canadian Tiger Swallowtail
from page 59

Insect ranges may shift as their host trees migrate in response to climate. The range of the Canadian tiger swallowtail, for example, is likely to retract northward as one of its preferred hosts, aspen, disappears from the southern Great Lakes region.

Photo Credit: Rick Lindroth

FIGURE 29
Virginia Possum's Range Expanding North
from page 60

Reduced winter mortality of nuisance mammals such as raccoons, skunks, and possums, pictured here, could increase their overall abundance, potentially increasing predation on ground-nesting songbirds and other vulnerable prey. White-tailed deer might also benefit from climate warming, while moose, already near their southern geographic limit, could be harmed both by warming and by greater density of deer.

Photo Credit: Point Pelee National Park, Parks Canada

FIGURE 30

Mixed Impacts for Agriculture

from page 61

Vast fields of wheat, corn, and soybeans, dairy farms, and fruit orchards are as much a part of the Great Lakes landscape as its forests and lakes. Higher CO_2 concentrations and a longer growing season may increase agricultural productivity. However, these prospects seem less favorable than projected in previous studies when damage is factored in from extreme weather events, pests, and ground-level ozone. Overall, technological advances and trends in markets will moderate the influence of climate change on both crops and livestock. A warmer and more variable climate, however, will likely increase the economic risks for smaller farms, such as the one pictured here in Pennsylvania, as well as for farming communities—altering the character of the region's rural landscapes.

Photo Credit: USDA

FIGURE 31

Climate Change and Agricultural Pests

from page 62

Crop losses and pesticide use may increase as pests and diseases become a bigger problem in the region. Already the range of the bean leaf beetle, a soybean pest, seems to be shifting northward as winter temperatures rise. The European corn borer, pictured here, may also be moving beyond its current northern limit in lower Wisconsin and producing multiple generations per year. Other insect pests may be limited by climate change.

Photo Credit: Clemson University–USDA Cooperative Extensive Slide Series, courtesy of Forestry Images

FIGURE 33

Climate Change Impacts on the Timber Industry

from page 65

Changes in forest species and growing fire and insect risks suggest adaptation will be needed in the forestry industry. Although it contributes less to the regional economy than manufacturing or agriculture, forestry remains locally important. The forest products industry in Ontario, for example, employs 90,000 people and generates $15 billion (Cdn) each year. In Wisconsin, the industry employs 74,000 workers and generates more than $18 billion (US).

Photo Credit: USDA Forest Service, Superior National Forest

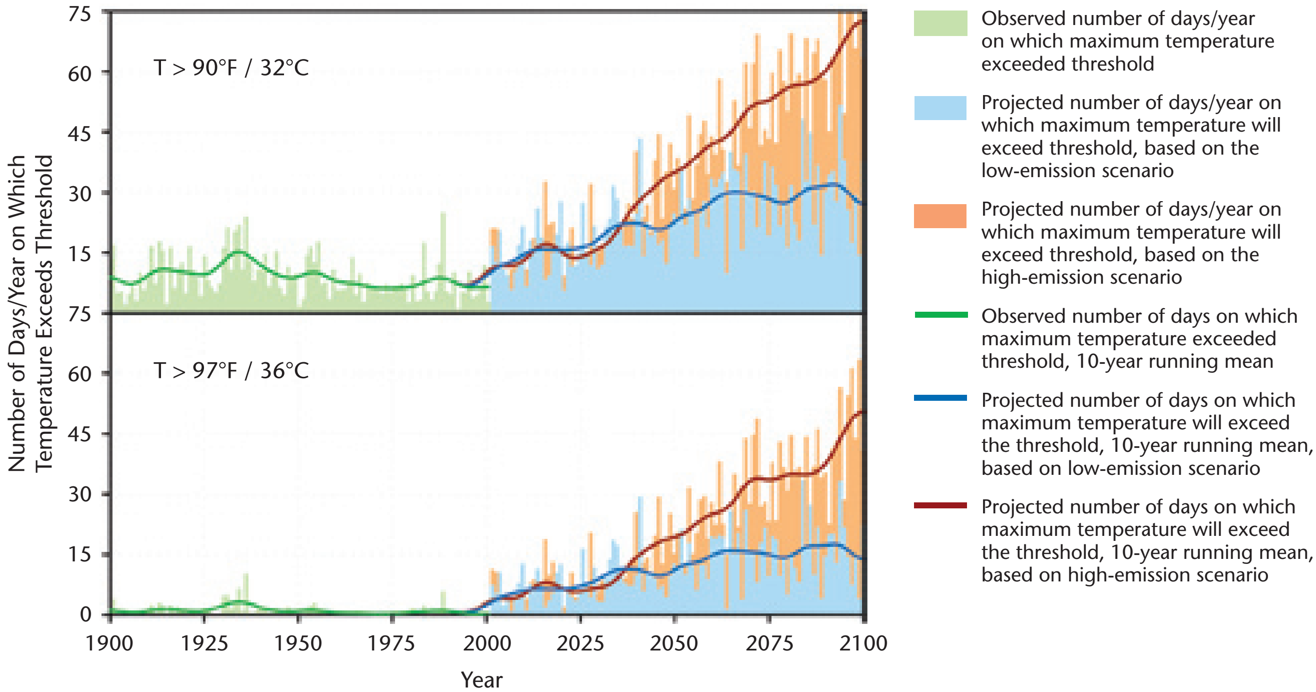


FIGURE 32A

Temperature Extremes in the Great Lakes Region

(Number of Threshold Exceedances per Year—Thresholds: Daily Maximum Temperature of 90°F/32°C and 97°F/36°C)

from page 63

The number of hot days is projected to increase, with years later in the century experiencing 40 or more days exceeding 90°F (32°C). For human health, an even greater concern is the projected dramatic increase in extreme heat days. Hardest hit will be northern cities such as Minneapolis/St. Paul or Toronto, where extremely high temperatures are now rare, although more southerly cities are not exempt. More than 700 people, mostly poor and elderly, died in the 1995 Chicago heat wave. Warning systems and extra public health attention can help mitigate heat disasters.

Source: Hayhoe and Wuebbles

FIGURE 32B

Concerns About Insect-borne Infectious Diseases

from page 64

The occurrence of many infectious diseases is strongly seasonal, suggesting that climate plays a role in transmission. Future changes in rainfall, temperatures, and land use could encourage greater reproduction or survival of disease-carrying ticks or mosquitoes. For example, regional outbreaks of St. Louis encephalitis, transmitted by mosquito, have been associated with extended periods of temperatures above 85°F (29°C) and little rainfall—the likely pattern of summers in a warming world.

Photo Credit: USDA Agricultural Research Service

FIGURE 34

Impacts on Summer Recreation

from page 66

The warm-weather recreation season will likely lengthen, helping to offset losses in winter recreation. Lower lake levels, however, will mean more aggravation and expense for boaters and marina operators, and could impact such popular vacation destinations as Door County, Wisconsin, Sleeping Bear Dunes, Michigan, and Pt. Pelee, Ontario. A variety of climate factors will increase the risk of water contamination, forcing more frequent beach closings—a situation that has already raised concerns about human health, quality of life, and the economic viability of shoreline communities.

Photo Credit: Rodney E. Rouwhorst, courtesy of Michigan Travel Bureau

FIGURE 35

Minnesota Wind Farm

from page 70

Reducing heat-trapping emissions will help slow down the rate and decrease the severity of climate change, thus forestalling the worst outcomes. Increasing energy efficiency and the amount of energy produced from renewable power sources will reduce emissions. Minnesota is already the nation's third-largest wind power producer, and new wind projects are underway in Illinois, Michigan, New York, and Ontario.

Photo Credit: Warren Gretz, courtesy of DOE/NREL

FIGURE 36

Illinois Fuel Cell Bus

from page 71

Another significant source of CO_2 emissions is the transportation sector. Increasing auto fuel efficiency, introducing hybrid and, eventually, fuel cell cars, developing low-carbon fuels, and reducing the number of miles driven can yield significant benefits. The hydrogen fuel cell-powered bus pictured left was tested for three years in a Chicago demonstration project and emits only water vapor. The Peoria, Illinois bus fleet includes a corn-derived ethanol-powered bus, emitting considerably less CO_2 than gasoline or diesel.

Photo Credit: Eric Unger, courtesy of the Joyce Foundation

FIGURE 37A

Toronto's "Green" City Hall

from page 72

Photo Credit: Jose San Juan, City of Toronto

Toronto, Canada's largest city, is truly a climate solutions leader. One of the first local governments worldwide to make voluntary cuts in heat-trapping gas emissions, the city reduced its emissions by 67 percent over eight years—three times its original goal in half the time. Toronto improved the energy efficiency of city buildings and streetlights, switched to alternative fuels for its vehicle fleet, developed clean power sources, created gardens on top of the new City Hall (left), and captured landfill gas for use in power production (right). The latter achieved large emissions reductions while generating $2.5 million (Cdn) in annual income for the city.

FIGURE 37B

Capturing Methane Gas from Landfill

from page 72

Source: US EPA (2001). Photo Credit: David Parsons, courtesy of NREL

FIGURE 38
Minimizing Sprawl
from page 74

Urban and rural land-use planning can reduce sprawl, which prevents habitat destruction and fragmentation, reduces impervious surfaces that contribute to flooding, cuts municipal spending on services, moderates the loss of valuable farmland, and reduces heat-trapping gas emissions from commuter traffic. A successful civic campaign in Grand Rapids, Michigan, for example, has resulted in comprehensive land-use policy reforms. Minimizing sprawl is one strategy to minimize pressure on the region's ecosystems, which will increase their resilience in the face of a changing climate.

Photo Credit: Gregor Beck, Federation of Ontario Naturalists

FIGURE 40
Managing the Lake and Stream Impacts of Climate Change
from page 77

Anticipating and planning for the impacts of change will help reduce future damage and expense. As lake levels drop, for example, costs and hazards to Great Lakes shipping will increase, and prudent managers in this industry will have to adapt by dredging harbors and channels more frequently, adjusting docks, and assessing changes to water intake pipes.

Photo Credit: Jerry Bielicki, courtesy of US Army Corps of Engineers

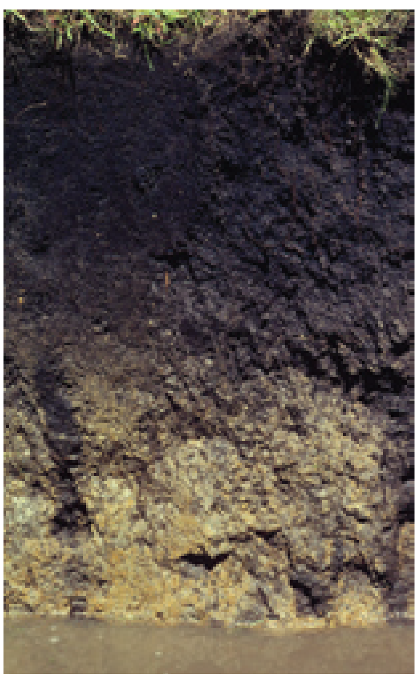


FIGURE 39A
Ecological Limits to Adaptation in Agriculture: Illinois Soil
from page 76

Because most heat-trapping gases remain in the atmosphere for many decades, society must prepare to manage future impacts that cannot be avoided. But even adaptation in relatively rich countries like the United States and Canada will likely be constrained by critical ecological limits. The photo on the left shows a Drummer soil, poorly drained, dark-colored soil typical of the prairies of Illinois, while the photo below shows a Kalkaska soil, a sandy, acidic, rapidly permeable soil typical of northern Michigan. Although optimal agricultural climates are expected to shift northward and eastward, certain crops cannot be grown competitively on northern soils, or their yields may be limited by soil quality.

Photo Credit: Robert Darmody, University of Illinois .

FIGURE 39B
Northern Michigan Soil

Photo Credit: USDA, NRCS, MLRA Soil Survey Office

ephemeral wetlands, for example, will threaten reproductive success of certain species such as wood frogs and many salamanders in the Great Lakes region (Figure 22).[112]

In times of drought, when individual wetlands are isolated from one another, deep wetlands serve as a safe haven or "refugia" for plants and animals until water levels are restored in dried-out wetlands. Loss of these refugia during longer or more severe droughts will threaten populations of amphibians and other less-mobile species. Landscape fragmentation exacerbates this situation, leaving refugia scarcer and more isolated.[113]

Wetland loss and degradation also threaten to drive the yellow-headed blackbird locally extinct in the Great Lakes region. This songbird's habitat is restricted to a small subset of marshes that have suitable vegetation in any given year as a result of fluctuations in water level. Land-use changes have greatly reduced the amount of suitable habitat, and further changes in water levels caused by increases in spring rain or summer drying could render remaining marshes unusable (see box, p.30).

Finally, most aquatic birds in the region depend upon seasonal flood pulses and gradual drops in water levels. Changes in the timing and severity of the flood pulse will affect the availability of safe breeding sites for birds and amphibians. Midsummer "spike" floods, for example, can flood bird nests in small wetlands and attract predators such as raccoons to areas where birds and amphibians breed. Changes in the timing of the spring melt also greatly alter migratory pathways and timing. Canada geese, which formerly wintered in flocks of hundreds of thousands in southern Illinois, now mainly winter in Wisconsin and further north in Illinois. The availability of seasonal mudflats for migratory shorebirds and endangered, beach-nesting species such as the piping plover will be affected by the drying or loss of wetlands.

FIGURE 22
Leopard Frog in Wisconsin Wetland

See page 44
for full-size color image of this figure

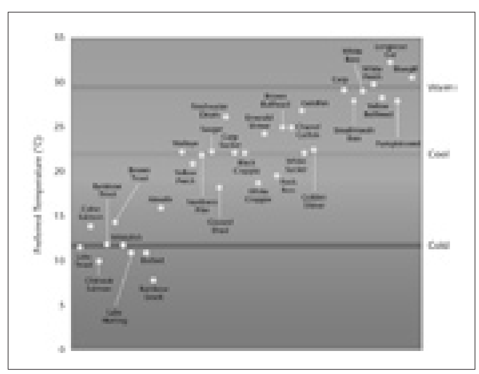
Fish Responses to Climate Change

The body temperature of a fish is essentially equal to the temperature of the water in which it lives, and each species has a characteristic preferred temperature. Rates of food consumption, metabolism, and growth rise slowly as the preferred temperature is approached from below, and drop rapidly after it is exceeded until reaching zero at the lethal temperature. Common species of fish can be grouped according to their preferred temperatures into "guilds" (Figure 23). Fish will respond strongly to changes in water volume, water flow, and water temperatures, either by shifts in distribution or in overall productivity.

Changes in Fish Distribution

Individual fish actively select and rapidly change living areas based on suitable temperatures, oxygen concentrations, and food availability. Cold-water fish actively avoid temperatures that exceed their preferred temperature by 3.5 to 9°F (2 to 5°C, depending on the species) and seek out refuges provided by sources of cooler water such as groundwater or seepage areas and headwater streams.[114] Physical constraints such as drainage patterns, waterfalls, and land-locked areas play a large role in determining the boundaries of a species' range and the rate at which it may respond to changing conditions. For example, temperature constraints prevented white perch from the Atlantic coast from invading Lake Ontario until the 1930s. Then, a series of warm winters over a 20-year

FIGURE 23
Temperature Groupings of Common Great Lakes Fish



See page 46
for full-size color image of this figure

period permitted this species to spread through the Hudson River and Erie barge canal and into Lake Ontario by 1950.[115] Table 6 summarizes the potential impacts of climate warming on the distribution of fish species in the Great Lakes region.

Populations living near the edge of the species' range often exhibit greater year-to-year variation in abundance than populations living near the center of the range.[116] Thus, when a southern boundary retracts northward, populations with historically stable abundances may become more variable. Populations living at the northern edge of the range tend to exhibit lower growth rates and greater sensitivity to exploitation. Thus, when a northern boundary extends northward, populations near the old boundary may become less sensitive to exploitation and exhibit more stable abundance.

Many studies have forecast a potential northward expansion of the distribution of smallmouth bass, a typical warm-water species that is native to the southern part of the Great Lakes basin.[117] Recent work indicates that the consequences of that expansion could include local extirpation of many native minnows and negative impacts on native top predators, particularly lake trout, in newly invaded lakes.[118] These findings clearly demonstrate the ecological disruptions that will occur throughout the region as cold-water species disappear and warm- and cool-water species vie to take their place in a warmer world.

These disruptions are likely to be compounded by invasions of nonnative organisms, many of which are capable of totally restructuring existing food chains and causing significant consequences for native fish communities.[119] The zebra mussel and European carp invasions in the Great Lakes region are perhaps the best examples of such major disruptive events. Climate warming is likely to permit zebra mussels and common carp to expand their existing ranges northward in the Great Lakes region.

As noted earlier, higher summer surface water temperatures and increased summer anoxia in deeper waters may lead to greater release of mercury from sediments.[120] That would lead to higher mercury levels in fish, which would harm not only fish populations but human consumers as well.[50]

TABLE 6 **Changes Observed, Predicted, and Possible in the Ranges of Fish Species in the Lakes and Rivers of the Great Lakes Basin**

Distributional Changes	Impacts on Species
Extension at northern limit	Perch, smallmouth bass: Predicted 300-mile extension of existing boundary across Canada with 7°F increase in mean annual air temperature[a]
	Smallmouth bass, carp: Predicted 300-mile extension of existing boundary in Ontario with 9°F increase in mean annual air temperature[b]
	Minnows (8 species), sunfishes (7 species), suckers (3 species), topminnows (3 species): Predicted extension into Great Lakes basin possible with warming[c]
Retraction at southern limit	Whitefish, northern pike, walleye: Predicted retraction because of northward shift in sustainable yields expected to result from climate change[d]
	Lake trout and other cold-water species: Retraction predicted in small shield lakes at southern limit because lower O_2 levels will shrink deep-water refuges from predation in summer[e]
	Brook trout: Retraction predicted for streams at lower elevations throughout the southern edge of the range because of expected increases in groundwater temperatures[f]
Barrier release and range expansion	White perch: Observed invasion and spread through Great Lakes basin when 1940s warming of Hudson River and Erie barge canal waters effectively removed thermal barrier and permitted access[g]
	Striped bass: Predictions indicate that warming may permit this species to invade the Great Lakes basin and thus expand its range eastward[h]

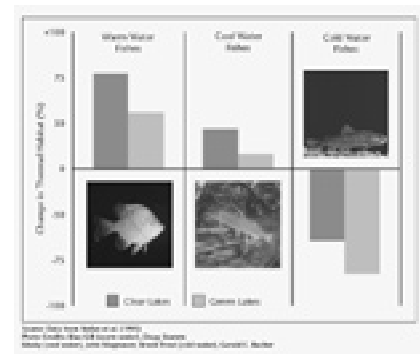
Sources: See note 121.

Changes in Fish Productivity

Within a lake, the productivity of a fish population is related to the amount of suitable living space, that is, the volume of thermally suitable water. Studies of walleye, lake trout, and whitefish have demonstrated that the abundance and productivity of fish increase with increased time spent at the optimal temperature.[122] There is also a trade-off between the positive effect of warmer temperatures on fish production and the negative effect of lower lake levels due to drying. For example, given a scenario where annual air temperature rises 5°F (3°C) and lake depth drops 3 feet, data from North American lakes suggest that fish production will decrease in lakes with a mean depth of 10 feet or less and increase in lakes with a mean depth greater than 10 feet.[123]

Production of several species of sport fish (lake trout, walleye, and pike) and commercially harvested fish (whitefish) in the region currently varies with the amount of thermally suitable habitat[122] (Figure 24). Predictions are that climate warming will greatly reduce the amount of thermally suitable habitat for lake trout in many inland lakes.[56] This would effectively eliminate lake trout from almost all shallow lakes in the region because of "summerkill," a lethal combination of high surface water temperatures and decreased oxygen in bottom waters. This forecast is consistent with earlier work that predicted cold-water fish living in large, cold lakes will be the most secure against the negative impacts of climate change.[124]

FIGURE 24
Water Temperature and Fish Distribution Changes



See page 46
for full-size color image of this figure

In contrast, other studies predict less winterkill of warm- and cool-water fish living in shallow inland lakes because shorter periods of ice cover would eliminate winter oxygen deficits.[56] Most northern lakes are likely to develop more suitable temperatures for walleye, a typical cool-water species in Ontario. However, a few southern lakes are likely to become less suitable, with summer temperatures reaching levels too warm for optimal growth.[26]

Economic Consequences of Climate and Ecological Change in Aquatic Systems

Water Levels, Shipping, and Hydropower Generation

Decreases in water levels have broad implications for both ecological and human systems in and around the large lakes. Ship clearance in channels and harbors is reduced, requiring ships to carry less weight in order to ride higher in the water. The Great Lakes Carriers Association estimates that with a one-inch drop in lake level, a 1,000-foot ship loses 270 tons of cargo capacity.[125] An earlier assessment based on milder projections of warming found that shipping costs could increase by 5 to 40 percent as a result of lower lake levels.[126] A potential counter to this negative impact is that reduced ice cover will lengthen the shipping season on the Great Lakes.

Stepped-up dredging of channels and harbors is often used to increase ship clearance in times of low water, incurring both direct economic costs and environmental costs. The direct costs of dredging could exceed $100 million (US) annually.[125] But dredging often stirs up buried pollutants, which may impose additional costs on society. The estimated costs for a four- to eight-foot drop in water level range from $138 million to $312 million (US), and the price for extending water supply pipes, docks, and stormwater out-falls to the new waterline would add another $132 million to $228 million (US).[125]

Decreased water levels could reduce hydropower generation by as much as 15 percent by 2050, an estimate that is likely to be conservative because it was based on older climate models.[126] Hydropower accounts for almost 25 percent of the electricity generated in Ontario,[16] while in the United States, significant hydropower is generated at the Moses Niagara Plant in New York State (Figure 25). Demand for more hydropower will be created in the future by the need

TABLE 7 **Climate Change Impacts on Fish Ecology and Consequences for Fisheries**

Climate Change Impacts on Fish Ecology	Consequences for Fisheries
Change in overall fish production in a particular aquatic ecosystem	Change in sustainable harvests for all fish populations in the ecosystem
Change in relative productivity of individual fish populations in a particular aquatic ecosystem	Change in the relative levels of exploitation that can be sustainably directed against the fish populations of the ecosystem
Large-scale shifts in geographic distribution of species	Change in mixture of species that can be sustainably harvested within a specific geographic area Change in location of profitable fishing grounds
Small-scale shifts in the spatial distribution of members of a specific population	Change in sustainable harvest for the population Change in efficiency of fishing gear, leading to change in sustainable levels of fishing effort

to reduce CO_2 emissions from fossil fuel-fired power plants. As hydropower opportunities decline in the Great Lakes region, pressure may increase to build such projects elsewhere, such as in the James Bay region.

Water withdrawals from the Great Lakes are already subject to contentious debate, and political leaders in the region have opposed further withdrawals, especially for water to be shipped out of the basin. Given projections for drier summers in the region, pressure to increase water extraction for irrigation, drinking, and other uses will grow even within the basin. One study found that the synergistic effects of predicted decreases in runoff and increases in irrigation could be devastating to the region's streams.[127]

FIGURE 25
Water Changes Affect Hydropower

See page 47
for full-size color image of this figure

Fisheries

Climate-driven changes in fish populations and communities will produce a variety of impacts on existing fisheries (Table 7). Most of these impacts will stem from two mechanisms: (1) the sustainable harvest of fish will rise and fall with shifts in overall aquatic productivity, and (2) sustainable harvests from a specific population in a specific location may increase substantially or fall to zero, depending on how new climate conditions and species-specific temperature needs interact.

The commercial fishing sector in the region is relatively small. Landed catches in the late 1990s were valued at about $47 million (US), including $33 million taken by Canadian fishers and $14 million taken by US fishers. Most of the commercial catch in Canada comes from Lake Erie and that in the United States from Lake Michigan.

In contrast, the recreational fishing sector is quite large in both countries. In the 1990s, 7.7 million recreational anglers spent $7.6 billion (US) on fishing in US waters[13] and 2 million anglers spent $3 billion (Cdn) on fishing in Canadian waters.[128] These anglers spent about 9 million fishing days on the Great Lakes alone, not counting fishing on inland lakes, rivers, and streams. Large changes in the distribution and productivity of fish species in the region will significantly impact the nearly 10 million anglers that actively fish these waters.

These dollar figures do not reflect the full value of ceremonial and artisanal fisheries practiced by Native Americans and First Nations in many settlements scattered throughout the Great Lakes basin. Fishing plays an important role in the traditional social structures of these communities, a role that defies easy quantification and will not be reflected in cost accountings of impacts that are based purely on market measures.

CHAPTER
Four

Ecological Vulnerability to Climate Change: Terrestrial Ecosystems

Forested Landscapes

The distribution of forest types in the Great Lakes region is controlled by a pattern of increasing rainfall as one moves from west to east, and colder temperature as one moves south to north. These climatic gradients gave rise to forests dominated by oaks and hickories in the southern Great Lakes region, northern hardwood forests composed of sugar maple, American beech, and American basswood farther north, and boreal forests dominated by white spruce and balsam fir in the northernmost portion of the region (Figure 26). In the drier western part of the region, closed canopy forests give way to scattered savannas consisting of bur oak and mixed prairie grasses.

Human land-use decisions have reshaped much of what climate, soils, and geology wrought. On drought-prone soils, frequent wildfires once maintained coniferous forests composed of white and red pine in the northern portion of the region. These were largely eliminated by intensive timber harvests during the late 1800s. In the southern Great Lakes region, large areas of fertile soils once in forest cover have been in agricultural production for almost 150 years. Major areas still dominated by forests lie mostly in the northern parts of Michigan, Minnesota, and Wisconsin and in Ontario, where climatic and soil conditions are less favorable for agriculture. Forests currently occupy 36 percent of the total land area in the US Great Lakes states and 63 percent of the land area in Ontario.[129]

Distribution and Productivity

Tree species have been migrating across the region in response to climate change since the end of the last ice age some 10,000 years ago.[130] The pace of climate change will accelerate over the next century, however, and the ability of forest trees to migrate in response will depend not only on their own traits (such as whether their seeds are dispersed on the wind or by animals) and natural geographic barriers (such as the Great Lakes), but also on human land-use decisions. Geographic variation in soil moisture and texture will also put strong constraints on the movement of plant species and the composition of future forests in any given location.

Warmer temperatures and a longer growing season are likely to result in the northward movement of many forest

FIGURE 26
The Northern Forests

See page 48
for full-size color image of this figure

species and a general decline in the extent of boreal forests in the region.[131] Northern conifers such as white pine and hemlock are likely to be restricted to isolated populations or lost completely from southern Illinois, Indiana, and Ohio.[132] Tree and prairie grass species in the western part of the region are likely to move eastward, especially if warmer temperatures result in more frequent drying out of soils or even droughts in their current range.[133]

Prior to widespread fire-suppression efforts during the twentieth century, fire was an important agent shaping the composition and distribution of forests in the region.[134] Fires swept through the northern forests every 10 to 50 years, maintaining nearly 75 percent of the land area as young, recently burned forest stands. Surface fires that consumed dead leaves and twigs lying on the ground were common in hardwood forests growing on moist soils, whereas severe canopy-consuming fire often destroyed red and jack pine forest on dry, sandy soil.[135] Fire history studies have shown that over the past 750 years, fire was more frequent during periods of warm temperatures and low precipitation,[136] which suggests forest fire frequency is likely to increase as the climate turns warmer and summers become drier. In fact, as a result of the projected higher temperatures and lower summer precipitation, models suggest decreased soil moisture during summer and autumn,* which would not only increase the fire risk but also limit forest growth in drier areas for more weeks per summer. In wetter areas, forest growth is rarely water limited. The response to changing soil moisture will also interact with changes in fire frequency, since forests in drier areas are more fire-prone.

Forest growth could potentially get a boost from the rise in atmospheric CO_2.

Forest growth could potentially get a boost from the rise in atmospheric CO_2 that is helping to drive climate change. CO_2 acts as a plant fertilizer, and native trees grown experimentally in elevated CO_2 have shown increased growth. Trembling aspen, an ecologically and economically important tree in the region, could increase its growth 16 to 32 percent as CO_2 levels rise. Aspen forests on fertile soil will experience greater growth enhancement than those on nutrient-poor soil.[137] Elevated CO_2 could also accelerate the pace of forest succession, speeding up the rate at which "pioneer species" such as aspen (which colonize sites following disturbances such as timber harvesting or fire) give way to species such as maple that establish in the shade of the pioneering trees. Maple trees grown under elevated CO_2 become more tolerant of shade and increase their growth rate. Faster forest development could shorten the harvest rotation for aspen managed for fiber production in the northern parts of the region.

Another factor that could boost forest growth and productivity is the availability of nitrogen, a key plant nutrient. Human activities, including the fossil fuel burning that is helping to drive climate change, have almost doubled the amount of nitrogen entering forests via rain, snow, and dry airborne particles. Much of the excess nitrogen falling on forests is deposited as nitrate, which is rapidly taken up by soil microorganisms and eventually made available to fertilize plant growth.[138] In this way, forests function as "living filters," preventing nitrate from leaching into groundwater, streams, and lakes where it becomes a pollutant. This filtering capacity may be exceeded in the long term, but in the short term, extra nitrogen from the atmosphere could enhance the ability of forest trees to grow faster in response to rising atmospheric CO_2.

Ozone, however, may counter the growth-enhancing potential of both CO_2 and nitrogen. Ground-level concentrations of ozone are increasing, especially downwind of major urban areas in the region. Elevated ozone concentrations can damage tree leaves, damping growth and rendering trees more vulnerable to insect pests and diseases. Susceptibility to ozone damage varies among tree species and also among different individuals within a species.[139] Experiments that exposed young aspen, paper birch, and sugar maple to both CO_2 and ozone indicate that relatively small increases in ozone can eliminate the growth-enhancing effects of elevated CO_2.

No one can yet predict exactly how changes in temperature, moisture, fire, CO_2, nitrogen, and ozone will interact over the coming decades to alter the

* For additional climate modeling results and other technical information, see www.ucsusa.org/greatlakes.

growth and distribution of forests. The uncertainty stems in part from the centuries-long lifespan of forest trees. Even multiyear experiments subjecting saplings to enhanced levels of CO_2 cannot determine, for example, whether the faster growth means trees will actually grow larger or will simply reach the same size faster than trees growing at current CO_2 levels. And no studies have attempted to look at all the interacting human and environmental factors that will shape the fate of future forests in the Great Lakes region.

Impacts on Forest Insects

Insects have the potential to shift both the magnitude and direction of plant responses to climate change. Through their roles as herbivores, pollinators, and decomposers, insects influence primary production, community composition, nutrient cycling, and successional processes in the forests. The fate of any particular insect species in a changed climate is difficult to predict, yet some general trends can be foreseen.

The northern limit of some devastating forest pests such as the gypsy moth is currently determined by cold winter temperatures, and these insects will almost certainly become more widely established throughout the region in a warmer climate (Figure 27).[140] Insect ranges may also shift as their host trees migrate in response to climate. For example, the range of the eastern tiger swallowtail is likely to expand northward, coincident with expansion of the range of its preferred host, the tulip tree. Simultaneously, the range of the Canadian tiger swallowtail will retract northward, as its preferred host, aspen, disappears from the southern Great Lakes region (Figure 28).

Climatic changes that alter the synchrony between key insects, desirable and undesirable, and their host plants could markedly affect forest ecosystems. Several of the most damaging pests in the region such as the forest tent caterpillar, gypsy moth, and spruce budworm are spring-feeding insects whose emergence is closely synchronized with the bud-break of their hosts. Although both insect emergence and bud-break are controlled by temperature, it is unclear whether climate warming will alter both processes at the same rate. Asynchrony by as little as a week could markedly alter insect fitness and the potential for outbreaks. The activity of insect predators and parasitoids that prey on insect pests is also controlled by temperature, and how warmer climates will alter their effectiveness as natural enemies is virtually unknown. Pollination services are another critical insect-plant interaction that could be disrupted if climate change decouples the timing of flowering and pollinator activity.

In addition to climate changes, both elevated atmospheric CO_2 and elevated ozone are likely to affect insects via changes in host quality. The leaves of plants grown under enriched CO_2 typically are reduced in food value, that is, lower in protein and higher in unpalatable compounds such as tannins.[141] Leaf-chewing insects fed this material generally eat more to compensate for low protein levels. They also experience slower development and reduced growth efficiency.[142] Whether this phenomenon will result in greater defoliation of forests is unknown because, although individual insects may eat more, overall insect population densities might decline. Elevated ozone concentrations in the lower atmosphere can also change plant chemistry. In trembling aspen, ozone exposure compromises production of the major chemical defense compounds, leading to improved performance by forest tent caterpillars.[143]

FIGURE 27
Forest Pests in a Changing Climate

See page 47
for full-size color image of this figure

FIGURE 28
Range Shifts of the Canadian Tiger Swallowtail

See page 48
for full-size color image of this figure

Despite numerous uncertainties, it is clear that coming changes will not affect all plants, insects, and their natural enemies uniformly. The fitness of some will improve, while that of others will deteriorate. Shifts in insect population and community dynamics will feed back to affect how forests of the region function as responders to, and modulators of, climate change.

Impacts on Wildlife

One important ecological implication of forest change is the possible degradation of migratory corridors for animals. A wide gap of largely agricultural lands exists between the extensive tropical forests of Central and South America and forests in the northern Great Lakes where many migratory songbirds such as scarlet tanagers, warblers, thrushes, flycatchers, and vireos breed. This gap is actually wider than the portion of the Gulf of Mexico that many of these tropical migrants must cross. The networks of wooded streams, woodlots, and even urban forests that dot the agricultural portions of this gap are critical stopover and refueling sites for the migrants.[144] Climate-driven shifts in the timing of tree leaf-out, seed production, and insect emergence, however, may throw these wooded remnants out of sync with the birds' arrival.[145]

Fragmentation and the disruption caused by climate change will increase the opportunities for exotic species to invade forests, further stressing native species.

Currently, for instance, migrating songbirds gather in oak trees in large numbers during spring migration to consume caterpillars that attack the oaks during leaf-out, a situation mutually beneficial to the trees and the birds.[146] But leaf-out of trees and hatching of caterpillar eggs is closely tied to temperature and is expected to occur earlier as the climate warms.[147] Because many birds migrate in response to day length rather than temperature, some songbirds may arrive from the tropics well after the spring flush of insects that accompanies leaf-out.[148] The same phenomenon may apply to the flush of spring insects coming out of wetlands that are vital to many migratory songbirds. Unlike migrants, however, some year-round resident birds may benefit from warming, a phenomenon that could further stress migratory birds (see box, p.30).

FIGURE 29
Virginia Possum's Range Expanding North

See page 48 for full-size color image of this figure

Popular gamebirds such as ruffed grouse, which are most abundant in aspen forests, might be especially likely to shift their ranges to the north. Indeed, the failure of efforts to reintroduce ruffed grouse to parts of their historical range in Illinois might be partly a result of changing forest conditions caused by climate change as well as human land use.

Climate warming may also benefit some resident mammals such as white-tailed deer, which are already experiencing record high populations in the region and are severely altering forest growth with their browsing. Reduced winter mortality during milder winters might exacerbate this damage to forests. Moose, which are already near their southern geographic limit in the region, could be negatively impacted both by warming and by the increasing density of deer.[149] Deer carry three parasites—brainworm, liver fluke, and winter tick—that severely stress moose.

Reduced winter mortality of omnivorous mammals such as raccoons, possums, and skunks could increase their overall abundance, potentially increasing predation on ground-nesting songbirds and other vulnerable prey (Figure 29).

The benefits of warming for some resident mammals and birds could be countered by potential changes in the dynamics of wildlife diseases or increased winter survival of pathogens and insect vectors. Such effects would be most pronounced in northern species that have not been exposed to or evolved defenses against diseases from warmer latitudes.

Climate change will also interact with forest fragmentation, particularly in heavily agricultural areas, to create greater stress on many breeding birds and some reptiles and amphibians. The impact will be most severe on relatively immobile species, restricting their ability to move northward to colonize newly suitable patches or escape newly inhospitable climates. On the other hand, some predators that already thrive in fragmented habitats will benefit from warming. Rat snakes, for example, are more active in warmer temperatures in fragmented habitats where they are exposed directly to sunlight on the forest edge.[150] Some of these predators will also move north, increasing the stresses on nesting birds. Snakes are dominant nest predators south of the Corn Belt, but are actually an endangered species in Canada where they depend heavily upon edge habitats.

Fragmentation and the disruption caused by climate change will also increase the opportunities for non-native species to invade forests, putting further pressures on native species.

Agricultural Landscapes

The six Great Lakes states contain 100 million acres of farmland and send more than $40 billion (US) in products to market. Agricultural production from 14 million acres of farmland in Ontario is valued at $10 billion (Cdn). In general, livestock is more important in the northern areas (Minnesota, Wisconsin, western Ontario) while row crops dominate the southern areas. All of the Great Lakes states rank in the top 20 for the value of dairy products and crops sold nationally (Figure 30). The region also ranks high in production of horticultural crops and fresh market products, from vegetables to fruit.[151]

Crop production in the region is primarily rainfed, and weather is the most important uncontrolled factor influencing crop production. Production can be harmed by heat stress, pests, ozone, extreme weather events such as rains that delay planting or harvest, and below-normal precipitation, especially during critical stages of plant growth (see Figure 15, p.19).[152] Historical influences of weather on yields are difficult to separate from the influences of technological and cultural improvements, which have dramatically increased yields over the past century[153] but have also led to a transformation and in some cases impoverishment of the Great Lakes regional landscape.

Climate Impacts on Crops

Most predictions from large-scale simulations suggest that while climate change is likely to shift crop production patterns, the region's agricultural capacity is unlikely to be seriously disrupted over the next century.[154] Indeed, yield increases of 15 to 20 percent for many crops have been projected based on earlier climate models projecting less warming, although these studies concluded that tropical or warm-season crops such as corn may increase less than soybeans and wheat. Another recent analysis suggests that soybean biomass could increase by 40 percent and soybean yield by 24 percent.[155] Such predictions remain highly uncertain, however, because the strength and even direction of crop responses can shift with different climate change scenarios.[156] Unless temperatures actually warm beyond crop growth thresholds, factors other than climate change will have as great or greater influence on trends in agriculture. These factors include regional population growth, access to resources including emerging technology, and market fluctuations.[157]

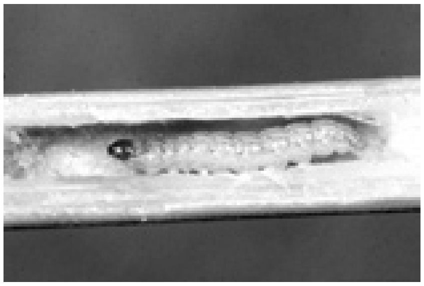
FIGURE 30
Mixed Impacts for Agriculture

See page 49
for full-size color image of this figure

Producers may take no comfort in predictions for "average" responses of crop yields to various climate change factors. Averages mask site-to-site and increasing year-to-year variability in yield, which at the farm level translates to higher risk. One study of impacts of climate variability on farm-level risk of crop failure in Illinois and Wisconsin found, not surprisingly, that risk exposure was greater for smaller farms and varied regionally and among crops.[158] Such impacts on variability and risk are likely to reinforce the trend toward increasing farm size and industrialization of agriculture in the region.

Models run at smaller scales consistently show that the effects of changing climate will vary across the Great Lakes region. Optimal weather conditions will shift northward and eastward, typically bringing the greatest benefits to Michigan, Minnesota, Wisconsin, and eastern Ontario.[159] Shifts in the distribution of agriculture may be constrained in northern areas by thin and acidic soils[160] (see Figure 2, p.8). If more intensive production moves upward from the southern edge of the Great Lakes region onto shallower,

FIGURE 31
Climate Change and Agricultural Pests



See page 49
for full-size color image of this figure

coarser textured soils in the northern areas, chemicals and nutrients used to increase soil fertility may increasingly run off into aquatic systems. Agriculture is currently a chief source for chemical contamination of ground and surface waters, but there has been little investigation of how redistribution of agriculture in a changing climate may interact with this problem.

One recent study projected increases in production thanks to a longer growing season and warmer temperatures,[161] but that study relied on a model that predicts precipitation trends that are much more favorable for crop production than this report assumes. Yield trends are likely to fall short of those predictions if summer rainfall decreases, as suggested by the climate scenarios used in this report (see Figures 12 and 13, p.18). These scenarios project wetter periods occurring during times that could delay harvest or planting, and dry spells during times when crops demand water. As models improve and include factors such as extreme weather events or the influence of pests, they are likely to produce less favorable outcomes for agriculture than have been predicted to date.

The complexity of agricultural responses to climate change is highlighted by an integrated assessment that focused on five upper Midwest states: Illinois, Indiana, Michigan, Ohio, and Wisconsin.[162] Trends in southern areas of Ontario would be expected to resemble those projected for Michigan. The assessment predicted mean increases in corn yield of 5 percent, but the range of both increases in some northern areas (+0.1 to +45 percent) and decreases in southern areas (0 to –40 percent) was large. The largest corn-yield decreases were projected for western Illinois.[163] In addition, the assessment predicted that CO_2 fertilization and earlier planting dates could increase soybean yield up to 120 percent above current levels in the central and northern portions of the region. In the southern areas, comparatively small yield increases (0.1 to 20 percent) or small decreases (–0.1 to –25 percent) were predicted. Wheat yields may also increase approximately 20 percent as a result of CO_2 fertilization; however, increases resulting from earlier planting dates might be limited because they overlap the growing season of a previous crop.

CO_2 fertilization may also influence crop yield in indirect ways. Initial results from a large-scale experiment that began in Champaign, Illinois, in 2001 showed, as expected, that elevated CO_2 enhanced soybean yields. The results also indicated that elevated CO_2 increased the water use efficiency of the soybean plants, a response that has the potential to reduce crop water requirements and reduce the flux of water into the atmosphere.

Ozone concentrations can counter positive trends in crop yields just as in forest productivity. In addition to urban sources of ozone in the region, agricultural application of fertilizers can cause local peaks in ozone levels, and warmer temperatures can also increase ozone formation. Already, regional ozone concentrations frequently reach levels that damage crops,[164] and ozone exposure is credited with causing, alone or in combination with other pollutants, about 90 percent of the air pollution–based crop losses.[165] Ozone damage is expected to cause localized areas of losses in soybean yields of 11 to 20 percent in the Mississippi and Ohio valleys.[166] Similar losses are projected for horticultural crops, which are at least as sensitive to ozone damage as soybeans.

> After factoring in extreme weather events or the influence of pests, the picture for agriculture is less favorable than previous predictions suggested.

Impacts on Agricultural Pests

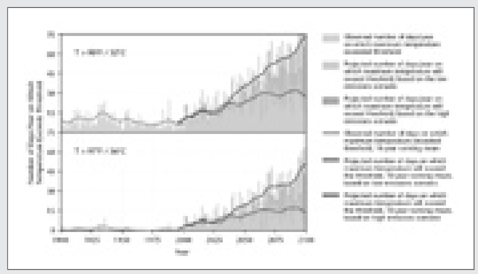
Warming temperatures may influence pest and disease incidence in several ways. First, warmer and shorter winters will allow more southerly pests such as corn earworms and fall armyworms to expand their range northward. Indeed, such a shift already appears to be happening with bean leaf beetles, which

Extreme Events, Public Health, and the Human Environment

Extreme events such as heavy downpours, floods, heat waves, droughts, tornadoes, and snowstorms are expected to play a growing role in a warmer world. This will put increasing burdens on emergency management, public works, and health care services and exact a growing financial toll from governments, businesses, and homeowners. Illinois has experienced a stark preview of this future scenario during the past 15 years with a severe drought in 1988, Mississippi River flooding in 1993, a 1995 heat wave, a severe rainstorm in Chicago in 1996, a 1996 heat wave, a 1999 windstorm in Bloomington, another Mississippi River flood in 2002, and numerous tornadoes and severe storms.[40]

The disruptions and losses society faces were dramatically demonstrated during the record-breaking 24-hour rainstorm that occurred on July 17–18, 1996, in south Chicago. Chicago and 21 suburbs experienced flash flooding that broke regional records and killed six people, damaged 35,000 homes, and caused evacuation of more than 4,300 people. Losses and recovery costs reached $645 million (US), making that single storm Illinois' second most costly weather disaster on record after the 1993 Mississippi River flood. In adjacent rural areas, flood damage to crops cost farmers $67 million (US).[167]

FIGURE 32A
Temperature Extremes in the Great Lakes Region



See page 50
for full-size color image of this figure

Other changes that will impact human health and environmental quality are expected to include the following:

An increase in extreme heat and heat waves

The number of hot days is projected to increase in the Great Lakes region through 2100 (Figure 32a), with many years experiencing 40 or more days exceeding 90°F (32°C) by the last few decades of the century. Of greater concern for human health is the projected increase in days reaching 104°F (40°C) or more. In the upper Great Lakes, the impacts are likely to be greatest in urban areas, especially in cities such as such as Toronto or Minneapolis/St. Paul where extremely high temperatures have historically been rare. A recent health impacts study for the Toronto-Niagara region found that the current number of days with maximum temperatures above 86°F (30°C) could double by the 2030s and surpass 50 days by the 2080s. The annual heat-related death rate of 19 per year in Toronto alone could increase 10- to 40-fold, depending on the climate scenarios used.[168] On the other hand, cold-related health risks are likely to decline over time if the frequency of extreme cold weather periods during winters decreases.

A potential boost to air pollution

Higher temperatures may enhance the formation of ozone and also increase demand for electricity for summer air-conditioning, thereby boosting emissions of air pollutants that can exacerbate respiratory disease. Studies using older climate models indicate that weather conditions conducive to high ozone are likely to occur more often by the end of the century.[169] Indeed, the number of hot days conducive to high ozone might increase by 5 to 100 times present levels for Detroit. Newer climate models predict even higher temperatures and thus greater exacerbation of air pollution.

Water quality changes

Climate-related risks to the region's water supply include potential increases in nitrate pollution, nuisance algal blooms, pesticide residues and other toxins stored in lake and river sediments, and the spread of parasitic and pathogenic microorganisms. For example, some waterborne infectious diseases such as *cryptosporidiosis* or giardiasis may become more frequent or widespread if extreme rainstorms occur more often.[170] One of the best known examples of a *cryptosporidium* outbreak occurred in Milwaukee in 1993 after an extended period of rainfall and runoff overwhelmed the city's drinking water purification system and caused 403,000 cases of intestinal illness and 54 deaths.[171] Milwaukee's drinking water originates in Lake Michigan.

FIGURE 32B
Concerns About Insectborne Infectious Diseases

See page 50
for full-size color image of this figure

Potential changes in vectorborne infectious disease risks

The occurrence of many infectious diseases is strongly seasonal, suggesting that climate plays a role in influencing transmission.[172] St. Louis encephalitis outbreaks in the Great Lakes region, for example, have been associated with extended periods of temperatures above 85°F (29°C) and little rainfall.[173] Some vectorborne diseases such as Lyme disease or, more recently, West Nile encephalitis have expanded widely across the region. While this spread is attributed largely to land use changes, future changes in rainfall or temperatures could encourage greater reproduction or survival of the disease vectors, which are ticks and mosquitoes, respectively (Figure 32b).[172]

not only feed on soybeans but also serve as vectors for a virus that causes disease in soybeans. Second, warming will increase the rate of insect development and the number of generations that can be completed each year, contributing to a build-up of pest populations. Extended growing seasons are likely to allow the northward expansion of some pests with multiple generations per year, such as a race of European corn borer now limited to southern Wisconsin and further south (Figure 31, p.62). Increased pests may also drive farmers to use more pesticides or related chemicals, placing an additional burden on water quality.

The decline in the food value of plant leaves under increasing CO_2 will also interact in complex ways with a warming climate to affect both plants and insects. For example, one study found that warming accelerated insect development to such an extent that the larvae could not feed long enough to compensate for the poorer quality of the foliage.[174]

Impacts on Livestock

Climate change will affect livestock production indirectly through influences on forage quantity and quality, and directly through influences on animal physiology or facility requirements. Direct impacts include warmer summer temperatures that suppress appetite and decrease weight gain in animals. For example, a 9°F (5°C) increase in temperature is projected to reduce animal productivity by 10 percent for beef and dairy operations in the southern parts of the United States,[175] although other studies predict only 1 percent losses.[176] Higher temperatures are likely to reduce stocking rates on pastures[177] and can reduce milk quality by reducing forage quality and stressing animals. Any extreme weather events such as heat waves, droughts, and blizzards have severe effects on livestock health, although intensively managed livestock operations are better able to buffer the effects of extreme events.

Negative impacts on forage and grassland productivity and forage quality can result from summer drought stress or extreme winter weather. One study predicts that warmer fall temperatures will reduce fall hardening of forage crops, rendering them less hardy during the winter.[178] Additionally, there will be less protection by snow cover.

FIGURE 33
Climate Change Impacts on the Timber Industry

See page 49
for full-size color image of this figure

Economic Consequences of Climate and Ecological Changes in Terrestrial Systems

Forests and Wildlife

Commercial forestry is a substantial industry in northern parts of the region, and significant forest products industries exist in Ontario and all Great Lakes states except Illinois (Figure 33).[4] Climate warming will drive changes in forest extent and in the types of trees found in various parts of the region. During the transition, however, while trees ill-suited to new climate conditions persist and better-suited species are taking hold, forest productivity and forest industries may suffer.

Changes in the types of trees in the forest may also be jarring to many residents' sense of place. Shifts from boreal fir to hardwood forests in the northern Great Lakes region could occur in the lifetime of current residents, fundamentally changing the character of these locations. While a "sense of place" is felt strongly by many people, it is hard to assign it a dollar value equivalent to dollar values for changes in harvestable timber.

Changes in forest composition and extent will also affect wildlife and the recreational industry that has grown up around harvesting or watching wildlife. Approximately 13 million adults in the Great Lakes states participate in bird watching or other wildlife viewing, and another 3.3 million hunt.[13] Declines in bird species would have direct economic consequences in terms of hunting or bird watching as well as indirect consequences through loss of the birds' services in controlling insects and other pests. The loss of goose hunting from southern Illinois, where more than a million geese once wintered, has seriously affected the economy of one of the poorest regions of that state.

Agriculture

Whether climate change will be economically advantageous or harmful for Great Lakes farmers remains uncertain. Hotter, drier summer conditions with more frequent droughts, as predicted in this report, could disrupt production, although increased CO_2 fertilization could boost yields of some crops. The fate of agricultural production will also depend upon how climate change affects the variability and predictability of weather patterns. Extreme events such as severe storms, late spring or early fall frosts, and drought all depress productivity.

Apart from extreme events, crop farmers can adapt to moderate changes in temperature or precipitation if such changes can be predicted. Knowing that conditions will be warmer and drier, or warmer and wetter, will allow farmers to plant crop varieties better suited to such conditions. If there is greater uncertainty, however, farmers will not be able to choose the right varieties for conditions that actually occur, leading to a much greater risk of loss. Thus the impacts of climate change on annual crops in the Great Lakes region appear to depend more on predictability and variability of weather patterns than the change in overall averages.[179] Greater climate variability is more problematic for perennial crops such as fruit trees and vineyards where adjustments cannot be made as frequently and long-term investments are at risk.

FIGURE 34
Impacts on Summer Recreation

See page 50
for full-size color image of this figure

Climate changes may also affect production costs. If drier summer conditions and increased drought prevail, investments in irrigation may become necessary. Such a shift would impose costs directly on farmers and increase tensions over water allocations. Without irrigation, however, agricultural productivity can drop sharply during drought. For example, a 1988 drought reduced US corn production by 45 percent.[126]

Increased soil erosion and runoff of agricultural wastes are likely if the frequency of flooding increases.[180] Greater erosion would increase off-site costs of sediments, which are already estimated at $98 million (US) for the lake states of Michigan, Minnesota, and Wisconsin and $216 million (US) for the Corn Belt states of Illinois, Indiana, Iowa, Missouri, and Ohio.[181]

Whatever the overall outcome, certain groups may gain at the expense of others. For example, if climate change tends to increase production, resulting price declines may help consumers but hurt producers. Regional producers will do better if climate change lowers productivity elsewhere, resulting in lower supply and higher prices, but does little to change their own productivity. In an era of expanding global trade, however, prices to farmers and costs to consumers in the Great Lakes region may be influenced more by how drought or rain is playing out in crop fields half a world away than by harvests at home.

Recreation and Tourism

Travel and tourism brought in $65 billion (US) in revenue in the Great Lakes states in 1999[10] and $20 billion (Cdn) in Ontario in 2000.[14] The most certain impacts of climate change will be on winter sports activities. Warm winter temperatures and little snow mean red ink for ski areas, or at least increased costs for snowmaking. Communities and businesses dependent on revenues from cross-country or downhill skiing, snowmobiling, or especially ice fishing, could be hard hit. Some of these communities and businesses, however, will make up the loss by expanding warm weather tourism and recreation (Figure 34).

CHAPTER
Five

Meeting the Challenges of Climate Change

This report has highlighted a variety of challenges the Great Lakes region will face as climate change magnifies the pressures imposed by a growing human population on the region's environment and natural resources. Many of the impacts explored here are not inevitable. The negative consequences of change can in some cases be minimized or avoided. This chapter examines actions that people and policymakers can take now to reduce the vulnerability of ecosystems and vital ecological services and to safeguard the economy and well-being of the human population of the region.

Three overlapping approaches are needed to meet the challenges posed by a changing climate. The first is to reduce the region's contribution to the global problem of heat-trapping greenhouse gas emissions. Some warming is already inevitable because historical emissions of CO_2 will continue to have a warming effect for decades; nevertheless, many of the most extreme outcomes for the region can be avoided if the pace and eventual severity of climate change are damped. Many scientists agree that ultimately worldwide emissions of heat-trapping gases need to be reduced significantly in order to avoid dangerous changes in the climate system. The sooner these reductions are begun, the lower the cost of making necessary changes and dealing with potentially disruptive economic and social impacts.

Second, minimizing human pressures on the global and local environment now will lessen the severity of future impacts and reduce the vulnerability of ecosystems to further stresses from climate. Finally, anticipating and planning for the impacts of change through both short-term adjustments and long-term adaptations will help to reduce future damage. The cost of these adjustments and adaptations serve as an additional incentive to slow climate change by reducing the emissions of heat-trapping gases as soon as possible.

Although there is uncertainty in predictions of specific climate change impacts on the region, we have much greater confidence in the general predictions for change (see box, p.68). Even where uncertainty remains, taking actions now to reduce emissions and minimize threats to ecosystems is the prudent and responsible course. Waiting to begin reducing emissions or to plan for managing the effects of climate change only increases the eventual expense and urgency and the possibility of irreversible losses. Furthermore, many actions that can be taken now provide immediate collateral benefits such as cost savings, cleaner air and water, or improved quality of life in our communities.

Reducing Emissions by Sector

Reducing emissions of greenhouse gases, and thus the rate and eventual severity of climate change, could forestall many of the worst outcomes. Some emission reduction measures can be implemented with no net cost. Others involve net costs but will also stimulate new technological development, economic growth, jobs, and opportunities.

None of the Great Lakes states currently has mandatory greenhouse gas registries (although Wisconsin is developing one), but Ontario and all the states except Michigan have inventories of their greenhouse gas emissions for 1990 (Table 8, p.70). Overall

How Confident Can We Be About Climate Change Impacts on Great Lakes Ecosystems?

The climate change assumptions that underlie the assignment of confidence levels* include:

- an increase in air temperature of 5 to 12°F (3 to 7°C) in winter and 5 to 20°F (3 to 11°C) in summer (high confidence).
- a concurrent increase in surface water temperatures and reductions in ice cover on all lakes (high confidence).
- precipitation increases in winter and spring, but declines in summer and autumn, producing most notably a general drying in the southwest part of the region. In response, levels of surface water, ground water, and soil moisture are expected to drop in summer (medium confidence).
- a continued increase in extreme rain events lasting from 24 hours to 7 days that could cause increased flooding (medium confidence).

The projected impacts are viewed against the backdrop of continued increases in population, urbanization, and landscape fragmentation across the region. For example, urbanization will increase the area of pavement and other impervious surfaces in watersheds, which in combination with increased likelihood of extreme downpours will result in more flooding.

Confidence Levels*

Potential Impacts on Great Lakes Ecosystems	High Confidence	Medium Confidence	Lower Confidence
Across All Systems	Significant alterations in the climate that we feel as temperature and precipitation changes Longer growing seasons Altered productivity and distribution of a variety of organisms	Decrease in ecosystem services due to greater variability in all climate and ecological drivers Earlier flowering, breeding, and emergence of biota that use temperature rather than day length as a cue	

Potential Impacts	High Confidence	Medium Confidence	Lower Confidence
Aquatic Ecosystems	Increased water temperatures in the Great Lakes, inland lakes, streams, and wetlands Decreases in ice-cover duration and extent Shifts to earlier ice-out dates and spring melt Altered timing of hydrologic flows; increased variability in timing, frequency, and duration of disturbances Altered distributions of current fish species and other aquatic organisms; increased invasions by nonnative species	Decreased water levels in all aquatic habitats, especially in summer Increased flooding from climate interactions with urbanization and land management practices Decreased safe breeding sites for amphibians, migratory shorebirds, and waterfowl Altered timing and extent of migration for waterfowl	Increased ultraviolet radiation damage to organisms in shallow-water habitats
Terrestrial Ecosystems	Altered plant distribution, including northern movement of forest species Range shifts in insects, including expansions of forest and agricultural pest species (e.g., gypsy moths and bean leaf beetles) Impacts on crop and livestock sectors (+ or –) will be moderated by technological advances and trends in market sectors	Short-term increases in forest growth from CO_2 fertilization and nitrogen deposition; long-term growth responses are unclear Lowered food availability to migrant birds, especially those that time their migration by daylength rather than weather Crop yields in the region vary from positive in northern to negative in southern areas because of temperature and precipitation changes	Increased vulnerability of crop yields to weather extremes as production shifts northward, away from prime production areas
Human Impacts	Shorter, warmer winters will result in losses in winter recreation such as skiing, ice fishing, and snowmobiling; possibly longer season for warm-weather recreation	Increased health risks from respiratory disease, heat-related morbidity or mortality, extreme weather events, and infectious disease Decreased health risks from cold-related morbidity or mortality	

* "Confidence" refers to the level of scientific certainty and is based on expert understanding and judgment of current information supporting the likely ecological impacts of the climate-related changes described above. Confidence is not related to the degree of ecosystem vulnerability or the relative economic or social importance of a potential impact. A "lower" confidence level does not imply that the change is unlikely or that the impact will be small.

TABLE 8 **Total Greenhouse Gas Emissions by State/Province and Sector (1990)**

Total GHG (in Million Metric Tons of Carbon Equivalent—MMTCE) for 1990 State/Province[a]

SECTOR	IL	IN	MN	NY	OH	PA	WI	ONT
Energy - Residential	6.9	2.6	2.1	8.5	5.6	6.2	2.6	4.9[b]
Energy - Commercial	3.4	1.4	1.4	6.5	2.8	3.0	1.3	2.5
Energy - Industrial	14.7	15.2	2.3	4.5	15.7	16.8	3.3	11.4
Energy - Transport	15.8	11.2	7.2	22.5	15.2	15.4	6.6	13.1
Energy - Utility	15.7	25.6	7.9	19.1	31.4	24.2	8.9	7.1
Energy - Exported Electricity	*	*	*	*	*	*	*	*
Energy - Other	-2.31	1.0	0.5	1.2	6.3	*	0.8	*
Total Energy	56.6	57.0	21.3	62.3	76.9	68.3	23.4	39
Waste	6.9	1.7	1.2	11.6	11.3	3.6	0.9	2
Agriculture	2.3	1.8	2.5	0.9	1.7	3.3	2.5	3.3
Industry	0.3	1.0	*	0.9	0.6	0.7	0.1	4.1
Land Use	0.02	-0.4	-2.4	*	-1.6	0.1	0.2	0.3
TOTAL	**66.1**	**61.3**	**22.5**	**75.7**	**88.9**	**76.0**	**27.1**	**48.7**
PER CAPITA [c]	**5.8**	**11.0**	**5.1**	**4.2**	**8.2**	**6.4**	**5.5**	**4.8**

Sources: See note 182.
Notes: An asterisk (*) indicates that GHG emissions from this sector were zero, insignificant, or not reported.
(a) US and Canadian GHG inventory methodologies not necessarily comparable; no emissions information available for MI
(b) Residential and agricultural energy use combined in Canadian GHG inventory
(c) GHG emissions in MMTCE per million population. Average per capita emissions in 1995 in the US was 6.6 and in Canada was 6.0. Canadian population data from 1991.

emissions have increased in every state and province since 1990, but these inventories—while not always perfectly accurate—offer a starting point to identify opportunities for reducing the output of heat-trapping gases. In fact, Canada in 2002 ratified the Kyoto Protocol and made a commitment to reduce country-wide emissions by about 6 percent below 1990 levels by 2008–2012.

FIGURE 35
Minnesota Wind Farm

See page 51
for full-size color image of this figure

Far and away the major sources of emissions throughout the region are the utilities and transportation sectors, followed by energy use in the industrial sector, emissions from landfills and waste incinerators, and other locally important sources such as commercial, agricultural, or residential sectors. There are opportunities for emission reductions in all these sectors. Moreover, changes in forestry practices and agricultural soil management offer the potential for reducing emissions and sequestering carbon, a process that can be thought of as "negative emissions."

Energy

Opportunities for emission reductions in the energy sector include:

- Increasing energy efficiency and conservation in industry and by consumers, using both technological and behavioral changes
- Increasing the amount of energy produced from renewable power sources such as wind, solar, and organic wastes
- Switching from carbon-intensive energy sources such as coal to natural gas and biofuels
- Achieving more efficient fossil fuel generation of electricity

Several Great Lakes states and Ontario currently employ some of these strategies and can serve as models for others. In Indiana, for example, the Industrial Energy Efficiency Fund provides zero-interest loans to increase the energy efficiency of manufacturing processes.[183] Minnesota and Wisconsin have established targets and timetables for increasing electricity production from renewable energy and, together with Illinois and New York, are also financing investments in renewable energy and efficiency for homes and businesses.[184]

Most Great Lakes states have commercially viable wind energy resources. Minnesota is already the third largest wind power producer in the nation (Figure 35), and new wind projects are being built in Illinois, Michigan, New York,[185] and in Ontario.[186] Illinois has the technical potential to produce 83 percent of its electricity needs (based on 2000 usage) from its wind resources and 35 percent from its bioenergy resources.[187]

A recent study shows Ontario can practically and economically reduce energy waste and generate enough green energy for the province to phase out all five of its coal-fired power plants.[188] The approach would involve demand-side management programs that increase energy efficiency, shift subsidies away from fossil fuel–derived energy toward support of renewable energy, and reform electricity prices to reflect their real cost to human health and the environment.

> Minnesota and Wisconsin finance investments in renewable energy and efficiency for homes and businesses.

Developing these alternative energy resources promises a number of benefits. A study by the Environmental Law and Policy Center examined the impacts of 22 percent use of renewable energy in the US states of the region by 2020. It found that CO_2 emissions could be cut in half, while increasing electricity costs by only 1.5 percent in 2010 and 3.4 percent in 2020. Additional benefits would include reducing air emissions of sulfur dioxide and nitrogen oxides, creating 200,000 new jobs, and generating $5.5 billion (US) in additional income.[189]

Transportation

Opportunities for emission reductions in the transportation sector include

- Increasing the efficiency of conventional vehicles
- Introducing hybrid and fuel cell cars
- Developing low-carbon fuels such as ethanol
- Reducing the number of miles driven, in part through anti-sprawl planning and better public transportation

FIGURE 36
Illinois Fuel Cell Bus

See page 51
for full-size color image of this figure

Fuel economy (CAFE) standards are set at the national level. While the United States has had mandatory standards in place since the oil crises of 1975, Canada currently has only a voluntary fuel efficiency initiative and levels mimic those in the United States. Raising the CAFE standard over the next 20 years to 55 miles per gallon for new cars and light-trucks would take advantage of the tremendous potential for technological innovation and could save US drivers billions of dollars at the fuel pump, while reducing millions of tons of heat-trapping gases, smog-forming pollutants, and other toxic emissions. Although the federal Energy Policy Act of 1992 required state government fleets to purchase alternative fuel vehicles, few state governments actually fulfill this requirement. An exception is Minnesota, which has developed state vehicle fleet efficiency standards. Indiana encourages the building of alternative fueling sites through its Alternative Fuel Vehicle Infrastructure Program (Figure 36).

Even at local scales, travel-reduction strategies including ride-share, telecommuting, bicycle and pedestrian programs, transit promotion, and parking management can produce multiple benefits such as emission reductions, healthier air, and higher quality of life.[190] Large cities with heavy commuter traffic such as Chicago, Detroit, and Toronto are particularly amenable to such improvements.

Toronto: A Leader Among Cities in Reducing Greenhouse Gas Emissions

While nations, states, and provinces continue to debate the economic wisdom of reducing greenhouse gas emissions, key cities across North America have taken the lead in showing that cutting carbon emissions can not only save energy but also generate revenue. One of the first local governments in the world to commit to voluntary cuts in greenhouse gas emissions, and one of the most successful, is Toronto. In 1990, Canada's largest city committed to a goal of reducing its emissions 20 percent below 1988–1990 levels by 2005. By 1998, Toronto had already exceeded its 2005 goal more than three times over, achieving emission reductions of 67 percent below 1990 levels. That represents a drop from 2.3 million tons of carbon dioxide released into the atmosphere to 765,000 tons released, one of the largest reductions achieved anywhere in Canada.

Toronto used a wide range of measures to achieve its emission goals: improving the energy efficiency of city buildings and streetlights (Figure 37a), improving energy efficiency and switching to alternative fuels for its vehicle fleet, procuring and developing "green" power sources, and capturing landfill gases for use in power production (Figure 37b). The latter strategy, in fact, produced the greatest reduction in emissions and also generates $2.5 million (Cdn) in yearly income for the city. Although energy efficiency measures resulted in much smaller emission reductions, they save the city $10 million (Cdn) in energy costs each year.

FIGURE 37A
City Hall, Toronto

See page 51
for full-size color image of this figure

FIGURE 37B
Toronto Shows Climate Solutions Leadership

See page 51
for full-size color image of this figure

To help pay for the program and educate the public about its goals, the city in 1991 contributed $23 million (Cdn) in revenues from the sale of city property to set up the Toronto Atmospheric Fund (TAF). While many cities around the world have committed to greenhouse gas reductions, Toronto remains the only one that has created an independent agency to fund such projects. TAF-sponsored projects to date have financed emission reductions of more than 225,000 tons, saved the city $2.7 million (Cdn) a year in energy and maintenance costs, and jump-started organizations such as Green$aver, Greenest City, the Toronto Renewable Energy Cooperative, and the Black Creek Regional Transportation Management Association. Among its other initiatives, TAF also holds an annual Smog Summit and funds studies on transportation and smart growth issues. TAF believes that Toronto has the potential to achieve another 31 percent emission reductions between 1998 and 2010.[191]

More than 500 communities worldwide, including 100 in the United States, have joined Toronto as participants in the Cities for Climate Protection Campaign of the International Council for Local Environmental Initiatives. Together these local communities, which collectively account for 8 percent of global greenhouse gas emissions, are not only cutting their emissions and pioneering cost-effective strategies for reducing their impact on the global climate, but also setting examples for nations to follow.

Waste Management

Opportunities for emission reduction in the waste management sector include

- Waste avoidance
- Waste recovery and recycling, including use of waste for biomass energy
- Capture of methane emissions

Again, several Great Lakes states and Ontario have programs that could be emulated throughout the region. Indiana, for example, has a Recycling Market Development Program that aims to boost recycling rates and the purchase of recycled products. In methane recapture, Ontario's City of Welland Landfill Gas Recovery Program currently collects and destroys more than 100,000 tons of methane per year—the equivalent of taking 560,000 cars off the road.[192]

Forestry and Agriculture

Opportunities for emission avoidance and carbon capture in forestry and agricultural land use include

- Forest protection
- Reforestation or afforestation
- Sustainable soil management to increase carbon sequestration

Forestry opportunities may be particularly relevant in the northern parts of the region, although other areas could also benefit. For example, Minnesota's ReLeaf Program promotes and funds the planting and maintenance of trees as a means to store carbon and save energy.[193] Several other forest carbon sequestration projects are under way in Indiana, Ohio, and Ontario. In Wisconsin, several projects on land owned or managed by The Nature Conservancy are funded by utilities needing to offset CO_2 emissions. Maintaining and increasing urban tree cover is becoming more important both for storing carbon and for reducing the urban "heat island" effect that intensifies summer heat.

In the agricultural sector, numerous studies have shown that certain best practices in soil management such as no till, low input, and use of cover crops can enhance short-term soil carbon sequestration. In addition, the Environmental Protection Agency supports several programs that can reduce methane emissions from livestock and livestock wastes, such as the AgSTAR Program and the Ruminant Livestock Efficiency Program.[194]

Integrated Emission Strategies

Several states in the region have comprehensive climate change action plans. All will require strong support for implementation, however, and none specifies reduction targets by certain dates. Similarly, at least 14 American municipalities in the region have committed themselves to local emission reductions through the International Cities for Climate Protection Campaign.[195] In Ontario, more than 20 municipalities participate in the Partners for Climate Protection program of the Federation of Canadian Municipalities[196] (see box, opposite).

Another possible strategy for reducing emissions cost-effectively is through carbon credits and trading. The US leader in developing voluntary carbon-trading strategies is the Chicago Climate Exchange.[197] In Canada, the federal government's Tradable Permits Working Group has set up a prototype trading system in Ontario, which could be adapted in the future to include heat-trapping gases.[198] In anticipation of this, utilities have begun to purchase emission-reduction credits from elsewhere to offset their own CO_2

FIGURE 38
Minimizing Sprawl

See page 52
for full-size color image of this figure

emissions. Thus, timely research and development activities could position the Great Lakes region as a leader in the emerging carbon-trading market. Principles guiding effective emissions trading have yet to be developed in both the United States and Canada. In general, effective emissions trading systems share several traits: At minimum they are fair by rewarding leaders rather than laggards; they are cost-effective; and they lead to actual emission reductions through absolute, progressively lowered caps on emissions.

Scientific evidence demonstrates that the most desirable approaches to reducing emissions not only achieve real climate benefits, but also avoid exacerbating other environmental problems. Policymakers have to agree on principles that define best practices such as the following: First, the results of emissions reduction efforts are easily verified and ensure that carbon is stored permanently. Second, emission reduction approaches go beyond standard practices and existing regulations.[199] Third, projects must minimize and account for leakage, or the potential that the project may simply displace emissions elsewhere. Finally, forest-based projects for climate should enhance, and not detract from, biodiversity protection.[200]

Minimizing Human Pressures on the Environment

Reducing or minimizing human pressures on the environment often results in long-term economic benefits that outweigh the initial cost. These benefits include flood protection, human health benefits from water and air purification, improved agricultural and forestry productivity, water supply security, safeguarding of habitat for native plants and animals, aesthetic benefits, and recreational opportunities. The following are key strategies for reducing human stresses.

Air Quality Improvements

Air pollutants, such as ozone, damage the natural environment as well as human health and crops. Strategies to reduce heat-trapping gas emissions, whether from coal-fired power plants or commuter traffic, have the ancillary benefit of reducing air pollution.[201] In Ontario alone, air pollution claims the lives of an estimated 1,900 people a year and costs the medical system about $1.1 billion (Cdn) annually, according to an analysis by the Ontario Medical Association.[202] Recognizing this problem, the city of Mississauga in southern Ontario's industrial and commuter belt established in 1998 the Mississauga Air Quality Advisory Committee, which implemented a comprehensive air quality improvement plan. The results have included significant utility savings, reductions in energy use and pollution, an expanded transit service and bike path network, greater tree cover, and reduced air pollution.[203]

Water Quality Protection and Demand/Supply Management

Protecting ground and surface water supplies, as well as the ecological quality of aquatic habitats and the species that live in them, offers benefits for human health and well-being in the water-rich Great Lakes region. Water management and conservation efforts also increase the reliability of supplies for economic sectors and industries dependent on steady availability of high-quality water. Key water quality improvements that need to be more widely implemented include efforts to upgrade sewer and septic systems and to contain nonpoint pollution from roads, farmland, and other dispersed sources.[204] Many smaller Great Lakes communities still have sewer outflow systems that release untreated sewage and industrial waste directly into surface water bodies during storm events that overwhelm the capacity of local water treatment facilities. If the frequency of heavy rain events increases in the future, that will increase the urgency of technological upgrades to these systems to prevent water-and foodborne diseases and also to protect people from illnesses contracted during recreational activities such as swimming, boating, and fishing.

Water supply concerns in the region can be addressed by developing more effective water-conservation strategies for use during summer months and in water-intensive agricultural and industrial operations. A more controversial issue concerning future water supplies involves schemes to divert water to users outside the basin. Such diversions would have significant ecological and social implications for the entire Great Lakes basin and potentially create legal, policy, and procedural conflicts within the region.[205]

Urban and Land Use Planning

Urban and rural land use planning can reduce sprawl, which in turn reduces greenhouse gas emissions from commuter traffic. Reducing sprawl has added benefits of preventing habitat destruction and fragmentation, reducing or at least containing the area of impervious surfaces that contribute to flooding, reducing municipal spending on services, and decreasing the loss of valuable farmland (Figure 38). In Grand Rapids, Michigan, which is quickly becoming the poster-child of the nation's growing antisprawl movement, a civic campaign led to comprehensive land-use policy reforms, including preservation of connected open lands and natural areas, establishment of com-pact business centers served by mass transit, and establishment of boundaries on extending water and sewer services.[206]

Habitat Protection and Restoration

Rehabilitation of wooded riparian buffer strips, restoration of floodplain forests, wetland preservation and restoration, and reduction of the extent of impervious surfaces are strategies that help to main-

TABLE 9 **Examples of Adaptive Measures for Mitigating Impacts of Climate Change on Fisheries**

Adaptation Strategy	Specific Option	Limitations
Choose/Change:		
Location	Encourage fishers to move fishing grounds as locations of preferred fish habitat change	Most stocks of desirable fish species are heavily exploited already
Use	Exploit previously unused or underused resources	Local aquatic ecosystems will become generally overexploited as the focus of fishers extends to all levels of the food web
Reduce Losses:		
Prevent effect	Not possible	
Modify effect	Artificially accelerate natural rates of range extension for warm-water species	Careless actions will exacerbate problems
	Reduce impacts from other agents of stress; particularly relevant for fisheries located in areas of high human population density	Resistance to limit destructive environmental impacts of industry and other human activities
	Remove potential barriers to migration and range extension	
Accept Losses:		
Share loss	Compensation/insurance programs for fishers	Such actions provide only short-term mitigation, if the precipitating environmental changes are permanent
Bear loss	Do nothing to save species or stocks	

tain and restore valuable habitat, improve recreational experiences, and provide vital human services such as water purification and flood control. Given the already large threat to Great Lakes biodiversity from invasive species, it is also vital to continue to implement strong protection against invasive aquatic and terrestrial organisms. One example is the Great Lakes-wide effort to contain the spread and expansion of nonnative Eurasian water milfoil, an imported waterweed that forms thick, smothering mats in lakes and streams, depleting oxygen and crowding out native plants.[207] Invasive species such as water milfoil are likely to exacerbate problems created by a warming climate, especially in shallow lakes and wetlands.

Managing the Impacts of Climate Change

Even if our societies, regional and global, are successful in relieving human pressures on ecosystems and minimizing climate change by reducing emissions, climate changes already in progress will continue for decades or more. Because of this, society must begin planning and preparing to manage future impacts that cannot be avoided. A robust strategy in the face of uncertainty, or even unpredictability, is one that will be flexible enough to fare well under a wide range of possible outcomes. The sections below describe some "no regrets" actions that may be taken to manage the impacts of climate change on the Great Lakes economy, peoples, and environment.

FIGURE 39
Ecological Limits to Adaptation in Agriculture

See page 52
for full-size color image of this figure

Fisheries

The histories of aboriginal, commercial, and sport fisheries provide many examples of the adaptability of fishers. When traditionally exploited stocks fail, effort is quickly redirected and fishing methods are adjusted to other stocks and species. Likewise, as regional waters warm, fisheries may be able to adapt to a new mix of fish species. This does not mean, however, that individual fishers or specific fishing communities will necessarily avoid serious negative effects, in part because habits and cultural preferences are typically slow to change (Table 9, p.75).

Effective adaptation will likely involve reallocation of harvest from adversely affected populations, such as lake trout in southern inland lakes, to populations that are positively affected, such as walleye in northern waters and smallmouth bass throughout the basin. However, the fish community may face a prolonged period of restructuring while productivity and water temperatures are in transition. This transitional stage may create great uncertainty in determining sustainable harvests of any fish species. Also, both fishermen and consumers have preferences for particular species that may be difficult to change and may prolong exploitation of populations that should be protected. Overall, robust fisheries management should be guided by some basic principles, including:

- Maintaining exploitation rates at levels that include a safety margin based on historical uncertainties in fish stocks
- Reducing the negative impacts of other human stressors such as acidification and habitat destruction
- Initiating concerted efforts to reduce overinvestment in a fishery that can exploit certain species at unsustainable rates
- Ensuring that no practice applied for a short time could produce extreme outcomes

Aquatic Ecosystems, Resources, and Wildlife

To help sustain aquatic resources and ecosystems, efforts should focus on protecting riparian zones of rivers, existing wetlands and headwater streams, groundwater systems, and lakes. Protecting and revegetating riparian zones, for example, can yield a large return on investment in terms of reducing damages and economic losses from flooding and improving water quality. Native species chosen for such projects should be evaluated in terms of their suitability for a warmer climate and their ability to withstand frequent floods and droughts. To boost the chances for wetland survival, efforts can be initiated to increase water retention in wetlands and to restore or maintain connections between wetlands and lakes or rivers.

Increasing water conservation and reducing human demands for water are vital goals that can be achieved through changes in human behavior in households, farms, and industries. Water management policies can also be reviewed to insure that they are adequate and flexible enough to meet the long-term challenges of a changing and potentially drier climate.[208]

Climate change will affect individual farms as well as local farming communities, potentially changing the character of rural landscapes across the region.

Finally, an effective strategy for sustaining habitats and wildlife populations will benefit from active planning and implementation of development regulations designed to minimize landscape fragmentation. Preserving or restoring migration corridors across the landscape will allow species to move to more suitable climates and will also help to sustain populations of native plants and animals that are large and genetically diverse enough to cope with future disturbances.

Agriculture

Many factors other than climate will heavily influence the ease with which agriculture in the region adapts to future changes, and also the direction that adaptation takes (Figure 39). Typically, assessments of agriculture's capacity to adapt to climate change produce relatively favorable predictions because they assume that farmers, accustomed to having to make adjustments every season, have the ability to shift planting times, crop varieties, fertilizer inputs, irrigation methods, and other factors to optimize production.[209] Such assessments also point out that changes in technology, availability of resources, subsidies, and management policies as well as climate will affect both trends in crop yields and shifts in national and global markets. Usually missing from these assessments, however, are the costs of adaptation and change that individual farmers must bear, and the differing impacts on small versus large farms. On the farm, management choices in a changing climate will be governed not only by farmers' technological options and resources, but also by their ability and desire to change. Finally, an indirect impact of climate change often ignored involves the influence that changes on the farm will have on local farming communities. These impacts have the potential to change the character of rural landscapes across the Great Lakes region.

Forestry

The following approaches may help forestry operations in the northern portion of the Great Lakes region adjust to a warmer and potentially drier climate:

- Shifting species and genetic varieties of trees as well as forestry practices to increase water use efficiency of trees
- Improving soil management, spacing, and tree rotation length to enhance the success of forests under new or variable climate patterns
- Moving toward greater production of saw timber and less pulp production, which will help sequester carbon in long-lived products
- Creating biologically diverse rather than single-species tree plantations to enhance and hasten species' dispersal to more suitable new ranges
- Investing more in prevention, management, and containment of large forest fires, especially during dry periods, while developing improved fire management strategies for relatively small fires

FIGURE 40
Managing the Lake and Stream Impacts of Climate Change

See page 52
for full-size color image of this figure

Many of the best practices common in sustainable forestry today could help ensure the resilience of biologically diverse forests and habitat protection for birds and other wildlife under future climate stresses. Particularly important are adaptive strategies that retain management flexibility in the face of uncertainty, together with improved land use planning and pest management.[210] As in the agricultural sector, however, many market-related and industry-wide changes occurring nationally and globally will affect the economic viability, technological changes, and productivity of forestry in the Great Lakes region.[211]

Infrastructure Protection and Built Environments

People have traditionally responded to climate variability and weather extremes by shielding themselves through both structural measures such as bulkheads along shorelines, levees in floodplains, or dredging of lakes (Figure 40, p.77), and nonstructural measures including insurance coverage, warning systems, emergency management plans, and land use planning. These same tools can help society adapt to climate change, although many current applications fail to include the necessary long-term perspective or even an awareness of climate change. For example, when levees and other structures are being upgraded or replaced, it may be inadequate to engineer replacements based solely on historical frequencies of extreme events or water-level fluctuations. Complementary strategies may be needed because of current trends in the insurance industry, including ever more expensive coverage and withdrawal from high-risk areas. For example, progressive relocation of homes and businesses out of the most hazardous areas and other improvements in zoning, planning, and building codes can avoid creating greater vulnerability and liability in the future.

Human Health

Coordinated health management plans that specifically take into account changing patterns of disease threats in a warmer climate will be vital in managing future health risks, as suggested in a recent report on adaptation options for the Toronto-Niagara region.[168] As the frequency or intensity of extreme heat events increases, earlier forecasting, better public education efforts, and assistance directed at elderly, low-income, and other high-risk populations will be needed. Earlier warnings during periods of increased ground-level air pollution could also help the elderly and people with preexisting respiratory conditions reduce their exposure. Public education can help people reduce their risk of exposure to many vectorborne diseases in the region, including Lyme disease, Eastern equine encephalitis, and West Nile encephalitis, by modifying outdoor activity, clothing, or housing.

Obviously, limiting construction of houses in flood plains and improving housing construction standards could reduce risk of flood damage, injuries, and deaths. In general, infrastructure improvements that maintain or improve sanitation, sewage treatment, waste disposal, stormwater drainage, and water supply will all help reduce health risks.

Meeting the Challenges

Global warming is under way and already causing changes to our environment. Much uncertainty remains about specific ecological and economic changes that a warmer climate with drier summers will bring to the Great Lakes region, but it is certain that the impacts will magnify in importance in the future. This knowledge provides no excuse for inaction or fatalism, however, because innovative, affordable, and prudent solutions are available to help reduce the severity of climate change globally, increase the health and resilience of ecological and economic systems vital to the region, and begin planning and preparing now to adapt to those future changes that cannot be avoided. By acting now, we can protect the rich natural heritage, vibrant economy, and well-being of people and communities in North America's heartland.

References

1. US Census Bureau (2000). Census. Washington, D.C.: Department of Commerce.

2. Statistics Canada (2002). Population data for Ontario from 1929 to 2001. Provided by Ontario Ministry of Finance. Toronto, Ont.

   Thorp, S., R. Rivers, and V. Pebbles (1996). Impacts of Changing Land Use. State of the Lakes Ecosystem Conference (SOLEC) 1996 background paper. Ann Arbor, Mich.: Great Lakes Commission, and Burlington, Ont.: Environment Canada. Available on the EPA website at *www.epa.gov/glnpo/solec/96/landuse/index.htm.*

3. Statistics Canada (2003). Manufacturing shipments, provinces and territories. Available on the Statistics Canada website at *www.statcan.ca/english/Pgdb/manuf28.htm.*

4. US Census Bureau (2000). Statistical Abstract of the United States 1999, Table 975 Manufactures—Summary by State. Washington D.C.: US Census Bureau.

5. Allardice, D.R., and S. Thorp (1995). A Changing Great Lakes Economy: Economic and Environmental Linkages. Paper presented at the State of the Lakes Ecosystem Conference, Chicago, Ill.: US Environmental Protection Agency.

6. US Department of Agriculture (2000). Economic Research Service. State Facts. Value of receipts 2000. Department of Agriculture: Washington, D.C.

7. Statistics Canada (2001). Census of Agriculture. Gross Farm Receipts and Expenses, Provinces. Ottawa, Ont.: Ministry of Agriculture, Food and Rural Affairs. Available from Statistics Canada website at *www.statcan.ca/english/Pgdb/econ114a.htm.*

8. Ontario Investment Service (2001). The Heart of North America's Forest Industry. Available at *www.2ontario.com/industry/forestry.asp.* Accessed on February 17, 2003.

9. US Census Bureau (2002). Annual Survey of Manufactures. Geographic Area Statistics 2000. Washington, D.C.: Department of Commerce.

10. Travel Industry Association of America (1999). Impact of Travel on State Economies. Available on the TIAA website at *www.tia.org/Pubs/pubs.asp?PublicationID=90.*

11. National Park Service (2000). National Park Service Statistical Abstract 1999. Denver, Col.: Statistical Office, US Department of the Interior. Available on the NPS website at *www2.nature.nps.gov/stats/abst99.pdf.*

12. Ontario Parks (2001). Ontario Provincial Parks Statistics. Pub. No. CA2ON NR O56. Toronto, Ont.: Queens Printer.

    Parks Canada (2001). Parks Canada Attendance: 1995–96 to 1999–00. Available on the Communication Canada website at *dsppsd.communication.gc.ca/Collection/R62-332-2000E.pdf.*

13. US Fish and Wildlife Service (1997). 1996 National Survey of Fishing, Hunting and Wildlife-Associated Recreation. Washington, D.C.: US Fish and Wildlife Service. Available on the US Census website at *www.census.gov/prod/3/97pubs/fhw96nat.pdf.*

14. Ontario Ministry of Tourism and Recreation (2002). Tourism Expenditures in Ontario by Origin 1980–2001. Available on the OMTR website at *www.tourism.gov.on.ca/english/tourdiv/research/pdf/expenditures-origin-1980-2001-e.pdf.*

15. US Energy Information Administration (2000). State Energy Data Report 1999. Washington, D.C.: US Energy Information Administration.

16. Natural Resources Canada (1999). Canada's Emissions Outlook: An Update. Ottawa, Ont.: Analysis and Modeling Group National Climate Change Process. Available on the Natural Resources Canada website at *www.nrcan.gc.ca/es/ceo/outlook.pdf.*

17. See Thorpe et al. (1996) in reference 2.

18. Blaustein, A.R., D.B. Wake, and W.P. Sousa (1994). Amphibian declines: Judging stability, persistence, and susceptibility of populations to local and global extinctions. *Conservation Biology* 8(1):60–71.

    Gibbs, J.P. (1998). Distribution of woodland amphibians along a forest fragmentation gradient. *Landscape Ecology* 13:263–268.

19. Paul, M.J., and J.L. Meyer (2001). Streams in the urban landscape. *Annual Review of Ecology and Systematics* 32:333–365.

20. Arnold, C.L., and C.J. Gibbons (1996). Impervious surface coverage: The emergence of a key environmental condition. *American Planners Association Journal* 62:243–258.

21. Galli, F.J. (1991). Thermal Impacts Associated With Urbanization and Stormwater Management Best Management Practices. Washington, D.C.: Washington Council of Governments.

22. Kabat, P., et al., eds. (in press). *Vegetation, Water, Humans and the Climate: A New Perspective on an Interactive System.* A synthesis of the IGBP Core Project, Biospheric Aspects of the Hydrological Cycle. Global Change—The IGBP Series, New York: Springer.

Pielke Sr., R.A., et al. (2002). The influence of land-use change and landscape dynamics on the climate system: Relevance to climate change policy beyond the radiative effect of greenhouse gases. *Philosophical Transactions of the Royal Society London,* 360(Special Theme Issue):1705–1719.

23. Mortsch, L.D. (1998). Assessing the impact of climate change on the Great Lakes shoreline wetlands. *Climate Change* 40:391–416.

US Global Change Research Program (2000). US National Assessment of the Potential Consequences of Climate Variability and Change. Washington, D.C.: US Climate Change Science Program/US Global Change Research Program. Available on the USGCRP website at *www.usgcrp.gov/usgcrp/nacc/.*

24. Kunkel, K.E., et al. (1998). An expanded digital daily database for climatic resources applications in the Midwestern United States. *Bulletin of the American Meteorological Society* 79:1357–1366.

25. McCormick, M.J., and G. L. Fahnenstiel (1999). Recent climatic trends in nearshore water temperatures in the St. Lawrence Great Lakes. *Limnology and Oceanography* 44:530–540.

26. Shuter, B.J., C.K. Minns, and N. Lester (2002). Climate change, freshwater fish and fisheries: Case studies from Ontario and their use in assessing potential impacts. In Fisheries in a Changing Climate. N.A. McGinn, ed. Bethesda, Md.: American Fisheries Society, pp. 77–88.

27. King, J.R., B.J. Shuter, and A.P. Zimmerman (1997). The response of the thermal stratification of South Bay (Lake Huron) to climatic variability. *Canadian Journal of Fisheries and Aquatic Science* 54:1873–1882.

King, J.R., B.J. Shuter, and A.P. Zimmerman (1999). Signals of climate trends and extreme events in the thermal stratification of multibasin Lake Opeongo. *Canadian Journal of Fisheries and Aquatic Science* 56: 847–852.

Shuter et al. (2002) in note 26.

28. Gitay, H., et al. (2001). Ecosystems and their goods and services. In *Climate Change 2001: Impacts, Adaptation and Vulnerability.* Report by Working Group II for the IPCC. Cambridge, U.K.: Cambridge University Press, pp. 237–342.

Magnuson, J.J., et al. (2001). Lake and river ice as a powerful indicator of past and present climates. *Verhandlungen der Internationalen Vereinigung für Limnologie* 27:2749–56.

Magnuson, J.J. (2002). Signals from ice cover trends and variability. In Fisheries in a Changing Climate. N.A. McGinn, ed., Bethesda, Md.: American Fisheries Society, pp. 3–13. Available on the AFS website at *www.fisheries.org/publications/catbooks/x54032.shtml.*

29. Wynne, R.H., et al. (1998). Satellite monitoring of lake ice breakup on the Laurentian Shield (1980–1994). *Photogrammetric Engineering and Remote Sensing* 64: 607–617.

30. Benson, B., T. Kratz, and J. Magnuson (2001). Variability and extreme events in long-term lake and river ice phenology across the northern hemisphere. Paper presented at the Ecological Society of America, 2001 Annual Meeting, Madison, Wis.

31. Magnuson (2002) in note 28.

32. Intergovernmental Panel on Climate Change (2001). *Climate Change 2001: The Scientific Basis.* Technical report. Cambridge, U.K.: Cambridge University Press.

33. Magnuson (2002) in note 28.

Robertson, D.M., R.H. Wynne, and W.Y.B. Chang (2001). Influence of El Niño on lake and river ice cover in the Northern Hemisphere from 1900–1995. *Verhandlungen der Internationalen Vereinigung für Limnologie* 27:2784–2788.

34. Lofgren, B.M., et al. (2002). Evaluation of potential impacts on Great Lakes water resources based on climate scenarios of two GCMs. *Journal of Great Lakes Research* 28:537–554.

35. Magnuson, J.J., et al. (in press). Wisconsin waters and climate: Historical changes and possible futures. *Transactions of the Wisconsin Academy of Sciences, Arts, and Letters.*

36. Sousounis, P.J., and J.M. Bisanz (2000). Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change. Great Lakes Overview. Great Lakes Regional Assessment Group. Ann Arbor, Mich.: University of Michigan. Available on the Great Lakes Regional Climate Change Assessment website at *www.geo.msu.edu/glra/assessment/assessment.html.*

37. Lenters, J.D. (2001). Long-term trends in the seasonal cycle of Great Lakes water levels. *Journal of Great Lakes Research* 27: 342–353.

38. Kunkel, K.E., K. Andsager, and D.R. Easterling (1999). Long-term trends in heavy precipitation events over North America. *Journal of Climate* 12: 2513–2525.

39. Arnell, N., et al. (2001). Hydrology and water resources. In *Climate Change 2001: Impacts, Adaptation and Vulnerability.* Report by Working Group II for the IPCC, Cambridge, U.K.: Cambridge University Press, pp. 190–233.

Lettenmaier, D.P., et al. (1999). Water resources implications of global warming: A US regional perspective. *Climatic Change* 43: 537–579.

40. Changnon, S.A., and K.E. Kunkel (1995). Climate-related fluctuations in Midwestern flooding. *Journal of Water Resources Planning and Management Division* 121:326–334.

41. Karl, T.R., et al. (1995). Indices of climate change for the United States. *Bulletin of the American Meterological Society* 77:279–292.

Kunkel, K.E., R.A Pielke Jr., and S.A. Changnon (1999). Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* 80:1077–1098.

42. Intergovernmental Panel on Climate Change (2000). *Special Report on Emissions Scenarios*. A report by the Intergovernmental Panel on Climate Change, Cambridge, U.K.: Cambridge University Press.

43. Wuebbles, D.J., and K. Hayhoe (2003). Climate Change: A Real Issue with Real Concerns for the Midwest. Proceedings of the International Conference on Climate Change and Environmental Policy, November 11–12, 2002. Urbana, Ill.: University of Illinois at Urbana-Champaign. Available on the conference website at *www.ace.uiuc.edu/pERE/conference/papers/*.

44. National Research Council, Committee on Abrupt Climate Change (2002). *Abrupt Climate Change: Inevitable Surprises.* Washington, D.C.: National Academy Press.

45. Alley, R.B., and P.U. Clark (1999). The deglaciation of the Northern Hemisphere: A global perspective. *Annual Review of Earth and Planetary Sciences* 27:149–182.

Yu, Z.C., and H.E. Wright (2001). Response of interior North America to abrupt climate oscillations in the North Atlantic region during the last deglaciation. *Earth-Science Reviews* 52:333–369.

46. Lang, C., M. Leuenberger, J. Schwanter, and S. Johnsen (1999). 16°C rapid temperature variation in Central Greenland 70,000 years ago. *Science* 286: 934–937.

47. Hill, D.K., and J.J. Magnuson (1990). Potential effects of global climate warming on the growth and prey consumption of Great Lakes fish. *Transactions of the American Fisheries Society* 119:265–275.

McCormick, M.J. (1990). Potential changes in thermal structure and cycle of Lake Michigan due to global warming. *Transactions of the American Fisheries Society* 119:183–194.

48. Hondzo, M., and H.G. Stefan (1991). Three case studies of lake temperature and stratification response to warmer climate. *Water Resources Research* 27:1837–1846.

Hondzo, M., and M.G. Stefan (1993). Regional water temperature characteristics of lakes subjected to climate change. *Climatic Change* 24:187–211.

Stefan, H.G., et al. (1996). Simulated long-term temperature and dissolved oxygen characteristics of lakes in the north-central US and associated fish habitat limits. *Limnology and Oceanography* 41:1124–1135.

49. Kalff, J. (2002). *Limnology Inland Water Ecosystems*. Toronto, Ont.: Prentice Hall.

Magnuson, J.J., et al. (1997). Potential effects of climate change on aquatic systems: Laurentian Great Lakes and Precambrian Shield Region. In *Freshwater Ecosystems and Climate Change in North America: A Regional Assessment.* C.E. Cushing, ed. New York: John Wiley & Sons, pp. 7–53.

50. Bodaly, R.A., et al. (1993). Mercury concentrations in fish related to size of remote Canadian shield lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 50:980–987.

Yediler, A., and J. Jacobs (1995). Synergistic effects of temperature-oxygen and water-flow on the accumulation and tissue distribution of mercury in carp (*Cyprinus carpio* L.). *Chemosphere* 31:4437–4453.

51. Dollar, N.L., et al. (2001). Chemical fractionation of metals in wetland sediments: Indian Dunes National Lakeshore. *Environmental Science and Technology* 35: 3608–3618.

Perkins, S.M., G.M. Filippelli, and C.J. Souch (2000). Airborne trace metal contamination of wetland sediments at Indiana Dunes National Lakeshore. *Water, Air and Soil Pollution* 122:231–260.

52. Boyce, F.M., et al. (1993). Response of the thermal structure of Lake Ontario to deep cooling water withdrawals and to global warming. *Journal of Great Lakes Research* 19:603–616.

Croley, T.E. (1994). Hydrological impacts of climate change on the Laurentian Great Lakes. *Trends in Hydrology* 1:1–25.

McCormick (1990) in note 47.

Schertzer, W.M., and A.M. Sawchuk (1990). Thermal structure of the lower Great Lakes in a warm year: implications for occurrence of hypolimnion anoxia. *Transactions of the American Fisheries Society* 119: 195–209.

53. Boyce et al. (1993) in note 52.

Croley (1994) in note 52.

54. Croley (1994) in note 52.

Peeters, F., et al. (2002). Modeling 50 years of historical temperature profiles in a large central European lake. *Limnology and Oceanography* 47:186–197.

55. Blumberg, A.F., and D.M. DiToro (1990). Effects of climate warming on dissolved oxygen concentrations in Lake Erie. *Transactions of the American Fisheries Society* 119:210–223.

56. Stefan, H.G., X. Fang, and J.G. Eaton (2001). Simulated fish habitat changes in North American lakes in response to projected climate warming. *Transactions of the American Fisheries Society* 130:459–477.

57. Assel, R.A. (1991). Implications of CO_2 global warming on Great Lakes ice cover. *Climate Change* 18:377–395.

    Lofgren et al. (2002) in note 34.

58. Jackson, D.A., and N.E. Mandrak (2002). Changing fish biodiversity: predicting the loss of cyprinid biodiversity due to global climate change. *American Fisheries Society Symposium* 32:89–98.

59. Brown, R.W., and W.W. Taylor (1993). Factors affecting the recruitment of Lake Whitefish in two areas of northern Lake Michigan. *Journal of Great Lakes Research*. 19:418–428.

60. Lofgren et al. (2002) in note 34.

    Mortsch, L., et al. (2000). Climate change impacts on the hydrology of the Great Lakes-St. Lawrence system. *Canadian Water Resources Journal* 25:153–177.

61. a. Lofgren et al. (2002) in note 34.

    b. Stefan, H.G., and X. Fang (1997). Simulated climate change effects on ice and snow covers on lakes in a temperate region. *Cold Regions Science and Technology* 25:137–152.

62. Hamilton, D.P., T.K. Kratz, and B.B. Wallace (in press). Heat fluxes, ice cover, and thermal regime in Crystal Lake, Wisconsin. *Limnology and Oceanography.*

    Lofgren et al. (2002) in note 34.

    Sousounis and Bisanz (2000) in note 36.

63. Fee, E.J., et al. (1992). Effects of lake size on phytoplankton photosynthesis. *Canadian Journal of Fisheries and Aquatic Sciences* 49:2445–2459.

    Regier, H.A., J.A. Holmes, and D. Pauly (1990). Influence of temperature changes on aquatic ecosystems: An interpretation of empirical data. *Transactions of the American Fisheries Society* 119:374–389.

64. Adams, M.S., T.W. Meinke, and T. K. Kratz (1993). Primary productivity in three northern Wisconsin lakes, 1985–1990. *Verhandlungen der Internationalen Vereinigung für Limnology* 25:406–10.

65. Magnuson et al. (1997) in note 49.

    Schindler, D.W., et al. (1996). The effects of climatic warming on the properties of boreal lakes and streams at the Experimental Lakes Area, northwestern Ontario. *Limnology and Oceanography* 41:1004–1017.

66. Boyce et al. (1993) in note 52.

    Peeters et al. (2002) in note 54.

67. Gerten, D., and R. Adrian (2002). Effects of climate warming, North Atlantic Oscillation, and El Niño-Southern Oscillation on thermal conditions and plankton dynamics in Northern Hemispheric lakes. *The Scientific World Journal* 2:586–606.

68. Beltaos, S., and T.S. Prowse, (2001). Climate impacts on extreme ice-jam events in Canadian rivers. *Hydrological Sciences* 46(1):157–182.

    Knox, J.C. (2001). Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. *Catena* 42:193–224.

69. Richards, R.P. (1990). Measures of flow variability and a new flow-based classification of Great Lakes tributaries. *Journal of Great Lakes Research* 16:53–70.

70. Adams, R.M., B.H. Hurd, and J. Reilly (1999). Agriculture and Global Climate Change: A Review of Impacts to US Agricultural Resources. Arlington, Va.: Pew Center on Global Climate Change.

    US Environmental Protection Agency (1993). Agriculture and the Environment: The Problem of Nonpoint Source Pollution. Washington, D.C.: EPA, EPA 840-F-93-001b.

71. D'Angelo, D.J., J.R. Webster, and E.F. Benfield (1991). Mechanisms of stream phosphorus retention: An experimental study. *Journal of the North American Benthological Society* 10:225–237.

    Mulholland, P.J., et al. (1985). Phosphorus spiraling in a woodland stream: Seasonal variations. *Ecology* 66:1012–1023.

    Munn, N.L., and J.L. Meyer (1990). Habitat-specific solute retention in two small streams: An intersite comparison. *Ecology* 71:2069–2082.

    Wallace, J.B., J.R. Webster, and J.L. Meyer (1995). Influence of log additions on physical and biotic characteristics of a mountain stream. *Canadian Journal of Fisheries and Aquatic Sciences* 52: 2120–2137.

72. Junk, W.J., P.B. Bayley, and R.E. Sparks (1989). The flood pulse concept in river-floodplain systems. *Canadian Special Publications of Fisheries and Aquatic Sciences* 106:110–127.

    Sparks, R.E., J.C. Nelson, and Y. Yin (1998). Naturalization of the flood regime in regulated rivers: The case of the upper Mississippi River. *BioScience* 48(9): 706–720.

73. Sparks, R.E. (1995). Need for ecosystem management of large rivers and their floodplains. *Bioscience* 45(3): 168–182.

74. Erman, N.A., and D.C. Erman (1995). Spring permanence, Trichoptera species richness and role of drought. *Journal of Kansas Entomological Society* 68:50–64.

Ladle, M., and J.A.B. Bass (1981). The ecology of a small chalk stream and its response to drying during drought conditions. *Archiv für Hydrobiologie* 90: 448–466.

75. Leopold, L.B., M.G. Wolman, and J.P. Miller (1964). *Fluvial Processes in Geomorphology*. San Francisco, Calif.: W.H. Freeman.

Meyer, J.L., and J.B. Wallace (2001). Lost linkages and lotic ecology: Rediscovering small streams. In *Ecology: Achievement and Challenge the 41st Symposium of the British Ecological Society.* M.C. Press, N.J. Huntly, and L. Levin, eds. Malden, Mass.: Blackwell Science.

76. Lake, P.S. (2000). Disturbance, patchiness and diversity in streams. *Journal of the North American Benthological Society* 19: 573–592.

77. Golladay, S.W., et al. (2000). Hydrologic and geomorphic controls on suspended particulate organic matter concentrations and transport in Ichawaynochaway Creek, Georgia. *Archiv für Hydrobiologie* 149:655–678.

78. Miller, A.M., and S.W. Golladay (1996). Effects of spates and drying on macro-invertebrate assemblages of an intermittent and a perennial prairie stream. *Journal of the North American Benthological Society* 15:670–689.

Power, M.A. (1995). Floods, food chains and ecosystem processes in rivers. In *Linking Species and Ecosystems.* C.G. Jones and J.H. Lawton, eds. New York: Chapman and Hill, pp. 52–60.

79. Poff , N.L. (1992). What disturbances can be predictable: A perspective on the definition of disturbance in streams. *Journal of the North American Benthological Society* 11:86–92.

80. DeVito, K.J., and A.R. Hill (1997). Sulfate dynamics in relation to groundwater-surface water interactions in headwater wetlands of the southern Canadian Shield. *Hydrological Processes* 11:103–110.

Dillon, P.J., L.A. Malot, and M. Futter (1997). Effect of El Niño-related drought on the recovery of acidified lakes. *Environmental Monitoring and Assessment* 46: 105–112.

Warren, F.J., et al. (2001). Effect of drought on hydrology and sulphate dynamics in a temperate swamp. *Hydrological Processes* 15(16):3133–3150.

81. Mohseni, O., T.R. Erickson, and H.G. Stefan (1999). Sensitivity of stream temperatures in the United States to air temperatures projected under global climate scenarios. *Water Resources Research* 35:3723–3733.

Pilgrim, J.M., X. Fang, and H.G. Stefan (1998). Stream temperature correlations with air temperatures in Minnesota: Implications for climate warming. *Journal of the American Water Resources Association* 34:1109–1121.

82. Hogg, I.D., and D.D. Williams (1996). Response of stream invertebrates to a global-warming thermal regime: an ecosystem-level manipulation. *Ecology* 77:395–407.

83. Morin, A., and N. Bourassa (1992). Modèles empiriques de la production annuelle et du rapport P/B d'invertébrés benthiques d'eau courante. *Canadian Journal of Fisheries and Aquatic Sciences* 49:532–539.

Shuter, B.J., and K.K. Ing (1997). Factors affecting the production of zooplankton in lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 54:359–377.

84. Verry, E.S. (1986). Forest harvesting and water: The Lake States experience. *Water Resources Bulletin* 22: 1039–1047.

85. Palmer, M.A., et al. (2000). Linkages between aquatic sediment biota and life above the sediments as potential drivers of biodiversity and ecological processes. *BioScience* 50:1062–1075.

86. Poff, N.L., et al. (2001). Global change and stream fish diversity. In *Global Biodiversity in a Changing Environment: Scenarios for the 21st Century*. F.S. Chapin III, O.E. Sala, and E. Huber-Saanwald, eds. New York: Springer-Verlag. pp. 315–350.

87. Hax, C.L., and S.W. Golladay (1998). Flow disturbance of macroinvertebrates inhabiting sediments and woody debris in a prairie stream. *American Midland Naturalist* 139:210–223.

Miller and Golladay (1996) in note 78.

88. Lindroth, R.L., et al. (2001). Consequences of elevated carbon dioxide and ozone for foliar chemical composition and dynamics in trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). *Environmental Pollution* 115:395–404.

Tuchman, N.C., et al. (2002). Elevated atmospheric CO_2 lowers leaf litter nutritional quality for stream ecosystem food webs. *Global Change Biology* 8:163–170.

89. Cotrufo, M.F., and P. Ineson (1996). Elevated CO_2 reduces field decomposition rates of *Betula pendula* (Roth) leaf litter. *Oecologia* 106:525–530.

Ostrofsky, M.L. (1997). Relationship between chemical characteristics of autumn-shed leaves and aquatic processing rates. *Journal of the North American Benthological Society* 16:750–759.

Tuchman et al. (2002) in note 88.

Tuchman, N.C., et al. (in press). Nutritional quality of leaf detritus altered by elevated atmospheric CO_2: Effects on development of mosquito larvae. *Freshwater Biology.*

Tuchman, N.C., et al. (in press). Elevated atmospheric CO_2 alters leaf litter nutritional quality for stream ecosystems: An in situ leaf decomposition study. *Hydrobiologia.*

90. Mitsch, W.J., and J.G. Gosselink, eds. (2000). *Wetlands.* 3rd ed. New York: John Wiley & Sons.

91. Keough, J.R., et al. (1999). Hydrogeomorphic factors and ecosystem responses in coastal wetlands of the Great Lakes. *Wetlands* 19(4):821–834.

92. Bradley, N.L., et al. (1999). Phenological changes reflect climate change in Wisconsin. *Proceedings of the National Academy of Sciences* 96:9701–9704.

Brown, J.L., S.H. Li, and N. Bhagabat (1999). Long-term trend toward earlier breeding in an American bird: A response to global warming? In *Proceedings of the National Academy of Science* 96:5565–5569.

Schneider, S.H,. and T.L. Root, eds. (2002). *Wildlife Responses to Climate Change: North American Case Studies.* Washington, D.C.: Island Press.

93. Root, T.L. (1988). *Atlas of Wintering North American Birds*. Chicago, Ill.: University of Chicago Press.

94. Strode, P. Unpublished data from a student at University of Illinois at Urbana-Champaign.

95. Price, J.T., and T.L. Root (2000). Effects of climate change on bird distributions and migration patterns. In Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change. Great Lakes Overview. Great Lakes Regional Assessment Group. Sousounis, P.J., and J.M. Bisanz, eds. Ann Arbor, Mich.: University of Michigan. pp. 65–68.

96. Brazner, J.C., et al. (2001). Assessing the ecological importance of coastal wetlands in a large lake context. *Verhandluugen der Internationalen Vereinigung für Theoretische und Angewandte Limnology* 26:1950–1961.

Jude, D.J., and J. Pappas (1992). Fish utilization of Great Lakes coastal wetlands. *Journal of Great Lakes Research* 18:651–672.

97. Keough et al. (1999) in note 91.

LaBaugh, J.W., et al. (1996). Changes in atmospheric circulation patterns affect mid-continent wetlands sensitive to climate. *Limnology and Oceanography* 41: 864–870.

Mortsch, L.D., and F.H. Quinn (1996). Climate change scenarios for the Great Lakes Basin ecosystem studies. *Limnology and Oceanography* 41:903–911.

98. Bridgham, S.D., et al. (1999). Ecosystem control over temperature and energy flux in northern peatlands. *Ecological Applications* 9:1345–1358.

Mortsch and Quinn (1996) in note 97.

99. Brinson, M.M., (1993). Changes in the functioning of wetlands along environmental gradients. *Wetlands* 13:65–74.

100. Poiani, KA., W.C. Johnson, and T.G.F. Kittel (1995). Sensitivity of prairie wetland to increased temperature and seasonal precipitation changes. *Water Resources Bulletin* 31:283–294.

101. Chao, P. (1999). Great Lakes water resources: Climate change impact analysis with transient GCM scenarios. *Journal of American Water Resources Association* 35: 1499–1507.

Quinn, F.H. (in press). Lake Erie water level fluctuations: Current perspectives. In *Lake Erie at the Millenium: Changes, Trends and Trajectories.* J.J.H. Ciborowski et al., eds. Toronto, Ont.: Canadian Scholars Press, Inc.

102. Adamus, P.R., et al. (1991). Wetland Evaluation Technique (WET) I. Literature Review and Evaluation Rationale. Wetlands Restoration Program Technical Report WRP-DE-2. Waterways Experiment Station, Vicksburg, Miss.: US Army Corps of Engineers.

Patterson, N.J., and T.H. Whillans (1984). Human interference with natural water level regimes in the context of other cultural stresses on Great Lakes wetlands. In *Coastal Lakes Wetlands.* H.H. Prince and F.M. D'Itri, eds. Chelsea, Mich.: Lewis Publishers. pp. 209–239.

Wilcox, D.A. (1995). Wetland and aquatic macrophytes as indicators of anthropogenic hydrologic disturbance. *Natural Areas Journal* 15(3):240–248.

103. Galatowitsch, S.M., N.O. Anderson, and P.D. Ascher (1999). Invasiveness of wetland plants in temperate North America. *Wetlands* 19:733–755.

104. Grigal, D.F. (2002). Inputs and outputs of mercury from terrestrial watersheds: A review. *Environmental Review* 10(1):1–39.

Mastalerz, M., et al. (2001). Anthropogenic organic matter in the Great Marsh of the Indiana Dunes National Lakeshore and its implications. *International Journal of Coal Geology* 46:157–177.

105. Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to global warming. *Ecological Applications* 1:182–195.

106. Bridgham, S.D., et al. (1995). Potential feedbacks of northern wetlands on climate change. *BioScience* 45: 262–274.

Updegraff, K., et al. (2001). Responses of CO_2 and CH_4 emissions from peatlands to warming and water table manipulations. *Ecological Applications* 11:311–326.

107. Morris, D.P., and B.R. Hargreaves (1997). The role of photochemical degradation of dissolved organic carbon in regulating the UV transparency of three lakes on the Pocono Plateau. *Limnology and Oceanography* 42:239–249.

108. Ankley, G.T., et al. (2002). Assessment of the risk of solar ultraviolet radiation to amphibians. I. Dose-dependent induction of hindlimb malformations in the northern leopard frog (*Rana pipiens*). *Environmental Science and Technology* 36:2853–2858.

Kiesecker, J.M., A.R. Blaustein, and L.K. Belden (2001). Complex causes of amphibian population declines. *Nature* 410:681–684.

Peterson, G.S., et al. (2002). Assessment of the risk of solar ultraviolet radiation to amphibians. II. In situ characterization of exposure in amphibian habitats. *Environmental Science and Technology* 36:2859–2865.

109. Diamond, S.A., et al. (2002). Assessment of the risk of solar ultraviolet radiation to amphibians. III. Prediction of impacts in selected northern Mid-western wetlands. *Environmental Science and Technology* 36:2866–2874.

110. LaBaugh et al. (1996) in note 97.

Mulholland, P.J., et al. (1997). Effects of climate change on freshwater ecosystems of the southeastern United States and the Gulf of Mexico. *Hydrological Processes* 11:949–970.

Poiani, K.A., et al. (1996). Climate change and northern prairie wetlands: Simulations of long-term dynamics. *Limnology and Oceanography* 41:871–881.

111. Gibbs (1998) in note 18.

Skelly, D. K. (1996). Pond drying, predators, and the distribution of Pseudacris tadpoles. *Copeia* 3:599–605.

112. Werner, E. (2003). Personal communication with George Kling, University of Michigan. January.

113. Gibbs, J.P. (1993). Importance of small wetlands for the persistence of local populations of wetland-associated animals. *Wetlands* 13:25–31.

114. Magnuson, J.J., L.B. Crowder, and P.A. Medvick (1979). Temperature as an ecological resource. *American Zoologist* 19:331–43.

Meisner, J.D. (1990). Potential loss of thermal habitat for brook trout, due to climatic warming, in two southern Ontario streams. *Transactions of the American Fisheries Society* 119:282–291.

115. Johnson, T.B., and D.O. Evans (1990). Size-dependent winter mortality of young-of-the year white perch: Climate warming and invasion of the Laurentian Great Lakes. *Transactions of the American Fisheries Society* 119:301–313.

116. Myers, R.A. (1998). When do environment-recruitment correlations work? *Reviews in Fish Biology and Fisheries* 8:285–305.

Shuter et al. (2002) in note 26.

117. Minns, C.K., and J.E. Moore (1992). Predicting the impact of climate change on the spatial pattern of freshwater fish yield capability in eastern Canadian lakes. *Climatic Change* 22:327–346.

Shuter, B.J., and J.R. Post (1990). Climate, population viability and the zoogeography of temperate fishes. *Transactions of the American Fisheries Society* 119:314–336.

118. Jackson and Mandrak (2002) in note 58.

Vander Zanden, M.J., J.M. Casselman, and J.B. Rasmussen (1999). Stable isotope evidence for the food web consequences of species invasions in lakes. *Nature* 401: 464–467.

119. MacIsaac, H.J., T.C. Robbins, and M.A. Lewis. (2002). Biological invasions of aquatic habitats in Europe and the Great Lakes: Modeling ships' ballast water as invasion threats to the Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 1245–1256.

120. Grigal (2002) in note 104.

121. a. Shuter and Post (1990) in note 117.

b. Minns, C.K., and J.E. Moore (1995). Factors limiting the distributions of Ontario's freshwater fishes: The role of climate and other variables, and the potential impacts of climate change. In *Climate Change and Northern Fish Population.* R.J. Beamish, ed. Canadian Special Publication in Fisheries and Aquatc Sciences 121. Ottawa, Ont.: NRC Research Press, pp. 137–160.

c. Mandrak, N.E. (1989). Potential invasion of the Great Lakes by fish species associated with climatic warming. *Journal of Great Lakes Research* 15:306–316.

d. Minns and Moore (1992) in note 117.

e. Schindler, D.W., et al. (1990). Effects of climatic warming on the lakes of the central boreal forest. *Science* 250:967–970.

Schindler et al. (1996) in note 65.

Stefan et al. (1996) in note 48.

Stefan et al. (2001) in note 56.

f. Meisner, J.D. (1990) in note 114.

g. Johnson and Evans (1990) in note 115.

h. Coutant, C.C. (1990). Temperature-oxygen habitat for freshwater and coastal striped bass in a changing climate. *Transactions of the American Fisheries Society* 119:240–253.

122. Christie, G.C., and H.A. Regier, (1988). Measures of optimal thermal habitat and their relationship to yields for four commercial fish species. *Canadian Journal of Fisheries and Aquatic Sciences* 45:301–314.

123. Matuszek, J.E. (1978). Empirical predictions of fish yields of large North American lakes. *Transactions of the American Fisheries Society* 107:385–394.

Schlesinger, D.A., and H.A. Regier (1982). Climatic and morphoedaphic indices of fish yields from natural lakes. *Transactions of the American Fisheries Society* 111:141–150.

124. Magnuson, J.J., J.D. Meisner, and D.K. Hill (1990). Potential changes in the thermal habitat of Great Lakes fish after global climate warming. *Transactions of the American Fisheries Society* 119:254–264.

Magnuson, J.J., and B.T. DeStasio (1997). Thermal niche of fishes and global warming. In *Global Warming: Implications for Freshwater and Marine Fish*. C.M. Wood and D.G. McDonald, eds. Cambridge, U.K.: Cambridge University Press, pp. 377–408.

125. Lindeberg, J.D., and G.M. Albercook. (2000). Climate change and Great Lakes shipping/boating. In Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change. Great Lakes Overview. Great Lakes Regional Assessment Group. P.J. Sousounis and J.M. Bisanz, eds., Ann Arbor: University of Michigan, pp. 39–42. Available on the Great Lakes Regional Climate Change Assessment website at *www.geo.msu.edu/ glra/PDF_files/ Regional%20Summary/04F_WRES_F.boating.pdf.*

126. National Assessment Synthesis Team (2001). *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*. New York: Cambridge University Press.

127. Eheart, J.W., and D.W. Tornil (1999). Low-flow frequency exacerbation by irrigation with drawls in the agricultural Midwest under various climate change scenarios. *Water Resource Research* 35:2237–2246.

128. Department of Fisheries and Oceans Canada (1994). 1990 survey of recreational fishing in Canada. In Economic and Commercial Analysis Report. Ottawa, Ont.: Fisheries and Oceans Canada, pp.148–156.

129. Ontario Ministry of Natural Resources (2002). Overview of Ontario's Forests. Available at *ontariosforests.mnr.on.ca/forestoverview.cfm.*

US Department of Agriculture, Forest Service (2003). Forest Inventory Analysis. Available on the USFS website at *www.ncrs.fs.fed.us/4801/.* Accessed February 17, 2003.

130. Davis, M.B. (1983). Quaternary history of deciduous forests of eastern North America and Europe. *Annals of the Missouri Botanical Garden* 70:550–563.

Davis, M.B., et al. (1986). Dispersal versus climate: Expansion of Fagus and Tsuga into the Upper Great Lakes region. *Vegetation* 67:93–103.

131. He, H.S., D.J. Mladenoff, and T.R. Crow (1999). Linking an ecosystem model and a landscape model to study forest species response to climate change. *Ecological Modeling* 114:213–233.

132. Ehman, J.L., et al. (2002). An integrated GIS and modeling approach for assessing the transient response of forests of the southern Great Lakes region to a doubled CO_2 climate. *Forest Ecology and Management* 155:237–255.

133. Clark, J.S., et al. (2001). Effects of Holocene climate change on the C_4 grassland/woodland boundary in the northern plains, USA. *Ecology* 82:620–636.

134. Heinselman, M.L. (1973). Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research* 3:329–382.

135. Barnes, B.V., D.R. Zak, S. Denton, and S.H. Spurr, eds. (1998). *Forest Ecology,* 4th edition. New York: John Wiley & Sons.

136. Clark, J.S., (1988). Effects of climate change on fire regime in northwestern Minnesota. *Nature* 334:233–235.

Clark, J.S. (1990). Fire and climate change during the last 750 years in northwestern Minnesota. *Ecological Monographs* 60:135–159.

137. Zak, D.R., et al. (2000). Atmospheric CO_2, soil-N availability, and allocation of biomass and nitrogen by *Populus tremuloides*. *Ecological Applications* 10:34–46.

138. Zogg, G.P., et al. (2000). Microbial immobilization and the retention of anthropogenic nitrate in northern hardwood forests. *Ecology* 81:1858–1866.

139. Broadmeadow, M.S.J., and S.B. Jackson (2000). Growth responses of *Quercus petraea, Fraxinus excelsior* and *Pinus sylvestris* to elevated carbon dioxide, ozone and water supply. *New Phytology* 146:437–451.

Kull, O., et al. (1996). Photosynthetic responses of aspen clones to simultaneous exposures of ozone and CO_2. *Canadian Journal of Forest Research* 26:639–648.

140. Williams, D.W., and A.M. Liebhold (1995). Forest defoliators and climatic change: Potential changes in spatial distribution of outbreaks of western spruce budworm (*Lepidoptera: Tortricidae*) and gypsy moth (*Lepidoptera: Lymantriidae*). *Environmental Entomology* 24:1–9.

141. Bezemer, T.M., and T.H. Jones (1998). Plant-insect herbivore interactions in elevated atmospheric CO_2: Quantitative analyses and guild effects. *Oikos* 82: 212–222.

Lindroth, R.L. (1996). Consequences of elevated atmospheric CO_2 for forest insects. In *Carbon Dioxide, Populations, and Communities*. C. Körner and F.A. Bazzaz, eds. San Diego, Calif.: Academic Press, pp. 347–361.

142. Bezemer and Jones (1998) in note 141.

Coviella, C., and J.T. Trumble (1999). Effects of elevated atmospheric CO_2 on insect-plant interactions. *Conservation Biology* 13:700–712.

Lindroth (1996) in note 141.

143. Kopper, B.J., and R.L. Lindroth (2002). Effects of elevated carbon dioxide and ozone on the phytochemistry of aspen and performance of an herbivore. *Oecologia* 134:95–103.

144. Kendeigh, S.C. (1982). *Bird Populations in East Central Illinois: Fluctuations, Variations, and Development over a Half-Century.* Illinois Biological Monographs 52. Champaign, Ill.: University of Illinois Press.

145. Peñuelas, J., and I. Filella (2001). Responses to a warming world. *Science* 294:793–795.

146. Graber, J.W., and R.R. Graber (1983). Feeding rates of warblers in spring. *Condor* 85:139–150.

Hunter, A.F., and M.J. Lechowicz (1992). Foliage quality changes during canopy development of some northern hardwood trees. *Oecologia* 89:316–323.

147. Tucker, C.J., et al. (2001). Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. *International Journal of Biometeorology* 45(4):184–190.

148. Both, C., and M.E. Visser (2001). Adjustment to climate change is constrained by arrival date in a long-distance migrant bird. *Nature* 422:296–298.

149. Peterson, R. (2002). Personal communication with Yvonne Baskin. Rolf Peterson is a professor of wildlife ecology at Michigan Technological University.

150. Blovin-Demers, G., and P.J. Weatherhead (2001). Thermal ecology of black rat snakes *Elaphe obsoleta* in a thermally challenging environment. *Ecology* 82: 3025–3043.

151. National Agricultural Statistics Service. (1999). Census of Agriculture 1997. Available on the USDA website at *www.nass.usda.gov/census/.*

Statistics Canada (2001) in note 7.

152. Andresen J.A., et al. (2001). Weather impacts on maize, soybean, and alfalfa production in the Great Lakes region, 1895–1996. *Agronomy Journal* 93(5): 1059–1070.

153. Robeson, S.M. (2002). Increasing growing-season length in Illinois during the 20th century. *Climate Change* 52:219–238.

Thompson, L.M. (1986). Climate change, weather variability, and corn production. *Agronomy Journal* 78:649–653.

154. Adams, R.M., et al. (1999). Economic effects of climate change on US agriculture. In *Effects of Climate Change on the US Economy*. R. Mendelsohn and J. Neumann, eds. New York: Cambridge University Press, pp. 18–54.

Intergovernmental Panel on Climate Change (2001). *Climate Change 2001: The Scientific Basis.* Summary for policy makers. Cambridge, U.K.: Cambridge University Press.

Reilly, J., et al. (2001). Agriculture: The Potential Consequences of Climate Variability and Change for the United States. In *US National Assessment of the Potential Consequences of Climate Variability and Change*. US Global Change Research Program. New York: Cambridge University Press, pp. 379–403.

155. Ainsworth, E.A., et al. (2002). A meta-analysis of elevated CO_2 effects on soybean (Glycine max) physiology, growth and yield. *Global Change Biology* 8:695–709.

156. Mavromatis, T., and P.D. Jones (1998). Comparison of climate change scenarios construction methodologies for impact assessment studies. *Agricultural and Forest Meteorology* 91:51–67.

157. Adams et al. (1999) in note 154.

158. Pfeifer, R.A., et al. (2002). Climate Variability and Farm Level Risk. In *Effects of Climate Change and Variability on Agricultural Productivity*. O.C. Doering III et al., eds. Boston, Mass.: Kluwer Academic Publishers, pp. 179–192.

159. Bootsma, A., and D.M. Brown (1995). Risk Analysis of Crop Heat Units Available for Corn and Other Warm-Season Crops in Ontario. Agriculture and Agri-food Canada technical bulletin 1E. Ottawa, Ont.: Center for Land and Biological Resources Research.

Bootsma, A. (2002). A summary of some results of research on the potential impacts of climate change on agriculture in eastern Canada. Conference proceedings from Climate Change and Agriculture in the Great Lakes Region: The Potential Impacts and What We Can Do. A workshop held March 22, 2002, at Michigan State University in East Lansing. Available on the MSU website at *www.geo.msu.edu/glra/workshop/03agriworkshp/report/bootsma.htm.*

160. Ecological Stratification Working Group (1996). A National Ecological Framework for Canada. Ottawa, Ont.: Agriculture and Agri-food Canada. Available on the AAFC website at *sis.agr.gc.ca/cansis/publications/ecostrat/intro.html.*

Keyes, J. Jr., et al. (1995). Ecological Units of the Eastern United States: First Approximation. Atlanta, Ga.: US Department of Agriculture, Forest Service.

161. Bootsma (2002) in note 159.

162. Doering, O.C. III, J.C. Randolph, J. Southworth, and R.A. Pfeifer, eds. (2002). *Effects of Climate Change and Variability on Agricultural Production Systems.* Boston, Mass.: Kluwer Academic Publishers.

163. Southworth, J., et al. (2000). Consequences of future climate change and changing climate variability on maize yields in the Midwestern United States. *Agriculture, Ecosystems and Environment* 82: 139–158.

164. Adams, R.M. (1986). Agriculture, forestry, and related benefits of air pollution control *American Journal of Agricultural Economics* 68:885–894.

165. Heck, W.W., et al. (1982). Assessment of crop losses from ozone. *Journal of the Air Pollution Control Association* 32:353–361.

166. Tingey, D.T., et al. (1994). Effect of Ozone on Crops. In *Tropospheric Ozone: Human Health and Agricultural Impacts*. D.J. McKee, ed. Boca Raton, Fl.: Lewis Publishers, pp. 175–205.

167. Changnon and Kunkel (1995) in note 40.

Changnon, S.A. (1999). Record flood-producing rainstorms of 17–18 July 1996 in the Chicago metropolitan area. III. Impacts and responses to the flash flooding. *Journal of Applied Meteorology* 38:273–280.

168. Chiotti, Q., I. Morton, and A. Maarouf (2002). Towards an Adaptation Action Plan: Climate Change and Health in the Toronto-Niagara Region. A report by Pollution Probe Foundation for Environment Canada and Health Canada. Toronto, Ont.: Pollution Probe.

169. Chiotti et al. (2002) in note 168.

Sousounis, P.J., C.P.J. Scott, and M.L. Wilson (2002). Possible climate change impacts on ozone in the Great Lakes region: Some implications for respiratory illness. *Journal of Great Lakes Research* 28(4):626–642.

Wilson, M.L., and P.J. Sousounis (2000). Quality of Life: Human Health. In *Preparing for a Changing Climate: The Potential Consequences of Climate Variability and Change.* P.J. Sousounis and J.M. Bisanz, eds. Ann Arbor, Mich.: The University of Michigan Press, pp. 81–86.

170. Curriero, F.C., et al. (2001). Analysis of the association between extreme precipitation and waterborne disease outbreaks in the United States, 1948–1994. *American Journal of Public Health* 91:1194–1199.

171. Rose, J.B., et al. (2001). Climate variability and change in the United States: Potential impacts on water- and foodborne diseases caused by microbiologic agents. *Environmental Health Perspectives* 109 (Suppl.2):211–222.

172. Gubler, D.J., et al. (2001). Climate variability and change in the United States: Potential impacts on vector- and rodent-borne diseases. *Environmental Health Perspectives* 109 (Suppl.2):223–233.

173. Monath, T.P., and T.F. Tsai (1987). St. Louis Encephalitis: Lessons learned from the last decade. *American Journal of Tropical Medicine and Hygiene* 37:40S–59S.

174. Coviella and Trumble (1999) in note 142.

175. Adams R.M., et al. (1998). Effects of global climate change on agriculture: An interpretive review. *Climate Research* 11:19–30.

176. Hanson, J.D., B.B. Backer, and R.M. Bourdon (1993). Comparison of the effects of different climate change scenarios on rangeland livestock production. *Agricultural Systems* 41:487–502.

177. Turnpenny, J.R., et al. (2001). Integrated models of livestock systems for climate change studies: Two intensive systems. *Global Change Biology* 7:163–170.

178. Bootsma (2002) in note 159.

179. Bryant, C.R., et al. (2000). Adaptation in Canadian agriculture to climatic change and variability. *Climatic Change* 45:181–201.

180. Adams et al. (1999) in note 154.

Adams, R.M., B.H. Hurd, and J. Reilly (1999) in note 70.

US Environmental Protection Agency (1993) in note 70.

181. Ribaudo, M.O. (1986). Regional Estimates of Off-site Damages from Soil Erosion. In The Off-Site Costs of Soil Erosion. Proceedings of a symposium held in May 1985. T.E. Waddell, ed. Washington D.C.: The Conservation Foundation, pp. 29–48.

182. Natural Resources Canada (1999) in note 16.

US Environmental Protection Agency (2003). EPA State Greenhouse Emission Inventories. Available on the EPA web site at *yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsState.html.*

Statistics Canada (2001). Census Analysis Series—A Profile of the Canadian Population: Where We Live. Available on the Statistics Canada website at *geodepot.statcan.ca/Diss/Highlights/Highlights_e.cfm.*

183. Terry, D., C. Guinn, and M. New (2002). State and Local Net Greenhouse Gas Emissions Reduction Programs: Case Studies. Arlington, Va.: Pew Center on Global Climate Change. Available on the Pew Center website at *www.pewclimate.org/states/index1.cfm.*

184. American Council for an Energy-Efficient Economy (2002). Summary table of public benefit programs and electric utility restructuring. Available on the ACEEE website at *www.aceee.org/briefs/mktabl.htm.*

Union of Concerned Scientists (2002). Renewable Energy Standards at Work in the States. Cambridge, Mass.: Union of Concerned Scientists. Available on the UCS website at *www.ucsusa.org/clean_energy/renewable_energy/page.cfm?pageID=47.*

185. American Wind Energy Association (2002). Wind Energy Projects Throughout the United States. Available at *www.awea.org/projects/index.html*

186. Ontario Power Generation (2002). Green Power: Good for Business, Good for the Planet. Available on the Ontario Power Generation website at *www.opg.com/envComm/E_greenPower.asp.*

187. Union of Concerned Scientists (2002). Renewing Illinois. Cambridge, Mass.: Union of Concerned Scientists. Available on the UCS website at *www.ucsusa.org/publication.cfm?publicationID=467.*

188. Elwell, C., and E. Rotenberg (2002). Green Power Opportunities for Ontario. Vancouver, B.C.: David Suzuki Foundation and Toronto, Ont.: Canadian Institute for Environmental Law and Policy.

189. Environmental Law & Policy Center (2001). Repowering the Midwest: The Clean Energy Development Plan for the Heartland. Minneapolis, Minn.: ELPC.

190. Federation of Canadian Municipalities (2002). Forming a Regional Transit System in the Region of Waterloo: Waterloo, Ontario. Available on the FCM website at *www.fcm.ca/scep/case_studies/transportation/waterloo_trans_sum.htm.*

191. Toronto Atmospheric Fund (2001). Toronto Atmospheric Fund 10th annual report. Toronto, Ont.: Toronto Atmospheric Fund. Available on the TAF website at *www.city.toronto.on.ca/taf/.*

Toronto Atmospheric Fund (2002). Moving Beyond Kyoto: Toronto's Emission Reductions 1990–1998 and the Future Outlook. Available on the TAF website at *www.city.toronto.on.ca/taf/reports.htm.*

192. Federation of Canadian Municipalities (2002). Landfill Gas Recovery and Utilization: Toronto, Ontario. Available on the FCM website at *www.fcm.ca/scep/case_studies/waste_management/toronto_waste_sum.htm.*

193. Rabe, B.G. (2002). Greenhouse and Statehouse: The Evolving State Government Role in Climate Change. Arlington, Va.: Pew Center on Global Climate Change. Available on the Pew Center website at *www.pewclimate.org/projects/states_greenhouse.cfm.*

194. US Environmental Protection Agency (2002). The AgSTAR Program. Available on the EPA website at *www.epa.gov/agstar/.*

US Environmental Protection Agency (2002). The Ruminant Livestock Efficiency Program (RLEP). Available on the EPA website at *www.epa.gov/rlep/.*

195. International Council of Local Environmental Initiatives (2002). Cities for Climate Protection Campaign US Participants. Available on the ICLEI website at *www3.iclei.org/us/participants.cfm.*

196. Federation of Canadian Municipalities (2002). Partners for Climate Protection Participants. Available on the FCM website at *www.fcm.ca/scep/support/PCP/pcp_participants.htm.*

197. Chicago Climate Exchange (2002). The Chicago Climate Exchange website at *www.chicagoclimatex.com/html/about.html.*

198. National Round Table on the Environment and the Economy (2002). Canada: Progress on Greenhouse Gas Emissions Trading. Available on the NRTEE website at *www.nrtee-trnee.ca/EmissionsTrading/en/overview_countries_Canada.htm.*

199. Anderson, D., R. Grant, and C. Rolfe (2001). Taking Credit: Canada and the Role of Sinks in International Climate Negotiations. Vancouver, B.C.: David Suzuki Foundation and West Coast Environmental Law.

200. Frumhoff, P.C., D.C. Goetze, and J.J. Hardner (1998). Linking Solutions to Climate Change and Biodiversity Loss Through the Kyoto protocol's Clean Development Mechanism. Briefing paper. Cambridge, Mass.: Union of Concerned Scientists.

Intergovernmental Panel on Climate Change (2000). *Land Use, Land-Use Change, and Forestry.* IPCC special report. Cambridge, U.K.: Cambridge University Press.

201. Burtraw, D., and M. Toman (1998). The Benefits of Reduced Air Pollutants in the US From Greenhouse Gas Mitigation Policies. Available on the Resources for the Future website at *www.rff.org/issue_briefs/summaries/ccbrf7.htm.*

202. Ontario Medical Association (2000). *The Illness Costs of Air Pollution in Ontario.* Toronto, Ont.: Ontario Medical Association.

203. Federation of Canadian Municipalities (2002). Air Quality Advisory Committee: Mississauga, Ontario. Available on the FCM website at *www.fcm.ca/scep/case_studies/air_quality/mississauga_air_sum.htm.*

204. Green Communities Association (2002). Rural Water Stewardship. Available on the GCA website at *www.gca.ca/water.htm.*

205. Michigan Land Use Institute (2001). Liquid gold rush: Citizens call for legislative action. Beulah, Mich.: Michigan Land Use Institute. Available from the MLUI website at *www.mlui.org/publications.asp.*

206. Schneider, K. (1999). Acting as a region to tame sprawl: Grand Rapids leads the way in Michigan. *Great Lakes Bulletin* 4(2):7–12.

207. Great Lakes Information Network (2002). Eurasian Watermilfoil in the Great Lakes Region. Available on the GLIN website at *www.great-lakes.net/envt/flora-fauna/invasive/milfoil.html.*

208. Gleick, P.H., et al. (2002). The Potential Consequences of Climate Variability and Change on the Water Sector. A report of the National Water Assessment Group for the USGCRP. Oakland, Calif.: Pacific Institute for Studies in Development, Environment and Security.

209. Lewandowski, J., and D. Schimmelpfenning (1999). Economic implications of climate change for US agriculture: Assessing recent evidence. *Land Economics* 75: 39–57.

210. Dale, V.H., et al. (2001). Climate change and forest disturbance. *BioScience* 51(9):723–734.

211. Irland, L.C., et al. (2001). Assessing socioeconomic impacts of climate change on US forests, wood product markets, and forest recreation. *BioScience* 51(9):753–764.

Contributing Authors

George Kling, the lead author of this report, is a professor of biology in the Department of Ecology and Evolutionary Biology at the University of Michigan. His areas of specialization include limnology (the study of lakes and streams), climate change, biogeochemistry, and ecosystem science. He has research programs that study the functioning of aquatic ecosystems in the Arctic, the tropics, and the temperate zone. Dr. Kling received a National Academy of Sciences Research Investigator award and a United Nations Sasakawa Certificate of Merit, and he is a National Science Foundation Presidential Faculty Fellow and a fellow of the AAAS. He has participated in over 30 international panels, review boards, and conferences held by NSF, NRC, and UNESCO, many of which involved issues of global change. Dr. Kling received his Ph.D. in 1988 from Duke University.

Katharine Hayhoe is an independent research consultant specializing in the science-policy interface. Her areas of expertise include the impact of human activities on climate, greenhouse gas emissions and control policies, and numerical modeling of the earth-atmosphere system. Ms. Hayhoe received her M.S. in Atmospheric Sciences from the University of Illinois at Urbana-Champaign. Her clients and collaborators span a wide range of government and private agencies on both sides of the border, including Environment Canada, the Environmental Protection Agency, the National Round Table on Energy & the Environment, the Ontario Ministry of Energy & the Environment, and the Department of Energy. Recently, she has been funded by the Illinois-Indiana Sea Grant through the University of Illinois to evaluate projections of climate change for the Great Lakes area. She provided the analyses of historical climate data and future model projections used as the basis of impact assessments throughout the report.

Lucinda Johnson is the Associate Director of the Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota, Duluth. Her research focuses on quantifying the effects of land use and geology on habitat and biota in wetlands and streams. Another research emphasis includes the development of indicators of stream and wetland ecosystem conditions, using amphibians, invertebrates and fish as focal species. As a landscape and aquatic ecologist, she has been involved in research and discussions about the causal factors of frog malformations over the past five years. The majority of her work has taken place in the Midwestern United States and in the Great Lakes Basin, with a particular emphasis on agricultural landscapes. In this report, she contributed to sections about land use patterns and confounding effects of human disturbances on ecosystems affected by climate change, as well as sections on the ecological impacts on rivers, wetlands, and amphibians. Dr. Johnson received her Ph.D. from Michigan State University and has worked in her current position at the Natural Resources Research Institute since 1991.

Richard Lindroth is Professor of Ecology in the Department of Entomology at the University of Wisconsin-Madison. His research interests include the impacts of global environmental change (e.g., elevated carbon dioxide, tropospheric ozone, and UV radiation) on plants and plant-feeding insects. Dr. Lindroth received his Ph.D. in ecology from the University of Illinois-Urbana, followed by an NSF Postdoctoral Fellowship at the University of Wisconsin. In 1997 he received a Fulbright Senior Research Scholar award to study the impacts of enhanced UV radiation in New Zealand. Dr. Lindroth has served on the editorial boards of several journals in ecology, and on grant review panels for the National Science Foundation and US Department of Agriculture. In this report, he contributed to sections dealing with insect responses to climate change.

John J. Magnuson is an Emeritus Professor of Zoology and past Director of the Center for Limnology at the University of Wisconsin-Madison. His research interests are in long-term regional ecology, fish and fisheries ecology, and the effects of climate change and variability on inland waters, biodiversity, and invasions. He played a lead role in the lakes and streams portions of the 1995 and 2001 Assessments by Intergovernmental Panel on Climate Change. He has served on the Science Advisory Boards of the International Joint Commission on Water Quality and the Great Lakes Fisheries Commission. He served on the Ocean Studies Board of the National Research Council and has chaired several Committees for NRC. Dr. Magnuson has authored more than 350 publications and five books and was Principal Investigator of the North Temperate Lakes Long-Term Ecological Research Site. He earned his Ph.D. from University of British Columbia, Canada, in zoology with a minor in oceanography. In this report he contributed to sections on lakes, ice, wetlands, fisheries, and solution strategies.

Susanne Moser is staff scientist for climate change at the Union of Concerned Scientists. Her current work focuses on providing sound scientific information to support policy-making on climate change. Her research interests include climate change impacts on coastal areas, environmental hazards, the human dimensions of global change, and the interaction between science and policy. Dr. Moser received her Ph.D. in Geography from Clark University, Worcester, Mass., and completed a two-year post-doctoral research fellowship at Harvard's Kennedy School of Government before joining UCS. Over the last 10 years, she has participated in reviews of EPA's Global Change Programs, the US Global Change Research Program and its successor, the Climate Change Science Program, as well as of various chapters of IPCC and US National Assessment reports. In this report she contributed to sections dealing with climate change impacts on urban areas, human health, and solutions strategies.

Stephen Polasky holds the Fesler-Lampert Chair in Ecological/Environmental Economics at the University of Minnesota. He is a faculty member of the Department of Applied Economics and of the Department of Ecology, Evolution and Behavior, and is also co-director of Graduate Studies for the Conservation Biology Program. He received his Ph.D. in economics from the University of Michigan in 1986. He is currently serving as a member of the Environmental Economics Advisory Committee of US EPA's Science Advisory Board, as a member on a National Research Council Committee on Assessing and Valuing Services of Aquatic and Related Terrestrial Ecosystems, and as Co-Chair for Core Project 3: Developing the Science of Conservation and Sustainable Use of Biodiversity for DIVERSITAS. His research interests include biodiversity conservation and endangered species policy, integrating ecological and economic analysis, game theory applications to natural resource use, common property resources, and environmental regulation. He recently edited a book entitled *The Economics of Biodiversity Conservation*. In this report he contributed to sections on the economic impacts of climate change and climate change solutions.

Scott Robinson is a professor in the Department of Animal Biology at the University of Illinois. His research interests include the effects of forest fragmentation on migratory birds, especially during the breeding season. Most of his recent work has been in the Midwestern United States, but he has also worked extensively in the Neotropics and in North American grasslands and scrublands. His students also work on effects of global climate change on the timing of migration and on the effects of hydrology on birds of floodplain forests. Dr. Robinson has also been involved in developing management plans for grassland and forest reserves. Dr. Robinson received his Ph.D. from Princeton University. As of May 2003, he will be moving to the Florida Museum of Natural History (University of Florida), where he will be the Katherine Ordway Chair of Ecosystem Conservation. In this report, he contributed to sections on the effects of global climate change on wildlife.

Brian Shuter is a research scientist with the Ontario Ministry of Natural Resources and adjunct professor in the Department of Zoology, University of Toronto. His research has focused on the population dynamics of freshwater fish, and particularly on the role of weather in generating short-term variation in abundance and the role of climate in shaping boundaries of species' distributions. He has worked on populations of smallmouth bass, walleye, and lake trout in the Great Lakes and in the smaller lakes of Algonquin Park. He has authored over 50 papers in the peer reviewed scientific literature, and is a member of the Board of Technical Experts of the Great Lakes Fisheries Commission. Dr. Shuter worked on the limnology and fisheries sections of this report.

Michelle Wander is an associate professor in the University of Illinois' Department of Natural Resources and Environmental Sciences, where she teaches about soil ecology, composition, and processes and advises both graduate and undergraduate students. She has served as the Chair of the North Central Region Committee on Soil Organic Matter and Biochemistry, on USDA-NRI Review Panels for Soil Biology and Biochemistry and Managed Ecosystems, and has participated as an expert on teams evaluating long-term agricultural studies. She is an Associate Editor for the Soil Science Society of America (SSSA) Journal and now serves on the committee for the Special Publication *Soil Carbon Management Guide* as well as the Ad Hoc Committee on Global Enhancement of Soil Organic Matter. Dr. Wander received her Ph.D. in 1992 in Agronomy/Soil Science from the Ohio State University. In this report, she contributed sections on agricultural response to climate change and potential mitigation and adaptation strategies.

Mark Wilson is currently Director of the Global Health Program and Associate Professor of Epidemiology at the University of Michigan, where his research and teaching cover the broad area of ecology and epidemiology of infectious diseases. After earning his doctoral degree from Harvard University in 1985, he worked at the Pasteur Institute in Dakar Senegal (1986–90), was on the faculty at the Yale University School of Medicine (1991–96), and then joined the University of Michigan. Dr. Wilson's research addresses the environmental determinants of zoonotic and arthropod-borne diseases, the evolution of vector-host-parasite systems, and the analysis of transmission dynamics. He is an author of more than 100 journal articles, book chapters, and research reports, and has served on numerous governmental advisory groups concerned with environmental change and infectious disease epidemiology. He recently served as a member of the NRC panel on Climate, Ecosystems, Infectious Diseases and Human Health and the IOM panel on Emerging Microbial Threats in the 21st Century. He contributed to the health impacts sections and solutions in this report.

Donald Wuebbles is Head of the Department of Atmospheric Sciences at the University of Illinois and Professor in that department, as well as in the Department of Electrical and Computer Engineering. His research has emphasized the development and use of mathematical models of the atmosphere to study the chemical and physical processes that determine its structure. He is the author of over 300 scientific articles and directs a number of research projects to improve our understanding of the impacts that human-made and natural trace gases may be having on the Earth's climate, atmospheric chemistry, and ozone. He developed the concept of Ozone Depletion Potentials—used in most policy-making to protect the ozone layer (e.g., the Montreal Protocol and its amendments)—and is co-author of an analogous concept, Global Warming Potentials, currently used to describe greenhouse gases and their potential effects on climate. Dr. Wuebbles has led the development of several new research centers at the University of Illinois, including a center on the regional impacts of climate change on the Midwest. He is a lead author on a number of international assessments related to stratospheric ozone and climate change. Dr. Wuebbles led the analysis of regional effects of climate change for this report.

Donald Zak is a professor in the School of Natural Resources and Environment at the University of Michigan. His research focuses on the function of soil microbial communities in the biogeochemical cycling of carbon and nitrogen in terrestrial ecosystems. He and several colleagues have established large-scale, field experiments to investigate the influences of rising atmospheric CO_2 and O_3 on forests in the upper Great Lakes. They also have initiated long-term experiments to study the influence of atmospheric nitrogen deposition on forest in the region. Dr. Zak serves on the editorial boards of Ecology, Ecological Monographs, and Soil Science Society of America. He received his Ph.D. degree from Michigan State University, conducted post-doctoral research at the University of Minnesota, and has been a Professor at the University of Michigan since 1988. Dr. Zak contributed to sections on forest and forestry impacts as well as impacts on other terrestrial ecosystems in this report.

Steering Committee

A national steering committee provided guidance and oversight to ensure the scientific review and integrity of the report. The Steering Committee members were

Dr. Louis F. Pitelka *(Chair)*, Appalachian Laboratory, University of Maryland Center for Environmental Science, Frostburg, Md.

Dr. Mary Barber, Ecological Society of America, Washington, D.C.

Dr. Christopher Field, Carnegie Institution of Washington, Department of Plant Biology, Stanford, Calif.

Dr. Peter C. Frumhoff, Union of Concerned Scientists, Cambridge, Mass.

Dr. Geoff Heal, Columbia University, Graduate School of Business, New York, N.Y.

Dr. Jerry Melillo, Marine Biological Laboratories, Woods Hole, Mass.

Dr. Judy Meyer, University of Georgia, Institute of Ecology, Athens, Ga.

Dr. William Schlesinger, Duke University, Nicholas School of the Environment, Durham, N.C.

Dr. Steven Schneider, Stanford University, Department of Biological Sciences and the Institute for International Studies, Stanford, Calif.

Confronting Climate Change in the Great Lakes Region

Impacts on Our Communities and Ecosystems

The Union of Concerned Scientists is a nonprofit partnership of scientists and citizens combining rigorous scientific analysis, innovative policy development and effective citizen advocacy to achieve practical environmental solutions. Established in 1969, we seek to ensure that all people have clean air, energy and transportation, as well as food that is produced in a safe and sustainable manner. We strive for a future that is free from the threats of global warming and nuclear war, and a planet that supports a rich diversity of life. Sound science guides our efforts to secure changes in government policy, corporate practices and consumer choices that will protect and improve the health of our environment globally, nationally and in communities throughout the United States. In short, UCS seeks a great change in humanity's stewardship of the earth.

The Union of Concerned Scientists
Two Brattle Square, Cambridge, MA 02238-9105
Phone: 617-547-5552 • Fax: 617-864-9405

E-mail: ucs@ucsusa.org • Web: www.ucsusa.org

Founded in 1915, the Ecological Society of America (ESA) is a scientific, nonprofit organization with more than 7,000 professional members. Through its reports, journals, membership research, and expert testimony to Congress, ESA seeks to promote the responsible application of ecological data and principles to the solution of environmental problems.

The Ecological Society of America
1707 H Street NW, Ste. 400, Washington, DC 20006
Phone: 202-833-8773 • Fax: 202-833-8775

E-mail: esahq@esa.org • Web: esa.sdsc.edu