Lake Superior
Climate Change Impacts and Adaptation

January 2014

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Lake Superior Climate Change Impacts and Adaptation

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Lake Superior Lakewide Action and Management Plan

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Disclaimer: This report reflects the best efforts of the authors to accurately represent and interpret the available literature, expertise, and information on Lake Superior climate change impacts and adaptation. Every effort has been made to ensure the accuracy of the information contained in this report. Suggestions for improvements are welcome.

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City of Thunder Bay, Environment Canada, Great Lakes Commission, Habitat Solutions, Lakehead Region Conservation Authority, Laurentian University, Michigan Department of Environmental Quality, Michigan Technological University, Minnesota Department of Natural Resources, National Oceanic and Atmospheric Administration, National Park Service, Ontario Ministry of the Environment, Ontario Ministry of Natural Resources, The Nature Conservancy, U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, University of Minnesota, University of Wisconsin, and Wisconsin Department of Natural Resources.

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Executive Summary

Changing climate conditions will impact efforts to protect and restore Lake Superior. Current observations in the Lake Superior basin demonstrate that some changes in climate are already occurring, including increases in surface water and air temperatures and a decrease in the extent and duration of ice cover. Projected climate changes could have a range of future potential effects on Lake Superior ecosystems, including a decrease in the abundance of cold water fish and changes to coastal wetlands.

This report synthesizes available science and identifies adaptation strategies and actions for Lake Superior ecosystems. The report provides a structure to track and share climate science related to Lake Superior and outlines potential climate change adaptation strategies and actions that can be implemented in the future. The report focuses specifically on adaptation of Lake Superior ecosystems and does not discuss impacts related to human infrastructure. Similarly, the report does not identify climate change mitigation actions (i.e., greenhouse gas [GHG] emission reductions), but rather serves as a regional resource for complementary initiatives that are promoting the importance of reducing GHG emissions. Projected climate changes are determined from the output of general circulation models (GCMs), which simulate changes in climate under scenarios of future GHG emissions. While specific changes may vary by location, a range of plausible future climate conditions is projected for the Lake Superior region during the 21st century.

What is the Lake Superior Lakewide Action and Management Plan (LAMP)?

In 2012, a protocol amended the Great Lakes Water Quality Agreement (GLWQA) between Canada and the United States. The purpose of the GLWQA is to "restore and maintain the chemical, physical and biological integrity of the waters of the Great Lakes." The GLWQA calls for documentation and coordination of management actions through the development of LAMPs. The Lake Superior LAMP is co-led by the U.S. Environmental Protection Agency and Environment Canada in cooperation with dozens of federal, provincial, state and tribal organizations. For more information, please visit www.binational.net.

Summary of Projected Changes to the Lake Superior Climate

Air Temperature

- Annual average air temperatures are expected to increase in the range of 3 to 4.5 ºC (5 to 8 ºF) by the end of the 21st century, depending on the particular GCM and emissions scenario utilized.

Precipitation

- Annual precipitation is expected to increase in the Lake Superior basin by the end of the 21st century, but only slightly (5 to15%).
- Seasonal shifts are expected, with decreases in summer precipitation and increases in winter precipitation.
- More winter precipitation may fall as rain and less as snow.
- Little or no change is expected in the frequency of lake effect snowfall.
- Increased frequency and intensity of storms are projected for the Great Lakes region, but specific changes for the Lake Superior basin have not been reported.

Water Temperature

- An increase in annual average water temperatures is projected throughout the 21st century, with magnitudes of approximately 5 to 7 ºC (8 to 12 °F), depending on the particular GCM and emissions scenario utilized.

Ice Cover

- The extent of ice cover on Lake Superior is expected to continue to decrease through the 21st century, assuming air temperatures continue to increase. Average February ice cover is projected to be only 2 to 11% for the eastern and western Lake Superior basins by 2090.
- The duration of ice cover is also expected to continue to decrease in the 21st century, perhaps by as much as 1 to 2 months by 2100.

Wind Speeds

- No GCM projections of wind speeds over Lake Superior for the 21st century are available.
- Wind speeds over the lake are likely to increase as the atmospheric surface layer above the lake becomes increasingly destabilized due to increasing air temperatures and lake water temperatures and a reduction in the temperature gradient between air and water.

Lake Water Levels

- Variations in model simulations indicate a high degree of uncertainty in projected future lake levels.
- Lake Superior water levels may decrease slightly, beginning mid-century, on the order of 0.1 to 0.2 m (0.3 to 0.7 ft).
- Periodic increases in lake water levels are also possible.
- The magnitude of any changes in Lake Superior water levels are expected to be less than for the other Great Lakes.
- Overall, decreases in Lake Superior water levels similar to those observed over the past 20 years are likely, although they will probably not be as large as previous studies have predicted, and periodic higher-than-average levels are possible.

Onset of Seasons

- Spring and summer are expected to begin earlier and the growing season to last longer in the Lake Superior basin through the 21st century.
- The length of the frost-free season in the Midwestern U.S., including the southern Lake Superior basin, may increase by an additional 4 to 8 weeks through the end of the 21st century. In addition, the date of the last spring frost is expected to become earlier by as much as 15 to 35 days, and the date of first autumn frost will be delayed by up to 35 days.
- The length of the growing season at Pukaskwa National Park in Ontario, on the northern shore of Lake Superior, may increase by 22.6 days by the end of the 21st century.

Projected changes in climate are expected to have a variety of effects on the physical, chemical, and biological aspects of Lake Superior ecosystems in the 21st century. Some of the most significant potential effects are described in the table below.

Summary of Expected Effects on Lake Superior Ecosystems

Coastal Wetlands

- Coastal wetlands could progress toward terrestrial ecosystems.
- If Lake Superior water levels decline below historical annual averages, possible results include:
  - Limited extent of marshes that serve as breeding and nursery areas for fish and wildlife,
  - Inability of fish to reach spawning areas,
  - Reduced fisheries production,
  - Decline in habitat for waterfowl migration,
  - Decline in wildlife populations (e.g., muskrat) due to starvation, disease, and increased attacks from predators.

Forest Habitat

- Higher air temperatures and changes in precipitation patterns may result in a northward shift in forest habitat. Forest species throughout the Lake Superior region are expected to experience increased mortality and eventually be replaced by species from forests further south.
- Increased mortality of forested regions may compromise their value as carbon sinks.

Shoreline Effects

- Stronger wave action and lower water lake levels may leave shoreline regions more vulnerable to erosion and damage.
- Over half of Apostle Islands National Lakeshore shoreline has a high to very high potential for shoreline change, particularly gravel and sand beaches not immediately backed by bluffs.

Toxic Chemicals and Pollutants

- Variations in the frequency and intensity of precipitation may increase concentrations of toxic pollutants in Lake Superior, with adverse effects on wildlife.
- Potentially lower lake water levels may expose formerly submerged toxic sediments and cause existing levels of nutrients, contaminants, and sediments to become more concentrated.

Lake Superior Water Quality

- The dissolved oxygen content in Lake Superior may decrease due to higher water temperatures and an increase in the length of the summer stratification season, potentially causing the overall productivity of the lake to decrease.
- A potential increase in the frequency and extent of algal blooms caused in part by warmer waters could degrade water quality.

Phytoplankton/Zooplankton

- Warmer Lake Superior surface water may impact the life cycle of phytoplankton, decreasing primary productivity and reducing food available for zooplankton and the prey of predator fish.
- Warmer Lake Superior surface water may also cause copepods (the largest component of zooplankton in Lake Superior) to become smaller and more abundant, which may result in an unknown impact on the lake's aquatic ecosystem and food web.

Fish

- Warmer Lake Superior waters may cause a decrease in the abundance of cold water fish species (e.g., trout and salmon) and an increase in the abundance of warm water fish species (e.g., bass and carp).
- Overall fish productivity may be lowered as a result of changes in the extent and duration of thermal stratification, timing of vertical turnover, and wind-driven currents, which may impact the entire food chain and lead to declines in the population and health of fish and other species dependent upon cold, well-oxygenated water.

Mammals

- Increasing air temperatures and changes in snow depth are causing declines in populations of small northern mammal species (e.g., woodland deer mice, southern red-backed voles, woodland jumping mice, northern flying squirrels, least chipmunks) and foraging animals (e.g., deer), which are expected to continue.
- Increasing air temperatures may decrease the abundance of mammals in predator/prey relationships, such as lynx/hare in Minnesota and wolf/moose in Isle Royale National Park.

Birds

- Climate change may cause shifts or losses of suitable habitats for many bird species in the Lake Superior region, such as loons and ruffed grouse, as well as several general categories of birds, including warblers, shorebirds, and wintering birds.
- A warmer climate may benefit several year-round resident bird species (e.g., chickadees, woodpeckers, northern cardinals) and allow southern bird species to move into the Lake Superior region.

Trees and Plants

- Climate change will likely exacerbate existing stresses on trees, including drought, wind, fires, and insects.
- Climate change may cause shifts or losses of suitable habitats for many tree species in the Lake Superior basin, such as pine, spruce, maple, and birch species.
- A warmer climate may allow the suitable habitat for many tree species to increase, such as oak and hickory species.
- Warmer air temperatures and lower lake water levels associated with climate change may reduce the habitat for northern boreal plant species and disjunct arctic and sub-alpine plant species that live along the coast of Lake Superior.

Invasive Species

- Higher lake water temperatures may permit increases in the populations of aquatic invasive species in Lake Superior, such as Sea Lampreys[1] and zebra and quagga mussels.
- Increasing air temperatures may enhance the spread of invasive pests in the Lake Superior region, such as the gypsy moth, emerald ash borer, forest tent caterpillar, and spruce budworm.
- The proliferation of *Phragmites australis* (common reed) will be favored by lower Lake Superior water levels and higher water temperatures that may result from climate change.
- It is not clear how warmer lake water associated with climate change will affect the spread of viral hemorrhagic septicemia (VHS) in Lake Superior.

Adapting to climate change is critical for management agencies to maintain diverse, abundant populations of native species. Future ecosystem restoration and protection of investments must respond to the inevitable changes in climate that have begun to occur. This report outlines both the current knowledge of climate change and its impacts in the basin, as well as adaptation opportunities that may help Lake Superior ecosystems adapt to changing climate conditions. The report was developed with input from academia, state/provincial agencies, federal agencies, tribes/First Nations, and environmental groups. The report complements climate plans that have been developed at state, provincial, tribal, and federal levels. While reducing GHG emissions is an important component of a climate response strategy, the report focuses on understanding and managing, rather than mitigating, climate change.

To help Lake Superior's ecosystems adapt to a changing climate, potential climate adaptation actions are presented. These actions are organized around six broad adaptation categories:

[1] Common names of fish are capitalized throughout this document per the April 21, 2009 decision by the American Fisheries Society and the American Society of Ichthyologists and Herpetologists Joint Names Committee.

1 Manage Non-Climate Stressors,
2 Manage Habitats, Species, and Ecosystem Functions,
3 Conserve and Connect Habitat,
4 Enhance Adaptive Management Capacity,
5 Increase Knowledge, and
6 Provide Public Outreach and Motivate Action to Adapt.

Section 4 presents the full list of potential adaptation strategies and actions for assisting Lake Superior ecosystems in adapting to climate change.

List of Abbreviations and Acronyms

AIS	Aquatic Invasive Species
AMIC	Annual Maximum Ice Concentration
ANSI	Area of Natural and Scientific Interest
AOC	Area of Concern
CAKE	Climate Adaptation Knowledge Exchange
CCCSN	Canadian Climate Change Scenarios Network
CCSM	Community Climate System Model
CCSP	Climate Change Science Program
CCTP	Climate Change Technology Program
CPI	Change-Potential Index
CSMI	Cooperative Science and Monitoring Initiative
ER	Eco-region
GCM	General Circulation Model
GHG	Greenhouse Gas
GLCCSESN	Great Lake Climate Change Science and Education Systemic Network
GLIFWC	Great Lakes Indian Fish and Wildlife Commission
GLISA	Great Lakes Integrated Sciences and Assessments
GLOS	Great Lakes Observing System
GLRI	Great Lakes Restoration Initiative
GLWQA	Great Lakes Water Quality Agreement
IJC	International Joint Commission
IPCC	Intergovernmental Panel on Climate Change
IUGLS	International Upper Great Lakes Study
KBIC	Keweenaw Bay Indian Community
LAMP	Lakewide Action and Management Plan
MCAC	Michigan Climate Action Council
MCC	Michigan Climate Coalition
MCCAG	Minnesota Climate Change Advisory Group
MCMP	Michigan Coastal Management Program
MODIS	MODerate resolution Imaging Spectroradiometer
MOU	Memorandum of Understanding
mph	Miles Per Hour
NASA	National Aeronautics and Space Administration
NIACS	Northern Institute of Applied Climate Science
NMCA	National Marine Conservation Area
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OCCIAR	Ontario Centre for Climate Impacts and Adaptation Resources
PCB	Polychlorinated Biphenyl
TNC	The Nature Conservancy
U.S. EPA	United States Environmental Protection Agency
USGCRP	U.S. Global Change Research Program
VHS	Viral Hemorrhagic Septicemia
WCA	Wetland Conservation Act

WICCI	Wisconsin Initiative on Climate Change Impacts
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

1 Introduction

1.1 Lake Superior

Lake Superior is the largest freshwater lake in the world, with a surface area of 82,100 km^2 (31,700 mi^2), and it holds approximately 10% of the world's surface fresh water. Located upstream (north and west) of the other Great Lakes, Lake Superior is also the coldest and deepest of the Laurentian Great Lakes, with an average depth of 147 m (483 ft) and a maximum depth of 405 m (1,330 ft) (Figure 1). The drainage basin of Lake Superior, shown in Figure 2, is an additional 127,686 km^2 (49,300 mi^2) in area; 85% of the drainage basin is forested, 10.4% is water, 1.7% is agriculture, 1.5% is developed, and 1.0% is wetland (Beall, 2011).

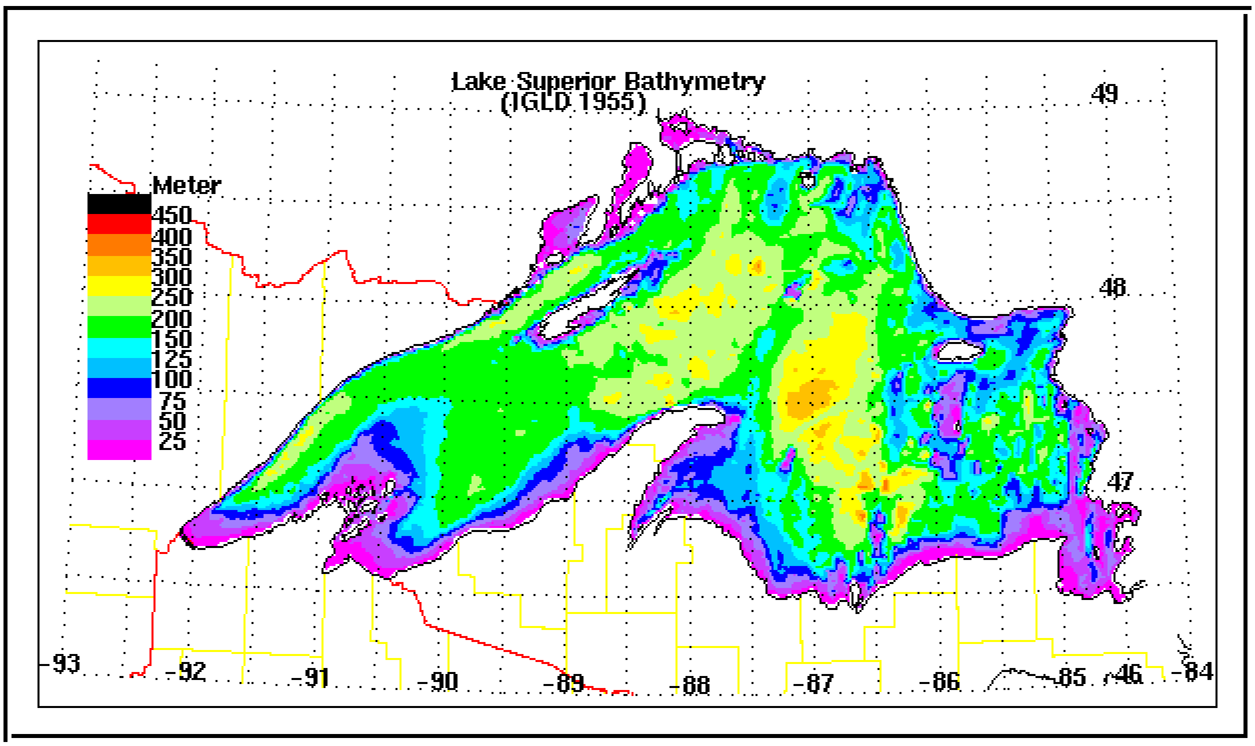

Figure 1. Lake Superior bathymetry (depth). [Image courtesy of NOAA Great Lakes Environmental Laboratory (http://www.glerl.noaa.gov/pr/ourlakes/lakes.html)]

Lake Superior is a unique natural resource that supports an abundance of aquatic communities whose ecological health is vulnerable to changing climatic conditions. The Lake Superior basin hosts a number of natural resources and protected areas that support native plant and animal species and may be sensitive to changing climate conditions. A map highlighting many of the identified important habitats in the Lake Superior basin is located at http://www.nrri.umn.edu/lsgis2/data/importanthabitat.html. One Canadian and five U.S. national park units are located on Lake Superior, shown in Figure 3: Pukaskwa National Park, Isle Royale National Park, Grand Portage National Monument, Apostle Islands National Lakeshore, Keweenaw National Historical Park, and Pictured Rocks National Lakeshore. The basin encompasses portions of four U.S. national forests (Hiawatha, Ottawa, Chequamegon-Nicolet, and Superior, including a portion of the Boundary Waters Canoe Area Wilderness), two U.S. National Wildlife Refuges (Huron and Whittlesey Creek), and one National Estuarine Research Reserve, which is located in the St. Louis River. Located in the northern part of Lake Superior, Parks Canada's proposed Lake Superior National Marine Conservation Area (NMCA) would be the largest freshwater marine conservation area in the world, encompassing over 10,000 km^2 (3,861 mi^2) of protected wildlife habitat (U.S. Environmental Protection Agency [U.S. EPA] and Environment Canada, 2006). The basin includes many state and provincial parks, such as Sleeping Giant and Lake Superior Provincial Parks (Ontario), Fort Wilkins State Park (Michigan), Porcupine Mountains Wilderness State Park (Michigan), and Split Rock Lighthouse State Park (Minnesota). Ontario has a total of 12 provincial parks in the basin. In addition, more than a dozen Areas of Natural and Scientific Interest (ANSIs) in the Lake Superior basin complement Ontario's provincial parks and conservation reserves. Located on both public and private lands, ANSIs are areas of land and water containing natural landscapes or features that are not found in protected areas.

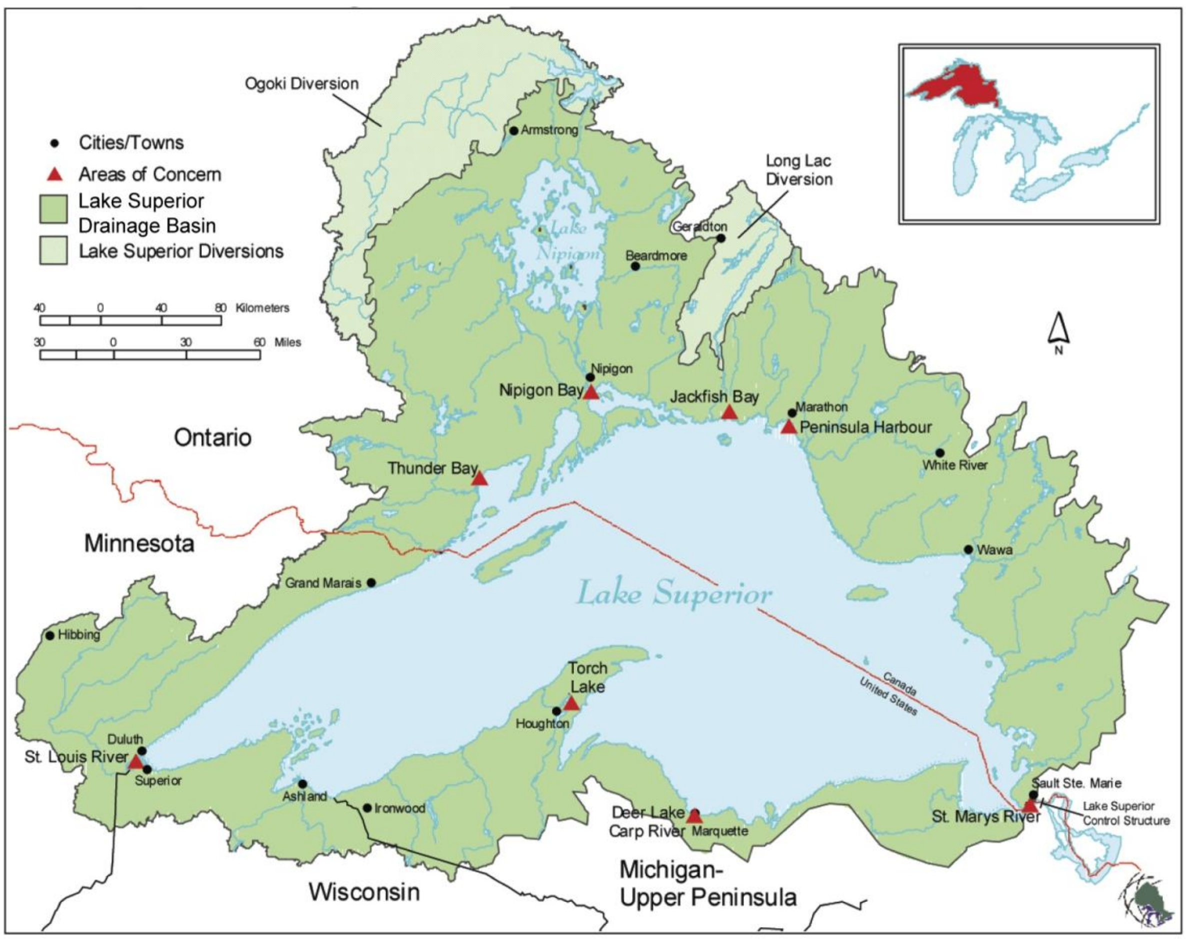

Figure 2. Lake Superior drainage basin. [Image courtesy of Environment Canada]

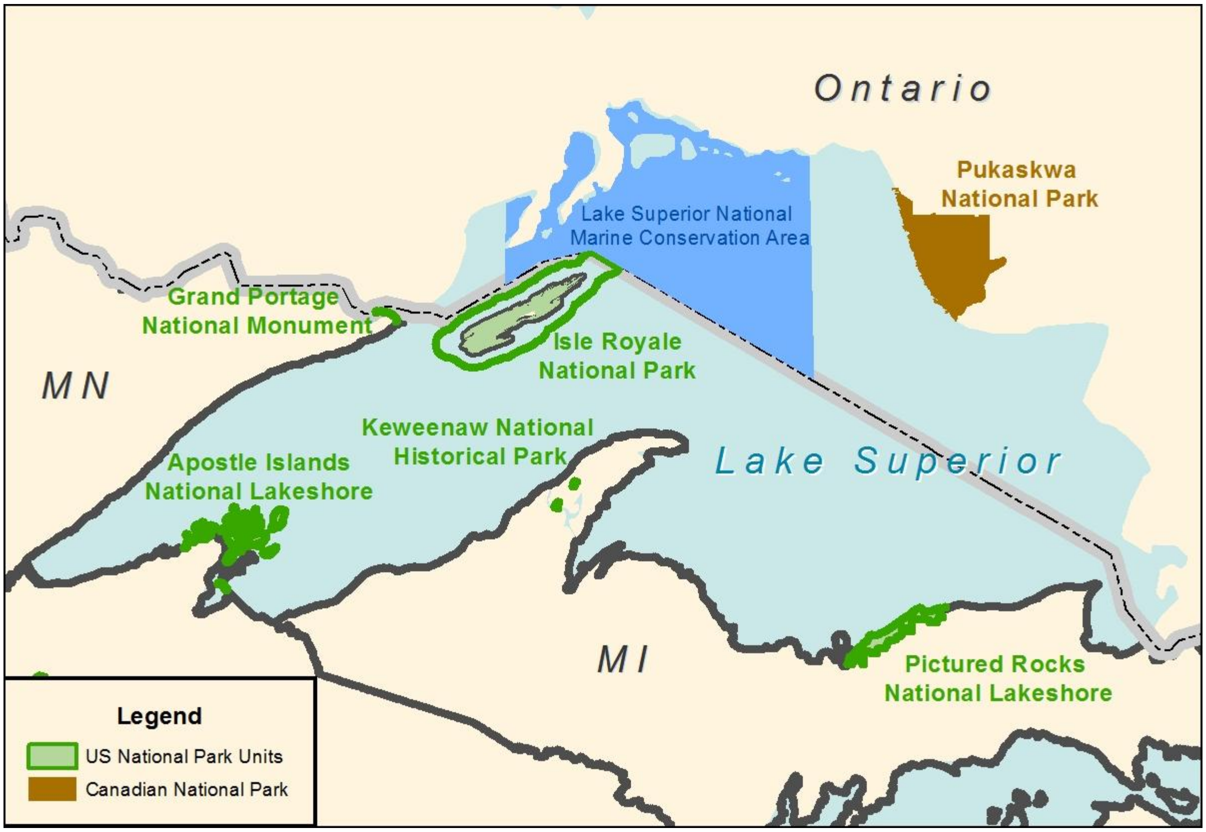

Figure 3. National parks and conservation areas in the Lake Superior basin.

The Lake Superior ecosystem is in generally good condition. The fisheries are healthy, and the lower food web is robust. Legacy contaminants are generally decreasing or remaining stable across the Lake Superior basin, with a few exceptions. Forest cover has increased in the basin since the 1980s, although the composition of the forests is changing in some locations.

Although Lake Superior is still considered the most pristine of the Great Lakes and has many protected areas, it faces a variety of ongoing challenges, such as the spread of invasive species, declines in the populations of some aquatic species, primarily as a result of habitat loss and shoreline development, and land use changes. Hydropower dams are poised to increase in the Lake Superior basin, which will impact fish habitat and also release pulses of mercury when lands are flooded. Concentrations of legacy pollutants in Lake Superior are continuing to cause fish advisories and exceedances of water quality standards. In addition, concentrations of some substances of emerging concern, such as flame retardants, are increasing in the region. Mining activities and explorations have also greatly increased in the Lake Superior basin in recent years, with associated environmental impacts (Schuldt, 2011). The basin also includes seven Areas of Concern (AOCs): four in Canada and three in the U.S. AOCs are locations that have experienced environmental degradation and are in various stages of remediation (www.epa.gov/glnpo/aoc/index.html). In addition to all of these stresses, climate change impacts are being observed in the Lake Superior ecosystem.

Ecosystem Services

Lake Superior's ecosystems provide a wide benefit to the people around it. Ecosystem services are the benefits people obtain from ecosystems. Humans are fundamentally dependent on the flow of ecosystem services, which can be organized into four general categories (Millennium Ecosystem Assessment, 2005):

- **Provisioning Services** are the products obtained from ecosystems (e.g., food, fresh water, timber, fiber),
- **Regulating Services** are the benefits obtained from the regulation of ecosystem processes (e.g., stable water levels, disease prevention, water purification),
- **Cultural Services** are the non-material benefits people obtain from ecosystems (through spiritual enrichment, cognitive development, reflection, recreation, aesthetic experiences, etc.), and
- **Supporting Services** are the ecosystem services that are necessary for the production of the other categories of ecosystem services (e.g., nutrient cycling, soil formation, primary production, photosynthesis).

Although the value of Lake Superior's ecosystem services has not been fully appraised, Lake Superior is recognized as a unique natural resource that provides value to human society in a number of ways. Lake Superior contains 9% of the world's surface fresh water. Lake Superior's ecosystems provide economic value to society through tourism, recreation, and renewable resources, such as fish and lumber. Lake Superior's ecosystems are of cultural value to tribes and First Nations who depend on coastal resources to maintain their traditional ways of life. Furthermore, viewing one of the many natural landscapes in the basin can be an inspirational experience.

1.2 Climate Change and Climate Change Adaptation

A growing body of evidence suggests that the Earth's climate is changing in a significant way. Scientists have documented changes at the local, regional and global scales in multiple variables, including air temperature, water temperature, and precipitation. These changes are attributed to observed increases in levels of greenhouse gases (GHGs), such as carbon dioxide, in the atmosphere. Carbon dioxide and other GHGs are added and removed from the atmosphere through various naturally occurring and human processes. For example, carbon dioxide can be added by the human process of burning fossil fuels and removed by the natural process of plant respiration. The result of all of these processes is a net gain of carbon dioxide that is being added to the atmosphere faster than it is being removed, and is therefore accumulating over time. In the atmosphere, carbon dioxide acts as an insulator to retain infrared radiation emitted by the Earth's surface. This process causes the earth's air temperature to increase, which has a domino effect on many other environmental variables and processes, such as water temperature, atmospheric circulation, and precipitation patterns.

Projections of future climate change are derived from the output of general circulation models (GCMs). GCMs are complex models that simulate atmosphere, ocean, and land processes. They typically project changes in temperature and precipitation for a given region, from which changes in related climate parameters (e.g., lake water temperature, ice cover, wind speed over the lake, lake water levels) are derived. GCMs generally have relatively low spatial resolutions, on the order of 400 to 125 km (249 to 78 mi), and downscaling methods are typically used to obtain projections on local and regional scales, such as for the Lake Superior region.

GCMs simulate changes in climate under scenarios of future GHG and aerosol emissions. Scenarios are internally consistent narratives of plausible future states that may evolve from present conditions, given various driving forces (Groves and Lempert, 2007). Scenarios are used when reliable projections of future conditions are not available, as is the case for climate change. They attempt to constrain the range of plausible future conditions, based on climate and socio-economic variables. Methods for constructing climate change scenarios are described by the Intergovernmental Panel on Climate Change (IPCC) (2000). Characteristics of the four basic scenarios used for current GCM projections are listed in Table 1. At present, it is not possible to predict with certainty which scenario is most likely to occur. GCMs that utilize a range of climate scenarios provide an indication of the most likely future climate conditions.

What is Climate Change Adaptation?

Adaptation is "the adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities."

– *Intergovernmental Panel on Climate Change (IPCC, 2007a)*

Some of the effects of climate change have already been observed, and significant changes are expected to occur in the 21st century. Adapting to climate change is critical for management agencies to maintain diverse, abundant, and healthy populations of native species. Adapting to climate change involves the development of practical, cost-effective measures and technologies that allow individuals, businesses, governments, and others to reduce an ecosystem's vulnerability to climate change impacts. Climate adaptation also requires careful planning to manage changing resources and necessitates continued investment in science and analytical tools to understand and predict future climate scenarios (Interagency Climate Change Adaptation Task Force, 2010).

Table 1. Summary of IPCC emissions scenarios for GCMs. [Adapted from IPCC, 2000]

Scenario	Economic Development	Global Population	Technology Changes	Theme
A1	Very rapid	Peaks around mid-21st century and declines thereafter	Rapid introduction of new and more efficient technologies	Convergence among regions; increased cultural and social interactions
A2	Regionally oriented	Continuously increasing	Slower and more fragmented than A1, B1, and B2	Self-reliance and preservation of local identities
B1	Rapid change toward service and information economy	Same as A1	Introduction of clean and resource-efficient technologies	Global solutions to economic, social, and environmental sustainability
B2	Intermediate levels of economic development	Continuously increasing, but not as fast as A2	Less rapid and more diverse changes than A1 and B1	Local solutions to economic, social, and environmental sustainability

1.3 Purpose of the Report

The chemical, physical, and biological aspects of Lake Superior's ecosystems are susceptible to changes in climate. Lake Superior's fish, wildlife, and water quality are, to a great extent, temperature dependent. Warmer conditions and other effects of climate change will increase the susceptibility of Lake Superior ecosystems to invasive species, threaten the ability of native habitat to survive, drive changes in species composition, and disrupt the water balance (Hall et al., 2007; Chiotti and Lavender, 2008; Galatowitsch et al., 2009; Swanston et al., 2011). There is evidence that some projected changes in climate are already occurring in the Lake Superior basin, including increases in surface water and air temperature, and decreases in ice cover (discussed in Section 2.1). These climate changes will have a myriad of impacts on ecosystems in the Lake Superior region, and some effects are already being felt. For example, in Isle Royale National Park, substantial declines in moose and wolf populations in recent years have been linked to a warmer climate (Lenarz et al., 2009), and higher temperatures have enabled ticks carrying Lyme disease to reach Isle Royale (Saunders et al., 2011). Wild rice, a culturally significant plant to the Lake Superior Band of Chippewa, has experienced increased competition from invasive species and is susceptible to potential fluctuations in water levels arising from climate change (Hoene, 2010). Future ecosystem restoration and protection investments must respond to the inevitable changes in climate that have begun to occur.

Recognizing the need to prepare for, manage, and adapt to the observed and projected changes in climate, this report identifies actions that are necessary for Lake Superior's habitats, species, and water quality to best adapt to a changing climate. This report responds to the Great Lakes Water Quality Agreement (GLWQA) obligation to consider climate change impacts in the implementation of the Agreement. This report complements existing climate change plans that have been developed by Michigan, Minnesota, Wisconsin, and Ontario, and it supports the recommendations of the Great Lakes Restoration Initiative Action Plan (U.S. EPA Science Advisory Board, 2012). While reducing GHG emissions is an important component of a climate response strategy, this report focuses on climate change adaption actions, rather than identifying actions to reduce GHG emissions (mitigation).

The adaptation actions outlined in Section 4 of this report seek to:

1. Maximize the ability of Lake Superior's ecosystems to adapt to climate change risks.
2. Address changing resources and management needs arising from climate change.
3. Outline science and monitoring priorities that support the identified actions, address key uncertainties and assumptions, and contribute to the future collection of information and adjustment of actions, as necessary.

1.4 The Lake Superior LAMP

The GLWQA, as amended in 2012, represents a shared commitment by Canada and the U.S. to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes (U.S. EPA and Environment Canada, 2012). The GLWQA calls for the development and implementation of Lakewide Action and Management Plans (LAMPs) that take an ecosystem approach to addressing, on a lakewide scale, environmental stressors that adversely affect the waters.

The Lake Superior LAMP builds from a 20-year history of successful coordination of Canadian and U.S. federal, provincial, state, tribes/First Nations, and the public in restoring and protecting the lake. The LAMP takes action to achieve shared Lake Superior ecosystem objectives and the goals of the Zero Discharge Demonstration Program. LAMP initiatives, such as the *Aquatic Invasive Species Complete Prevention Plan*, allow the LAMP to identify the most worthwhile actions and track results.

In 2008, the Lake Superior LAMP formally adopted shared objectives to investigate the impacts of climate change and to develop adaptation strategies. Many LAMP organizations are already taking actions to adapt to climate change. This history and experience has positioned the Lake Superior LAMP to facilitate and coordinate adaptation actions on a lakewide scale to address climate change impacts.

1.5 Methodology

Several climate change vulnerability and adaptation assessments were used in the development of this report (e.g., United Nations Framework Convention on Climate Change, 2008; IPCC, 2001). This report compiles assessments of climate change vulnerabilities and published adaptation actions for the Lake Superior region from the existing literature. It does not attempt to specify the relative severity of anticipated changes in climate or impacts on ecosystems in the Lake Superior basin. Throughout the report, terms such as “may,” “could,” “suggest,” and “likely” are used in a general sense and do not convey any specific, defined levels of probability of expected outcomes.

Expert judgment was utilized to evaluate the vulnerabilities and to select adaptation actions that meet multiple criteria, namely the objectives outlined for this report and the LAMP’s ecosystem goals for the Lake Superior basin. To solicit expert judgment, the Lake Superior LAMP recruited an Expert Group of participants from academia, state/provincial agencies, federal agencies, tribes/First Nations, and environmental groups with expertise in issues related to changing climate conditions in the Lake Superior region.

During various stages of report development, members of the Lake Superior LAMP and Expert Group provided comment on a) the compilation of climate science and vulnerabilities presented in Section 2, b) the discussion of existing climate programs and policies in Section 3, and c) the synthesis of proposed adaptation options in Section 4. The Expert Group also provided insight into gaps and uncertainties related to anticipated impacts on the Lake Superior ecosystem. Pooled judgments of Expert Group members were combined to select adaptation actions for Lake Superior ecosystems from the range of adaptation measures identified from the literature.

2 Expected Impacts of Climate Change on Lake Superior Ecosystems

2.1 Regional Climate Change Projections for Lake Superior

2.1.1 Historical Climate of the Lake Superior Basin

Before addressing expected impacts to the Lake Superior region associated with climate change, it is necessary to understand the historical climate as a baseline for future changes. The Lake Superior basin currently has a mid-latitude continental climate, with warm summers and cold winters. Figure 4 illustrates the annual range of average monthly high and low temperatures, for the period 1961-1990, for Duluth, MN, as a representative location in the Lake Superior basin. Winter low temperatures average approximately -15 to -20 °C (5 to -4 ºF), while summer high temperatures average around 20 to 25 °C (68 to 77 ºF). Some areas experience colder or warmer conditions, depending on their exact location. Figure 5 shows the corresponding annual monthly average total precipitation for Duluth for the period 1961-1990. Although local amounts of precipitation vary, precipitation falls year round in the Lake Superior region, and the largest amounts of precipitation (measured as liquid equivalent) generally fall during the summer due to contributions from thunderstorms and other convective systems (World Meteorological Organization [WMO], 2011; Hayhoe et al., 2010). However, the eastern portion of the basin tends to receive higher amounts of precipitation in the fall and winter due to the effect of the lake.

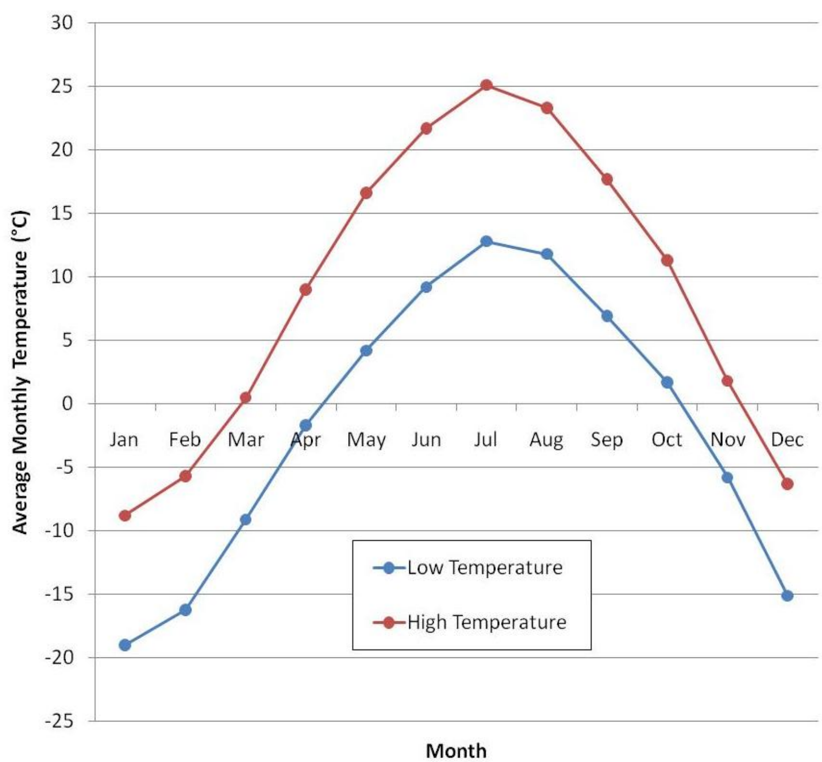

Figure 4. Observed historical monthly average daily low (blue line) and high (red line) temperatures (°C) for Duluth, Minnesota, for the period 1961-1990. [Data from WMO, 2011]

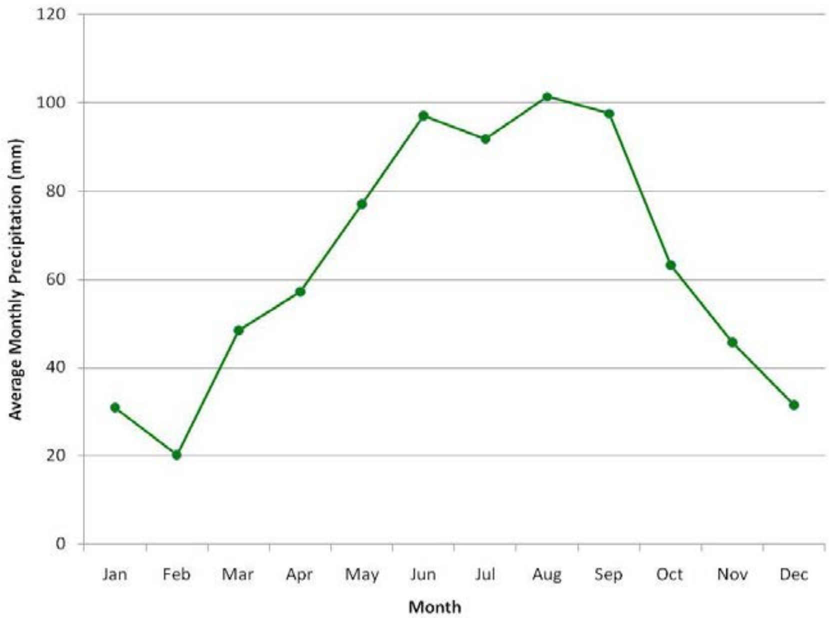

Figure 5. Observed historical monthly average total precipitation (mm) for Duluth, Minnesota, for the period 1961-1990. [Data from WMO, 2011]

Lake Superior itself has a strong influence on the climate of the surrounding region, creating localized microclimates that feature moderated temperatures, lake effect snowfall, and the lake breeze. The moderating effect of the lake results in cooler temperatures during the summer and warmer temperatures in the winter for areas located along the shore of Lake Superior compared to inland locations (Minnesota Department of Natural Resources, 1999; Wisconsin Initiative on Climate Change Impacts [WICCI], 2011; Environment Canada, 2005). Figure 6 demonstrates the effect of Lake Superior on coastal areas of Ontario during the winter, causing January average temperatures in coastal communities to be warmer on average than inland areas at the same latitude (Environment Canada, 2005).

Lake effect snowfall occurs during the fall and winter when cold, dry air passes over the relatively warmer Lake Superior and absorbs heat and moisture from the open water. The enhanced moisture is deposited as snow on the downwind side of the lake, typically the southern and eastern shores of Lake Superior. In these locations, contributions from lake effect snow can result in significantly higher annual snowfall amounts compared to inland areas. For example, northern Iron County in Wisconsin typically receives 2,540 mm (100 in.) of snow per year, more than any other area in Wisconsin (Swanston et al., 2011). Figure 7 illustrates the variation in annual average precipitation along the Canadian coast of Lake Superior due to lake effect snow. The coastal region between Wawa and Sault Ste. Marie, Ontario, on the eastern shore of Lake Superior, receives over 1,250 mm (49.2 in.) of snow per year, making it the snowiest region in Ontario due to lake effect enhancement (Environment Canada, 2005).

The lake breeze is a thermally produced wind that blows during the day from the surface of Lake Superior inland toward the shore. It is caused by the difference in daytime heating rates between the surface of the land, which heats up faster, and the surface of the lake, which heats up more slowly. Lake breezes typically occur in the spring and early summer, when the surface of Lake Superior is still relatively cold. Figure 8 is an image of the western portion of the Lake Superior basin on May 20, 2010 from the MODerate resolution Imaging Spectroradiometer (MODIS) on the National Aeronautics and Space Administration's (NASA's) Terra satellite. The distinctive inland cloud line associated with the lake breeze is evident in the satellite image. Cooler air from the lake blows inland, warms, and rises, forming cumulus clouds. The strip of land around the lake that is under the influence of the lake breeze has clear, cloud-free skies. In some cases, cumulus clouds along the lake breeze front can build during the morning and develop into rain showers and even thunderstorms during the afternoon.

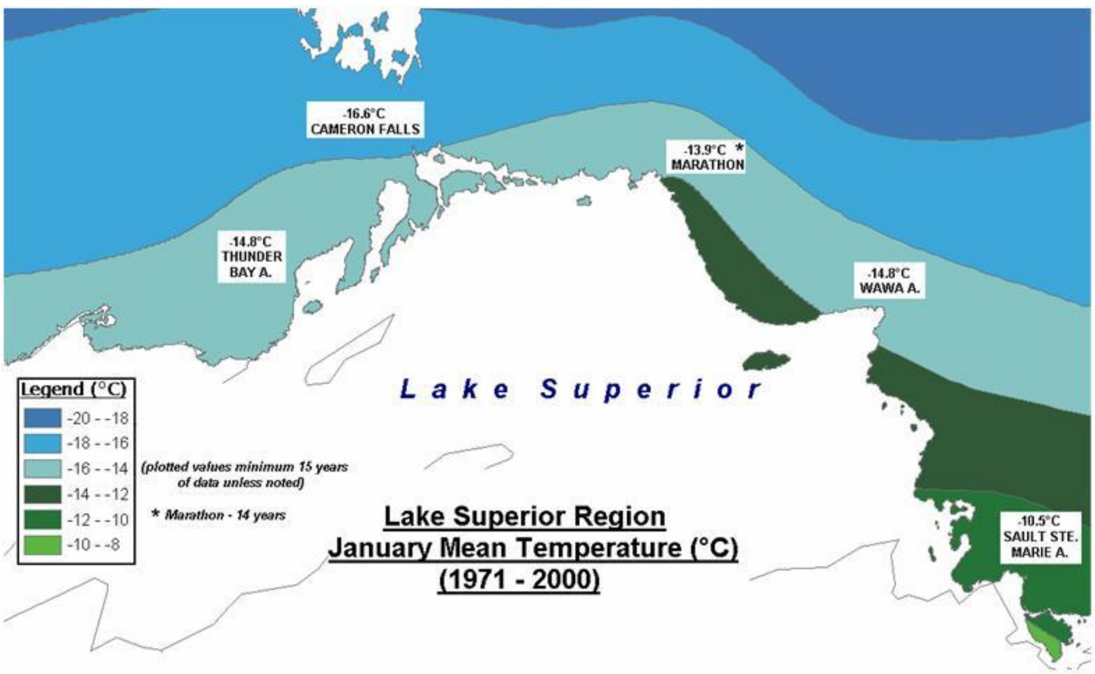

Figure 6. Observed historical January average air temperatures (ºC) for the portion of Ontario that borders Lake Superior, for the period 1971-2000. [Image courtesy of Environment Canada, 2005]

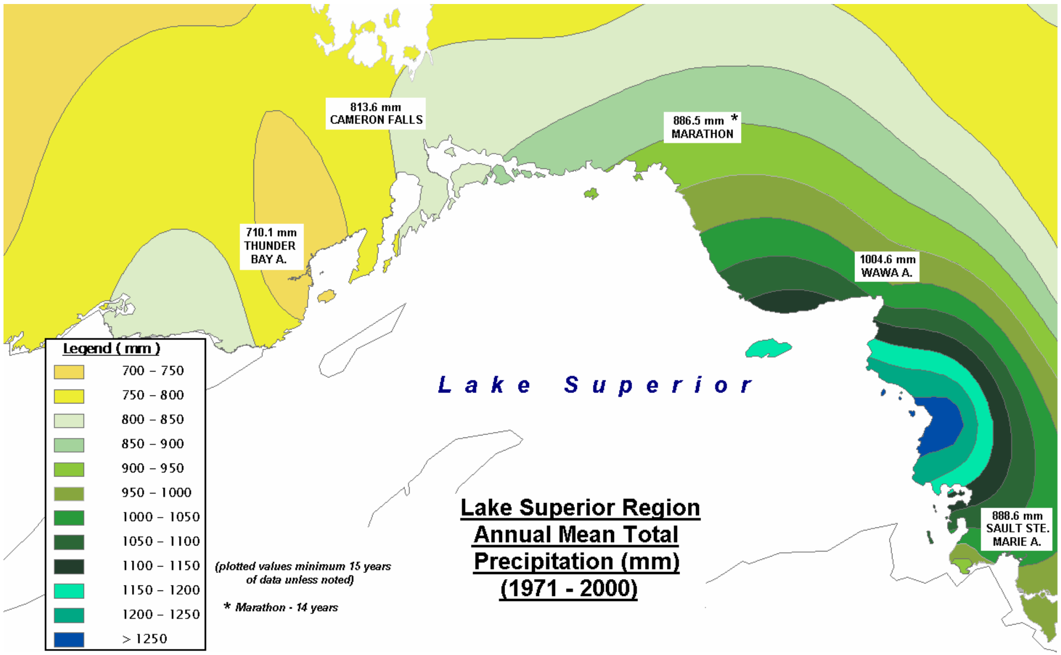

Figure 7. Observed historical annual average precipitation (mm) for the portion of Ontario that borders Lake Superior, for the period 1971-2000. [Image courtesy of Environment Canada, 2005]

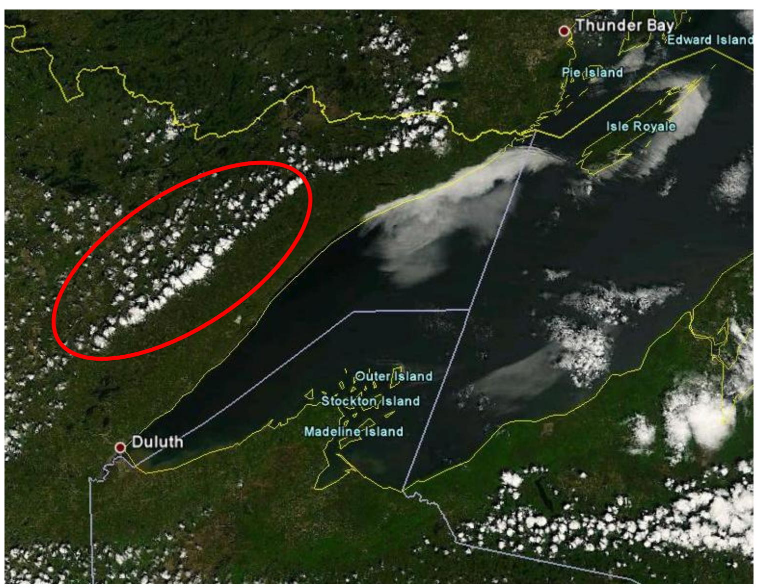

Figure 8. MODIS true color satellite image showing the distinctive cloud line around the periphery of Lake Superior associated with a lake breeze on May 20, 2010. [Image courtesy of the MODIS Today: USA Composite website, http://ge.ssec.wisc.edu/modis-today/]

2.1.2 Summary of Expected Climate Change Impacts

It is now generally accepted in the scientific community that anthropogenic climate change is occurring and is impacting global ecosystems (IPCC, 2007b). A variety of changes to the climate in the Lake Superior region are anticipated during the course of the 21st century, with specific changes varying by site. These changes are described in detail in Sections 2.1.3-10. Key expected changes include:

- Increase in annual average air temperatures,
- Slight increase in annual average precipitation,
- Change in seasonal precipitation patterns – less precipitation in summer and more precipitation in winter,
- Change in precipitation type – more precipitation falling as rain and less as snow, but little or no change in the frequency of lake effect snow events,
- Increase in annual average lake water temperatures,
- Increase in the length of the summer temperature stratification season,
- Reduction in the extent and duration of ice cover on Lake Superior,
- Increase in wind speeds over Lake Superior,
- Increase in the rate of evaporation from Lake Superior, resulting in slightly lower water levels, and
- Increase in the length of the growing season.

Historical observations suggest that many of these changes are already occurring in the Lake Superior region. The expected changes in the climate of the Lake Superior basin are similar to those anticipated for the entire Great Lakes basin and are summarized in Figure 9.

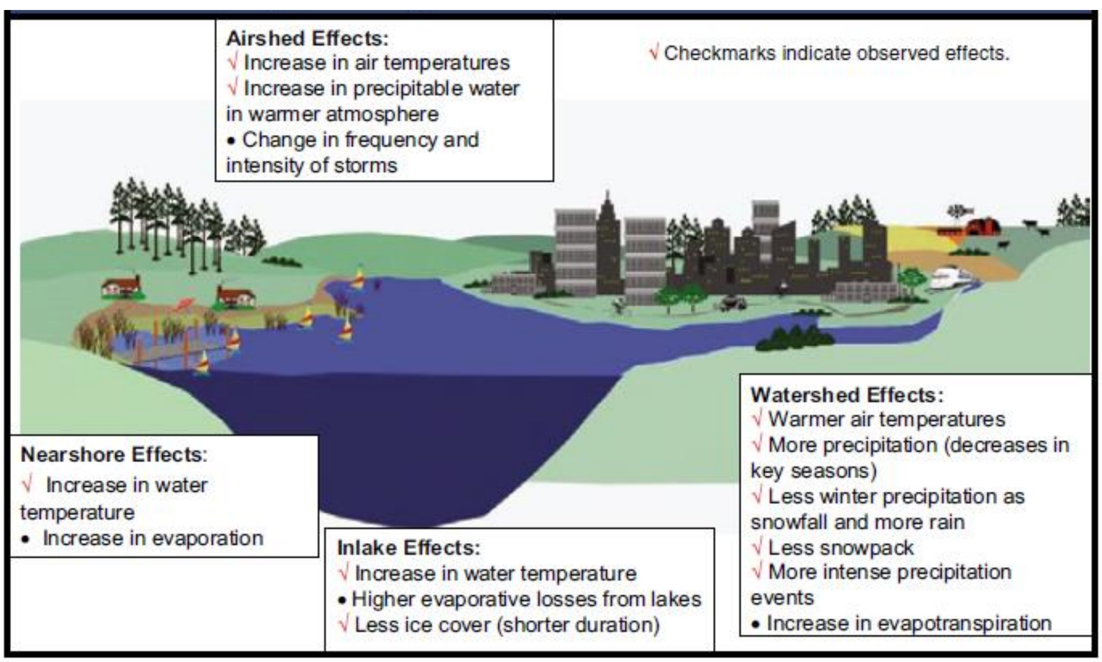

Figure 9. Overview of expected changes in climate for the Great Lakes basin. [Image courtesy of U.S. EPA and Environment Canada, 2009]

2.1.3 Air Temperature

Rising concentrations of GHGs in the global atmosphere during the 21st century are expected to cause a net warming of the Earth's surface. In the Lake Superior region, air temperatures affect a variety of key processes, including the length of the growing season, the extent of the frost-free season, freeze/thaw cycles of water and soil, lake surface temperatures, rates of chemical reactions, biological activity, and the prevalence of pests and diseases (International Joint Commission [IJC], 2003).

Historical Observations of Air Temperature

There is evidence that air temperatures in the Lake Superior basin are already increasing, as summarized in Table 2. Historical climate data from Environment Canada for four stations in Ontario along the coast of Lake Superior – Thunder Bay, Cameron Falls, Wawa, and Sault Ste. Marie – show a significant increase of approximately 1.0 °C (1.8 ºF) in annual average air temperatures and a larger increase of 1.6 °C (2.9 ºF) in minimum average air temperatures over approximately 1895-2005 (Environment Canada, 2005). At Sault Ste. Marie, Ontario, historical climate trends data compiled by the Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR) indicate that annual average air temperatures have increased 1.2 °C (2.2 ºF), winter average air temperatures have increased 2.7 °C (4.9 ºF), and summer average air temperatures have increased 1.2 °C (2.2 ºF) during the period 1962-2008 (OCCIAR, 2010).

Table 2. Observed historical trends in air temperature for the Lake Superior region.

Source	Location	Time Period	Measurement	Trend	Magnitude of Change
Environment Canada, 2005	Ontario coast of Lake Superior	1895-2005	Annual average temperature	Increasing	1.6 °C (2.9 ºF)
OCCIAR, 2010	Sault Ste. Marie, Ontario	1962-2008	Annual average temperature	Increasing	1.2 °C (2.2 ºF)
			Winter average temperature	Increasing	2.7 °C (4.9 ºF)
			Summer average temperature	Increasing	1.2 °C (2.2 ºF)
Saunders et al., 2011	Munising, Michigan	2000-2010	Decadal average temperature	Increasing	1.5 °C (2.7 ºF) > global average
Kucharik et al., 2010a	Northwestern Wisconsin	1950-2006	Annual average temperature	Increasing	1.4 °C (2.5 ºF)
			Winter average temperature	Increasing	2.5 °C (4.5 ºF)
			Spring average temperature	Increasing	1.9 °C (3.5 ºF)
			Summer average temperature	Increasing	0.8 to 1.1 °C (1.5 to 2.0 ºF)

Increasing air temperature trends are not confined to the Canadian side of the Lake Superior basin. Analysis of air temperature data from the U.S. Historical Climatology Network weather station at Munising, Michigan, presented in Figure 10, indicates an increasing trend in air temperatures near Pictured Rocks National Lakeshore. These results show that average air temperatures at Munising for 2000-2010 were 1.5 ºC (2.7 ºF) higher than corresponding global average air temperatures (Saunders et al., 2011). Data from 1950-2006 collected by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service Cooperative Observer Program indicate that annual average air temperatures over northwestern Wisconsin increased 1.4 °C (2.5 ºF), with the greatest increase observed in winter, followed by spring and summer (Kucharik et al., 2010a). In addition, a recent study of decreases in near-surface soil temperatures at 194 U.S. National Weather Service (NWS) stations in Wisconsin and Michigan suggests that air temperatures have increased in the vicinity of Lake Superior in the last 50 years (Isard et al., 2007). Soil is a buffered system that responds slowly to changes in atmospheric temperature, so it is a good proxy indicator of climate change. The observed cooling trends in soil were attributed to decreases in snowfall due to warmer air temperatures (Isard et al., 2007).

Future Projections of Air Temperature

As described in Section 1.2, climate model projections are a function of the particular climate scenario utilized. In general, scenarios with higher GHG emissions project higher air temperature increases than scenarios with lower emissions. As a result, the range of available absolute temperature projections for the Lake Superior basin over the 21st century varies. The models are consistent in projecting higher annual average temperatures for the Lake Superior region, however. In addition, increases in temperature are projected to be greater later in the 21st century. This acceleration in warming is a result of the cumulative effect of increasing levels of long-lived GHGs in the atmosphere.

A number of researchers have conducted individual analyses of GCM projections of air temperature changes for the Lake Superior region under different scenarios for a range of time periods in the 21st century; recent results are summarized in Table 3. Lofgren et al. (2002) analyzed the output from two GCMs using a transient model methodology to derive potential impacts on the water resources of the Great Lakes basin. The GCMs projected increases in average annual air temperature for the Lake Superior basin of 1.2 to 1.9 ºC (2.2 to 3.4 ºF) by 2030, 1.6 to 2.9 ºC (2.9 to 5.2 ºF) by 2050, and 2.9 to 5.4 ºC (5.2 to 9.7 ºF) by 2090, relative to 1961-1990 average values.

Wuebbles and Hayhoe (2004) analyzed GCM projections for the Midwestern U.S., including the Great Lakes region. Results for GCMs run under a medium-high (A2) emissions scenario suggest that temperatures in the Lake Superior basin will increase approximately 2 to 4 ºC (3.6 to 7.2 ºF) in winter and 4 to 6 ºC (7.2 to 10.8 ºF) in summer by 2070-2099, relative to 1961-1990 average values. In a follow-up to the 2004 study, Hayhoe et al. (2010) investigated changes in temperature for the Great Lakes region using statistically downscaled projections from an average of three GCMs under a medium-high (A2) emissions scenario, as shown in Figure 11. Results suggest that by 2070-2099, average annual air temperatures in the Lake Superior region will increase 4 to 4.5 ºC (7.2 to 8.1 ºF), relative to 1961-1990 average values.

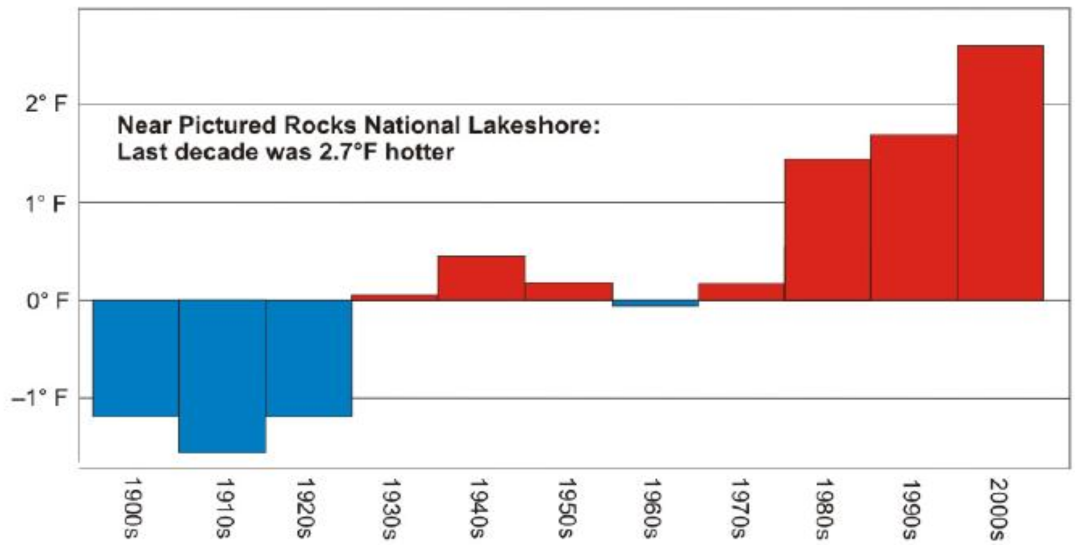

Figure 10. The difference between global decadal average air temperatures (ºF) for 1900-2010 and corresponding average air temperatures measured by the U.S. Historical Climatology Network weather station at Munising, Michigan (near Pictured Rocks National Lakeshore). [Image modified from Saunders et al., 2011]

Saunders et al. (2011) recently analyzed GCM projections of average annual air temperatures for three U.S. National Parks within the Lake Superior basin: Apostle Islands National Lakeshore, Isle Royale National Park, and Pictured Rocks National Lakeshore. Results for a lower (B2) emissions scenario suggest that on average, annual average temperatures at the three parks will increase approximately 2.0 ºC (3.6 ºF) for the period 2040-2069 and 2.7 ºC (4.8 ºF) for the period 2070-2099, relative to 1971-2000 average values. Under a medium-high (A2) emissions scenario, annual average temperatures are projected to increase 2.6 ºC (4.6 ºF) on average at the parks for the period 2040-2069 and 4.4 ºC (8.0 ºF) for the period 2070-2099, relative to 1971-2000 average values. GCM projections also indicate a consistent increase in summertime temperatures at the three national parks that signals a significant shift in climate. For example, by the end of the 21st century, summers in Isle Royale National Park in Michigan could be as hot as recent summers in Kenosha, Wisconsin, a city on the Lake Michigan coast just north of the Illinois-Wisconsin border.

As part of the WICCI, researchers at the University of Wisconsin-Madison developed climate projections for Wisconsin using 14 different climate models downscaled to a localized grid. Under a moderate (A1B) emission scenario, WICCI projected Wisconsin's annual average temperature to increase by 2 to 5 ºC (4 to 9 ºF) from 1980 to 2055 relative to 1950-2006 average values, with annual average temperatures increasing 3 ºC (6 ºF) along the coast of Lake Superior in Wisconsin; increased temperatures of 3 to 6 ºC (5 to 11 ºF) were projected during winter, with the largest increases expected in northwestern Wisconsin (WICCI, 2011).

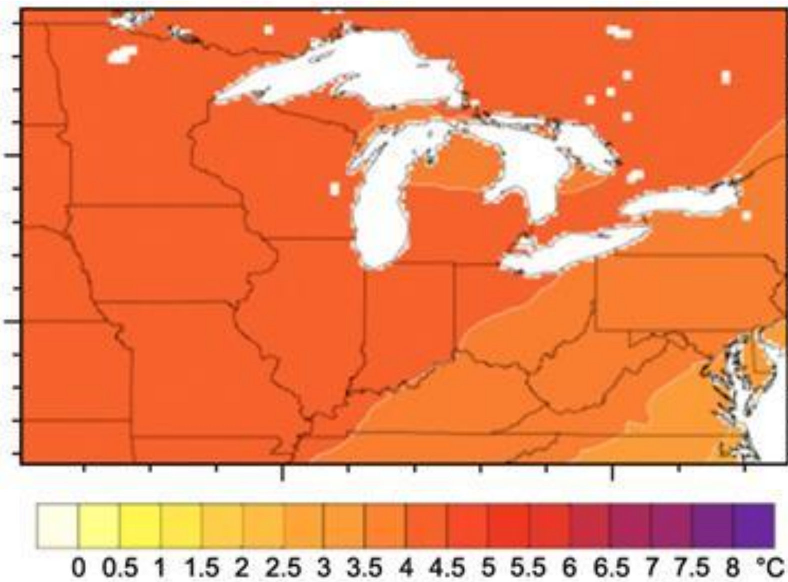

Figure 11. Projected changes in annual average air temperatures (ºC) by 2070–2099, relative to 1961-1990 average values, from statistically downscaled projections of an average of three GCMs under a medium-high (A2) emissions scenario. [Image courtesy of Hayhoe et al., 2010]

Investigating regional climate changes over the Great Lakes Basin into the next century, Gula and Peltier (2012) used the Weather Research and Forecasting (WRF) model to dynamically downscale global warming projections from the Community Climate System Model (CCSM) for the Lake Superior region. The study produced climate projections at a spatial resolution of 10 km (6 mi) under a medium-high (A2) emissions scenario. Annual average temperatures are projected to increase 3 to 4 °C (5 to 7 °F) and winter average temperatures are projected to increase 5 °C (9 °F) by 2050-2060, relative to 1979-2001.

Huang et al. (2012) of the University of Regina produced probabilistic climate change projections for Ontario at 25 km (15 mi) resolution using the UK PRECIS model under a moderate (A1B) emissions scenario, based on historical temperature data from the Sault Ste. Marie, Ontario, weather station. Results indicate that there is a 90% probability that mean daily air temperatures in Ontario north of Lake Superior will increase 2.8 to 3.2 °C (5.0 to 5.8 °F) by 2020-2049, 4.5 to 5.0 °C (8.1 to 9 °F) by 2040-2069, and 6.0 to 7.0 °C (10.8 to 12.6 °F) by 2070-2099, relative to 1968-1998.

In addition to the results from these in-depth academic investigations, projections of future air temperature and precipitation from a variety of current GCMs are available from interactive websites, including the Canadian Climate Change Scenarios Network (CCCSN, 2011) and the The Nature Conservancy's (TNC's) Climate Wizard (http://www.climatewizard.org/). Users can select the region, model, scenario, climate parameter (e.g., air temperature, precipitation), and future time period of interest and then generate a map of projected values. Figure 12 is an example of air temperature projections from the Climate Wizard for the U.S. portion of the Lake Superior basin for the end of the 21st century using an average of several GCMs under a moderate (A1B) scenario (Maurer et al., 2007). This projection indicates that average annual air temperatures in the areas of Michigan, Minnesota, and Wisconsin that border Lake Superior will increase by approximately 3.6 to 4.2 ºC (6.5 to 7.5 ºF) by the 2080s, relative to 1961-1990 average values. Figure 13 is an example of air temperature projections from the CCCSN interactive tool for the Great Lakes region for the middle of the 21st century under an average of the A1B and B2 scenarios (moderate emissions) (CCCSN, 2011). This model output suggests that average annual air temperatures in the vicinity of Lake Superior will increase by 2.7 to 2.9 ºC (4.9 to 5.2 ºF) by the 2050s, relative to 1961-1990 average values (Expert Panel on Climate Change Adaptation, 2009).

Summary of Projected Changes in Air Temperature

Results of various GCM analyses consistently suggest that air temperatures will increase in the Lake Superior basin. Projected changes in annual average air temperatures will be on the order of 3 to 4.5 ºC (5.4 to 8.1 ºF) by the end of the 21st century, depending on the particular model and scenario utilized.

Table 3. Future projections of air temperature for the Lake Superior region. Magnitudes of change are annual averages unless otherwise specified.

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
Lofgren et al., 2002	Lake Superior	IS92a	1961-1990	2030	Increasing	1.2 to 1.9 ºC (2.2 to 3.4 ºF)
			1961-1990	2050	Increasing	1.6 to 2.9 ºC (2.9 to 5.2 ºF)
			1961-1990	2090	Increasing	2.9 to 5.4 ºC (5.2 to 9.7 ºF)
Wuebbles and Hayhoe, 2004	Lake Superior	A2 (medium-high)	1961-1990	2070-2099	Increasing	2 to 4 ºC (3.6 to 7.2 ºF) (winter average)
					Increasing	4 to 6 ºC (7.2 to 10.8 ºF) (summer average)
Hayhoe et al., 2010	Lake Superior	A2 (medium-high)	1961-1990	2070-2099	Increasing	4 to 4.5 ºC (7.2 to 8.1 ºF)
CCCSN, 2011	Lake Superior	A1B and B2 average (moderate)	1961-1990	2050s	Increasing	2.7 to 2.9 ºC (4.9 to 5.2 ºF)
Gula and Peltier, 2012	Lake Superior	A2 (medium-high)	1979-2001	2050-2060	Increasing	3 to 4 °C (5 to 7 °F)
						5 °C (9 °F) (winter average)
Maurer et al., 2007	U.S. coast of Lake Superior	A1B (moderate)	1961-1990	2080s	Increasing	3.6 to 4.2 ºC (6.5 to 7.5 ºF)
Galatowitsch et al., 2009	Northern Superior Uplands region (MN)	A2 (medium-high)	1970-1999	2030-2039	Increasing	1.7 ºC (3.1 ºF)
				2060-2069	Increasing	4.5 ºC (8.1 ºF)
WICCI, 2011	Coast of Lake Superior in Wisconsin	A1B (moderate)	1950-2006	1980-2055	Increasing	3 ºC (6 ºF)

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
Colombo et al., 2007	Ontario coast of Lake Superior	A2 (medium-high)	1971-2000	2041-2070	Increasing	2 to 3 °C (3.6 to 6 ºF) (summer average)
						3 to 4 °C (6 to 7.2 ºF) (winter average)
Huang et al., 2012	Ontario north of Lake Superior	A1B (moderate)	1968-1998	2020-2049	Increasing (90% probability)	2.8 to 3.2 °C (5.0 to 5.8 °F) (mean daily air temp)
				2040-2069		4.5 to 5.0 °C (8.1 to 9.0 °F) (mean daily air temp)
				2070-2099		6.0 to 7.0 °C (10.8 to 12.6 °F) (mean daily air temp)
Saunders et al., 2011	Pictured Rocks National Lakeshore	B2 (lower)	1971-2000	2040-2069	Increasing	1.9 ºC (3.5 ºF)
		B2 (lower)	1971-2000	2070-2099	Increasing	2.6 ºC (4.7 ºF)
		A2 (medium-high)	1971-2000	2040-2069	Increasing	2.5 ºC (4.5 ºF)
		A2 (medium-high)	1971-2000	2070-2099	Increasing	4.3 ºC (7.7 ºF)
	Apostle Islands National Lakeshore	B2 (lower)	1971-2000	2040-2069	Increasing	2.1 ºC (3.7 ºF)
		B2 (lower)	1971-2000	2070-2099	Increasing	2.7 ºC (4.8 ºF)
		A2 (medium-high)	1971-2000	2040-2069	Increasing	2.6 ºC (4.7 ºF)
		A2 (medium-high)	1971-2000	2070-2099	Increasing	4.5 ºC (8.1 ºF)
	Isle Royale National Park	B2 (lower)	1971-2000	2040-2069	Increasing	2.0 ºC (3.6 ºF)

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
		B2 (lower)	1971-2000	2070-2099	Increasing	2.7 ºC (4.8 ºF)
		A2 (medium-high)	1971-2000	2040-2069	Increasing	2.6 ºC (4.6 ºF)
		A2 (medium-high)	1971-2000	2070-2099	Increasing	4.4 ºC (8.0 ºF)

Figure 12. Projected changes in annual average air temperatures (°F) for the U.S. portion of the Great Lakes region by the 2080s, relative to 1961-1990 averages, under moderate GHG emissions (A1B scenario). [Image generated from the Climate Wizard, http://www.climatewizard.org/; data from Maurer et al., 2007]

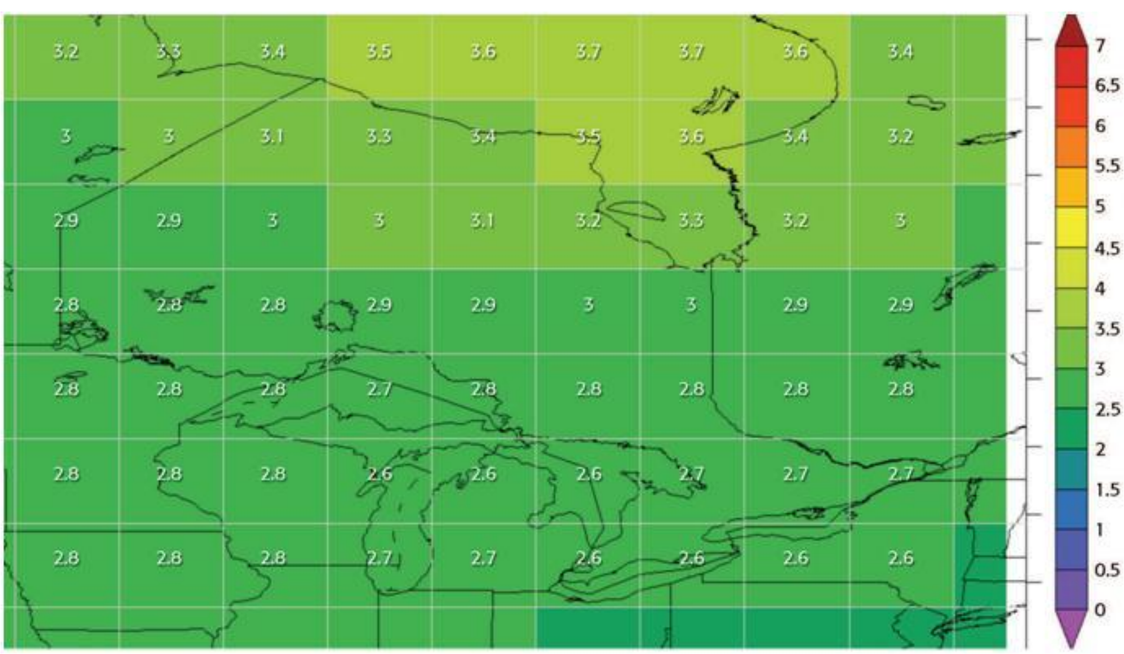

Figure 13. Projected changes in annual average air temperatures (°C) for the Great Lakes region by the 2050s, relative to 1961-1990 averages, under moderate GHG emissions (average of A1B and B2 emission scenarios). [Image courtesy of Expert Panel on Climate Change Adaptation, 2009 using output from the CCCSN, 2011]

2.1.4 Precipitation

Warmer air temperatures associated with rising concentrations of GHGs in the atmosphere are expected to enhance surface evapotranspiration and thus increase the amount of water vapor in the atmosphere, leading to overall increases in global precipitation during the 21st century. Evapotranspiration is the loss of water to the atmosphere through evaporation from the Earth's surface and the transpiration of plants (Kling et al., 2003; Environment Canada, 2004). In the Great Lakes-St. Lawrence basin, almost two-thirds of the water that falls into the lakes as precipitation returns to the atmosphere by means of evapotranspiration (IJC, 2003; Mortsch et al., 2000).

Historical Observations of Precipitation

Observational evidence suggests that precipitation amounts are increasing at some locations in the Lake Superior region, although the trends are less clear than for air temperature, as summarized in Table 4. The coast of Lake Superior in Wisconsin has experienced a wide variation in precipitation from 1950 to 2006, based on statewide data from the U.S. NWS Cooperative Observer Program. An analysis by the University of Wisconsin-Madison indicated little change in annual average precipitation from 1950 to 2006 for locations along Lake Superior's coast in northwestern Wisconsin but increases of 127 to 178 mm (5.0 to 7.0 in) of precipitation for the area around Chequamegon Bay (WICCI, 2011).

Historical climate data from Environment Canada for five stations in Ontario along the coast of Lake Superior – Thunder Bay, Cameron Falls, Marathon, Wawa, and Sault Ste. Marie – shown in Figure 14, indicate that annual total precipitation increased significantly at Thunder Bay (from 1895 to 1992) and Cameron Falls (from 1924 to 1996) (Environment Canada, 2005). However, an analysis of annual total precipitation at Thunder Bay for the period 1941-2010 (Saunders, 2011) indicates an overall decreasing trend, as shown in Figure 15. Changes in snowfall vary by location. Historical observations of snowfall on the western coast of Lake Superior suggest a decreasing trend in recent years. Annual total snowfall rose significantly at Thunder Bay for the period 1895-1992 and at Cameron Falls for the period 1924-1996 (Environment Canada, 2005). However, an analysis of snowfall at Thunder Bay for the period 1941-2010 (Saunders, 2011) indicates a steep decrease in annual total snowfall since 1981. On the eastern coast of Lake Superior, total snowfall decreased approximately 240 cm (94 in.) at Wawa Airport over the period 1915-2003 , but there was little change at Sault Ste. Marie for the period 1964-2006 (Environment Canada, 2005). A more detailed seasonal analysis of historical climate trends data compiled by OCCIAR shows that at Sault Ste. Marie, annual total precipitation decreased 10 mm (0.4 in.), winter total precipitation decreased 48 mm (1.9 in.), and summer total precipitation decreased 18 mm (0.7 in.) over the period 1962-2008 (OCCIAR, 2010).

In general, observed precipitation trends in the Lake Superior basin over the last century appear to vary by location and type of precipitation. Data collected in northwest Wisconsin during the latter half of the 20th century indicate wide variations in precipitation, depending on location (WICCI, 2011). Based on historical observations for locations in Ontario for the 20th century, annual total precipitation at locations along the western shores of Lake Superior appears to be increasing, while along the eastern coast, annual total precipitation seems to be decreasing or remaining constant (Environment Canada, 2005; OCCIAR, 2010). At Thunder Bay, on the western shore of Lake Superior, recent data (through 2010) suggest a shift from an increasing trend to a decreasing trend in annual total precipitation (Saunders, 2011).

Table 4. Observed historical trends of precipitation and snowfall in the Lake Superior region.

Source	Location	Time Period	Trend	Measurement	Magnitude of Change
Environment Canada, 2005	Cameron Falls, Ontario	1924-1996	Increasing	Annual total precipitation	not reported
Environment Canada, 2005	Cameron Falls, Ontario	1924-1996	Increasing	Annual total snowfall	not reported
Environment Canada, 2005	Thunder Bay, Ontario	1895-1992	Increasing	Annual total precipitation	not reported
Saunders, 2011	Thunder Bay, Ontario	1941-2010	Decreasing	Annual total precipitation	not reported
Environment Canada, 2005	Thunder Bay, Ontario	1895-1992	Increasing	Annual total snowfall	not reported
Saunders, 2011	Thunder Bay, Ontario	1941-2010	Decreasing	Annual total snowfall	not reported
Environment Canada, 2005	Wawa, Ontario	1915-2003	Decreasing	Annual total snowfall	not reported
OCCIAR, 2010	Sault Ste. Marie, Ontario	1962-2008	Decreasing	Annual total precipitation	10 mm (0.4 in.)
				Winter total precipitation	48 mm (1.9 in.)
				Summer total precipitation	18 mm (0.7 in.)
Environment Canada, 2005	Sault Ste. Marie, Ontario	1960-2002	Increasing	Annual total precipitation	8 mm (0.3 in.)
				Annual total rainfall	13 mm (0.5 in.)
			Decreasing	Annual total snowfall	4 mm (0.15 in.)

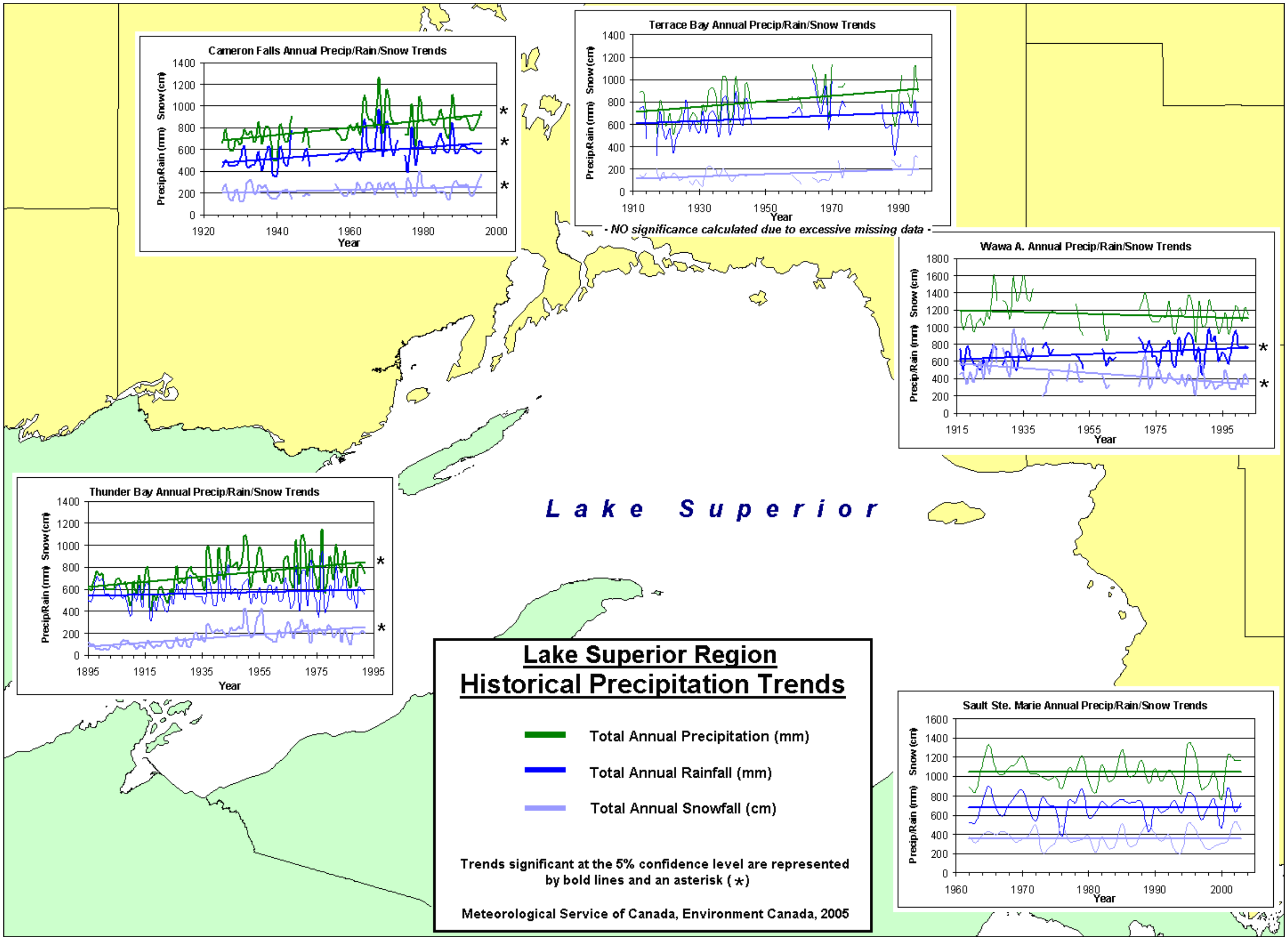

Figure 14. Observed historical precipitation trends for five cities in Ontario on Lake Superior. [Image courtesy of Environment Canada, 2005]

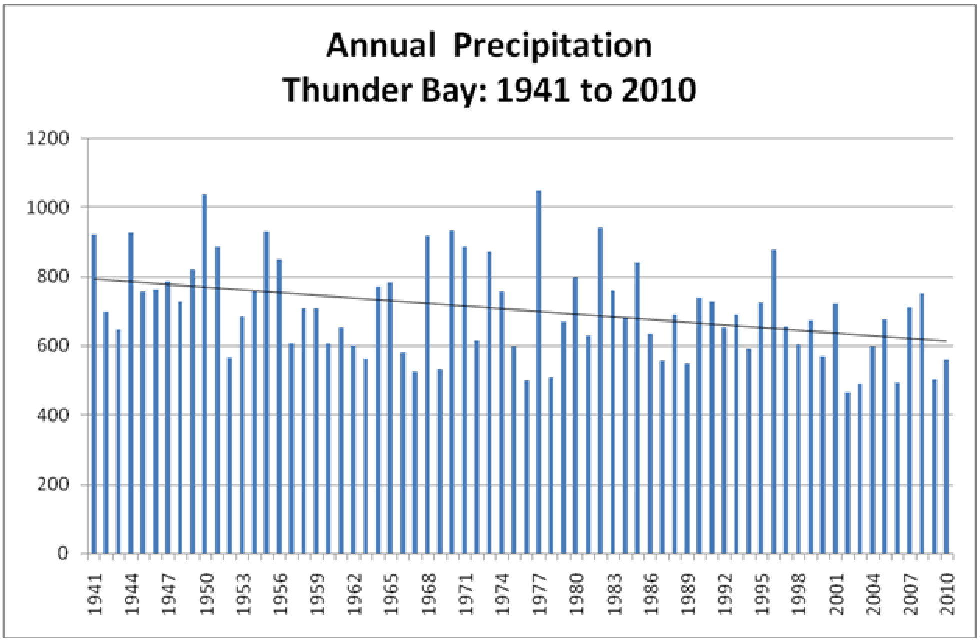

Figure 15. Observed historical annual total precipitation (mm) for Thunder Bay, Ontario, 1941-2010. [Image courtesy of Saunders, 2011, using data from Environment Canada]

Future Projections of Precipitation

It is important to note that GCM projections of temperature changes for a given region are generally consistent in sign and magnitude, but precipitation projections can vary widely due to the difficulty in simulating the myriad of factors that influence precipitation frequency, duration, and intensity. An additional complicating factor is that precipitation in the Lake Superior region varies naturally both seasonally and annually. In model simulations, any precipitation changes associated with future climate change are overlaid on this natural variability, making it difficult for GCMs to resolve contributions from natural and anthropogenic influences. The result is increased uncertainty in expected precipitation changes associated with future climate change.

Many of the same researchers who analyzed GCM projections of air temperature also used GCMs to project changes in precipitation for the Lake Superior region under different scenarios and time periods in the 21st century, as summarized in Table 5. As part of their investigation of the potential impacts of climate change on water resources in the Great Lakes region, Lofgren et al. (2002) worked with GCMs that projected average annual increases in precipitation for Lake Superior of 4% by 2030, 5% by 2050, and 14 to 16% by 2090, relative to 1961-1990 average values. Wuebbles and Hayhoe (2004) found that GCM projections of precipitation for the Midwestern U.S., including the Great Lakes region, were complex and had a seasonal component. Model results for the medium-high (A2) emissions scenario suggest that by 2070-2099, winter precipitation will increase by 5 to 15% but summer precipitation will decrease by 5 to 10%, relative to 1961-1990 average values, resulting in little or no net annual change in precipitation for the region (Wuebbles and Hayhoe, 2004). Hayhoe et al. (2010) found similar results in a follow-up study. Statistically downscaled output averaged from three GCM simulations under a medium-high (A2) emissions scenario showed a seasonal variation in precipitation projections, with increases in winter and spring precipitation and decreases in summer precipitation, leading to an overall increase in annual average precipitation of 0 to 10% by 2070-2099, relative to 1961-1990 average values, as shown in Figure 16. Hayhoe et al. (2010) concluded that climate change is expected to bring the Great Lakes region only slight increases in annual average precipitation, but these relatively small annual changes will mask large shifts in precipitation on the seasonal scale.

Results from an analysis of precipitation projections from the CCCSN (2011) conducted by the Expert Panel on Climate Change Adaptation (2009) provide further evidence for seasonal variations in precipitation for the Lake Superior basin. Figure 17 shows that only modest increases in annual average precipitation on the order of 5.5 to 7.5% are projected by the 2050s, relative to 1961-1990 average values, under a moderate emissions scenario (average of A1B and B2 scenarios). As Figures 18 and 19 illustrate, however, these annual changes are the sum of substantial increases in average winter precipitation of about 9 to 14% and changes in summer average precipitation of approximately -1.5% to +1.5%.

Projections by Gula and Peltier (2012) suggest that annual precipitation in the Lake Superior region may increase 5 to 15%, winter precipitation may change between -15% and 5%, and summer precipitation may increase approximately 30% by 2050-2060, relative to 1979-2001, under a medium-high (A2) emissions scenario. The results of Huang et al. (2012) suggest the change in average daily precipitation rate in Ontario north of Lake Superior will be variable depending on location, with a 90% probability that the average daily precipitation rate will increase 5.8 to 11.4% by 2020-2049, 11.4 to 17.0% by 2040-2069, and 14.2 to 17.0% by 2070-2099, relative to 1968-1998, under a moderate (A1B) emissions scenario.

On a more localized scale, climate models indicate a 75% probability that annual average precipitation will increase in Wisconsin in the 21st century. There is consensus that precipitation will increase during winter and that a higher percentage of winter precipitation will fall as rain rather than snow, due to the rise in winter air temperatures (WICCI, 2011).

Although climate change is expected to increase the occurrence of heavy rainfall events associated with increases in the frequency and intensity of storms in the Great Lakes region (Hayhoe et al., 2010), there are no published studies documenting anticipated changes specifically for the Lake Superior basin. Historical observations show that there were only zero to four occurrences of heavy rainfall during the period 1979-2004 in the portion of Ontario that borders Lake Superior (Chiotti and Lavender, 2008), as shown in Figure 20. Any future increases in storm intensity or frequency may increase the incidence of flash flooding and the flow of pollutants to Lake Superior and surrounding wetlands from runoff (Hayhoe et al., 2010; Chiotti and Lavender, 2008).

Two sets of researchers have found that little change is expected in the frequency of lake effect snow in the Lake Superior region through 2099, despite projected increases in water temperature and number of ice-free days. Kunkel et al. (2002) determined that only a small decrease of 5% is projected in the frequency of favorable air temperatures for lake effect snow in the Lake Superior snowbelt, despite an overall warming of 3 °C (5.4 °F) projected for the region. Similarly, based on GCM projections for the Lake Superior snowbelt, Sousounis and Bisanz (2000) concluded that the average winter air temperature will remain below 0 ºC (32 °F), and the number of below-freezing days and the frequency of favorable ranges of other variables that impact lake effect snow will remain relatively unchanged through the end of the 21st century.

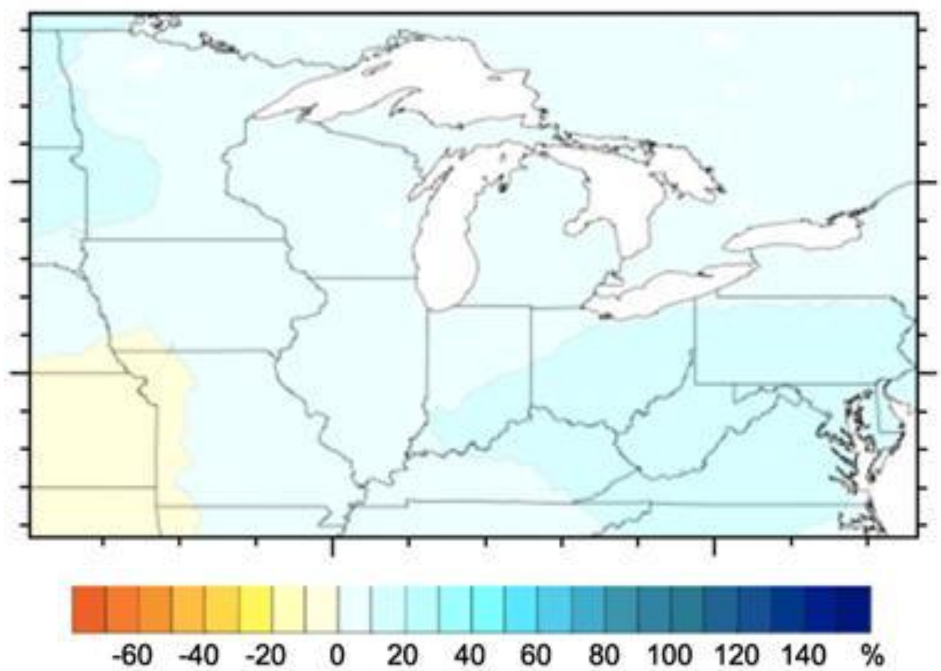

Figure 16. Projected changes in annual average precipitation (%) by 2070–2099, relative to 1961-1990 average values, from statistically downscaled projections of an average of three GCMs under a medium-high (A2) emissions scenario. [Image courtesy of Hayhoe et al., 2010]

Summary of Projected Changes in Precipitation

GCM projections of precipitation for the Lake Superior region suggest that annual precipitation will increase by the end of the 21st century, but only slightly (5 to 15%). Shifts in seasonal precipitation are expected, with decreases in summer precipitation and increases in winter precipitation. It is possible that more winter precipitation will fall as rain and less as snow, although little or no change is expected in the frequency of lake effect snowfall. Climate change is expected to increase the occurrence of heavy rainfall events associated with increases in the frequency and intensity of storms in the Great Lakes region, but specific changes for the Lake Superior basin have not been studied.

Table 5. Future projections of precipitation for the Lake Superior region. Magnitudes of change are annual averages unless otherwise specified.

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
Lofgren et al., 2002	Lake Superior	IS92a	1961-1990	2030	Increasing	4%
			1961-1990	2050	Increasing	5%
			1961-1990	2090	Increasing	14-16%
Wuebbles and Hayhoe, 2004	Lake Superior	A2 (medium-high)	1961-1990	2070-2099	Increasing	5 to 15% (winter average)
					Decreasing	5 to 10% (summer average)
Hayhoe et al., 2010	Lake Superior	A2 (medium-high)	1961-1990	2070-2099	Increasing	0-10%
CCCSN, 2011	Lake Superior	A1B and B2 average (moderate)	1961-1990	2050s	Increasing	5.5 to 7.5%
					Increasing	9 to 14% (winter average)
					Variable	-1.5 to +1.5% (summer average)
Gula and Peltier, 2012	Lake Superior	A2 (medium-high)	1979-2001	2050-2060	Increasing	5 to 15%
					Variable	-15% to 5% (winter average)
					Increasing	30% (summer average)
Colombo et al., 2007	Ontario coast of Lake Superior	A2 (medium-high)	1971-2000	2041-2070	Increasing	0 to 10% (summer average)
						0 to 10% (winter average)
Huang et al., 2012	Ontario north of Lake Superior	A1B (moderate)	1968-1998	2020-2049	Increasing (90% probability; average daily precipitation rate)	5.8 to 11.4%
				2040-2069		11.4 to 17.0%
				2070-2099		14.2 to 17.0%

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
Galatowitsch et al., 2009	Northern Superior Uplands region (MN)	A2 (medium-high)	1961-1990	2060-2069	No change	1.8 to 2.2 mm/day (0.071 to 0.087 in/day)

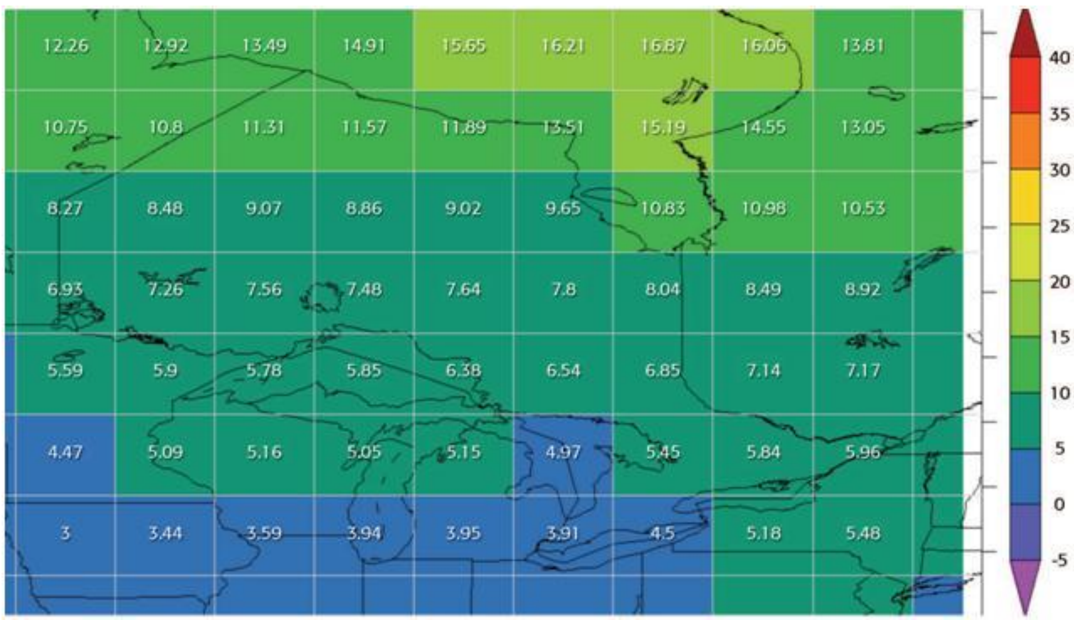

Figure 17. Projected changes in annual average precipitation (%) for the Great Lakes region by the 2050s, relative to 1961-1990 average values, under moderate GHG emissions (average of A1B and B2 scenarios). [Image courtesy of Expert Panel on Climate Change Adaptation, 2009 using output from CCCSN, 2011]

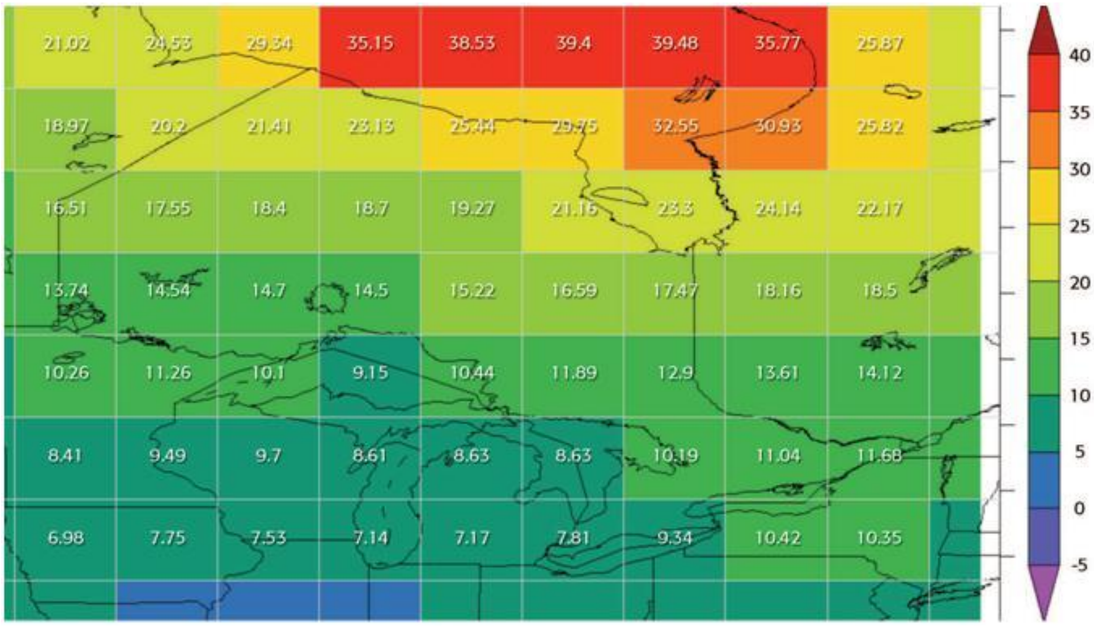

Figure 18. Projected changes in annual average winter precipitation (%) for the Great Lakes region by the 2050s, relative to 1961-1990 average values, under moderate GHG emissions (average of A1B and B2 scenarios). [Image courtesy of Expert Panel on Climate Change Adaptation, 2009 using output CCCSN, 2011]

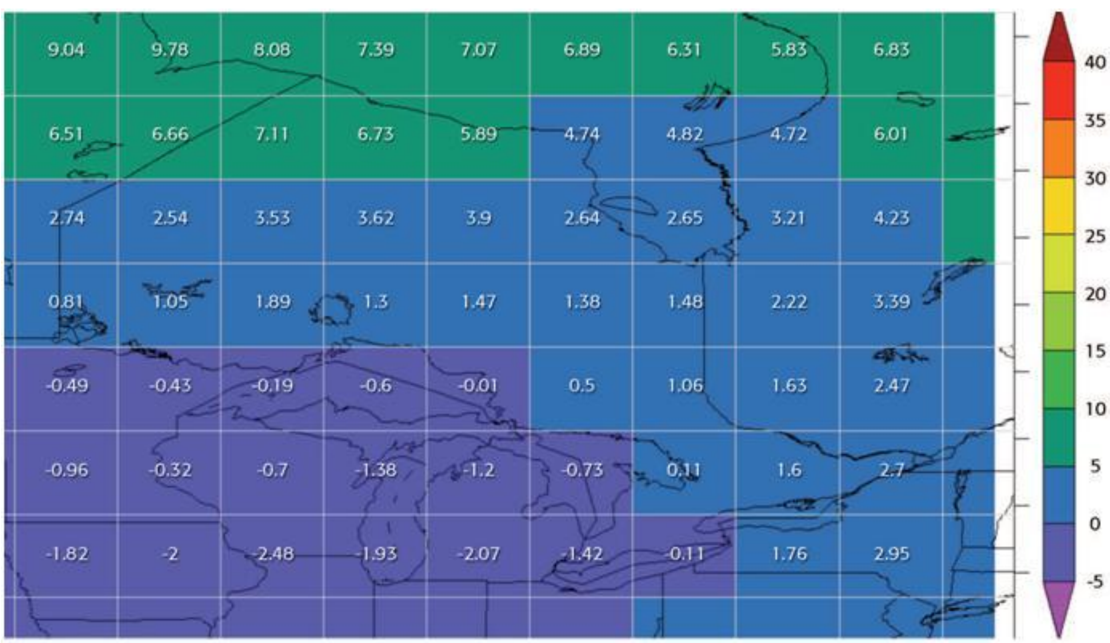

Figure 19. Projected changes in annual average summer precipitation (%) for the Great Lakes region by the 2050s, relative to 1961-1990 average values, under moderate GHG emissions (average of A1B and B2 scenarios). [Image courtesy of Expert Panel on Climate Change Adaptation, 2009 using output from CCCSN, 2011]

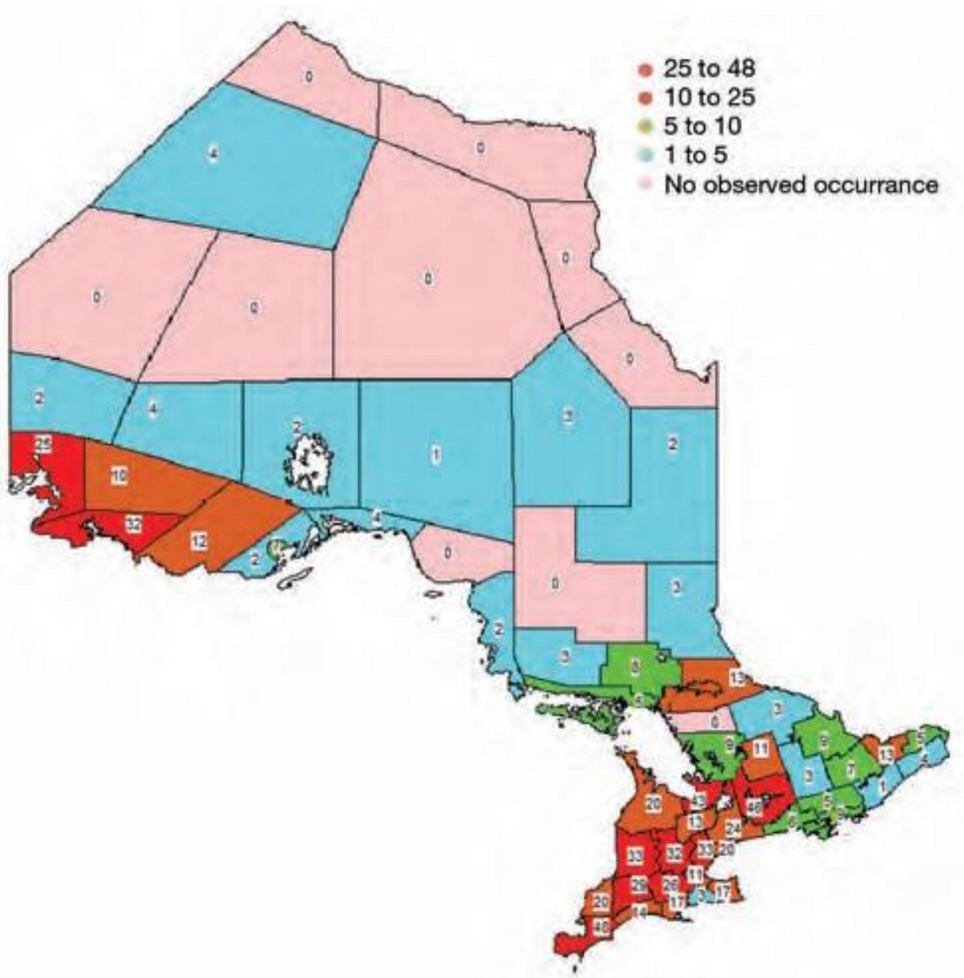

Figure 20. Historical observed occurrences of heavy rainfall in Ontario for the period 1979-2004. Heavy rainfall is defined as rainfall that is ≥50 mm/hour (≥2.0 in/hour) or ≥75 mm (≥3.0 in) in three hours. [Image courtesy of Chiotti and Lavender, 2008]

2.1.5 Migrating Climate Analyses

By relating future climate changes for a state or region to current conditions at a different location, migrating climate analyses can provide an illustrative example of the impacts of climate change. Hayhoe et al. (2010) conducted a migrating climate analysis for Michigan based on projected changes in average summer temperatures and precipitation from GCMs under higher (A1F1) and lower (B2) emissions scenarios. Figure 21 illustrates that the summer climate of Michigan will feel as if it is migrating southward and westward during the course of the 21st century. By 2080-2099, summers in the Upper Peninsula of Michigan, adjacent to Lake Superior, may feel like current summers in southwestern Kansas (if a higher emissions scenario is realized) or central Missouri (if a lower emissions scenario is realized).

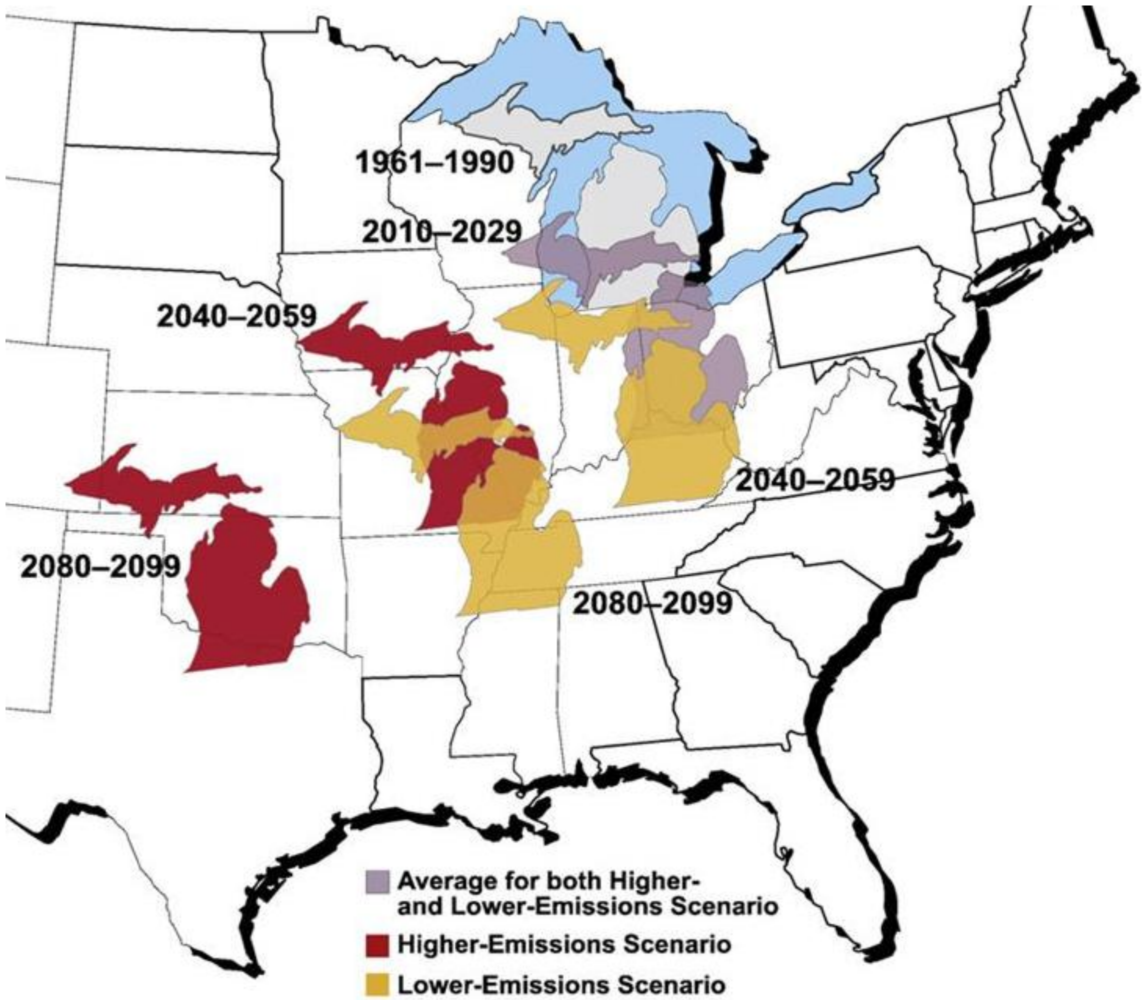

Figure 21. Migration of Michigan's summer climate throughout the 21st century based on average summer temperature and precipitation GCM projections under the A1F1 (higher) and B1 (lower) future emissions scenarios, relative to 1961-1990 average values. [Image adapted from Hayhoe et al., 2010]

In a comprehensive analysis of changes in air temperature and precipitation in Minnesota, Galatowitsch et al. (2009) examined GCM projections by landscape region using a migrating climate analysis. Results suggest that by 2060-2069, for a medium-high (A2) emissions scenario, projected changes in annual average air temperature and precipitation for the Northern Superior Uplands region, adjacent to Lake Superior, will correspond to the current climate of southern Minnesota, as shown in Figure 22. Specifically, the results indicate that annual average maximum air temperatures in the Northern Superior Uplands region are projected to increase 1.7 ºC (3.1 °F) by 2030-2039 and 4.5 ºC (8.1 °F) by 2060-2069, relative to 1970-1999 average values. Summer (June-August) average maximum air temperatures are projected to increase 1.6 ºC (2.9 °F) by 2030-2039 and 3.4 ºC (6.1 °F) by 2060-2069, relative to 1970-1999 average values. Precipitation rates for this region are projected to remain relatively constant for the region, with annual average rates of 1.8 to 1.9 mm/day (0.071-0.075 in/day) (minimum amount) and 2.1 to 2.2 mm/day (0.083 to 0.087 in/day) (maximum amount) and summer average rates of 3.0 mm/day (0.12 in/day) (minimum amount) and 3.3 mm/day (0.13 in/day) (maximum amount).

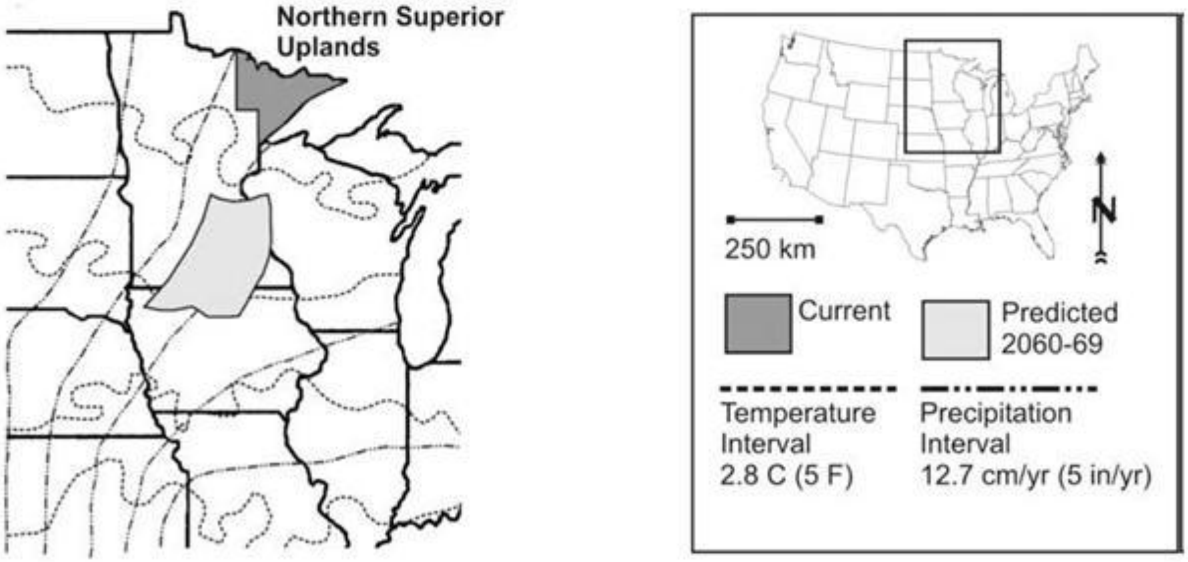

Figure 22. Migration of climate for the Northern Superior Uplands region of Minnesota, based on annual average temperature and precipitation GCM projections under a medium-high (A2) emissions scenario for 2060–2069, relative to 1961-1990 average values. [Image modified from Galatowitsch et al., 2009]

2.1.6 Water Temperature

Rising air temperatures associated with climate change are expected to increase the water temperatures of Lake Superior and impact the lake's vertical circulation (Hall et al., 2007). Due to the sensitivity of coldwater fish species to water temperature, changes in water temperature can substantially impact fish in Lake Superior, as discussed in detail in Section 2.3.

The current annual average water temperature of Lake Superior is approximately 4.5 °C (40 °F) (Environment Canada, 2005), and surface water temperatures generally peak in September at 15 to 25 ºC (59 to 77 ºF) (Croley et al., 1998). These warm surface temperatures create a stable summertime temperature stratification in the water column of the lake, as low density warm water floats above high density cool water. Surface water temperatures decrease during the fall and winter, and once surface water temperatures reach approximately 4 ºC (39 °F), the temperature at which water has its maximum density, high density surface water sinks and lower density deep water rises, causing vertical mixing in the water column. This "turnover" occurs again in the spring as surface temperatures rise above 4 ºC (39 °F) (Croley et al., 1998). The twice-annual vertical turnovers bring oxygen from the surface to the deeper waters and re-suspend nutrients previously trapped at the bottom of the lakes (Hall et al., 2007).

Historical Observations of Water Temperature

Observational evidence indicates that Lake Superior surface water temperatures have increased over the past 35 to 40 years, and these changes are impacting the lake's vertical water circulation, as summarized in Table 6. Austin and Colman (2007) studied changes in Lake Superior surface water temperatures for the period 1979-2006 using buoy measurements (Figure 23). They found that summer (July-September) surface water temperatures increased approximately 2.5 ºC (4.5 °F), which is equivalent to a rate of 0.11 ± 0.0 ºC/yr (0.20 ± 0.11 ºF/yr). The beginning date of the summer temperature stratification period was observed to have occurred nearly two weeks earlier in 2006 compared to 1979, corresponding to a rate of change of half a day earlier per year. In a subsequent study, Austin and Colman (2008) used data from two locations on the St. Marys River, near Sault Ste. Marie, Ontario, as a proxy for interannual water temperature variability in Lake Superior. Results are similar to the 2007 study and indicate that Lake Superior summer (July-September) average water temperatures increased approximately 3.5 °C (6.3 °F) over the period 1906-2006; most of the warming has occurred since 1976. In addition, the length of the summer temperature stratification season increased approximately 25 days during the 100-year analysis period.

The observed increases in water temperature of 2.5 to 3.5 °C (4.5 to 6.3 °F) measured by Austin and Colman (2007, 2008) are more than twice that of the corresponding observed increases of 1 to 1.2 °C (1.8 to 2.2 °F) in annual average air temperatures for the Lake Superior region (Environment Canada, 2005; OCCIAR, 2010). This result suggests that increases in air temperature are not solely responsible for the observed changes in water temperature. Austin and Colman (2007, 2008) concluded that the main factor responsible for their observed increases in surface water temperature was the recent decrease in observed ice cover on Lake Superior (described in Section 2.1.7). These results reinforce the hypothesis that large natural systems, such as Lake Superior, will undergo a complex response to global climate change.

Table 6. Observed historical trends in surface water temperature for Lake Superior.

Source	Location	Time Period	Trend	Magnitude of Change in Summer Average (July-September)
Austin and Colman, 2007	Lake Superior	1979-2006	Increasing	2.5 °C (4.5 °F)
Austin and Colman, 2008	St. Marys River (proxy for Lake Superior)	1906-2006	Increasing	3.5 °C (6.3 °F)

Future Projections of Water Temperature

Relatively few GCM studies analyzed changes in lake water temperature and summer stratification, but the models are consistent in projecting warmer water temperatures and longer stratification periods for the 21st century, as summarized in Table 7. Lehman (2002) investigated possible future mixing patterns and primary production in the Great Lakes using projections from two GCMs. Results show that the relative magnitudes of change are expected to be largest in Lake Superior. Annual average surface water temperatures in Lake Superior are projected to increase approximately 5 ºC (9 °F) by 2071-2090, relative to 1954-1995 averages, and summer average surface water temperatures are expected to exceed 20 °C (68 °F) by 2071-2090. The time period of summer stratification is also projected to increase from approximately 100 days to 160-245 days by 2090.

In a more recent study, Trumpickas et al. (2009) estimated future water temperatures in Lake Superior using the output from two GCMs in conjunction with an empirical relationship between surface water temperatures and local air temperatures. Results for the A2 and B2 emissions scenarios indicate that annual average surface water temperatures in Lake Superior will increase 2.0 to 2.1 ºC (3.6 to 3.8 °F) by 2011-2040, 3.2 to 3.9 ºC (5.8 to 7.0 °F) by 2041-2070, and 4.6 to 6.7 ºC (8.3 to 12.1 °F) by 2071-2100, relative to 1971-2000 average values. This approach assumes that surface lake temperatures will respond linearly to future changes in local air temperatures.

Summary of Projected Changes in Surface Water Temperature

Although there are relatively few GCM projections of water temperature for Lake Superior, the models are consistent in projecting an increase in annual average surface water temperatures throughout the 21st century, with magnitudes of approximately 4.6 to 6.7 ºC (8.3 to 12.1 °F) by 2090-2100, depending on the particular model and scenario utilized.

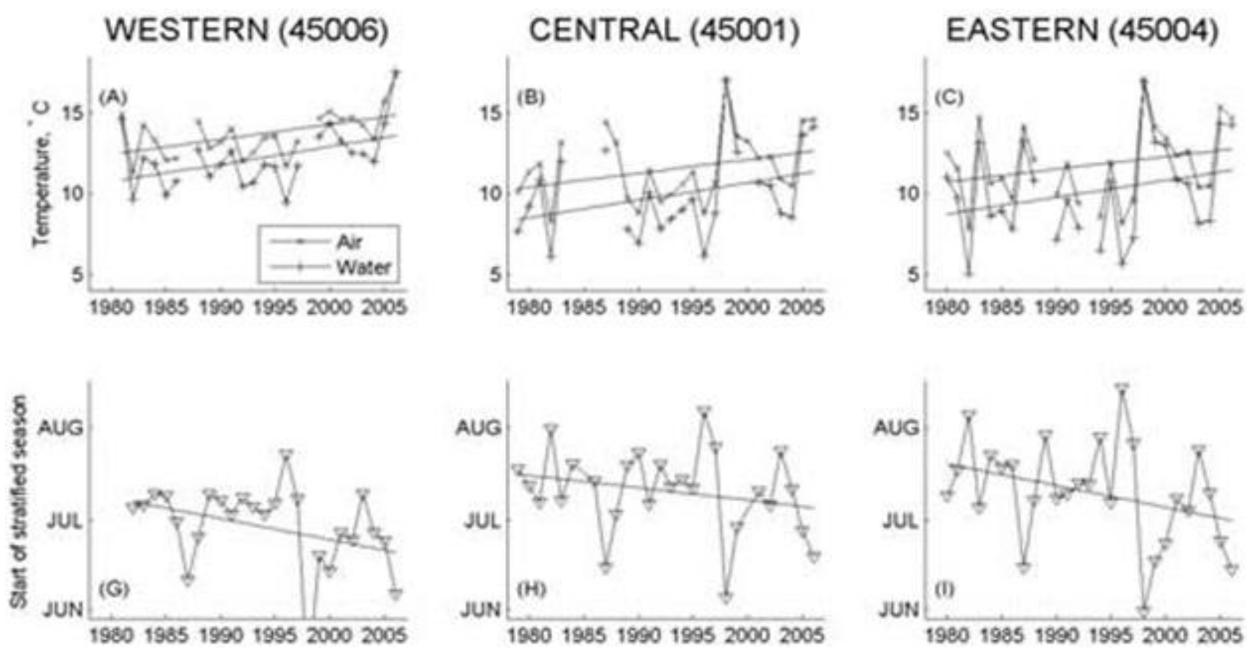

Figure 23. Observed historical changes in summer (July-September) average surface water temperature (top) and start of stratified season (bottom) for 1979-2006 from measurements of three NOAA buoys in the eastern (buoy 45004), central (buoy 45001), and western (buoy 45006) portions of Lake Superior. [Image modified from Austin and Colman, 2007]

Table 7. Future projections of surface water temperature for Lake Superior. Magnitudes of change are annual averages.

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
Lehman, 2002	Lake Superior	unspecified	1954-1995	2071-2090	Increasing	5 °C (9 °F)
Trumpickas et al., 2009	Lake Superior	A2 (medium-high)	1971-2000	2011-2040	Increasing	2.0 °C (3.6 °F)
				2041-2070		3.9 °C (7.0 °F)
				2071-2100		6.7 °C (12.1 °F)
		B2 (lower)		2011-2040		2.1 °C (3.8 °F)
				2041-2070		3.2 °C (5.8 °F)
				2071-2100		4.6 °C (8.3 °F)

2.1.7 Ice Cover

Changes in air temperature and surface water temperature on Lake Superior are tied to changes in the extent and duration of ice cover on the lake. Normal ice cover on Lake Superior reaches a maximum of approximately 75% of lake surface area in February (Croley et al., 1998). A recent analysis of historical observations of ice cover on Lake Superior for the period 1973-2010 (Wang et al., 2012) indicates that on average over the 37-year analysis period, ice cover on Lake Superior reached its peak in early March and then declined quickly thereafter (Figure 24).

Historical Observations of Ice Cover

Historical observations, presented in Table 8, indicate that the extent of ice cover on Lake Superior decreased in the 20th century. Assel et al. (2003) analyzed a 39-year (1963-2001) winter record of annual maximum ice concentration (AMIC) for the Great Lakes. AMIC is defined as the maximum percentage of lake surface area covered by ice in a given year. Results indicate that ice cover on Lake Superior for the winters of 1998-2001, the most recent four-year period analyzed, was the lowest four-year average on record. The average AMIC value for 1998-2001 was 27%, compared to an average value of 68% for 1963-2001. The previously discussed results of Austin and Colman (2007, 2008) suggest that the extent of average ice cover on Lake Superior decreased approximately 11% over the period 1906-2006; most of that change occurred since 1976. The results of Wang et al. (2012) indicate that Lake Superior ice cover decreased by a rate of 2% per year for the period 1973-2010, for a total decrease of 79% over the course of the 37-year analysis period. Figure 25 illustrates the decreasing trend in the extent of Lake Superior ice observed by Wang et al. (2012).

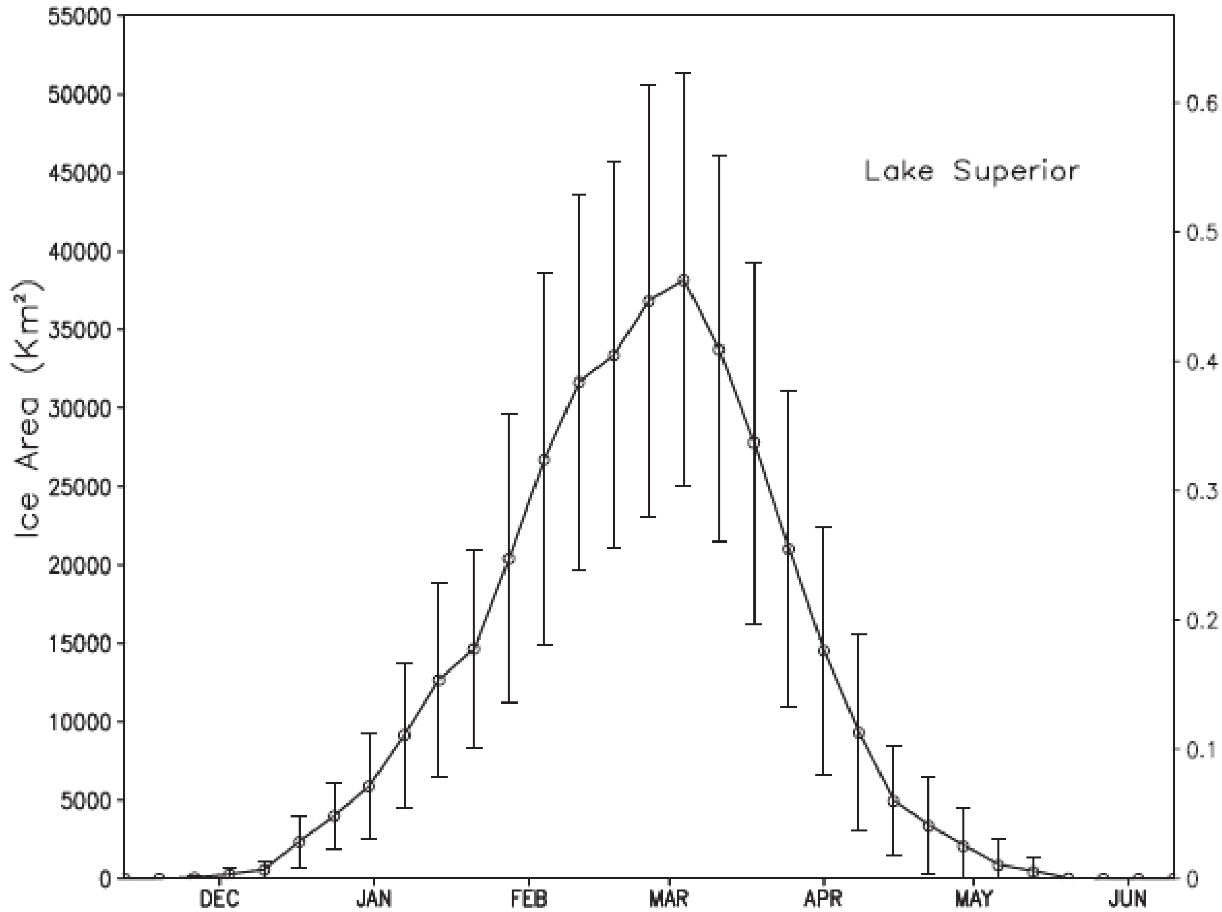

Figure 24. Variation of weekly ice extent for Lake Superior for the period 1973-2010; the right y-axis is the fraction of ice extent. The vertical error bars represent one standard deviation. [Image courtesy of Wang et al., 2012]

Although ice cover on Lake Superior was nearly 100% in 2009 (U.S. NWS, 2009), minimal ice cover was observed on Lake Superior during 2010, as indicated in Figure 25. Figure 26 is a MODIS true color satellite image of Lake Superior from March 5, 2010 (U.S. NWS, 2010) that shows the extremely small amount of ice on the lake. Comparison to historical ice cover data from the NOAA Great Lakes Ice Atlas for 1973 to 2002 (Assel, 2003) indicates that by March 1-7, approximately 25% of the winters between 1973 and 2002 had about the same amount of ice cover as that observed on March 5, 2010. This comparison, illustrated in Figure 27, suggests that by March 1-7, Lake Superior had more ice cover during approximately 75% of winters from 1973 to 2002 than during winter 2010 (U.S. NWS, 2010).

Howk (2009) investigated the duration of ice cover on Lake Superior using a 150-year record (1857-2007) of the opening and closing of navigation in Bayfield, Wisconsin. Bayfield is located on the southwest shore of Lake Superior, and the date that the last boat is able to navigate in the Bayfield Harbor indicates the onset of ice cover on Lake Superior. Results show that the duration of ice cover on Lake Superior at Bayfield decreased over the past 150 years by approximately 3 days per decade or 45 days over the course of the study. The most dramatic changes have occurred since 1975; during the period 1975-2007, the ice season began an average of 11.7 days later and ended 3.0 days earlier every decade. These results suggest that decreases in the duration of ice cover on Lake Superior are occurring in conjunction with decreases in the extent of ice cover.

Summary of Projected Changes in Ice Cover

Based on observational evidence, and assuming air temperatures in the Lake Superior region continue to increase as projected by GCMs, the extent of ice cover on Lake Superior is expected to continue to decrease through the 21st century (Ferris and Andrachuk, 2009). GCM projections support the empirical evidence and suggest that average February ice cover will be only 2 to 11% for the eastern and western Lake Superior basins by 2090 (Lofgren et al., 2002). The duration of ice cover is also expected to continue to decrease in the 21st century, perhaps by as much as 50 days by 2050-2060 (Gula and Peltier, 2012) or 1 to 2 months by 2100 (Easterling and Karl, 2000).

Table 8. Observed historical trends in ice cover for Lake Superior.

Source	Location	Time Period	Trend	Measurement	Magnitude of Change
Assel et al., 2003	Lake Superior	1963-2001	Decreasing	AMIC	
Austin and Colman, 2008	St. Marys River (proxy for Lake Superior)	1906-2006	Decreasing	Extent of Ice Cover	11%
Wang et al., 2012	Lake Superior	1973-2010	Decreasing	Extent of Ice Cover	79% (2.07%/yr)
Howk, 2009	Bayfield, WI (proxy for Lake Superior)	1857-2007	Decreasing	Duration of Ice Cover	3 days/decade

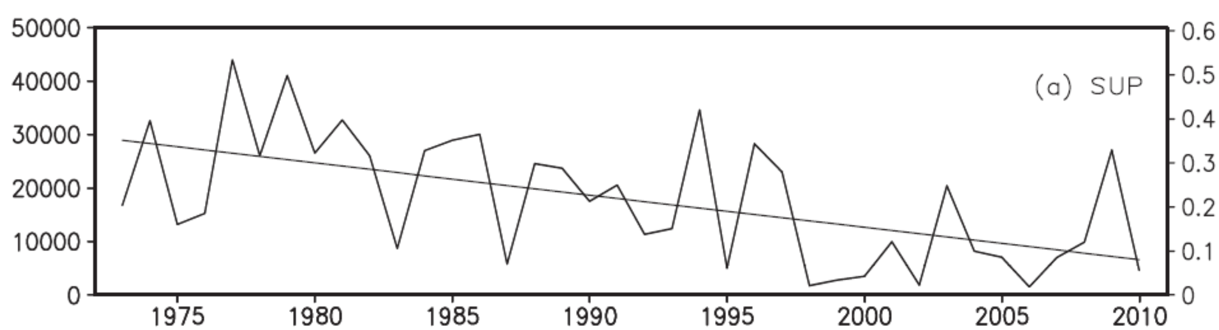

Figure 25. Observed historical annual mean lake ice area for Lake Superior during the period 1973-2010. The linear line is the trend in annual lake ice coverage calculated from the least squares fit method. The left y-axis is in units of km^2 and the right y-axis is the fraction of ice extent. [Image courtesy of Wang et al., 2012]

Figure 26. MODIS true color satellite image of Lake Superior showing minimal ice cover on March 5, 2010. [Image courtesy of U.S. National Weather Service, 2010]

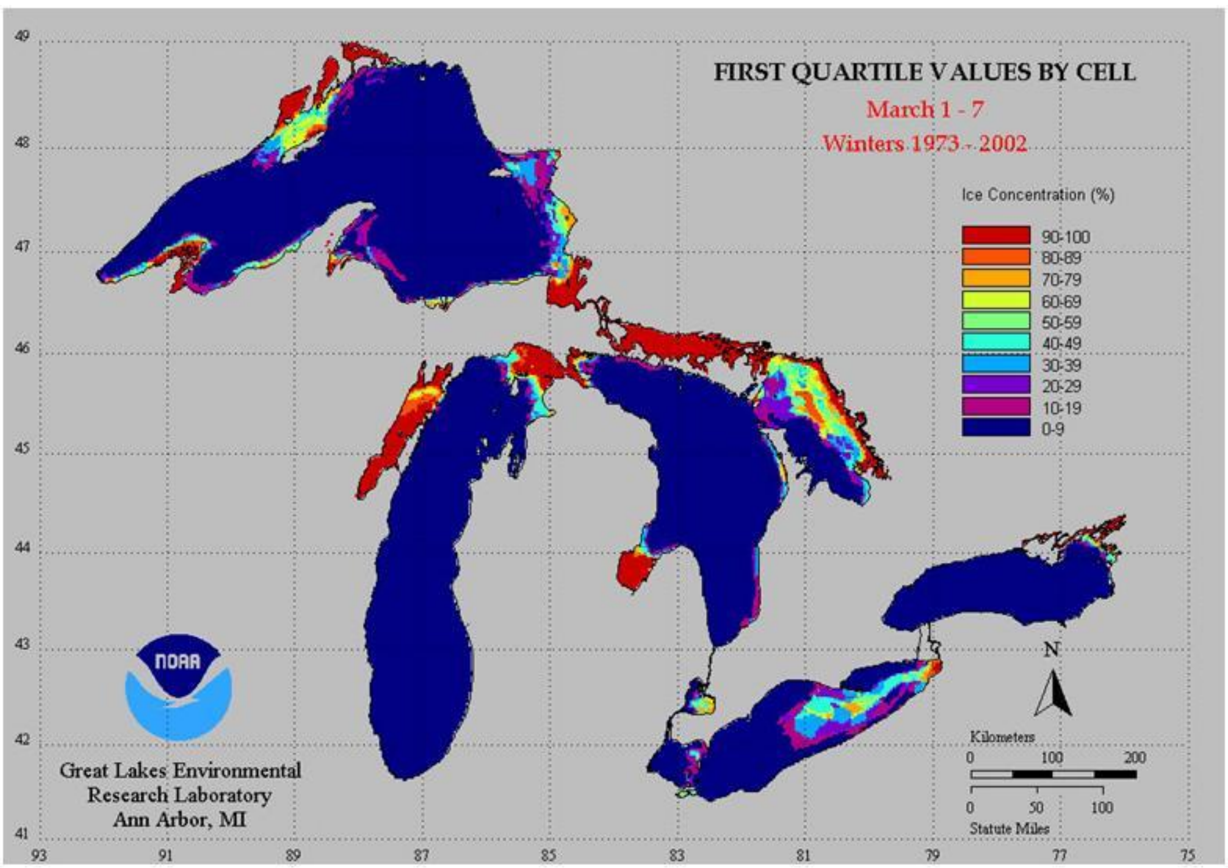

Figure 27. Great Lakes Ice Atlas for winters 1973-2002, 25% quartile frequency distribution of ice cover for March 1 to 7. [Image courtesy of U.S. National Weather Service, 2010 from data of Assel, 2003]

2.1.8 Wind Speeds

In addition to mesoscale wind phenomena, such as the lake breeze (described in Section 2.1.1), wind in general is an important component of Lake Superior's climate. Year-round, the predominant winds are westerly (Wilcox et al., 2007), although winds from all directions impact the region. Sustained high winds can create seiches or storm surges by pushing the water level up at one end of the lake, which causes the level to drop by a corresponding amount at the other end. For example, northerly winds blowing into Chequamegon Bay can cause flooding in the city of Ashland, and northeasterly winds blowing down the length of the lake can cause flooding in the city of Superior (Moy et al., 2010).

Increasing air and surface water temperatures in the Lake Superior basin associated with climate change may cause wind speeds to increase. As air temperatures at the Earth's surface increase, the lower atmosphere will become more unstable, since increasingly warmer, less dense air will be below relatively colder, denser air. As a result, atmospheric turbulence will increase, and stronger winds from aloft will mix down to the surface, causing an increase in surface wind speeds (National Wildlife Federation, 2010). Faster winds may impact a variety of features in the Lake Superior region, including the lake's biogeochemical cycles, the lake breeze, lake currents, and the depth of the lake's mixed-layer (Desai et al., 2009; Austin and Colman, 2007).

Historical Observations of Wind Speed

Historical evidence suggests that Lake Superior wind speeds are already increasing, as summarized in Table 9. Desai et al. (2009) analyzed buoy and satellite observations for Lake Superior and found that surface wind speeds above the lake during the summer months (July-September) increased 0.52 ± 0.20 m/s (1.2 ± 0.45 mph) over the period 1985-2008, an increase of nearly 12%. This trend corresponds to a nearly 5% increase in wind speed per decade for 1985-2008, which exceeds observed trends in wind speed over land. Results from numerical model simulations of the lake circulation suggest that increasing wind speeds will lead to increases in lake current speeds. As part of their study of trends in Lake Superior surface water temperatures, Austin and Colman (2007) also observed a general trend towards higher average wind speeds during the summer months (July-September). They found that wind speeds had increased at open-water buoy sites by approximately 0.05 m/s per year (0.1 mph per year) over the period 1979-2006, which is on the order of the increase observed by Desai et al. (2009). This change is significant compared to average summer wind speeds of 4 to 6 m/s (9 to 13 mph) over Lake Superior. The increasing trend in wind speeds was attributed to increasing air and surface water temperatures and a reduction in the temperature gradient between air and water, which are destabilizing the atmospheric surface layer above the lake (Desai et al., 2009; Austin and Colman, 2007).

Summary of Projected Changes in Wind Speeds

No GCM model projections of wind speeds over Lake Superior for the 21st century are available, but if air temperature and lake water temperatures continue to increase as projected, wind speeds over the lake are likely to increase concomitantly due to destabilization of the atmospheric surface layer above the lake.

Table 9. Observed historical trends in wind speed for Lake Superior.

Source	Location	Time Period	Trend	Magnitude of Change in Summer Average (July-September)
Desai et al., 2009	Lake Superior	1985-2008	Increasing	0.52 ± 0.20 m/s (1.2 ± 0.45 mph) over entire period
Austin and Colman, 2007	Lake Superior	1979-2006	Increasing	0.05 m/s (0.1 mph) per year

2.1.9 Water Levels

The waters of Lake Superior are critical for regulating natural ecosystems and providing resources for human activities, such as recreation and hydropower production. The water level of Lake Superior varies naturally on a range of timescales, including seasonal and annual. Water enters the Lake Superior basin primarily via precipitation, and evapotranspiration is the major removal mechanism (Wilcox et al., 2007).

Seasonal changes in Lake Superior water levels are caused by differences in net basin supply associated with snowmelt, precipitation, and evaporation (Wilcox et al., 2007). Water level rises in the spring as the runoff from snowmelt enters the lake and begins dropping in late summer and fall as surface water evaporates (Mortsch et al., 2000; Kling et al., 2003). The highest water level usually occurs in August or September on Lake Superior, and the lowest water level typically occurs in March (Wilcox et al., 2007). Lake Superior reaches its maximum summer water level later than the other Great Lakes because of the relatively long snow cover season in its northern drainage basin (Mortsch, 1998).

To help minimize extremes in water level fluctuations, the outflow of Lake Superior has been regulated by control structures on the St. Marys River since about 1914 (IJC, 2003; Wilcox et al., 2007). Regulation of Lake Superior is designed to maintain stable water levels that reflect long-term, average conditions (Mortsch, 1998). Figure 28 shows the annual average water levels of Lake Superior for the period 1860-2010. Although significant annual variation is apparent, Lake Superior water levels are more consistent than they would be in the absence of regulation (Wilcox et al., 2007).

Since evapotranspiration increases with increasing air temperature, climate change is expected to cause an overall net decrease in the water level of Lake Superior in the 21st century (Environment Canada, 2004). Reductions in the extent and duration of ice cover (as described in Section 2.1.7) may also increase the rate of evaporation from Lake Superior during the winter, thereby impacting the water level of the lake. The issue is further complicated by the uncertainty in projections of precipitation changes for the Lake Superior region, as described in Section 2.1.4. If annual average precipitation amounts decrease in conjunction with increases in evapotranspiration, then substantial declines in the Lake Superior water level are probable. On the other hand, if annual average precipitation amounts increase, the effect of increasing evapotranspiration may be offset, and little or no change in Lake Superior water levels may occur (Angel and Kunkel, 2010).

Historical Observations of Water Levels

There is evidence that the water level of Lake Superior may be on a downward trend. Figure 28 indicates that there was an overall decrease in annual average lake water levels during the period 1995-2010. In August 2007, Lake Superior was at its lowest level since 1925. Although the average lake water level has increased recently, it is still below the long-term average level of approximately 183.41 m (601.73 ft), as illustrated in Figure 28. While it is clear that temperature and precipitation exert a strong influence on lake water levels, the exact relationship between these variables is not well understood, in part because neither precipitation nor evaporation are measured over Lake Superior (Chiotti and Lavender, 2008).

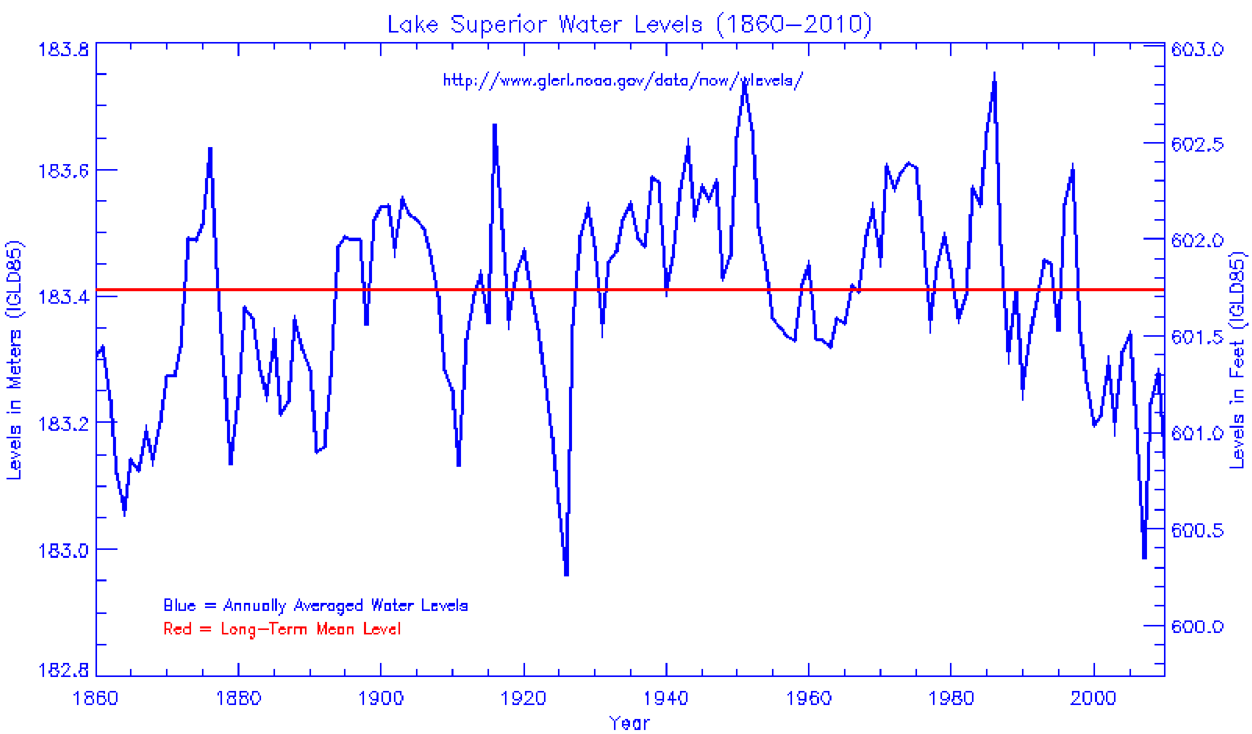

Figure 28. Observed historical annual average Lake Superior water levels (m, ft) for 1860-2010. [Image courtesy of Moy et al., 2010]

Future Projections of Water Levels

To ensure adequate water levels in Lake Superior in the coming years for ecosystem and human needs, water managers and planners require information on the most probable future changes in lake water levels. To that end, many GCM simulations have been conducted to provide projections of Lake Superior water levels for the 21st century, as summarized in Table 10. It is important to note GCMs do not directly project changes in future lake water levels. Instead, projections of future Lake Superior water levels are derived from hydrologic models that input projections of changes in air temperature and precipitation from GCMs. In an early study, Hartmann (1990) linked output from GCMs to estimates of basin runoff, over-lake precipitation, and lake evaporation for the Great Lakes. Results suggest a very small decline in Lake Superior water levels of about 13 mm/decade (0.51 in/decade) through the middle of the 21st century.

The U.S. Army Corps of Engineers conducted an assessment of Great Lakes water resources impacts using GCMs and found that Lake Superior water levels are expected to decrease approximately 0.1 to 0.9 m (0.3 to 3.0 ft) by 2020-2050, relative to 1951-1990 average values (Chao, 1999). In a similar study, Lofgren et al. (2002) used two GCMs to determine the potential impacts of climate change on the water resources of the Great Lakes basin. The models projected decreases in annual average water levels for Lake Superior of 0.01 to 0.22 m (0.03 to 0.72 ft) by 2021-2040, 0.01 to 0.31 m (0.03 to 1.0 ft) by 2041-2060, and 0.11 to 0.42 m (0.36 to 1.4 ft) by 2081-2100, relative to 1961-1990 average values. These amounts for Lake Superior were the smallest projected decreases in lake levels for all of the Great Lakes.

More recent GCM analyses have found that projections of lake levels depend on the selected GCM emissions scenario, similar to GCM projections for temperature and precipitation. Hayhoe et al. (2010) used projected changes in air temperature and precipitation for the Great Lakes region from GCMs under two emissions scenarios to determine expected changes in lake water levels. Results show that Lake Superior average annual water levels are anticipated to remain relatively constant under a lower emissions scenario (B1) through the 21st century. As illustrated in Figure 29, results of a moderate (A1B) emissions scenario indicate that Lake Superior water levels will begin to decrease in the early 21st century, with a total decrease of approximately 0.20 m (0.66 ft) by 2040-2069, relative to 1961-1990 average values. The differential effects of changing temperature and precipitation are expected to balance each other out over much of the 21st century, resulting in little net change to Lake Superior water levels through approximately 2039 (Hayhoe et al., 2010). In a similar study, but on a larger modeling scale, Angel and Kunkel (2010) estimated possible future water levels of the Great Lakes using the output of 18-23 GCMs under the A2 (medium-high) emission scenario. Results show that Lake Superior median water levels are expected to decrease 0.07 m (0.23 ft) by 2050-2064 and 0.12 m (0.39 ft) by 2080-2094, relative to 1970-1999 average values. At least 75% of the GCMs indicated steady or declining water levels in Lake Superior by 2080-2094, which supports the findings of Hayhoe et al. (2010) that Lake Superior water levels are likely to decrease later in the 21st century.

Many of the most recent projections of future Lake Superior water levels (e.g., Hartmann, 1990; Chao, 1999; Lofgren et al., 2002; Angel and Kunkel, 2010) are derived from a hydrologic model that uses GCM projections of air temperature as a proxy for potential evapotranspiration. Lofgren et al. (2011) recently developed a new method that utilizes GCM predictions of net radiative energy instead of air temperature in the hydrologic model. Their results indicate that the new "energy adjustment" method projects a smaller drop in lake water levels, or possibly even a slight increase, compared to the older "temperature adjustment" method. For example, based on output from a GCM run with a moderate (A1B) emissions scenario, Lake Superior water levels are projected to decrease 0.71 m (2.3 ft) by 2081-2100, relative to 1950-2005, using the temperature adjustment, but to decrease only 0.33 m (1.08 ft) using the energy adjustment method of Lofgren et al. (2011). Furthermore, using the energy adjustment with output from a GCM run with a medium-high (A2) scenario, Lake Superior water levels are projected to increase 0.13 m (0.43 ft) by 2081-2100, relative to 1950-2005. These results suggest that the magnitudes and possibly the signs of previous lake level projections based on hydrologic models that utilized a "temperature adjustment" are overestimated (Lofgren et al., 2011), further increasing the uncertainty in future changes of Lake Superior water levels.

The recent International Upper Great Lakes Study (IUGLS) report on Lake Superior Regulation confirmed that GCM projections of future lake water levels introduce uncertainties that are very difficult to reconcile with historical data (IUGLS, 2012). The report also found that water levels for the upper Great Lakes, including Lake Superior, are almost entirely unpredictable more than a month ahead, which makes it challenging to estimate the impacts of climate change (IUGLS, 2012). The report also notes that increasing evaporation over the past 60 years in the Lake Superior basin has not been compensated for by increased precipitation, which has led to the general decline in lake water levels discernible in Figure 28. This decrease in Lake Superior water levels is expected to continue, on average, unless increases in precipitation amounts and duration occur. As a result, continued overall decreases in Lake Superior water levels are likely, although they will probably not be as large as previous studies have predicted, and periodic higher than average levels are possible (IUGLS, 2012). In a recent study, MacKay and Seglenieks (2012) dynamically downscaled GCM results using the Canadian Regional Climate Model and then bias-corrected the simulated overall net basin supply. Their results support the conclusions of the IUGLS report by suggesting a decrease in Lake Superior levels of 0.03 m (0.1 ft) by 2021-2050 relative to 1962-1990, as well as an amplified seasonal signal for lake levels into the future compared to the present.

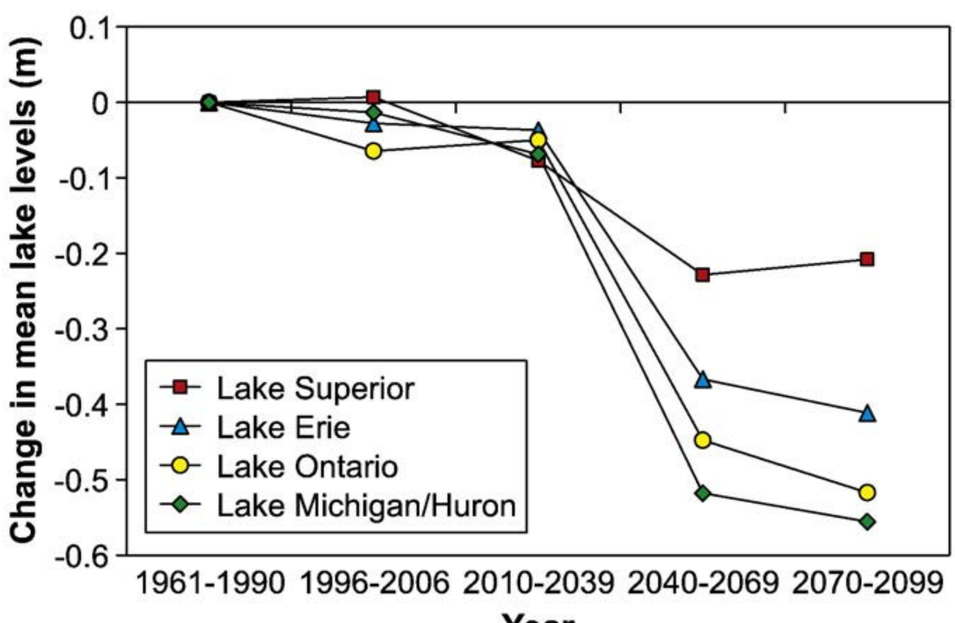

Figure 29. Projected changes in annual average water levels (m) for the Great Lakes, relative to 1961-1990 average values, under the A1B (moderate) emissions scenario. [Image courtesy of Hayhoe et al., 2010]

Summary of Projected Changes in Lake Water Levels

It is difficult to predict future changes in Lake Superior water levels, due to competing impacts from variations in evapotranspiration and precipitation. The potential impacts of changes in ice cover and duration on wintertime evaporation from Lake Superior are also not definitively known. GCM simulations suggest that Lake Superior water levels will decrease slightly, beginning mid-century, on the order of 0.10 to 0.20 m (0.33 to 0.66 ft). Periodic increases in lake water levels are also possible. The variation in results for different GCMs under different emissions scenarios suggests a high degree of uncertainty in possible future lake levels. A recent study (Lofgren et al., 2011) indicates that the magnitudes and possibly the signs of previous lake level projections based on hydrologic models that utilized a "temperature adjustment" are overestimated. Current research also suggests that the magnitude of any decreases in Lake Superior water levels will be less than for the other Great Lakes. The recent IUGLS report on Lake Superior Regulation (IUGLS, 2012) affirmed these conclusions and suggests that continued overall decreases in Lake Superior water levels are likely, although they will probably not be as large as previous studies have predicted, and periodic higher than average levels are possible.

Table 10. Future projections of Lake Superior water levels.

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Trend	Magnitude of Change
Hartmann, 1990	Lake Superior	Equilibrium CO_2	1973-1980	1981-2060	Decreasing	1.3 mm/yr (0.051 in./yr)
Chao, 1999	Lake Superior	IS92a	1951-1990	2020-2050	Decreasing	0.1 to 0.9 m (0.3 to 3.0 ft)
Lofgren et al., 2002	Lake Superior	IS92a	1961-1990	2021-2040	Decreasing	0.01 to 0.22 m (0.03 to 0.72 ft)
				2041-2060		0.01 to 0.31 m (0.03 to 1.0 ft)
				2081-2100		0.11 to 0.42 m (0.36 to 1.4 ft)
Hayhoe et al., 2010	Lake Superior	A1B (moderate)	1961-1990	2040-2069	Decreasing	0.20 m (0.66 ft)
Angel and Kunkel, 2010	Lake Superior	A2 (medium-high)	1970-1999	2050-2064	Decreasing	0.07 m (0.23 ft)
				2080-2094		0.12 m (0.39 ft)
Lofgren et al., 2011	Lake Superior	A2 (medium-high)	1950-2005	2081-2100	Increasing	0.13 m (0.43 ft)
		A1B (moderate)	1950-2005	2081-2100	Decreasing	0.33 m (1.08 ft)
MacKay and Seglenieks, 2012	Lake Superior	A2 (medium-high)	1962-1990	2021-2050	Decreasing	0.03m (0.1 ft)

2.1.10 Onset of Seasons

Climate change-induced increases in air temperature are expected to impact the onset of seasons in the Lake Superior region.

Historical Observations of Onset of Seasons

There is some evidence that seasons are already beginning earlier, as summarized in Table 11. A recent study (Stine et al., 2009) indicates that surface temperatures trended toward earlier seasons by approximately 1.7 days globally and by 3 to 5 days in the vicinity of Lake Superior for the period 1954-2007. This shift is larger than can be explained by natural variability, and may have been caused by alterations in atmospheric circulation associated with climate change. These results are similar to those of Wuebbles and Hayhoe (2004), who examined the changes in the length of frost-free seasons for the Midwestern U.S. (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) for the period 1900-2000, and found that the longest frost-free seasons occurred in the 1990s. Results showed that frost-free seasons in the 1990s were approximately one week longer than in the early 20th century, due mainly to earlier dates for the last spring freeze (Wuebbles and Hayhoe, 2004). In addition, WICCI found that diverging spring and fall freeze dates led to an increase in the length of the growing season of 7 to 35 days during the period 1950-2006 for the counties in northwestern Wisconsin that border Lake Superior (Kucharik et al., 2010b).

Table 11. Observed historical trends in onset of seasons for the Lake Superior region.

Source	Location	Time Period	Measurement	Trend	Magnitude of Change
Stine et al., 2009	Lake Superior region	1954-2007	Onset of spring	Earlier	3 to 5 days
Wuebbles and Hayhoe, 2004	Midwestern U.S.	1900-2000	Length of frost-free season	Increasing	7 days
Kucharik et al., 2010b	Northwestern WI, on shore of Lake Superior	1950-2006	Length of growing season	Increasing	7 to 35 days

Future Projections of Onset of Seasons

Table 12 lists the GCM projections related to changes in the onset of seasons for the Lake Superior region. GCM projections using the A1F1 and B1 emissions scenarios suggest that the length of the frost-free season in the Midwestern U.S., including the southern Lake Superior basin, will continue to increase by an additional 4 to 8 weeks through the end of the 21st century, compared to 1961-1990 (Wuebbles and Hayhoe, 2004). The date of the last spring frost is expected to become earlier by as much as 15 to 35 days, and the date of first autumn frost will be pushed back by up to 35 days (Wuebbles and Hayhoe, 2004). GCM projections for Pukaskwa National Park in Ontario using the A2 emissions scenario show a similar trend, with the length of the growing season expected to increase by 22.6 days by 2071-2100, compared to 1971-2000 (McKenney et al., 2010).

Summary of Projected Changes in Onset of Seasons

GCM projections suggest that the length of the frost-free season in the Midwestern U.S., including the southern Lake Superior basin, will continue to increase by an additional 4 to 8 weeks through the end of the 21st century, compared to 1961-1990 (Wuebbles and Hayhoe, 2004). The date of the last spring frost is expected to become earlier by as much as 15 to 35 days, and the date of first autumn frost will be pushed back by up to 35 days (Wuebbles and Hayhoe, 2004). Results are similar for Pukaskwa National Park in Ontario, on the northern shore of Lake Superior, with GCM projections indicating an increase in the length of the growing season of 22.6 days by 2071-2100, compared to 1971-2000 (McKenney et al., 2010). If air temperatures continue to increase as projected by GCMs, it is likely that spring and summer will begin earlier and the frost-free season will last longer throughout the Lake Superior basin during the course of the 21st century.

Table 12. Future projections of onset of seasons for the Lake Superior region.

Source	Location	Emissions/ Concentration Scenario	Benchmark	Time Period	Measurement	Trend	Magnitude of Change
Wuebbles and Hayhoe, 2004	Mid-western U.S.	A1F1 (high) and B1 (low)	1961-1990	2001-2099	Length of frost-free season	Increasing	4 to 8 weeks
					Date of last spring frost	Earlier	15 to 35 days
					Date of first autumn frost	Later	Up to 35 days
McKenney et al., 2010	Pukaskwa National Park	A2 (medium-high)	1971-2000	2011-2040	Length of growing season	Increasing	5.9 days
				2041-2070		Increasing	14.3 days
				2071-2100		Increasing	22.6 days

2.2 Effects of Climate Change on Lake Superior Ecosystems

2.2.1 Summary of Expected Effects on Lake Superior Ecosystems

The climate change impacts described in Section 2.1 are expected to have a variety of effects on physical, chemical, and biological aspects of Lake Superior ecosystems in the 21st century. In some cases, climate change may result in expanding habitats for fish, bird, and tree species in Lake Superior ecosystems. All of these changes are described in detail in Sections 2.2.2-6. Some of the most significant potential effects include:

- The current extent of coastal wetlands may experience an overall decrease if lake levels decline below historical annual averages, with negative consequences for a variety of plant and animal habitats.

- Higher air temperatures and changes in precipitation patterns may result in a northward shift in forest habitat. Forest species throughout the Lake Superior region are expected to experience increased mortality and eventually be replaced by species from forests further south.
- Stronger wave action and lower water lake levels could leave shoreline regions more vulnerable to erosion and damage, resulting in degradation of fish spawning areas.
- The concentrations of toxic chemicals and pollutants in Lake Superior may increase due to variations in the frequency and intensity of precipitation, with adverse effects on wildlife.
- The dissolved oxygen content in Lake Superior may decrease due to higher water temperatures and an increase in the length of the summer stratification season, resulting in anoxic dead zones at the bottom of Lake Superior where few plants or animals could survive.
- Higher water temperatures are likely to cause major changes in the populations of plants and animals in the aquatic ecosystem, such as a shift in fish composition from cold water species (e.g., trout and salmon) to warm water species (e.g., bass and carp).
- Warmer air temperatures and changes in precipitation patterns may cause a reduction in the extent of northern plant and animal species and an increase in that of southern species.
- Higher water temperatures may permit increases in the populations of aquatic invasive species in Lake Superior, such as Sea Lampreys and zebra and quagga mussels.

Although these effects on ecosystems in the Lake Superior region are probable based on current research, uncertainty in climate change impacts exists, especially changes associated with future precipitation patterns (Carstensen et al., 2008). Results from recent modeling studies of the sensitivity of natural ecosystems to potential climate change in the U.S., both at regional and national levels, show that different, equally plausible emissions scenarios can generate significant differences in the simulated future response of ecosystems to climate change, particularly due to variations in projected precipitation (Lenihan et al., 2008). Simulating the response of ecosystems to climate changes adds an additional layer of uncertainty, since changes in climate will interact with changes in other processes, such as land use (Carstensen et al., 2008; Lenihan et al., 2008).

In general, however, climate change seems likely to stress Lake Superior ecosystems by altering the air temperature and precipitation patterns in the region, which will in turn affect Lake Superior's water temperature, ice cover, and water levels. A warmer climate may exceed the thermal tolerances of some species, causing them to migrate to cooler locations. The changing climate may also create suitable habitats for predators or competitors to move into the Lake Superior region and impinge on resident species. In this way, the impacts of climate change are expected to affect the composition and productivity of Lake Superior ecosystems. Many existing ecosystem stresses, including habitat fragmentation, accumulation of chemical pollutants, and the spread of invasive species, will be exacerbated by the effects of climate change. Future ecosystem stresses, such as enhanced water withdrawal to support expanding energy production, may also increase the vulnerability of Lake Superior ecosystems (Great Lakes Commission, 2011).

2.2.2 Physical Aspects of Vulnerable Ecosystems

Climate change is expected to affect the physical aspects of Lake Superior ecosystems, causing variations in habitat types. Coastal wetlands and forests will be particularly impacted and significant shoreline effects and consequences associated with ice cover are expected.

Coastal Wetlands

Coastal wetlands are transition zones between water and land, with vegetation ranging from submerged plants along the shore to woods and swampy forests in higher elevations. Lake Superior coastal wetlands include marshes, meadows, bogs, and swamps (Mortsch, 1998; Epstein et al., 1997). Examples of specific wetland community types in the Wisconsin portion of the Lake Superior basin include submergent aquatic, emergent aquatic, coastal fen (sedge fen), coastal bog (poor fen), open bog, northern sedge meadow, interdunal wetland, wet sand flats, alder thicket, shrub-carr, tamarack swamp, black spruce swamp, white cedar swamp (northern wet-mesic forest), hardwood swamp, and floodplain forest (Epstein et al., 1997).

Coastal wetlands provide habitats for a variety of plants and animals, including migratory and nesting birds, spawning fish, and other aquatic species (Hartmann, 1990). Because wetlands act as the interface between terrestrial and aquatic ecosystems, they are sensitive to changes in air temperature, regional precipitation, runoff, snow cover, length of the freezing season, and evapotranspiration caused by climate change. These climate change-induced stresses may amplify existing stresses to wetlands from urbanization, recreational development, conversion to agricultural land, and ecological damage (Mortsch, 1998). The historical natural cycles of water levels in the Lake Superior basin, described in Section 2.1.9, are critical for maintaining healthy coastal wetlands ecosystems. High lake levels confine the expansion of trees, shrubs, and canopy-dominating emergent plants, while low water levels promote seed germination and restrict the growth of plants that require very wet conditions, such as cattails, to the lowest elevations (Wilcox et al., 2007). Since the diversity of wetland plant communities and animal habitats in the Lake Superior region depends on water-level fluctuations, projected decreases in lake water levels associated with climate change are of particular concern. Consistently lower Lake Superior water levels could limit the extent of marshes that serve as breeding and nursery areas for fish and wildlife, and significantly reduce fisheries production (Hartmann, 1990; IJC, 2003; Environment Canada, 2005). Based on bathymetry data, Ciborowski et al. (2008) identified the areas on Lake Superior where a 1 m average decrease in water levels will have the most significant potential impact on near-shore and coastal habitats, shown in Figure 30.

Mortsch (1998) assessed the potential impacts of climate change on Great Lakes coastal wetlands. Although this study focused on coastal wetlands in the Great Lakes as a whole, the implications are applicable to the Lake Superior basin. Results of the study indicated that future lower mean lake water levels and a shift in seasonal water level cycles could have significant consequences for coastal wetlands, including a decline in habitat for waterfowl migration; reduced muskrat populations due to starvation, disease, and increased attacks from predators; and inability of fish to reach spawning areas. Marshes are expected to adapt more easily to lower water levels than swamps. Swamp ecosystems are more vulnerable because they contain primarily trees, which cannot regenerate and colonize quickly under changing conditions of lake water levels. Under extreme conditions of lower lake levels and reductions in precipitation associated with climate change, coastal wetlands could progress toward terrestrial ecosystems. The rate of climate change is another critical factor affecting wetland ecosystems. A relatively slow rate of change would allow steady adaptation and invasion of new vegetation and wildlife species, but a sudden, rapid change in climate could have catastrophic effects, as few wetland organisms would be able to adapt (Mortsch, 1998). It is possible that the extent of coastal wetlands may increase initially, as lake levels begin to decline, since more of the Lake Superior coastline will be exposed to allow the expansion of wetland communities (Mitsch, 2011).

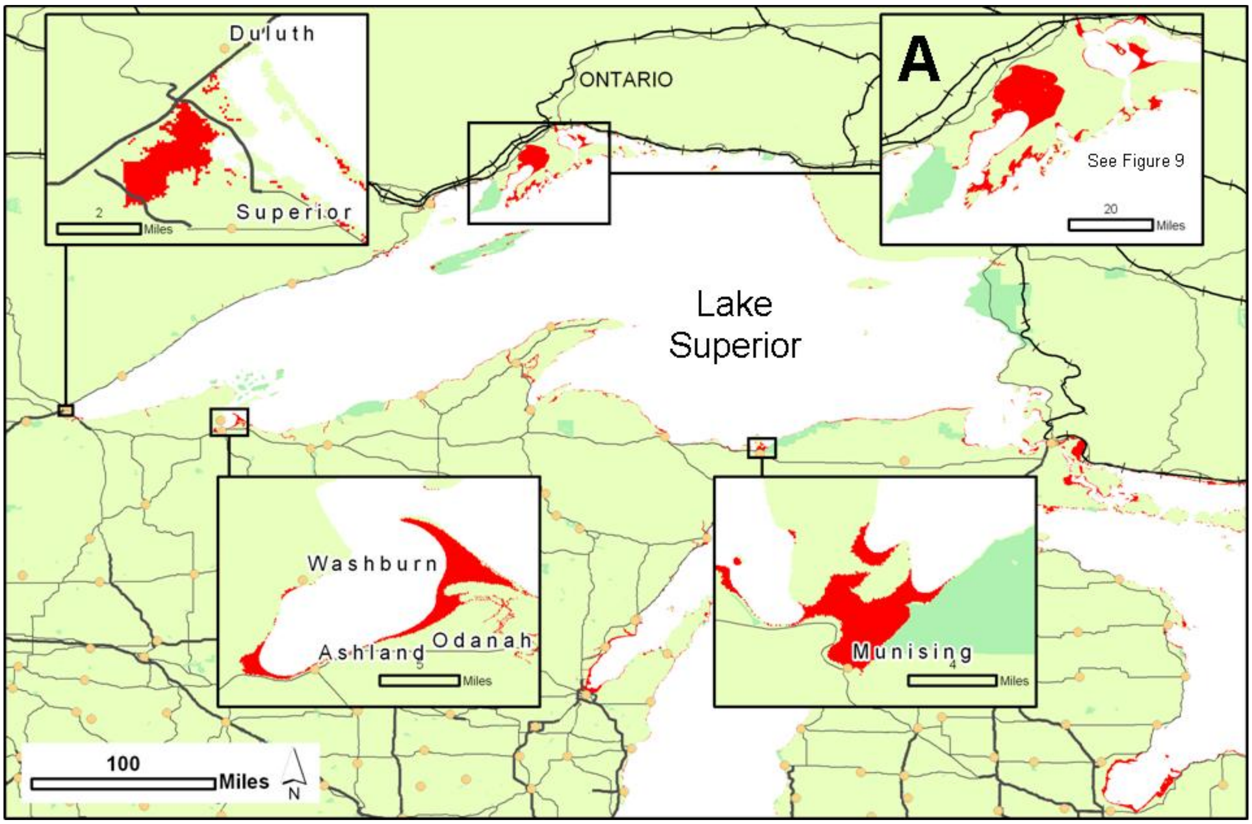

Figure 30. Coastal areas of Lake Superior most likely to be affected by a 1 m decrease in water levels (red shading). Green areas are provincial, federal, or state parks. The detailed pullout areas are representative and may not include all coastal areas in Lake Superior potentially affected by fluctuating water levels. [Adopted from Ciborowski et al., 2008]

Based on expert opinion and the latest understanding of climate change effects, the following coastal wetlands are recognized to be at risk:

- Bog ecosystems
- Fen ecosystems
- Lagoon ecosystems
- Swamp ecosystems

Forest Habitat

Warmer air temperatures and changes in precipitation patterns under a changing climate are expected to alter forest habitat in the Lake Superior region. Currently, the Lake Superior basin includes northern hardwood forests (called the Great Lakes-St. Lawrence forest in Ontario) and boreal forests. Boreal forests include conifer species (such as black and white spruce, jack pine, and balsam fir) and deciduous species (such as poplars and white birch) (Saunders et al., 2011; Ontario Ministry of Natural Resources, 2011a). Northern hardwood forests/Great Lakes-St. Lawrence forests contain coniferous trees (such as eastern white pine, red pine, eastern hemlock and white cedar) and deciduous broad-leaved species (such as yellow birch, sugar and red maples, basswood, and red oak) (Ontario Ministry of Natural Resources, 2011b). Tree species more common in boreal forests, such as white and black spruce, jack pine, aspen, and white birch, also exist in the northern hardwood forests/Great Lakes-St. Lawrence forests (Ontario Ministry of Natural Resources, 2011b).

Modeling studies are consistent in projecting a northward shift in forest habitats due to climate change in the 21st century. Forest species throughout the Lake Superior region are expected to experience increased mortality and eventually be replaced by species from forests further south (McKenney et al., 2010; IJC, 2003). Boreal forest tree species (e.g., black spruce, jack pine, white spruce, balsam fir, trembling aspen) are projected to migrate northwards of Ontario and out of the Lake Superior region (McKenney et al., 2010). Northern hardwood forests/Great Lakes-St. Lawrence forest tree species (e.g., white pine, red pine, sugar maple, and red oak) are expected to expand into the northern portion of the Lake Superior basin, as the amount of suitable habitat is projected to increase due to warmer conditions in the Ontario portion of the basin (McKenney et al., 2010). In the U.S. portion of the basin, modeling studies suggest a shift from predominately spruce-fir, white-red-jack pine, and aspen-birch forests to predominately oak-hickory and maple-beech-birch forests by 2099 (Ravenscroft et al., 2010; Iverson et al., 2008), as shown in Figure 31.

Although it seems clear that climate change will cause a shift in forest habitat in the Lake Superior region, the timescale of change is unclear. Migration rates, pests, disease, land use, and forest management will also impact forest health and composition in the 21st century (IJC, 2003). Insect infestations or wildfires may cause faster changes in forest types than suggested by climate models, or the long life expectancy and hardiness of some tree species may ameliorate the impacts of climate change on Lake Superior forests (Saunders et al., 2011).

In addition to providing a myriad of functions for wildlife, human recreation, and industry, forest ecosystems are also extremely valuable as carbon sinks. Plants utilize CO_2 for photosynthesis and thus, forests provide a natural sink for atmospheric CO_2. Large amounts of carbon are stored in trees, roots, and soils. Any significant loss of forested regions will decrease the Earth's ability to absorb carbon and prevent the release of CO_2 into the atmosphere. Responsible management of forest ecosystems to enhance carbon storage could help to mitigate the rate of climate change (U.S. Forest Service, 2010).

Based on expert opinion and the latest understanding of climate change effects, the following forest habitats are recognized to be at risk:

- Boreal forests (northern Lake Superior basin)
- Northern hardwood forests/Great Lakes-St. Lawrence forests (southern, western, eastern Lake Superior basin)

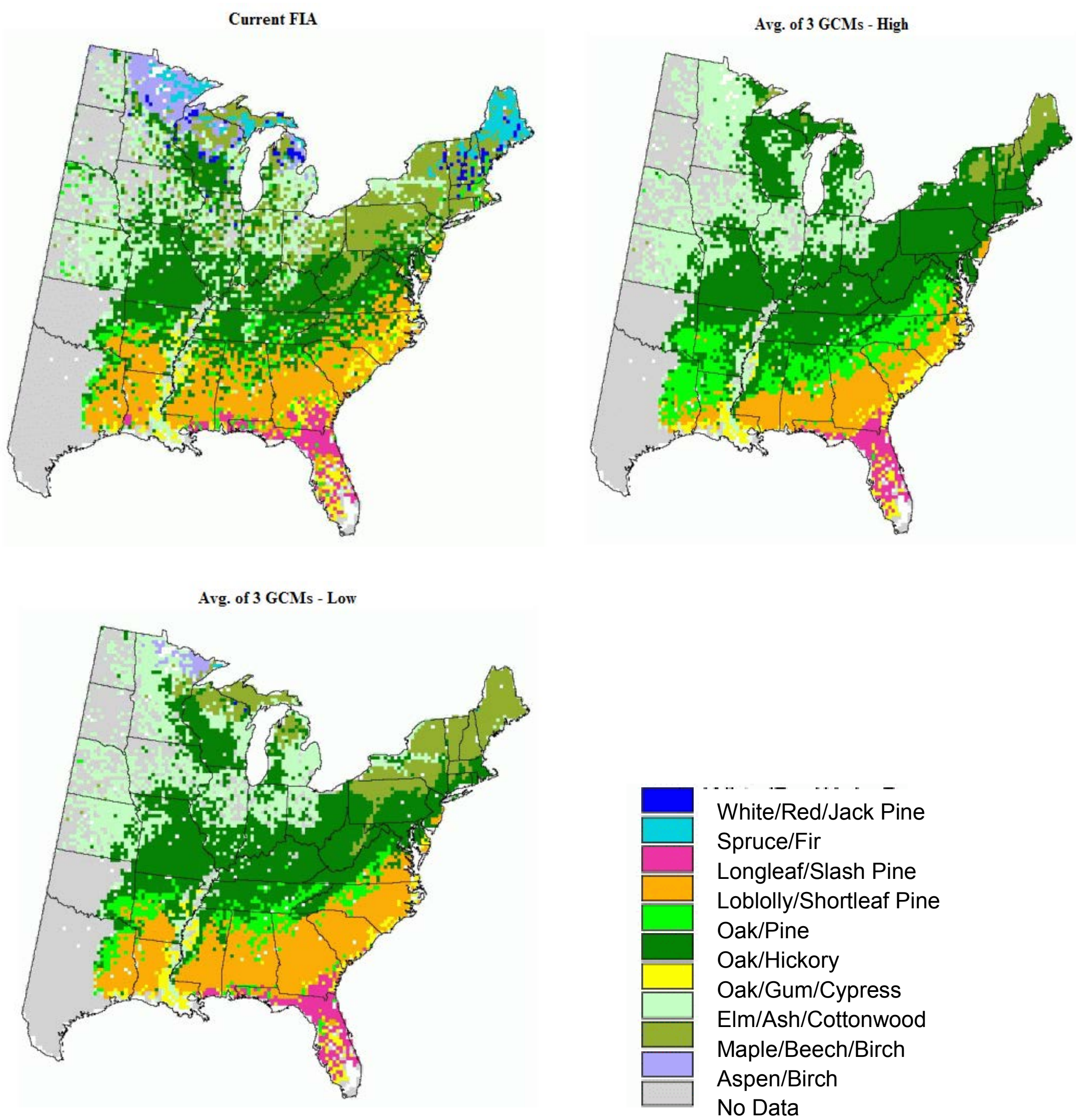

Figure 31. Potential future changes in suitable forest type habitat by 2099. Trees are categorized using USDA Forest Service forest types. Current habitat is based on the Forest Inventory and Analysis, and projections are based on the output of three GCMs run under "high" (A1F1) and "low" (B1) emissions scenarios. [Images courtesy of Prasad et al., 2007]

Shoreline Effects

Stronger winds over Lake Superior associated with climate change will create higher and stronger waves that will impact the lake shoreline, including bluffs and lakebeds (WICCI, 2011). Reduced ice cover will allow more waves to form on the lake during winter, especially during winter storms (Saunders et al., 2011). Consequently, the Lake Superior shoreline will be more vulnerable to erosion from wave action, particularly during the winter (WICCI, 2011; Saunders et al., 2011).

To investigate these effects on the Lake Superior shoreline, the United States Geological Survey used a change-potential index (CPI) to map the susceptibility of the shoreline in Apostle Islands National Lakeshore in Wisconsin to climate change-induced changes in Lake Superior water levels (Pendleton et al., 2007). The CPI was based on geomorphology, regional coastal slope, rate and direction (i.e., rise and fall) of relative lake-level change, historical shoreline change rates, annual ice cover and mean significant wave height. This approach combined the coastal system's potential for change with its natural ability to adapt to changing environmental conditions. Results showed that the areas of unconsolidated sediment where regional coastal slope is low and wave energy is high are likely to experience the most lake-level-related coastal change. Over half of the 300 km (185 mi) of shoreline at Apostle Islands National Park is rated as having a high to very high potential for shoreline change. High change-potential geomorphology includes gravel and sand beaches not immediately backed by bluffs (Pendleton et al., 2007). These results are likely applicable to other shoreline areas of Lake Superior, which suggests that the combination of stronger waves and lower lake water levels could leave shoreline regions vulnerable to degradation.

Based on expert opinion and the latest understanding of climate change effects, the following shorelines are recognized to be at risk:

- Shoreline of Apostle Islands National Lakeshore

2.2.3 Chemical Aspects of Vulnerable Ecosystems

Climate change is expected to affect the chemical aspects of Lake Superior ecosystems, causing deteriorations in water quality. Anticipated impacts include increases in the concentrations of toxic chemicals and pollutants in Lake Superior and decreases in dissolved oxygen content associated with warmer lake waters and changes in vertical circulation and stratification patterns.

Toxic Chemicals and Pollutants

Any variations in the frequency and intensity of precipitation associated with climate change have the potential to degrade the water quality of Lake Superior. Longer periods of dry weather between heavy rain events, particularly in the summer, will permit pollutants to build up on roads and land surfaces. Runoff from subsequent heavy rains will wash these pollutants into Lake Superior, potentially causing a spike in concentrations of hazardous chemicals in lake waters (IJC, 2003). An increase in rainfall intensity may result in increased erosion of the land surface and stream channels, higher sediment loads, and increased loadings of nutrients and contaminants (McBean and Motiee, 2008). Sporadic releases of relatively high concentrations of toxic pollutants may cause more adverse effects on wildlife than smaller, more frequent releases.

Potentially lower lake water levels due to climate change may also increase concentrations of toxic chemicals in Lake Superior. If lake water levels drop, formerly submerged toxic sediments could be exposed, releasing chemicals such as mercury, dioxins, and polychlorinated biphenyls (PCBs) into Lake Superior surface waters (Dempsey et al., 2008; Betz et al., 2010). Lower water levels may also cause existing levels of nutrients, contaminants, and sediments to become more concentrated, thereby affecting water quality and impacting coastal wetland ecosystems (Cápiro, 2009). Impacts on fish and wildlife may include increased tumors and higher mortality. Humans may also be affected through consumption of fish exposed to toxic chemicals and pollutants. In addition, stronger wave action in shallow waters associated with lower Lake Superior water levels could reduce water quality through increased turbidity (deLoë and Kreutzwiser, 2000). These shallow areas are important spawning regions for Lake Superior fish.

Based on expert opinion and the latest understanding of climate change effects, the following locations are recognized to be at risk for amplification of toxic chemicals and pollutants:

- Shallow waters, including shoreline areas
- Areas of the lake that are adjacent to communities or agricultural areas
- Areas prone to flooding and erosion
- Harbors and embayments,
- Heavily developed shorelines
- River mouths draining urban areas

Dissolved Oxygen Content

Warmer water temperatures associated with climate change will reduce the overall dissolved oxygen content of Lake Superior (IJC, 2003). Dissolved oxygen saturation values are lower for warmer water, so Lake Superior is expected to have less oxygen in the future as lake water warms due to climate change (Hall et al., 2007). In addition, as the lake water warms, the metabolic rates of oxygen-consuming sediment bacteria will increase, as will the biological productivity and respiration in the water column, which will further decrease dissolved oxygen content in Lake Superior (Hall et al., 2007). Other expected impacts associated with higher lake water temperatures include changes in the rate of chemical reactions in the water column, at the sediment-water interface, and at the water-atmosphere interface (IJC, 2003). Dissolved oxygen concentrations are critical for the health of aquatic ecosystems, including fish.

Water quality could also be degraded by an increase in the frequency and extent of algal blooms, including toxic blue-green algae (Moy et al., 2010). Algae growth is favored in warmer waters, so warmer water temperatures associated with climate change may enhance the growth of algae in Lake Superior. The alga are short lived, and as they begin to decompose, they deplete dissolved oxygen in the water. As a result, warmer waters with reduced levels of dissolved oxygen can experience further declines if algal blooms occur.

Vertical Circulation/Stratification Effects

As described in Section 2.1.6, Lake Superior undergoes a process of “turnover” twice per year, during which warm, oxygen-rich surface water sinks and mixes with colder, oxygen-depleted deep water (Figure 32). “Turnover” is the main mechanism that replenishes deep lake waters with dissolved oxygen. Currently, the Lake Superior water column undergoes “turnover” in the spring and fall each year (Croley et al., 1998). If the surface water temperature of Lake Superior does not fall to 4 ºC (39 °F; the temperature at which water has its maximum density) in the fall, due to warmer temperatures associated with climate change, then “turnover” will occur only once per year, in the spring (Hartmann, 1990; Croley et al., 1998; Hall et al., 2007). The result would be a reduction in the dissolved oxygen content of the deep water layers in Lake Superior, which would alter the deep water chemistry of the lake. In the absence of sufficient dissolved oxygen, cold water fish species would be unable to survive in deep water habitats, impacting the aquatic ecosystem (Croley et al., 1998; Lehman, 2002; Kling et al., 2003; Hall et al., 2007).

Climate variables projected by two GCMs suggest that thermal stratification will be up to 2 months longer in Lake Superior by 2090, with higher surface, mixed layer, and bottom water temperatures (Lehman, 2002). Warmer deep water will likely increase the metabolic rates of invertebrates and microbes, leading to accelerated consumption of dissolved oxygen during extended periods of stratification (Lehman, 2002). It may also deprive phytoplankton and detritus-eating organisms of nutrients necessary for growth and survival (Hall et al., 2007). The overall productivity of the lake may be lowered, impacting the entire food chain and leading to declines in the population and health of cold water fish and other species that depend on vertical lake circulation for survival (Dempsey et al., 2008; Hall et al., 2007; Saunders et al., 2011).

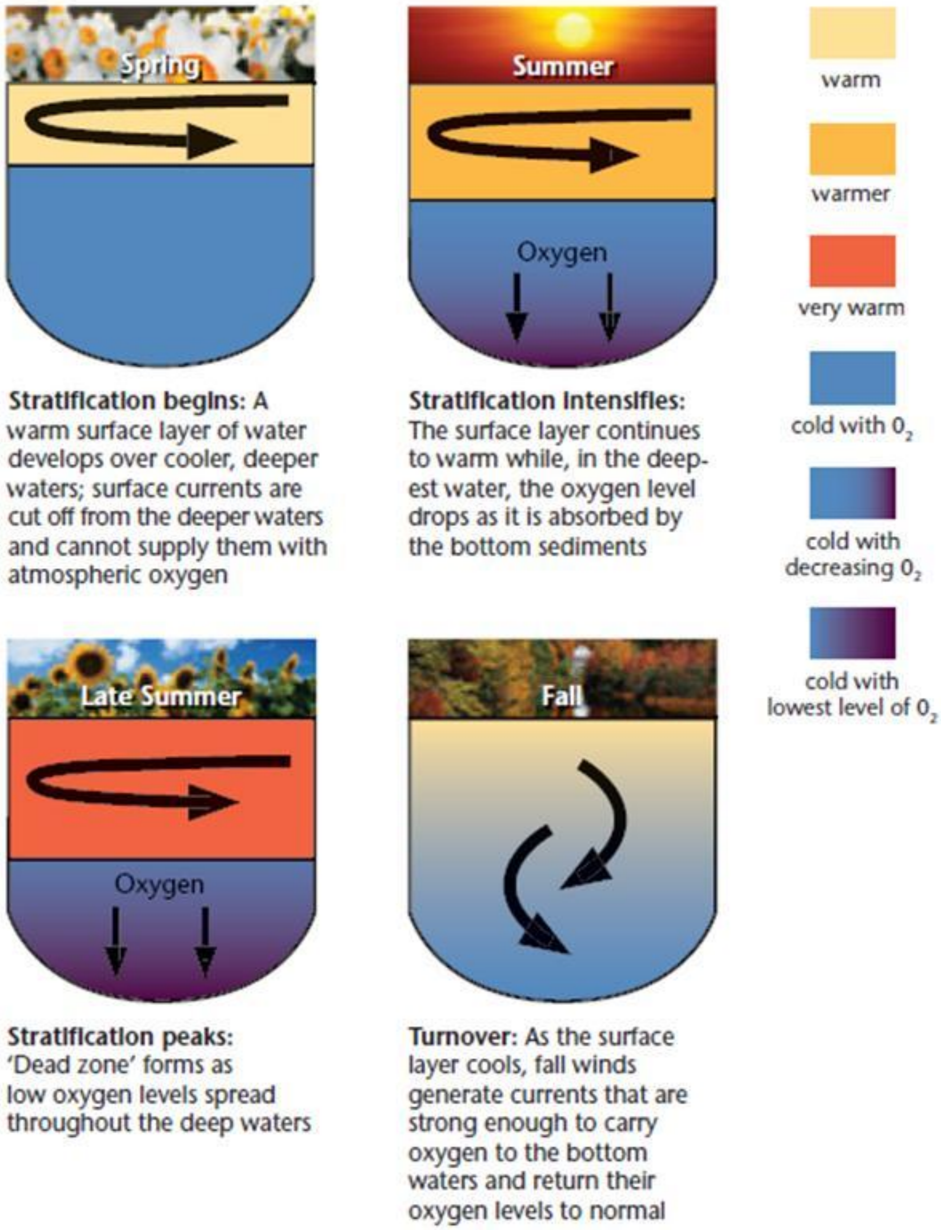

Figure 32. Illustration of lake stratification and "turnover" to distribute oxygen-rich waters throughout the vertical lake water column. [Image courtesy of Kling et al., 2003]

2.2.4 Biological Aspects of Vulnerable Ecosystems

Climate change is expected to affect the biological aspects of Lake Superior ecosystems, causing changes to a significant number of plants and animals. Major types of potentially impacted organisms include phytoplankton and zooplankton, fish, mammals, birds, and trees in forests. A pictorial overview of the Lake Superior food web is shown in Figures 33a and 33b.

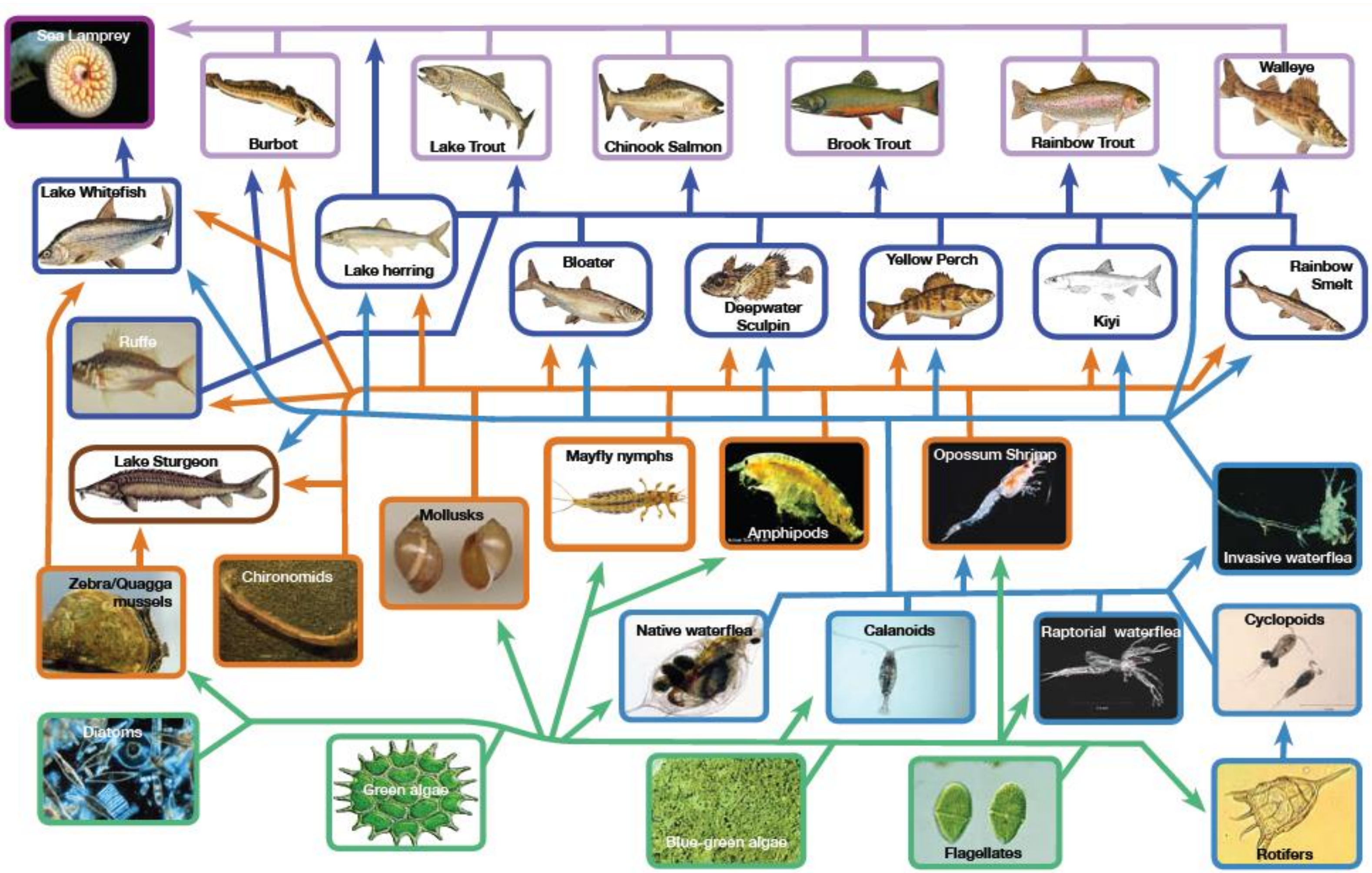

Figure 33a. The Lake Superior food web. [Image courtesy of NOAA Great Lakes Environmental Research Laboratory (http://www.glerl.noaa.gov/pubs/brochures/foodweb/LSfoodweb.pdf)]

Figure 343b. The Lake Superior food web. [Image courtesy of NOAA Great Lakes Environmental Research Laboratory (http://www.glerl.noaa.gov/pubs/brochures/foodweb/LSfoodweb.pdf)]

Phytoplankton/Zooplankton

Currently, Lake Superior has very low phytoplankton primary productivity rates to support its food web (Minnesota Sea Grant, 2010). Warmer surface lake water associated with climate change may impact the life cycle of phytoplankton, decreasing primary productivity and reducing food available for zooplankton and the prey of predator fish (Dempsey et al., 2008). Results from two GCMs suggest that as Lake Superior's water temperature increases, primary productivity will decline, principally due to the longer thermal stratification season (Sousounis and Bisanz, 2000). If phytoplankton become less abundant, the food web will become diminished, impacting cold water fish species and Lake Superior fishery production (Sousounis and Bisanz, 2000).

Warming Lake Superior surface water may affect the abundance of copepods, which are the largest component of zooplankton in the lake. A recent study indicates that water temperature shifts of 5 to 10°C (9 to 18 °F) can cause large changes in proportions of three copepod species in Lake Superior (Megart et al., 2009). In general, researchers expect that Lake Superior copepods will become smaller and more abundant as surface water temperature continues to increase in the future associated with climate change (Megart et al., 2009), which may cause an unknown impact on Lake Superior's aquatic ecosystem and food web.

Based on expert opinion and the latest understanding of climate change effects, the following phytoplankton/zooplankton are recognized to be at risk:

- Copepods

Fish

Fish in Lake Superior are a complex mix of native and non-native species. Several non-native fish were intentionally introduced to Lake Superior as game fish species, including Chinook Salmon, Coho Salmon, Brown Trout, and a variety of Rainbow Trout strains (Minnesota Department of Natural Resources, 1999). Invasive non-native fish species include Ruffe, Round Goby, and Sea Lamprey. The Sea Lamprey virtually eliminated Lake Trout in Lake Superior after its arrival in the mid-1900s (Minnesota Department of Natural Resources, 1999). Lake Trout rehabilitation efforts over the past 20 years, including Sea Lamprey control, harvest regulations and stocking programs, have resulted in the establishment of self-sustaining populations in most near-shore waters of Lake Superior (Great Lakes Fishery Commission, 2007). Natural reproduction of Lake Trout has been re-established and maintained in Lake Superior (U.S. EPA and Environment Canada, 2009). At this time, deepwater species of Lake Trout (Siscowet) are abundant in Lake Superior, and the lean, shallow-water species of Lake Trout are also plentiful due to restoration efforts (U.S. EPA and Environment Canada, 2008). More details about the impacts of climate change on invasive species in Lake Superior are provided in Section 2.2.6.

Fish in North American lakes can be divided into three main categories, based on temperature. Cold water fish require water temperatures of <15 °C (<59 °F), cool water fish require water temperatures of 15 to 25 °C (59 to 77 °F), and warm water fish require water temperatures of >25 °C (>77 °F) (Chiotti and Lavender, 2008). Climate change is expected to increase the water temperature of Lake Superior, potentially leading to a decrease in the populations of cold water fish species and an increase in warm water species and some cool water species. Examples of potentially affected cold water fish species in Lake Superior include Brown Trout, Rainbow Trout, Chinook Salmon, and Coho Salmon (Wisconsin Sea Grant, 2002; Stefan et al., 2001). Examples of cool water fish that may be impacted include Northern Pike, Walleye, White Sucker, and Yellow Perch (Wisconsin Sea Grant, 2002; Stefan et al., 2001). Increases in water temperature associated with climate change may also have a negative impact on cold water fish species that spend their life cycle in Lake Superior (e.g., Lake Trout, Burbot), but they will have the best chance of survival in Lake Superior compared to other North American lakes, since Lake Superior is a deep, stratified lake (Stefan et al., 2001).

Specific impacts on cold water fish will likely involve the timing of spawning, egg development, hatching, yolk sac development and potential for normal growth. For example, optimum temperatures for spawning occur in the autumn for Lake Trout (8 to 11°C; 46 to 52 °F) and in the spring for Northern Pike (4 to 12°C; 39 to 54 °F) (Lehman, 2002). These spawning windows may be shifted or compressed as lake temperatures warm. Figure 34 indicates the current locations for fish spawning in Lake Superior. Water temperature changes may also affect developmental responses in fish that are cued by temperature, such as hatching of resting eggs and resting stages (Lehman, 2002). Once fish are at the yearling stage, their growth will decrease if prey consumption remains constant in waters warmed by climate change (Hill and Magnuson, 1990). Potential changes in yearling fish growth are expected to be greatest in spring and fall due to an increase in the length of the period during which fish may behaviorally thermoregulate to find their optimal temperature for growth. Fish that are not able to thermoregulate in warmer waters will experience less growth in areas of Lake Superior where near-surface water temperatures are higher than a particular fish's optimum range (Hill and Magnuson, 1990).

The extent and duration of ice cover on Lake Superior will also have important consequences for fish. Ice provides protection for fish eggs against predators during late winter and early spring (Ferris and Andrachuk, 2009). Any reductions in the extent and duration of ice on Lake Superior associated with climate change will leave fish eggs exposed and vulnerable, curtail access to spawning beds, and may reduce the overwinter survival of fish (Easterling and Karl, 2000; Assel et al., 2003; IJC, 2003).

Based on expert opinion and the latest understanding of climate change effects, the following fish are recognized to be potentially at risk:

- Burbot
- Brown Trout
- Chinook Salmon
- Coho Salmon
- Lake Trout
- Northern Pike
- Rainbow Trout
- Walleye
- White Sucker
- Yellow Perch

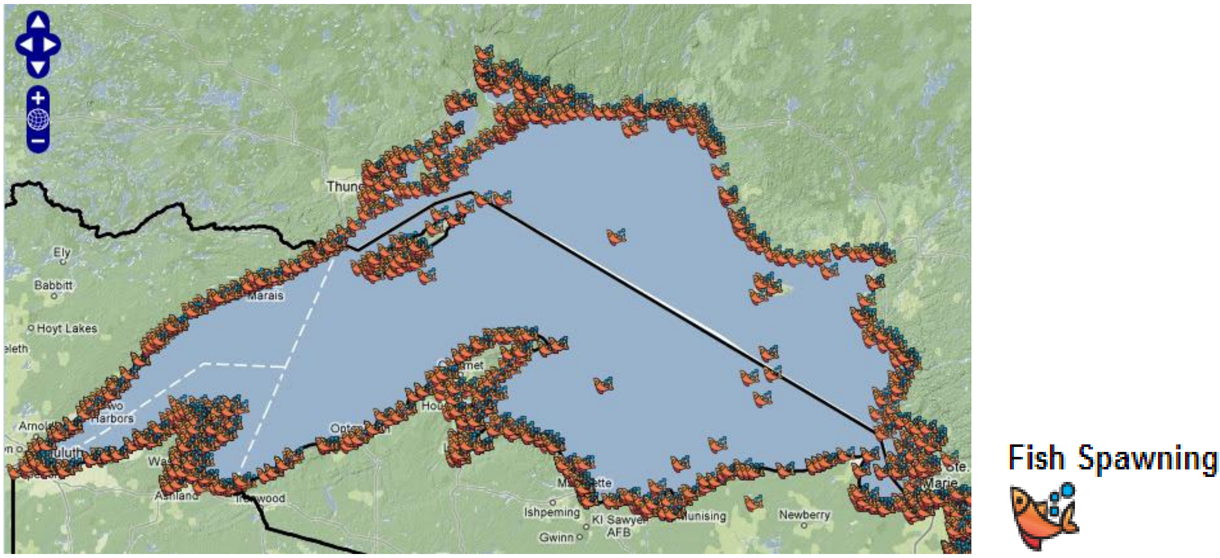

Figure 354. Locations of fish spawning on Lake Superior. [Image courtesy of Great Lakes Wind Atlas, http://erie.glin.net/wind/]

Mammals

A wide variety of mammals currently reside in the Lake Superior basin. Large mammals include white-tailed deer, black bears, wolves, moose, and woodland caribou. Smaller fur-bearing mammals include bobcats, coyotes, red foxes, beavers, otters, minks, muskrats, raccoons, lynx, and wolverines. Small forest mammals include porcupines, snowshoe hares, striped skunks, red squirrels, chipmunks, mice, shrews, and bats (Minnesota Department of Natural Resources, 1999).

A recent report on climate change in the U.S. National Parks in the vicinity of Lakes Superior and Michigan (Saunders et al., 2011) suggests that climate change will have negative impacts on some key species of wildlife in the region, including moose and lynx. In particular, changes in habitat and snow depth patterns associated with climate change may make the persistence of lynx in Minnesota less likely, especially during low periods of the lynx (predator)/ hare (prey) population cycle (Carstensen et al., 2008). This potential loss of lynx populations is of particular concern because the lynx is a state-threatened species in Michigan, Minnesota, and Wisconsin (Collins, 2012).

Another recent study demonstrated that as average air temperatures have increased over the period 1883-2006 in the northern U.S. Great Lakes region, the distribution and abundance of common southern small mammal species (e.g., white-footed mice, eastern chipmunks, southern flying squirrels) have increased, while that of comparable northern species (e.g., woodland deer mice, southern red-backed voles, woodland jumping mice, northern flying squirrels, least chipmunks) have decreased (Myers et al., 2009). For example, white-footed mice and southern flying squirrels were not present in 1971 in the Huron Mountains near the Lake Superior shoreline in the central Upper Peninsula of Michigan, but they have become commonplace in the last 35 years. Results of the study showed that southern species are not only moving into the Lake Superior region, but they are replacing northern species (Myers et al., 2009). The implications of these observed changes on Lake Superior ecosystems are potentially enormous because the small mammal species involved are so commonplace (Myers et al., 2009).

If deer migrate further north in response to an expansion of their habitat associated with climate change, they have the potential to severely impact moose and woodland caribou populations in northern Minnesota and the Ontario portion of the basin due to the spread of the meningeal worm parasite (*Parelaphostrongylus tenuis*). Deer carry the meningeal worm, and high deer population densities in moose/caribou habitat can result in the transfer of the parasite, with subsequent infection and mortality for moose and caribou (Lankester, 2010; Greenwood, 2012). Short, mild winters favor the growth of deer populations in moose/caribou habitat, and wetter conditions and longer snow-free periods enhance the opportunity for parasite transition from deer to moose and caribou (Lankester, 2010). These conditions are expected to occur due to climate change, which will likely increase the susceptibility of moose and woodland caribou populations in the Lake Superior region to the meningeal worm parasite. Furthermore, an increase in precipitation and winter air temperatures around Lake Superior may lead to a decline in the moose population along the southern edge of their range (Varrin et al., 2007).

Increasing air temperatures associated with climate change may also be impacting the famous moose/wolf system on Isle Royale, a remote island located in northwestern Lake Superior. The moose are the primary prey of the wolves on Isle Royale, and the wolves are the only predators of the moose. Researchers from Michigan Technical University and the U.S. National Park Service have been making annual observations of wolves and moose on Isle Royale since 1958. The Isle Royale wolf population typically comprises between 18 and 27 wolves, organized into three packs. The moose population historically includes between 700 and 1,200 moose. Between January 2010 and January 2011, the wolf population declined from 19 to 16, which is below the long-term average of 23 wolves (Figure 35) (Vucetich and Peterson, 2011). Moose abundance in February 2011 was estimated at 515; for the sixth consecutive year, the moose population was approximately half the long-term average of 1,000 moose (Figure 35) (Vucetich and Peterson, 2011). During the winter of 2011-2012, the wolf population dropped from 16 to 9 (Figure 35), which is the lowest number of wolves ever observed (Vucetich and Peterson, 2012). By February 2012, the moose population had risen to 750, continuing the recent increase in moose since the lowest recorded level of 400 in 2006 (Vucetich and Peterson, 2012). Despite the recent surge in moose population, numbers remain below the long-term average of 1,000 moose (Vucetich and Peterson, 2012).

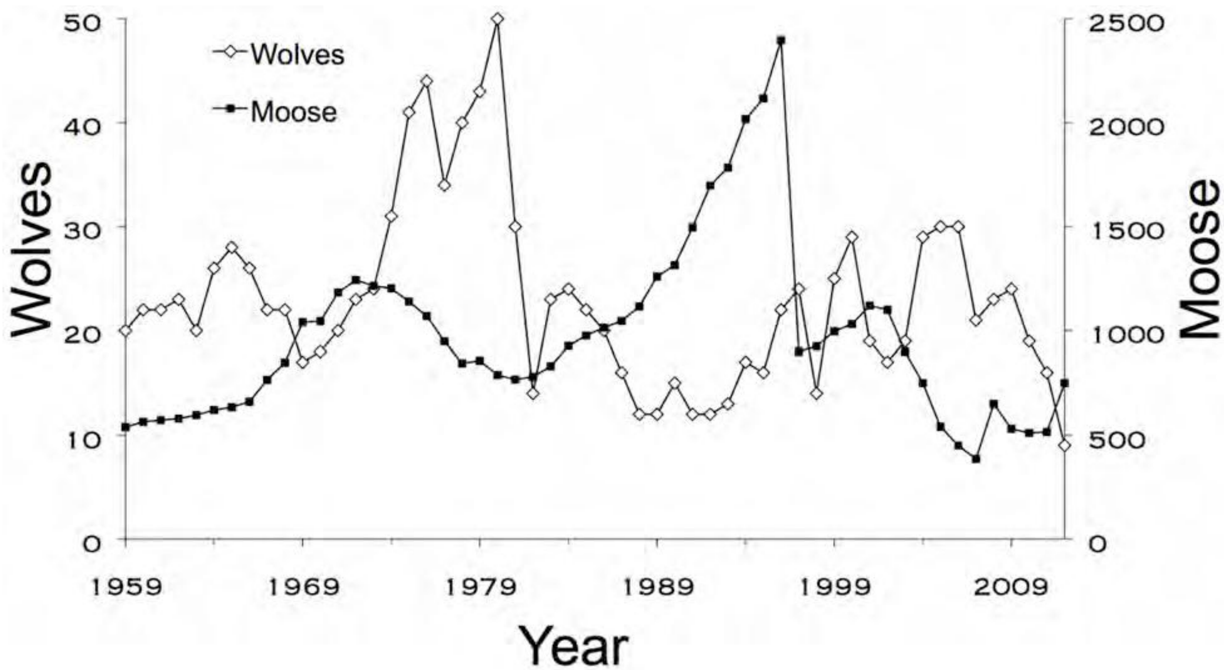

Figure 365. Wolf and moose fluctuations, Isle Royale National Park, 1959-2012. [Image courtesy of Vucetich and Peterson, 2012]

Although Figure 35 indicates there is substantial historical variability in the moose/wolf system, researchers attribute climate change, specifically a recent string of relatively hot summers, for the shrinking wolf and moose populations (Michigan Technical University, 2007). Hot weather causes moose to rest more and forage less during the summer, leaving them less prepared to survive the long, cold winters on Isle Royale. Warm spring and fall seasons also enhance the breeding of winter ticks, one of the main non-predatory factors that affect moose. Ticks feed on the blood of moose, weakening them and making them more vulnerable to attack by the wolves. Devastating tick infestations occurred on Isle Royale during the relatively warm years of 2002-2007, which was likely a contributing factor to the recent downturn in moose population (Michigan Technical University, 2007). Continued increases in average air temperature associated with climate change could promote the breeding of more ticks in future years, further threatening the moose population and consequently, the wolf population on Isle Royale.

Moreover, higher-than-average air temperatures and frequent high winds prevented the formation of an ice bridge between Isle Royale and the mainland during the winter of 2011-2012. Ice bridges are vital components of the Isle Royale moose/wolf system because they allow wolves to immigrate from the mainland, which is important for maintaining the genetic health of the Isle Royale wolf population. Annual observations indicate that the probability of an ice bridge forming has decreased substantially since 1965. For example, an ice bridge formed an average of every two out of three winters during the 1960s, but formed only about one year in 10 during the 2000s. This trend in declining winter ice bridge formation is likely due to climate change (Vucetich and Peterson, 2012).

The extent and duration of ice cover on Lake Superior may also impact mammals. Less ice cover associated with climate change will allow more water to evaporate from Lake Superior and fall as snow across the region. More snowfall and a deeper snowpack will impede foraging animals, such as deer, that must burrow through snow to find food (Ferris and Andrachuk, 2009).

Based on expert opinion and the latest understanding of climate change effects, the following mammals are recognized to be at risk:

- Least chipmunks
- Lynx
- Moose
- Moose and wolves in Isle Royale National Park
- Northern flying squirrels
- Southern red-backed voles
- Woodland deer mice
- Woodland jumping mice
- Wolverine
- Woodland caribou

Birds

A wide variety of birds reside in the Lake Superior basin, including ruffed grouse, spruce grouse, woodcocks, common ravens, American crows, hawks, owls, many species of songbirds, common loons, red-winged blackbirds, mallards, blue-winged teals, and wood ducks (Minnesota Department of Natural Resources, 1999). The Lake Superior watershed is also home to the piping plover, a U.S. Endangered species, the peregrine falcon, an Ontario Threatened species (Ontario Peregrine Falcon Recovery Team, 2010), and the bald eagle, an Ontario Species of Special Concern (Ontario Ministry of Natural Resources, 2008).

Climate change is expected to negatively impact many birds in the Lake Superior region, including loons and ruffed grouse. An example of the potential future changes in the incidence of the common loon (*Gavia immer*), which nests primarily on inland lakes in the Lake Superior region, by 2099 for the U.S. portion of the Lake Superior basin is given in Figure 36, based on output from three GCMs run under the A1F1 (high) and B1 (low) emissions scenarios (Prasad et al., 2009). As suitable habitats shift or are lost in the region due to climate change, general categories of birds may also be impacted, such as warblers, shorebirds, and wintering birds (Saunders et al., 2011). The effects of climate change on bird species will be tied to changes in associated plant communities. For example, populations of ruffed grouse may decline as the ranges of aspen, birch, and balsam fir trees shift north (Carstensen et al., 2008). As air temperatures warm and winters become milder due to climate change, southern bird species are expected to expand into the Lake Superior region. Several species have already moved into the region from the south in recent decades, such as mourning doves, ring-necked pheasants, and northern cardinals (Carstensen et al., 2008). In addition, Lake Superior is an important staging area for migratory waterfowl, and changes in lake water levels and food availability associated with climate change may affect migrant birds as they pass through the region.

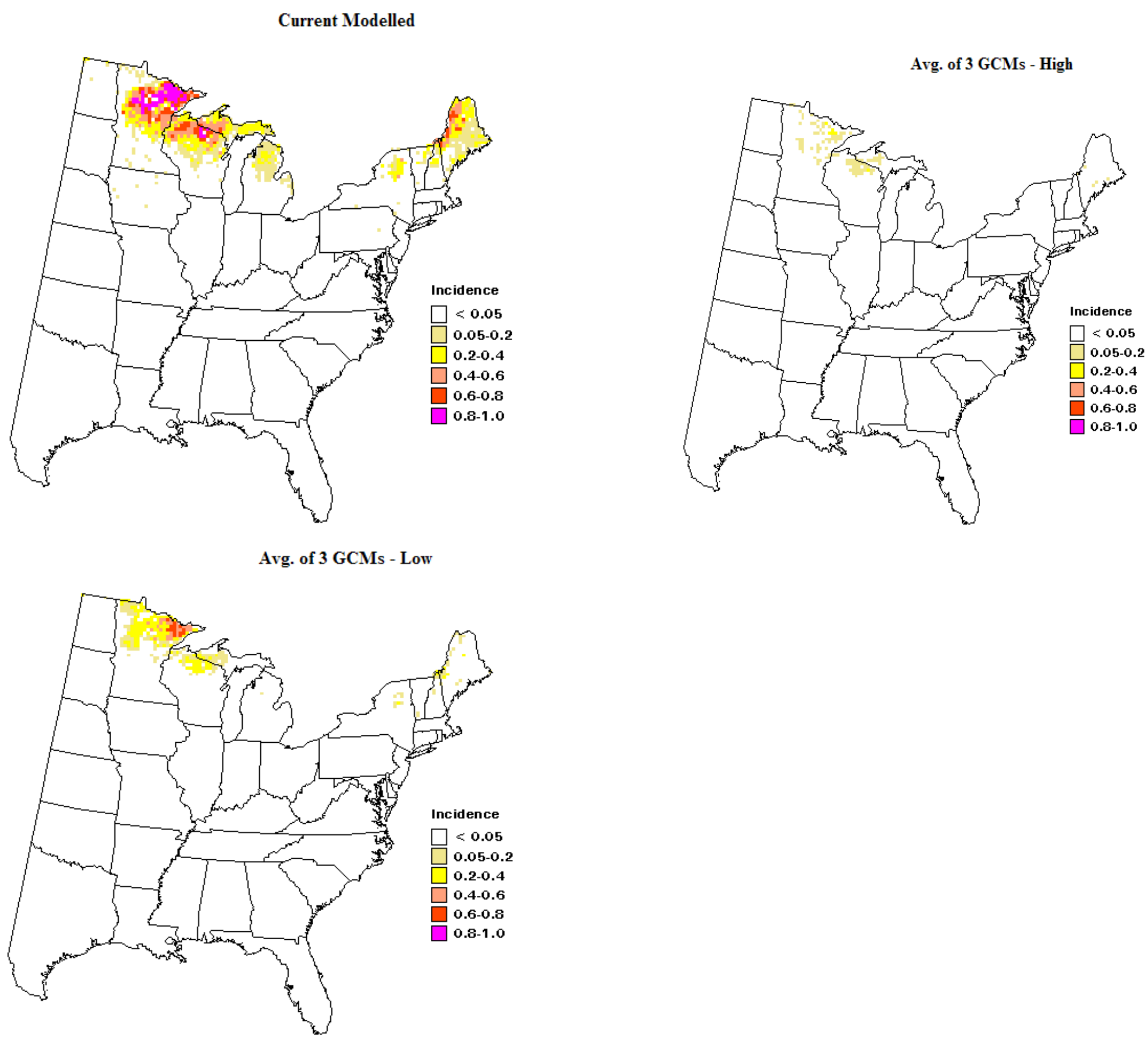

Figure 376. Potential future changes in incidence of the common loon (*Gavia immer*) by 2099. The current modeled data are based on the Breeding Bird Survey (BBS) and were used to derive bird incidence (proportion of years that a given species was observed on a particular route across ten years of sampling). The "high" emissions scenario corresponds to the A1F1 scenario, and the "low" emissions scenario corresponds to the B1 scenario. [Images courtesy of Matthews et al., 2007]

Based on expert opinion and the latest understanding of climate change effects, the following types of birds are recognized to be at risk:

- Loons
- Migratory waterfowl
- Ruffed grouse
- Shorebirds
- Warblers
- Wintering birds

Trees and Plants

Approximately 85% of the Lake Superior basin is forested, including a mix of aspen-birch, spruce-fir, maple-yellow birch, and white-red-jack pine trees (McKenney et al., 2010; Minnesota Department of Natural Resources, 1999). As described in Section 2.2.2, climate change is expected to cause a northward shift in the forest habitats of the Lake Superior region due to increasing average air temperatures. Climate change will also exacerbate existing stresses on trees, including drought, wind, fires, and insects (Galatowitsch et al., 2009). For example, the most significant ecosystem impacts associated with climate change that are expected in the northern Superior uplands region of Minnesota (adjacent to Lake Superior) include an increase in large-scale tree mortality, reduced regeneration of trees from increased deer herbivory, and loss of boreal forests (Galatowitsch et al., 2009).

There is some evidence that climate change may already be impacting some northern tree species. A recent study (Woodall et al., 2009) used the locations of tree seedlings relative to their respective forest stand biomass as an indicator of tree migration in the eastern U.S., including the U.S. portion of the Lake Superior basin. Results suggest that most northern tree species are exhibiting a northward migration. In particular, over 70% of the northern species studied had mean locations of seedlings significantly farther north (>20 km; >12.4 mi) than their respective geographic centers of biomass. Northern species considered in the study included balsam fir, tamarack, black spruce, red pine, northern white cedar, sugar maple, yellow birch, paper birch, black ash, balsam poplar, bigtooth aspen, quaking aspen, northern pin oak, northern red oak, and American basswood. The results of this study indicate that northward tree migration associated with climate change may already be occurring, with rates approaching 100 km (62.1 mi) per century for many species (Woodall et al., 2009).

The impacts of climate change in the Lake Superior region have been investigated for several specific tree species using GCMs and vegetation impact models. Two recent studies indicate that jack pine and black spruce trees in the vicinity of Lake Superior are currently growing at or near optimum levels, and an increase in air temperature associated with climate change may cause significant population losses of these trees (Thomson and Parker, 2008; Thomson et al., 2009). By 2041-2070, the optimum habitat for black spruce is expected to shift northward by approximately 3 to 4º latitude for areas north and northwest of Lake Superior (Thomson et al., 2009).

A more comprehensive study identified the species of trees in northern Wisconsin that are expected to experience habitat loss by the end of the 21st century due to climate change (Swanston et al., 2011). The most vulnerable forest ecosystems are expected to be low-diversity ecosystems that are currently dominated almost entirely by a single tree species (Swanston et al., 2011). The only species anticipated to completely lose suitable habitat is the mountain maple; it is very uncommon presently in northern Wisconsin. Twelve tree species are expected to have large declines in suitable habitat: black spruce, balsam fir, northern white cedar, yellow birch, paper birch, quaking aspen, white spruce, eastern hemlock, sugar maple, black ash, tamarack, and bigtooth aspen. Many of these species are currently very common in the forests of northern Wisconsin, and their loss has the potential to severely impact the forest ecosystem of southern and western Lake Superior. Six tree species are expected to experience small declines in suitable habitat, including balsam poplar, rock elm, jack pine, red maple, eastern white pine, and butternut. In addition, there are several species of trees in northern Wisconsin that are not expected to be impacted by climate change, such as green ash, northern pin oak, American basswood, northern red oak, chokecherry, and red pine (Swanston et al., 2011). Overall, these changes in forest communities will affect various aspects of forest ecosystems, such as wildlife habitat (Swanston et al., 2011).

Apostle Islands National Lakeshore provides important habitat for northern boreal plant species, such as butterwort (endangered species in Michigan) and birds-eye primrose (species of special concern in Michigan). Recent record low lake water levels, possibly associated with climate change, may be reducing the incidence of pools found on the wave-splashed shores of islands in the park. These splash pools are important to the survival of the northern boreal plant species, and as a result, the incidence of these plant species is decreasing. Apostle Islands National Lakeshore staff are conducting a survey to determine if the observed declines in the northern boreal plant species in recent years are related to climate change (Burkman and Van Stappen, 2009). The arctic and sub-alpine disjunct plant species that live along the northwestern Lake Superior coast are also vulnerable to the impacts of climate change. These plants were deposited by glaciers and have continued to survive on the cold coasts of Lake Superior. They include black crowberry, common butterwort, prickly saxifrage and many moss and lichen species (Nature Conservancy Canada, 2012). Increasing air temperatures associated with climate change may reduce or eliminate the habitat for these disjunct species.

Based on expert opinion and the latest understanding of climate change effects, the following trees and plants are recognized to be at risk:

- Balsam fir
- Balsam poplar
- Bigtooth aspen
- Birds-eye primrose
- Black ash
- Black crowberry
- Black spruce
- Butternut
- Butterwort
- Eastern hemlock
- Eastern white pine
- Jack pine
- Lichens
- Mosses
- Mountain maple
- Northern white cedar
- Paper birch
- Prickly saxifrage
- Quaking aspen
- Red maple
- Red pine
- Rock elm
- Sugar maple
- Tamarack
- White spruce
- Yellow birch

2.2.5 Expanding Habitats in Lake Superior Ecosystems

In some cases, climate change may result in expanding habitats for some biological aspects of Lake Superior ecosystems. Where these habitats are relatively healthy and well connected, and where other conditions are suitable, climate change may provide opportunities for species to expand, particularly some fish, bird, and tree species.

Fish

As described in Section 2.2.4, warmer Lake Superior waters associated with climate change will favor the expansion of warm and possibly some cool water fish populations. Particularly during the summer, the productive littoral zone of Lake Superior will likely have higher average water temperatures that will persist for a longer period of time. These changes should favor increases in the populations of many warm water fish, such as Smallmouth Bass, Rock Bass, Pumpkinseed, Carp, and Freshwater Drum (Chiotti and Lavender, 2008; Environment Canada, 2005; Wisconsin Sea Grant, 2002; Stefan et al., 2001). Examples of cool water fish that may be impacted include Northern Pike, Walleye, White Sucker, and Yellow Perch (Wisconsin Sea Grant, 2002; Stefan et al., 2001). In particular, the habitat for Yellow Perch is expected to expand in Lake Superior as water temperatures increase (Bronte et al., 2003).

Birds

A warmer climate in the Lake Superior region may benefit several year-round resident bird species, including chickadees, woodpeckers, and northern cardinals (Kling et al., 2003). One of the main advantages is expected to be a reduction in winter-related mortality, which should allow populations of these birds to increase (Kling et al., 2003). In addition, as described in Section 2.2.4, climate change will permit southern bird species to move into the Lake Superior region and flourish, thereby increasing and changing the biodiversity of the region.

Trees

In general, tree growth may be accelerated in the 21st century due to the rising atmospheric CO_2 concentrations that are driving climate change, as described in Section 1.2. Rising atmospheric CO_2 levels are expected to stimulate plant photosynthesis, which would result in faster tree growth. Higher CO_2 may also accelerate the rate at which “pioneer” trees (e.g., aspen trees) give way to species that grow in their shade (e.g., maple trees). Pioneer trees are the first to colonize sites following disturbances, such as timber harvesting or fire. Studies show that maple trees grown under elevated CO_2 conditions become more tolerant of shade and increase their growth rate (Kling et al., 2003). In a separate study (Goldblum and Rigg, 2005), the sugar maple showed greater potential than white spruce or balsam fir for increased growth rates under the projected warming and altered precipitation regime of climate change in Lake Superior Provincial Park, which is located on the northeastern shore of Lake Superior, north of Sault Ste. Marie, Ontario. By 2080, climate change is expected to enhance the status of sugar maple at its current northern limit and facilitate its expansion northward (Goldblum and Rigg, 2005). The climate change-induced expansion of red and sugar maple trees is projected in northeastern Minnesota as well (Ravenscroft et al., 2010). As stated in Section 2.2.4, climate change is expected to reduce the habitat of the sugar maple in northern Wisconsin (Swanston et al., 2011), but its habitat seems likely to increase in northeastern Minnesota and on the Canadian side of the Lake Superior basin (Ravenscroft et al., 2010; Goldblum and Rigg, 2005).

Based on projections from GCMs, the habitats of many tree species in northern Wisconsin are expected to increase by the end of the 21st century as a result of warmer annual and winter air temperatures associated with climate change (Swanston et al., 2011). Four species, all of which are currently common throughout northern Wisconsin, may experience a small increase in suitable habitat: American elm, eastern hophornbeam, American hornbeam, and white ash. Seventeen species are anticipated to have a large increase in suitable habitat, including American beech, bitternut hickory, black cherry, black oak, black walnut, black willow, boxelder, bur oak, eastern cottonwood, eastern red cedar, hackberry, osage orange, shagbark hickory, silver maple, slippery elm, swamp white oak, and white oak. Model projections for only three of these tree species (white oak, black oak, American beech) have high reliability scores, however, so there is some uncertainty in interpreting the range of trees that are expected to have a large increase in suitable habitat due to climate change in northern Wisconsin. Under high and low emissions scenarios, conditions are projected to be suitable for 11 new tree species in northern Wisconsin: black locust, flowering dogwood, honey locust, mockernut hickory, Ohio buckeye, pignut hickory, pin oak, red mulberry, river birch, sassafras, and yellow poplar. Under a high emissions scenario only, 16 tree species that have little or no presence currently in northern Wisconsin may have suitable habitat by the end of the 21st century, including black hickory, blackgum, blackjack oak, chestnut oak, chinkapin oak, common persimmon, eastern redbud, northern catalpa, peachleaf willow, pecan, post oak, scarlet oak, shingle oak, sugarberry, sycamore, and wild plum. Although suitable habitats may be available for these trees in northern Wisconsin in the future, many factors will influence whether they actually become established in the region, such as the dispersal ability of the species (Swanston et al., 2011).

2.2.6 Invasive Species

Many terrestrial and aquatic invasive species are currently present in Lake Superior, including the Round Goby, Eurasian Ruffe, New Zealand mudsnail, zebra mussel, Sea Lamprey, Eurasian watermilfoil, and purple loosestrife (Lake Superior Binational Program, 2010). These invasive species can be linked to many current ecosystem challenges, including the decline in the lower food web's *Diporeia* (a benthic invertebrate) populations, fish and waterfowl diseases, and excessive algal growth (U.S. EPA and Environment Canada, 2008). Climate change will likely enhance the spread of these existing invasive species (Kling et al., 2003) and increase the rate and incidence of non-native species invasions into the Lake Superior basin (Lehman, 2002; U.S. EPA and Environment Canada, 2008).

Cold winter weather currently limits the northern extent of some invasive insects, such as the gypsy moth (Kling et al., 2003; Régnière et al., 2009). Gypsy moths are present in the Lake Superior basin on the eastern shore near the city of Sault Ste. Marie (Régnière et al., 2009) and at Apostle Islands National Lakeshore. The park is approximately 50 miles west of a north-south line of gypsy moth advance in Wisconsin, and the spread of gypsy moths into the park is presumably due to park visitors transporting firewood from infested areas to the east (Burkman and Van Stappen, 2009). A future warmer climate region could enhance the spread of gypsy moths further north across the Lake Superior region. An increase in the onset of spring, caused by climate change, could allow several damaging forest pests, such as the forest tent caterpillar and spruce budworm, to flourish (Kling et al., 2003). In Ontario, model projections suggest a northward extension of spruce worm defoliation during the period 2011-2040 (Candau and Fleming, 2011). Ash trees in the region, such as green ash and white ash, are susceptible to the spread of the emerald ash borer (Collins, 2012). In addition, tree and flower pollination may be negatively impacted if climate change decouples the timing between flowering and insect pollination (Kling et al., 2003). In general, climate change may provide an advantage for invasive species that are able to shift quickly into a new geographic range and/or tolerate a wider range of environmental conditions. The spread of invasive species may also be favored by changes in land use patterns that increase habitat fragmentation (Dukes and Mooney, 1999).

Expansion of non-native plants and animals will increase the stress on native species populations in Lake Superior, particularly in shallow near-shore regions and coastal wetlands (Kling et al., 2003). The proliferation of *Phragmites australis* (common reed), an invasive plant that has spread very quickly across the lower Great Lakes region in recent years, will be favored by lower lake water levels and higher water temperatures that may result from climate change (Hall et al., 2007). Higher Lake Superior water temperatures in the 21st century are also expected to promote the expansion of existing non-native aquatic species, including Sea Lampreys, zebra mussels, and quagga mussels.

The viral hemorrhagic septicemia (VHS) virus has recently been found in fish in Lake Superior at four different locations (Paradise and Skanee in Michigan and St. Louis Bay and Superior Bay in Wisconsin) (Cornell University, 2010). It is not clear how warmer lake water associated with climate change will affect the spread of VHS in Lake Superior. Temperature is known to be a factor in the spread of VHS; for the European strains of the VHS virus (genotype I), fish mortality and the proportion of virus carriers decrease at higher temperatures, and deaths from VHS rarely occur in water at temperatures above 15 °C (59 °F) (McAllister, 1990). A laboratory study showed that the Great Lakes genotype IVb strain of VHS from Muskellunge in the Great Lakes grew fastest in water at 15 °C (59 °F) but did not grow in water at 25°C (77 °F) (U.S. Geological Survey, 2007). In a separate study, results showed that the temperature range of VHS virus genotype IVb appears to be the same as for VHS virus genotype I, which has an optimum of 9 to 12 °C (48 to 54 °F) and an upper limit of 18 to 20 °C (64 to 68 °F) (Goodwin and Merry, 2011). These results suggest that warmer water may inhibit the spread of VHS. However, a recent study of the comparative susceptibility of representative Great Lakes fish to VHS virus genotype IVb demonstrated that cool water fish species (e.g., Muskellunge, Largemouth Bass, Yellow Perch) are more susceptible to VHS than cold water fish species (e.g., Rainbow Trout, Brook Trout, Brown Trout, Chinook Salmon, Coho Salmon) (Kim and Faisal, 2010). This result suggests that fish which may thrive in increasing lake water temperatures could be more susceptible to the spread of VHS in Lake Superior.

Sea Lampreys

The estimated abundance of spawning-phase Sea Lampreys in Lake Superior was 65,500 in 2007, the most recent year for which data are available (U.S. EPA and Environment Canada, 2008). In the period 2000-2007, the average spawning-phase Sea Lamprey abundance was 94,000, which is equivalent to the average population found in Lake Superior in the early 1980s, as shown in Figure 37. In addition, wounding rates showed an upward trend for 2000-2007 (U.S. EPA and Environment Canada, 2008).

Sea Lampreys can live longer and grow larger in warmer water, particularly in water with temperatures >10 °C (50 °F) (National Wildlife Federation, 2010). Thus, as Lake Superior water temperatures increase due to climate change, Sea Lamprey populations are expected to grow, and the average size of lampreys will likely increase. Bigger lampreys kill more fish, leading to potentially serious consequences for fish in Lake Superior. Lamprey control managers are already adapting to the effects of climate change by monitoring the daily average temperature of Lake Superior (Figure 38). On days when water temperature is expected to be >10 °C (50 °F), Sea Lamprey control efforts are intensified (National Wildlife Federation, 2010).

Zebra and Quagga Mussels

Zebra and quagga mussels are a threat to Lake Superior because they increase water clarity, which leads to accelerated algae growth, and they also compete with native mussel species. In the lower Great Lakes, over 99% of the native freshwater mussel population has been devastated by invasive zebra and quagga mussels (U.S. EPA and Environment Canada, 2009). At the present time, the northward expansion of zebra and quagga mussels has been limited by the cold waters of Lake Superior (IJC, 2003; Hall et al., 2007). As the water in Lake Superior warms due to climate change, the prevalence of zebra and quagga mussels will likely increase, with populations potentially reaching the same extent as are currently found in the lower Great Lakes (Easterling and Karl, 2000; IJC, 2003; Hall et al., 2007; Moy et al., 2010).

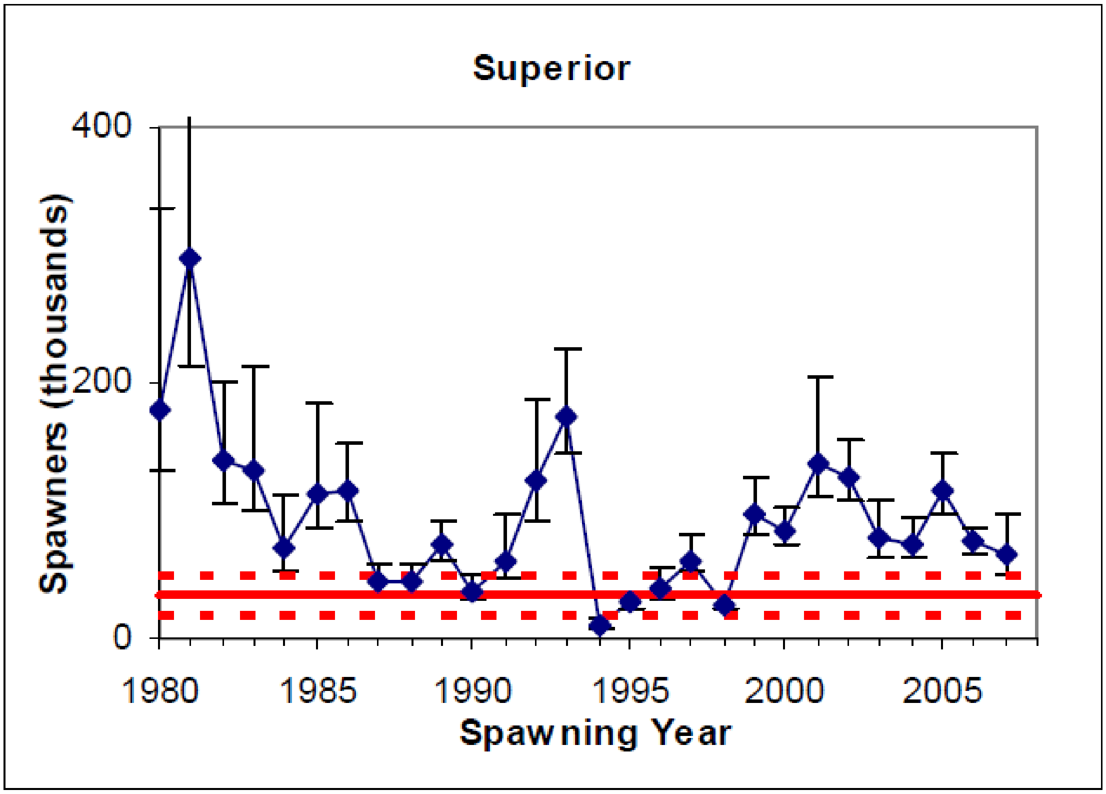

Figure 387. Abundance of spawning-phase Sea Lampreys in Lake Superior, 1980-2007. The error bars indicate 95% confidence intervals. The solid red line indicates the suppression target of 35,000 spawning-phase Sea Lampreys, and the dashed red lines are the 95% confidence intervals for the suppression target. [Image courtesy of U.S. EPA and Environment Canada, 2008]

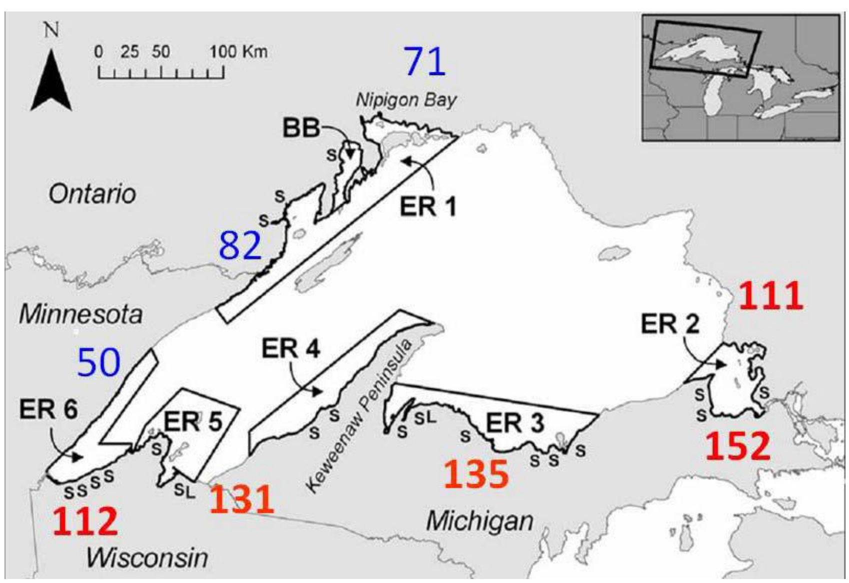

Figure 398. The number of days when Lake Superior water temperatures were >10ºC (50ºF) in 2009 by U.S. EPA Eco-region (ER); areas of particular urgency for Sea Lamprey management are indicated in red. [Image courtesy of National Wildlife Federation, 2010]

2.3 Gaps and Uncertainties in Available Science and Monitoring

One of the primary sources of uncertainty in assessing the impacts of climate change derives from the range of GCM projections of climate variables for a given region, particularly air temperature and precipitation (Easterling and Karl, 2000). As discussed in Section 1.2, climate projections are dependent on the specific GCM and emissions scenario used. Given the uncertainty regarding future GHG emission pathways, there are a range of possible values of future air temperatures and precipitation amounts. For the Lake Superior region, uncertainty is amplified because most existing climate model studies focus on a larger area, such as the entire Great Lakes region or the Midwestern U.S. To avoid generalizations that may not pertain to Lake Superior ecosystems, this report primarily utilizes science-based projections that are specific to Lake Superior. In cases where information on Lake Superior was not available, Great Lakes regional data, projections, etc. are presented. To that end, region-specific, downscaled climate projections are required to inform future development of climate change adaptation actions in the Lake Superior region.

Many specific data gaps exist, both for modeled and observed variables in the region. For example, future variations in storm intensity, groundwater, and soil moisture associated with climate change are essentially unknown, since there is no published research on these features specifically for the Lake Superior region. Numerical models that incorporate surface flux dynamics, horizontal exchange, and ice need to be developed for Lake Superior to make more accurate projections of future ice cover extent and duration (Austin and Colman, 2007). In addition, research that couples models of ecosystem productivity and land use change are needed for the Lake Superior basin (Sousounis and Bisanz, 2000). Second generation runoff models and improved lake evaporation models are also necessary to assess changes in vegetation, evapotranspiration, runoff, and lake evaporation associated with climate change (Sousounis and Bisanz, 2000). Two recent studies investigated the physical controls and processes and spatial distribution and variability of evaporation from Lake Superior over a 2.5 month period (Blanken et al., 2011; Spence et al., 2011); these results can be applied to lake evaporation models to potentially improve predictions of lake water levels associated with climate change. Data gaps also exist in assessment of the impacts of climate change on nearshore and coastal wetland vegetation (Cápiro, 2009), as well as the effects of rising CO_2 levels on fertilization of trees and other flora (Easterling and Karl, 2000).

WICCI (Moy et al., 2010) has identified several areas for future research that will help to define projected climate change impacts on Lake Superior and refine proposed adaptation strategies. These research needs include:

- Updated long-term projections of potential lake water levels based on downscaling of GCM output,
- Current, high resolution lidar observations that can be incorporated into integrated topographic/bathymetric models in order to visualize the impacts of variable lake water levels,
- More frequent and widespread coastal observations (e.g., buoys and other sensors measuring wind, waves, water levels),
- Detailed measurements of the extent of beaches and coastal wetlands,

- More information on the expected effects of changes in lake water temperature and chemistry on aquatic ecosystems (e.g., algae, invertebrates, exotic species), and
- Locations of known non-gamefish spawning areas near the current lake shoreline.

3 Existing Efforts on Adaptation of Lake Superior Ecosystems to Climate Change

This report complements or supplements a growing number of studies and government-supported climate change strategies that address climate change risks to Lake Superior ecosystems. Many of these actions call for further research on the impacts of climate change and increased cooperative management of corresponding impacts to priority ecosystems and ecosystem functions. This section highlights climate change regulations, policies, and programs affecting the Lake Superior basin. A list of additional tools and resources that support adaptation to climate change is presented in Appendix A.

3.1 Regulations

To date, federal, state, provincial, and First Nations/tribes in the Lake Superior basin have not directly addressed climate change adaptation through regulatory measures. Many of these agencies have enacted natural resource and agriculture management rules and regulations that relate to climate change indirectly, however. Current regulations pertain to the sustainable management of coastal areas, agriculture, forestry, wildlife, water resources, and other areas. For example, when farmers are required to manage their farmland in a sustainable manner (e.g., decreasing erosion, managing manure and nutrients), climate change-related ecosystem environmental effects are also mitigated, such as flooding that may result from increased precipitation. Some illustrative examples of these types of regulations are described below.

The *Great Lakes-St. Lawrence River Basin Water Resources Compact* (Great Lakes Compact; Council of Great Lakes Governors, 2006) is a legally binding interstate agreement among the U.S. Great Lakes states (Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania and Wisconsin). Since the Great Lakes Compact became law in December 2008, it has governed how the states manage the use of the Great Lakes' fresh water supply. The compact provides broad guidelines for the Great Lakes states to manage their water resource requirements. Under the Great Lakes Compact, the Great Lakes states can design and implement water management programs autonomously, with states' actions subject to other states' approval in only limited circumstances.

A strategic goal of Ontario's Expert Panel on Climate Change Adaptation is to integrate climate change adaptation into government activities, including legislation and regulations (Expert Panel on Climate Change Adaptation, 2009). An example of a regulation indirectly related to climate change is the *Provincial Parks and Conservation Reserves Act of 2006* (Ontario, 2006), which legally protects a system of parks and reserves that are home to sensitive ecosystems, which are representative of all of Ontario's natural regions. Biodiversity conservation and sustainable recreation and park usage are viewed as a form of natural and culture heritage.

To date, the State of Minnesota has enacted several ecosystem adaptation-related regulations. One example is the *Wetland Conservation Act* (WCA; Minnesota Board of Water and Soil Resources, 2011a), enacted in 1991, which maintains and protects Minnesota's wetlands. The WCA requires anyone who is proposing to drain, fill, or excavate a wetland to 1) try to avoid disturbing the wetland, 2) try to minimize any impact on the wetland, and 3) replace any lost wetland acres, functions, and values. The Minnesota Legislature has amended the WCA many times since 1991, primarily to account for the different geographic areas of Minnesota and their associated wetland issues (Minnesota Board of Water and Soil Resources, 2011b).

3.2 Policies and Adaptation Strategies

The Province of Ontario, states, and other jurisdictions in the Lake Superior basin are responding to current and future climate change impacts by developing adaptation strategies and action plans. All three states in the Lake Superior basin (Michigan, Minnesota, and Wisconsin) and Ontario have recommended GHG reduction policies. Minnesota, Wisconsin, and Ontario have developed climate adaptation strategies. Appendix B presents federal, state/provincial, and other climate action plans and strategies relevant to the Lake Superior basin. Many of these policies and action plans formed the basis for the recommended Lake Superior adaptation actions in Section 4.

Tribes

Tribes in the U.S. portion of the Lake Superior basin are beginning to develop adaptation strategies and action plans. The Bad River Band of Lake Superior Chippewa Indians, located on the shore of Lake Superior in northern Wisconsin, has actively managed invasive species, particularly in wetland systems, which promotes resilience in the ecosystem (a key component of adaptation). Similarly, ongoing forest management efforts indirectly provide mitigation benefits. In addition, the Bad River Band intends to develop a Comprehensive Climate Change Monitoring Plan for the Kakagon-Bad River Sloughs complex, a vital cultural and ecological resource in the Great Lakes region. The monitoring plan will establish baseline data on current environmental conditions, actively manage habitat to promote watershed resilience, and develop the capacity of the Bad River Band to proactively address climate change impacts. The plan will directly address climate change-related challenges by projecting climate-related impacts for the Bad River Band, proposing ecological adaptation strategies, and forming collaborative support frameworks to ensure conservation of the Kakagon-Bad River Sloughs for seven generations (Hester, 2011).

The Grand Portage Band of Lake Superior Chippewa Indians, located in the northeast corner of Minnesota along Lake Superior, is developing several climate change adaptation plans and strategies. Adaptation is a priority for the Grand Portage Band because climate change is expected to disproportionately affect tribes, whose natural resources are vital to maintaining a subsistence lifestyle. As part of their adaptive management practices, the Grand Portage Band has shifted a 61-acre inland lake from a cold water (Brook Trout) to a cool water (Walleye) fishery. In addition, the Grand Portage Native Fish Hatchery is utilizing re-circulating water systems to increase water temperatures needed for rearing cool water native fish species, which allows for better utilization and flexibility of hatchery and stocking operations. The Grand Portage Band is also working on a climate change project to assess moose habitat, since moose populations have been declining in Minnesota in recent years. The Grand Portage forestry department has been active in addressing issues related to climate change with their current management practices, including promotion of mixed tree species forests over mono-cultures, which will allow for greater flexibility with adaptive management of forest resources in the future. Native tree species are being planted annually to promote native forest communities and enrich species diversity. Furthermore, additional aquatic invasive species (AIS) surveys are planned for water bodies in Grand Portage, given that warmer water temperatures may increase or aid dispersal of AIS. Specific AIS assessments are planned for plants (e.g., curly leaf pondweed), fish (e.g., Ruffe, Goby), and invertebrates (e.g., rusty crayfish, spiny water flea, zebra mussels). Similarly, since increases in air temperatures associated with climate change may promote population growth of native and non-native forest pests and disease, the forestry department is active in the Slow-the-Spread gypsy moth program and the trapping of emerald ash borer in ash trees. Forestry personnel have also received training in invasive pest and disease first detector courses, with discussions about creating an emerald ash borer action plan (Isaac, 2011).

The Fond du Lac Band of Lake Superior Chippewa Indians, located in northeastern Minnesota west of Duluth, is engaged in a variety of activities designed to reduce the impacts of climate change. The Fond du Lac Band has developed an Integrated Resource Management Plan, which addresses invasive species and climate change interactions. The Fond du Lac Band's Forestry Division is working to re-forest agricultural land, and the Fond du Lac Band's Office of Water Protection has conducted sampling of stream water flow and temperature on its reservation to establish a baseline for future changes that may result from climate change. The Fond du Lac Band is also working with local, state, and national stakeholders on climate change issues, such as the Northeastern Minnesota Landscape Committee, which includes private, state, county, federal, and tribal landowners. In addition, the Fond du Lac Band is participating in the U.S. Forest Service's Climate Change Response Framework in northern Wisconsin (described in Section 3.4) and is working with the Minnesota Department of Natural Resources and the U.S. Fish and Wildlife Service to study the health of moose populations in northern Minnesota (Wiecks and Youngblood, 2012).

The Red Cliff Band of Lake Superior Chippewa Indians, located on the northern shoreline of Bayfield Peninsula in Wisconsin, has begun to investigate climate change and the impact on the tribe of mercury emissions from coal-burning power plants. The Red Cliff Band has not yet developed a climate action plan or strategy (Abel, 2011).

The Keweenaw Bay Indian Community (KBIC) in Michigan has hired staff specifically to address climate change and to develop a climate change action plan for the L'Anse reservation. The action plan will include assessments of vulnerable areas, climate impacts, and implications of climate change for the community (Johnston, 2011). KBIC is nearing completion of a 2-year wildlife and habitat inventory study, which will aid in the development of a wildlife management plan and the climate change action plan for the reservation. Other climate change-related activities include growing native and culturally significant plants in a greenhouse for habitat restoration on the reservation and building a Great Lakes Restoration Initiative (GLRI) funded 33.5 acre habitat restoration project along Lake Superior. KBIC has also hired staff to combat the spread of invasive species (Johnston, 2011).

The Great Lakes Indian Fish and Wildlife Commission (GLIFWC) is currently working to assess the impacts of climate change on the treaty-guaranteed resources that it regulates for its member tribes. GLIFWC is preparing a report that will document the key climate variables that should be analyzed for the species that are expected to be impacted by climate change. For example, the report will try to define the maximum limit for lake water temperatures before cold water fish species begin to decline. After identifying a set of variables to analyze, GLIFWC will use downscaled climate data from WICCI and other sources to identify areas expected to be most affected by climate change. Ultimately, GLIFWC will use this information to help manage their resources most effectively in a changing climate (Chiriboga, 2012).

Michigan

Michigan has developed policy recommendations to reduce GHG emissions as a means of mitigating the forecasted impacts of climate change. Michigan has also laid the groundwork for developing and implementing climate change adaptation strategies.

In 2007, by executive order, Michigan Governor Jennifer Granholm created the Michigan Climate Action Council (MCAC) to address climate change in the state. As directed by the governor, the MCAC prepared a Climate Action Plan, developed a GHG emissions inventory and forecast, and outlined policy recommendations for reducing GHG emissions by sector (e.g., energy supply, residential, commercial, industrial, transportation, land use, agriculture, forestry, waste management). The Climate Action Plan focuses on mitigating climate change through GHG reductions. Due to time and resource constraints, the MCAC did not examine the impacts of climate change on Michigan's ecosystems. Therefore, the MCAC recommended that additional analyses be conducted to determine the state's vulnerability to climate change, and that specific adaptation plans for key sectors be developed.

Minnesota

Minnesota has developed state-level policy recommendations to mitigate climate change through reductions in GHG emissions and to help wildlife adapt to predicted changes in climate.

Similar to Michigan's Climate Action Plan, Minnesota developed a *Minnesota Climate Change Action Plan: A Framework for Climate Change Action* (Ciborowski and Fenske, 2003), which presents estimates and forecasts of GHG emissions and a carbon sequestration inventory. The Action Plan also outlines recommended actions to reduce GHG emissions and considers existing state programs that could assist in controlling GHG emissions. Subsequently, the Minnesota Climate Change Advisory Group (MCCAG) developed the *Final Report: A Report to the Minnesota Legislature*, which presented an inventory of historical (by sector for 2005) and forecasted GHG emissions (through 2020) and recommended actions to reduce GHG emissions by sector (e.g., residential, commercial, industrial, energy supply, transportation, land use, agriculture, forestry, waste management) (MCCAG, 2008). The report also considered the costs and benefits of recommended options. The report's state-level policy recommendations were developed by consensus through a stakeholder process that involved more than 100 Minnesotans who were members of MCCAG and six technical work groups that supported the advisory group (MCCAG, 2008). The report did not propose adaptation actions for Minnesota ecosystems.

In 2007, the Minnesota Department of Natural Resources' Division of Fish and Wildlife convened a Wildlife Climate Change Working Group within the Section of Wildlife to respond to the challenge of developing approaches to address climate change. In 2008, the working group published *Climate Change: Preliminary Assessment for the Section of Wildlife of the Minnesota Department of Natural Resources*, which described expected climate change projections for Minnesota, effects of climate change on wildlife and landscapes in Minnesota, and recommended climate change actions for the Section of Wildlife, including specific adaptation and mitigation strategies. The report and recommendations focused on Minnesota as a whole (Carstensen et al., 2008).

The Minnesota Department of Natural Resources proposed a *Minnesota Moose Research and Management Plan* to address declining populations of moose due to climate change and other stressors. After a public review process, a final plan was released in December 2011 (Minnesota Department of Natural Resources, 2011).

Ontario

Ontario has confronted the challenge of climate change by implementing policies to reduce GHG emissions and by investing in renewable energies and energy efficiency. Ontario's Go Green plan outlines emission reduction targets and the strategies to achieve those goals. An annual scorecard also tracks progress and suggests new ways to reduce emissions.

In December 2007, the Ontario Minister of the Environment appointed the Expert Panel on Climate Change Adaptation to help the Ontario government, municipalities, and citizens prepare and plan for the impacts of a changing climate in several areas, including the environment. The Panel consulted with senior-level government managers from Ontario and other government agencies to identify climate change adaptation needs and develop implementation strategies for Ontario. The Panel, comprised of 11 leading scientists, industry representatives, and environmental experts, prepared a report titled *Adapting to Climate Change in Ontario*, which was submitted to the Ontario Minister of the Environment in 2009 (Expert Panel on Climate Change Adaptation, 2009). The report presents the expert panel's strategic goals and 59 recommendations to inform the development of a climate change adaptation strategy and action plan for Ontario. Several recommendations are relevant to adaptation of Lake Superior ecosystems.

Based on the recommendations of the Expert Panel on Climate Change Adaptation, Ontario developed *Climate Ready: Ontario's Adaptation Strategy and Action Plan 2011-2014*, which contains five broad goals and 37 actions to help prepare Ontario for expected changes in climate from 2011 to 2014 (Ontario Ministry of the Environment, 2011a). Actions pertaining to areas such as human health, the economy, and other issues are, for the most part, general and provincially based. Some of the specified adaption actions are applicable to Lake Superior ecosystems.

Wisconsin

In 2008, Wisconsin developed recommendations for reducing GHG emissions statewide. Wisconsin has also established a structure for addressing climate change and continues to identify adaptation strategies that apply within the state.

In 2008, in response to Wisconsin Governor Jim Doyle's executive order, the Governor's Task Force on Global Warming developed *Wisconsin's Strategy for Reducing Global Warming*, which presented an inventory of state GHG emissions and recommended short- and long-term goals for reducing GHG emissions in the utility, transportation, agriculture and forestry, and industry sectors, and in other areas (Wisconsin Department of Natural Resources and Public Service Commission of Wisconsin, 2008).

Wisconsin launched the Wisconsin Initiative on Climate Change Impacts to address climate change issues at appropriate scales for planning and action, including identifying the impacts of climate change in Wisconsin and strategies needed to adapt to them. The WICCI released its first report in 2011, *Wisconsin's Changing Climate: Impacts and Adaptation* (WICCI, 2011). The report is anticipated to be the first in a series of climate impact and adaptation reports as part of a long-term process to prepare for the challenges of a changing climate. The report summarizes expected climate changes in Wisconsin (by mid-century) and expected impacts on water resources, natural habitats, agriculture, coastal regions, society, and the built environment. The report synthesizes the findings of 15 working groups who contributed content for the report (e.g., Moy et al., 2010; Kucharik et al., 2010b). The working groups, comprised of more than 200 researchers, managers, educators, and other experts, continue to develop vulnerability assessments and to identify adaptation strategies. The 2011 report lays the groundwork for implementing adaptation strategies in Wisconsin, as recommended by the working groups.

In addition, the Northern Institute of Applied Climate Science of the U.S. Department of Agriculture, Forest Service, developed a tool to help land managers adapt forest ecosystems in northern Wisconsin to climate change. *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers*, released in 2011, guides land managers through a selection process to consider ecosystem vulnerabilities, select appropriate adaptation approaches, and implement those approaches. Case studies describe how the adaptation approaches can be applied to forested ecosystems, including those that border Lake Superior. In fact, the Chequamegon-Nicolet National Forest in northern Wisconsin served as a test-bed for the project. The approaches presented can be adjusted and applied to other locations to help forests adapt to the impacts of climate change (Swanston and Janowiak, 2012). The Northern Institute of Applied Climate Science also launched the Shared Landscapes Initiative, which is engaging stakeholders in the region on the potential ecological and land management pressures associated with climate change. A working group has been established as part of the initiative, including representatives from 30 federal, state, other public, tribal, and private organizations. The Shared Landscapes Initiative is conducting a climate change adaptation demonstration project, similar to the Chequamegon-Nicolet National Forest test-bed (Tillison, 2012).

3.3 Science and Monitoring

Several science and monitoring initiatives are ongoing in the Lake Superior region. In 2011, the Cooperative Science and Monitoring Initiative (CSMI), jointly led by Environment Canada and the U.S. EPA, concentrated its efforts on Lake Superior. CSMI focuses its activities on one Great Lake each year as part of a rotational cycle. Initiated in 2002, the CSMI brings together federal, provincial, state, tribal, and other agencies in a cooperative effort to address issues identified by LAMP management teams and their partners. Scientists from both Canada and the

U.S. began intensive field work and data collection activities on Lake Superior during 2011. Research included trends in water quality and quantity in selected streams to identify impacts of climate changes and land use. Monitoring results were being compiled in 2013 (U.S. EPA and Environment Canada, 2011).

The federal governments of Canada and the U.S. support research on adaptation measures and climate impacts. For more than 15 years, Environment Canada has conducted research on the science of climate adaptation and impacts. Environment Canada's multi-disciplinary research supports the development of appropriate adaptation actions for sustainable ecosystems. On a provincial scale, leading-edge science and research supported by the Climate Change program of the Ontario Ministry of Natural Resources has resulted in approximately 300 publications on climate change (http://www.mnr.gov.on.ca/en/Business/ClimateChange/index.html). These documents cover expected environmental changes and impacts for parks, forests, water, fish and wildlife. Many of the reports provide adaptation options and recommendations. As part of the U.S. Global Change Research Program (USGCRP), the U.S. Climate Change Science Program (CCSP) integrates federal research on climate and global change. The CCSP, comprised of various federal agencies, has published a number of reports on the impacts of climate change and approaches to adaptation or mitigation. For example, CCSP Synthesis and Assessment Product 4.4: *Preliminary Review of Adaptation Options for Climate-Sensitive Ecosystems and Resources* (CCSP SAP 4.4) recommends specific approaches for protecting climate-sensitive ecosystems, such as national forests, parks, and marine-protected areas, from the impacts of climate change (Baron et al., 2008). Also, as part of the USGCRP, the U.S. Climate Change Technology Program (CCTP) is a multi-agency research and development program for technologies that promote adaption and mitigation of climate change (http://www.climatetechnology.gov/).

The IJC's International Upper Great Lakes Study (2007-2012) contains an adaptive management strategy aimed at reducing the risk of water level-related impacts in a manner that can respond to evolving knowledge and future conditions, including climate change. The multi-year study examines various adaptive response actions for the improvement of Lake Superior outflow regulation (Donahue, 2011).

As mentioned in Section 3.2, the Bad River Band of Chippewa Indians plans to develop a Comprehensive Climate Change Monitoring Plan for the Kakagon-Bad River Sloughs that will establish baseline data on current environmental conditions (Hester, 2011).

Researchers at universities in the Lake Superior basin are also investigating climate change impacts in the region, as summarized by various references in Section 2 (e.g., Austin and Colman, 2007, 2008; Desai et al., 2009; Trumpickas et al., 2009). Several of these research efforts are conducted in conjunction with Sea Grant programs, such as the Minnesota Sea Grant, Michigan Sea Grant, and Wisconsin Sea Grant. John Lenters of the University of Nebraska is currently leading a project to study the impacts of climate change on evaporation in the Great Lakes, focusing on Lakes Superior and Huron (Great Lakes Integrated Sciences and Assessments [GLISA], 2011).

3.4 Programs

In the past few years, many programs have been initiated in Canada and the U.S. that address the changing climate of the Lake Superior basin. The state and provincial governments in the basin have dedicated resources to address climate change through outreach and education, mitigation, adaptation, and research. Federal programs in Canada and the U.S. likewise are addressing climate change issues in the Lake Superior basin, both directly, through climate change actions in national parks, for example, and also indirectly through federal research that supports adaptation to climate change. These state/provincial and federal programs can be leveraged to facilitate implementation of the recommended actions outlined in Section 4. A few programs are described below as examples, and a list of programs relevant to climate change in the Lake Superior basin is presented in Appendix C.

State/Provincial Programs

The Michigan Sea Grant is a cooperative program with the University of Michigan and Michigan State University that promotes the protection and sustainable use of the Great Lakes and coastal resources. Through research, education, and publications, Michigan Sea Grant works to identify adaptation strategies and help local communities plan for climate change (Michigan Sea Grant, 2011). Examples of Michigan Sea Grant's efforts include:

- CoastWatch is an online reporting system that presents maps of surface water temperatures on each of the Great Lakes. Surface water temperatures are automatically generated from satellite-derived sensors.
- Researchers developed training modules for leaders of coastal communities that provide the tools to develop climate adaptation plans for their communities.

Minnesota Sea Grant's climate change initiative is an ongoing program of research, outreach, and education to help citizens, communities, and industries understand and adapt to climate change in the region. Minnesota Sea Grant is a federal-state partnership funded by NOAA through the National Sea Grant College Program and the state of Minnesota through the University of Minnesota. As recommended in the 2010 Minnesota Sea Grant Implementation Plan, Minnesota Sea Grant is pursuing a number of activities related to climate change adaptation, including the following (Minnesota Sea Grant, 2010):

- Participate in Great Lakes Observing System (GLOS) activities. GLOS provides access to Lake Superior maps and data layers containing climate information, water quality, land facts, and pertinent data for community planning and resource management.
- Provide scientific information, resources, and assistance to communities to help them adapt and plan for climate impacts to stormwater infrastructure. Minnesota Sea Grant also helps communities understand climate models, and provide them with tools or resources to make infrastructure decisions that will mitigate damage from climate change to community infrastructure, property, and natural resources.

OCCIAR at Laurentian University in Sudbury has provided adaptation outreach and education since 2001. OCCIAR develops adaptation resources, including guides, frameworks, fact sheets, and case studies, to advance climate change adaption in Ontario. OCCIAR also hosts workshops to educate communities about climate change impacts, risks, and vulnerabilities and provides advice on climate change risk management and vulnerability assessment. OCCIAR uses a "community consultation model" that brings decision-makers, such as mayors, together with field practitioners in a variety of municipal departments to ensure that all partners work cooperatively to address local vulnerabilities, risks, and opportunities that arise as a result of climate change (Expert Panel on Climate Change Adaptation, 2009).

Wisconsin's Conservation Reserve Enhancement Program allows farmers to meet conservation goals related to soil and water resources. The program provides financial incentives for those with land along rivers and streams, such as paying landowners to install filter strips along waterways, creating and maintaining riparian buffers, or converting continually flooded fields back into wetlands. Farmers are able to enter portions of land into the program while maintaining other land for agricultural purposes.

Federal Programs

Parks Canada, the federal agency responsible for managing national parks and NMCAs in Canada, is responding to climate change through science, adaptation, and mitigation measures. Parks Canada monitors the ecological integrity of national parks by inventorying and monitoring plant and animal species. The information collected will be used to understand how park species and ecosystems are responding to climate change over time and to identify key habitat areas and species to protect. Parks Canada also plans to increase collaboration with adjacent landowners and agencies to allow species migration, given the geographic shifts projected as a result of climate change (Parks Canada, 2009).

The U.S. National Park Service is implementing a variety of strategies and programs to address climate change. The National Park Service has a national climate change response strategy that focuses on science, adaptation, mitigation, and communication (U.S. National Park Service, 2010). The National Park Service's Midwest Region, which includes five park units in the Lake Superior basin, is developing a regional climate change strategy (Krumenaker, 2012). The National Park Service's Great Lakes Inventory and Monitoring Network has developed and implemented a long-term ecosystem monitoring program that will facilitate the identification and measurement of impacts due to climate change and other ecosystem stressors (U.S. National Park Service, 2009). In addition, Apostle Islands and Pictured Rocks National Lakeshores were the first two Midwestern national park units to develop and implement comprehensive Climate Friendly Parks Action Plans (U.S. National Park Service, 2008a and 2008b). Both of these parks have also led efforts to provide climate change education to their gateway communities (Krumenaker, 2012).

The NOAA Climate Program Office manages NOAA's competitive research program to advance the understanding of Earth's climate system and its atmospheric, oceanic, land, and snow and ice components on national, international, and global scales. Outcomes of this research include increased knowledge of the impacts of climate change and variability on health and the economy. Funding activities are organized within four programs: Climate Observations and Monitoring; Earth System Science; Modeling, Analysis, Predictions, and Projections; and Climate and Social Interactions. The Climate Program Office also supports NOAA's contributions to the USGCRP and the U.S. Interagency Climate Change Adaptation Task Force (NOAA, 2011).

The Climate Change Response Framework Project is an effort initiated by the U.S. Forest Service in 2009 to provide information and resources relevant to climate change adaptation and mitigation strategies for forest ecosystems in northern Wisconsin. The project seeks to assist land managers in understanding the effects of climate change on forest ecosystems and implementing appropriate management strategies. The project brought partners together for two climate change workshops in 2010 and produced *An Ecosystem Vulnerability Assessment and Synthesis* (Swanston et al., 2011) that assesses vulnerable ecosystem components under a range of future climate scenarios. The project is also developing an expanded *Mitigation Assessment* that describes carbon stocks in northern Wisconsin and the effect of forest management, land use, and other practices on the amount of carbon currently stored (Northern Institute of Applied Climate Science, 2011). The Chequamegon-Nicolet National Forest was a major partner in these assessments, providing ecological and management expertise and serving as a pilot test area (Swanston et al., 2011). The Wisconsin Department of Natural Resources and WICCI, among other organizations and individuals, also contributed to the project. A final project document incorporates information from the two assessments to help land managers select strategies and approaches to help forest ecosystems adapt to a changing climate: *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers* (Swanston and Janowiak, 2012).

3.5 Climate Change Workshops, Meetings, and Conferences

Many workshops, meetings, and conferences on climate change have been held over the past few years in the Lake Superior basin. Discussion topics have included climate change research, impacts, vulnerable areas, adaptation and mitigation strategies, awareness efforts, and useful tools and resources. Selected workshops, meetings, and conferences relevant to climate change adaptation in the Lake Superior basin are listed in Appendix D. Summaries and conclusions from these meetings can be useful in developing adaptation actions for the Lake Superior basin.

4 Adaptation Actions

The following list of potential adaptation strategies and actions was compiled from the literature and an Expert Group of participants with expertise in issues related to changing climate conditions in the Lake Superior region. The list provides a range of potential measures for assisting Lake Superior ecosystems to adapt to climate change. These actions include the completion of "no-regret" projects, which are actions that support adaptation, address other stressors to the lakes, and provide a net social or economic benefit. The list may be used to structure LAMP organization discussions, to facilitate reporting, and to further the transfer of successful adaptation actions from one jurisdiction to another. This action list is presented to LAMP organizations to pursue implementation to the extent possible through ongoing domestic programs and organizational work plans.

1. Manage Non-Climate Stressors

Context

These actions will potentially reduce or manage the impact of key non-climate change ecosystem stressors, such as pollution, habitat degradation, and invasive species, which is a critical component of adaptation. Naturally functioning ecosystems are more resilient to the impacts of climate change than impaired ecosystems.

Strategies and Actions

1.1 Advance restoration and protection efforts under the GLWQA and the LAMP to reduce or manage the impacts of non-climate change ecosystem stressors, including:

- On-the-ground projects to further reduce critical pollutants, including implementation of the Zero Discharge Demonstration Program.
- Preventing new introductions and spread of aquatic invasive species, including implementation of the *Lake Superior Aquatic Invasive Species Complete Prevention Plan*.
- Work in cooperation with various levels of government, land-owners, the mining and water power sectors, and other stakeholders to achieve LAMP Ecosystem Objectives.
- Monitor nutrient loading in connecting streams and rivers and develop and apply nutrient abatement programs to improve water quality.

2. Manage Habitats, Species and Ecosystem Functions

Context

Adaptation actions that help protect habitats and maintain species biodiversity are essential. These actions could help to sustain the biodiversity of native plants and animals so they can cope with future disturbances arising from climate change.

Strategies and Actions

2.1 Develop and use habitat-specific, species-specific and ecosystem function-specific management approaches to address critical climate change impacts, where necessary.

2.1.1 Restore or construct riparian buffers where necessary to provide adequate shade along existing cold and cool water streams, and/or to manage heavy runoff of non-point source pollution and sediments associated with potentially more frequent and intense precipitation events.

2.1.2 Develop and implement a management plan(s) to help arctic and sub-alpine disjunct plant communities adapt to climate change.

2.1.3 Develop and implement a management plan(s) to help wild rice adapt to climate change.

2.1.4 Monitor and manage the viability of commercial fishing operations, especially fisheries that are significant economic enterprises for tribes.

2.1.5 Develop and implement increased water temperature thresholds, where necessary, for shifting local stocking and fisheries management from cold water fish (e.g., trout) to cool water fish (e.g., walleye).

2.1.6 Establish artificial reserves for at-risk or displaced species

2.1.7 Upgrade and replace existing infrastructure to handle the volume of runoff associated with potentially more frequent and intense precipitation events.

2.1.8 Use vegetation management strategies to closely mimic natural disturbances.

2.1.9 Use wind-resistant vegetation to minimize blow-downs and erosion along coastal shorelines.

2.1.10 Adapt sea lamprey control efforts to reflect changing habitat conditions for sea lamprey growth and survival in Lake Superior.

2.1.11 Develop a list of the aquatic invasive species that are most likely to reach Lake Superior and monitor appropriately.

2.1.12 Establish first response control and eradication protocols in anticipation of newly discovered aquatic invasive species.

2.1.13 Plant seeds or seedlings originating from seed zones that resemble the expected future conditions of the planting site.

2.1.14 Establish and expand refugia (e.g., protected areas, reserves, natural heritage areas) to link habitats and to protect threatened native species.

2.1.15 Support efforts to renew and implement adaptive forestry management practices that respond to climate change to minimize possible forest disturbances that impact Lake Superior. These practices should consider, as necessary:

- Assess and modify fire management and prescribed burning programs.
- Conduct regular prescribed fires, where appropriate, to help treat fuel loads and prepare forest stands for regeneration.
- Undertake, where appropriate, assisted migration of tree species.
- Develop a protocol for managing areas that can no longer sustain forest cover types due to climate change.
- Implement the “slow the flow” strategy into forestry management activities to help reduce runoff rates and decrease sedimentation into Lake Superior.
- Improve fire weather forecasting and fire monitoring.
- Improve soil management, spacing, and tree rotation length to minimize the vulnerability of forests to new or variable climate patterns.
- Increase planting rates to assist slow natural redistribution of tree/plant genotypes and species.

- Increase preparedness for insect and pest management, improve pest monitoring and maintain or improve the ability of forests to resist pests and pathogens.
- Manage for multi-age forest structure, where appropriate.
- Plant tree species that are more tolerant to a changing climate, including drought and disease-resistant varieties.
- Plant fire-resistant species, such as hardwoods, between more flammable conifers.
- Replant, particularly after disturbance, to assist slow natural regeneration.
- Manage herbivory (e.g., deer grazing) using fences and other barriers to promote regeneration.
- Diversify tree/plant species, where appropriate.
- Harvest forests at high risk of loss to disturbance or general decline, where appropriate, before they reach their otherwise optimal rotation age to allow better-adapted species or populations to move in.
- Maintain appropriate forest rotation lengths to decrease the period of time that an older stand is vulnerable to insect pests and pathogens.
- Promote reforestation and afforestation of marginal lands to increase soil moisture retention, provide shade, and increase habitat for species under stress.
- Manage and reduce the harvest of native tree species, where appropriate, that are particularly vulnerable to climate change.

2.2 Identify and pursue opportunities to improve regulatory and policy approaches to address climate change impacts.

2.2.1 Examine and adjust, where appropriate, fishing regulations to reflect fluctuations in aquatic carrying capacities and shifting fish breeding and migration patterns associated with climate change.
2.2.2 Revise provincial fish stocking guidelines to incorporate climate change effects.
2.2.3 Adjust Ontario compliance protocols (e.g., Fish Habitat Protocol, Harmful Alteration, Disruption and Destruction-HADD rules) to reflect changes to fish habitat protection due to climate change.
2.2.4 Create coastal development setbacks or rolling easements to allow ecosystems to migrate in response to changes in water levels due to climate change.
2.2.5 Develop ordinances to control runoff flow.
2.2.6 Restrict the use of shore protection structures.
2.2.7 Revise current best management practices used to prevent non-point source pollution to account for climate change impacts.
2.2.8 Zone development away from sensitive and hazard-prone areas.
2.2.9 Protect exposed or seasonally exposed wetland environments from off-road vehicular use that may be a vector for invasive plants (e.g., phragmites).
2.2.10 Adopt a Lake Superior water level regulation plan that supports ecosystem functioning and responds to future climate conditions.
2.2.11 Adjust harvest rates for trapped and hunted species.

2.3 Optimize use of restoration and protection funding to projects that have incorporated the impacts of climate change into the project design.

2.3.1 Identify and seek adjustments to funding programs to better integrate climate change considerations, where appropriate.

3. <u>Conserve and Connect Habitat</u>

Context
Protecting and establishing refugial habitats is a key step to help reduce the vulnerability of ecosystems to climate change impacts. Establishing and protecting migration corridors between ecosystems and across landscapes, where appropriate, could allow species to move to more suitable habitats when climate changes.

Strategies and Actions
3.1 Identify and conserve areas that are likely to be resilient to climate change and support a broad range of habitats and species.

3.1.1 Identify minimum standards of water levels required for in-stream biological uses.
3.1.2 Ensure climate change impacts are incorporated in Lake Superior place-based priority-setting, including the new GLWQA commitments to develop a LAMP habitat and species protection and restoration conservation strategy and an integrated nearshore framework.
3.1.3 Encourage and support water conservation through implementation of watershed-wide water conservation strategies.

3.2 Conserve and restore ecological connections to facilitate migrations and other transitions caused by climate change.

3.2.1 Ensure that wetlands identified as significant under Ontario's *Land Use Planning Provincial Policy Statement* are protected.
3.2.2 Establish ecological buffer zones around natural features.
3.2.3 Maintain and enhance connectivity in aquatic and terrestrial systems for the purpose of species migration.
- Increase connectivity, where possible, by removing dams, installing fish ladders, and utilizing other techniques to restore connectivity in freshwater systems.

4. <u>Enhance Adaptive Management Capacity</u>

Context
It is important for stakeholders and partners in the Lake Superior region to work together to adopt and implement climate management strategies that can be continuously improved as new information becomes available. Adaptive management strategies enable stakeholders to take action based on current knowledge and to gather information to inform future climate change adaptation actions.

Strategies and Actions
4.1 Promote and adopt available adaptive management support systems that are available to natural resource managers, as appropriate.

4.2 Integrate climate change considerations into existing and new management frameworks used by Lake Superior natural resource organizations.

- 4.2.1 Park management planning, including potential increase in number and duration of visitors due to a longer warm season.
- 4.2.2 Develop contingencies for Lake Superior water level extremes (high and low) and commit to ongoing drought- and flood-preparedness.
- 4.2.3 Recruit and train employees to improve incorporation of climate change information into the communications, management, technical assistance, and research and development programs of parks and protected areas.
- 4.2.4 Monitor effectiveness of the Lake Superior Regulation Plan (i.e., water levels) in protecting and preserving Lake Superior coastal ecosystems.
- 4.2.5 Modify aquatic invasive species pathway analysis and prediction models to include climate change parameters.
- 4.2.6 Incorporate integrated watershed planning (managing human activities and natural resources on a watershed basis) into water and aquatic resource management practices.
- 4.2.7 Integrate use of climate change scenarios and vulnerability assessments into land use plans and resource management plans, including but not limited to: economic development plans, nutrient management plans, municipal official plans, fisheries management plans, wildlife management plans, forest management plans, and Species at Risk Recovery plans.

4.3 Coordinate the Lake Superior LAMP organization contributions to complementary climate change adaptation initiatives, as it relates to protecting and restoring the ecosystem.

- 4.3.1 Develop a regional data management and access system for Lake Superior that facilitates the exchange of climate change data and information on expected impacts to ecosystems among researchers, stakeholders, and interested public.
- 4.3.2 To the extent possible, provide support to the development and implementation of adaptation initiatives at various scales, such as local, tribal, state, provincial, and national.

5. Increase Knowledge

Context

A variety of science and monitoring initiatives are ongoing in the Lake Superior region, but further research, including vulnerability assessments, are needed to fill the gaps in available climate change science and monitoring knowledge.

Strategies and Actions

5.1 Deliver coordinated monitoring and information systems to detect and describe climate impacts on the ecosystem.

- 5.1.1 Increase monitoring for harmful blue-green algal blooms.

5.1.2 Inventory and monitor natural systems and experiences in parks that may be affected by climate change.
5.1.3 Start tracking plant and animal phenology that coincides with management actions where timing is crucial.
5.1.4 Use parks or sentinel sites as long-term integrated monitoring sites for climate change (e.g., monitoring of species, especially those at-risk or extinction-prone).
5.1.5 Monitor data on aquatic invasive species movement and establishment in Lake Superior, as well as information on ecosystem conditions (e.g., water temperature, salinity levels, and water chemistry), to evaluate aquatic invasive species threats in the context of climate change.
5.1.6 Study genetic variability for fitness-related traits to identify species most at risk from climate change.
5.1.7 Continue to support and enhance scientific research designed to understand resilience of ecosystems to climate change and other cumulative effects.
5.1.8 Make climate models and scenarios available and accessible to inform large and small scale natural resource management decisions, growth plan decisions, and socio-economic analyses.
5.1.9 Improve flood plain mapping, given the increasing frequency of major flood events.

5.2 Undertake vulnerability and risk assessments, as appropriate.

5.2.1 Conduct a region-wide climate change vulnerability assessment for forests in the Lake Superior Basin, as well as more localized assessments of forest ecosystem vulnerability at scales that are appropriate for management.
5.2.2 Conduct a region-wide climate change vulnerability assessment of Lake Superior's fisheries, particularly for cold water fish.
5.2.3 Conduct region-wide climate change vulnerability assessments of Lake Superior's near-shore water quality, watersheds, and status of ecosystems in areas directly influenced by high volumes of storm water or discharges from industrial and municipal wastewater treatments plants.
5.2.4 Conduct climate change vulnerability assessments of special designation areas, areas of unique flora and fauna, and areas of essential ecosystem goods and services.
5.2.5 Develop socio-economic impact assessment tools for use with climate models and scenarios for the Lake Superior watershed.

5.3 Support cost-benefit assessments for implementing major adaptation activities, as necessary.

5.3.1 Assess the economic value of environmental services to develop accurate cost/benefit analyses.

6. <u>Public Outreach and Motivate Action to Adapt</u>

Context

Education and outreach are critical elements to build support among the public and key stakeholders for climate change adaptation and resource management. Engaging stakeholders early and substantively in actions and programs that will affect their lives, livelihoods, and recreation options will help facilitate the success of climate change adaptation.

Strategies and Actions

6.1 Increase public awareness and understanding of climate impacts to the ecosystem, related cultural history, and of the principles of climate adaptation.

- 6.1.1 Communicate to the public the expected impacts of climate that threaten parks and protected areas.
- 6.1.2 Support and enhance climate change education and outreach activities that are being conducted by Sea Grant programs, and other initiatives as identified.
- 6.1.3 Develop educational programs to teach the general public and key stakeholders about the principles of climate change science and the expected impacts of climate change on Lake Superior ecosystems.
- 6.1.4 Integrate climate change impacts and adaptation into school curricula.
- 6.1.5 Update natural history field guides and other knowledge-transfer products to reflect the changing species composition of the Lake Superior Basin.

6.2 Coordinate climate change communication across jurisdictions.

- 6.2.1 Regularly update the report on Lake Superior Climate Change Impacts and Adaptation to reflect new climate science related to Lake Superior.
- 6.2.2 Regularly discuss climate change issues during teleconferences, webinars, and meetings of the LAMP's Superior Work Group and other forums as appropriate.
- 6.2.3 Ensure that community engagement and interagency cooperation and coordination become part of all climate change and adaptation-related planning and management in the watershed.

6.3 Support public stewardship related to Lake Superior's adaptation to climate change.

- 6.3.1 Communicate the threats of new aquatic invasive species and how to respond to a sighting.
- 6.3.2 Encourage stewardship groups to protect and rehabilitate aquatic habitat, riparian zones, and wetlands.

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Appendix A. Additional Tools and Resources

A Practitioners Guide to Climate Change Adaptation in Ontario's Ecosystems. This guide from the Ontario Ministry of Natural Resources was developed to help practitioners respond to and prepare for climate change in Ontario. It introduces the concepts of climate change adaptation, vulnerability, and risk; describes vulnerability and risk assessment tools and techniques; and provides a framework that can be used to support adaptive management in a rapidly changing climate.

Adapting to Climate Change: First National Engineering Assessment Report. – This report, from the Public Infrastructure Engineering Vulnerability Committee, includes seven case study reports and literature reviews on adapting infrastructure to a changing climate in Canada.

Adapting to Climate Change: A Planning Guide for State Coastal Managers and Great Lakes Supplement. This guide from NOAA's Office of Coastal Resource Management provides information to help coastal managers reduce the risks of climate change impacts that may affect their coasts. The guide includes steps for setting up a planning process, assessing vulnerability, devising a strategy, and implementing the plan.

Adapting to Climate Change: A Risk-Based Guide for Ontario Municipalities. This guide presents a risk-based approach that can be used to facilitate municipalities' efforts to adapt to climate change through both longer term planning and short-term responses. It is envisioned to be used to assist municipal staff and risk management teams in planning and implementing adaptation strategies.

Adapting to Climate Change: An Introduction for Canadian Municipalities. This booklet from Natural Resources Canada provides resources for Canadian municipalities to develop adaptation measures, including a number of case studies.

Assessing the Vulnerability of Wildlife and Habitats to Climate Change. This website from the National Wildlife Fund provides tools for resource managers to protect wildlife from the impacts of climate change, including a user's guide to conducting a vulnerability assessment.

Canadian Climate Change Scenarios Network (CCCSN). The CCCSN is a partner interface for distributing climate change scenarios and adaptation research in Canada.

Center for Climate Strategies Adaptation Guidebook. Drawing from regional and national efforts to develop climate adaptation plans, this guidebook details a methodology for developing and implementing an adaptation strategy at the multi-state, state, regional, or local level. It provides a stepwise process for developing, implementing, and measuring areas, sectors, and services anticipated to be most vulnerable to the impacts of climate change.

Climate Adaptation Knowledge Exchange (CAKE). CAKE is a climate adaptation knowledge sharing database aimed at building a shared knowledge base for managing natural systems in the face of climate change.

Climate Change Adaptation Community of Practice. The Climate Change Adaptation Community of Practice is an interactive online community of researchers and practitioners who discuss the latest research and share knowledge on climate change adaptation. The Community of Practice is facilitated and maintained by the OCCIAR.

Climate Change Adaptation in the Great Lakes Region. This website describes The Nature Conservancy's climate change program, including links to case studies, partners, and a climate change adaptation survey.

Climate Change Adaptation: What Federal Agencies Are Doing. Developed by the Center for Climate and Energy Solutions (formerly the Pew Center on Global Climate Change), this updated report summarizes how federal agencies are considering climate change adaptation in their initiatives, strategies, programs, institutional mechanisms, tools, and resources. It includes several examples of federal projects that incorporate the impacts of climate change and adaptive actions into the planning, design, and implementation process.

Climate Change Tree Atlas and Bird Atlas. The Climate Change Atlas is a species distribution tool that models how ideal habitat for 134 tree species and 150 bird species in the U.S. may change by 2099 under a range of future climate scenarios.

Climate Change Publications from the Ontario Ministry of Natural Resources. This site lists links to climate change publications pertinent to Ontario.

Climate Change Resource Center. This website, sponsored by the U.S. Forest Service, provides land managers with information on climate-related tools, video presentations, and topic pages on natural resource management issues.

Climate Change Response Framework . The Climate Change Response Framework Project is collaborative effort working to help land managers in northern Wisconsin understand the potential effects of climate change on forest ecosystems and integrate climate change considerations into management. This site provides perspective, information, and tools for land managers on how to adapt forest ecosystems in northern Wisconsin to a changing climate.

Climate Ready Great Lakes Training Modules. These three training modules from NOAA are tailored toward educating the public on climate change in the Great Lakes region. Topics include 1) Predicted Impacts of Climate Change, 2) Planning Processes and Strategies for Adapting to Climate Change, and 3) Tools and Information.

Climate Ready Water Utilities. This initiative, funded by U.S. EPA, assists the water sector, including drinking water, wastewater, and stormwater utilities, in addressing climate change impacts. Practical and easy-to-use tools promote an understanding of climate science and adaptation options by translating complex climate projections into accessible formats. This information can help utility owners and operators prepare their systems for the impacts of climate change.

Climate Smart Restoration: Great Lakes On-the-Ground Examples. The National Wildlife Federation and EcoAdapt are partnering with NOAA's Restoration Center Great Lakes Region with funding from the Great Lakes Restoration Initiative to help make sure that Great Lakes restoration projects are climate-smart and have an increased chance of resiliency over time. Through this partnership the National Wildlife Federation and EcoAdapt are working with select projects to consider climate change in the design and implementation of Great Lakes restoration activities. This website describes climate-smart restoration projects at 6 locations in the Great Lakes region, including St. Marys River.

Climate Solutions University. Climate Solutions University works to empower local, rural communities in the U.S. to become resilient in the face of a changing climate by protecting their forest and water resources. Communities that participate are provided financial assistance to assess their climate risks and develop a climate readiness plan with goals that are location specific, driven by local decision makers, and aimed at benefiting the social, environmental, and economic needs of the community.

Coastal Climate Adaptation Online Resource. This website provides general information, case studies, adaptation planning, outreach materials, policies, risk assessments, training materials regarding climate change. Resources for U.S. states can be accessed, including some adaptation plans from state and local governments.

Coastal Climate Wiki. Funded by NOAA, this resource is a collaborative website that links climate scientists with the Sea Grant Climate Network of Sea Grant and NOAA partners involved in climate research, outreach and education.

Collaboratory for Adaptation to Climate Change. This website is a resource for research, education, and collaboration in the area of adaptation and climate change. It is funded by the National Science Foundation and the University of Notre Dame. The Collaboratory provides a platform for accessing resources, using and learning about tools, and sharing information with colleagues.

Data Basin Climate Center. The Data Basin is an on-line database with data manipulation tools created by the Conservation Biology Institute. The Climate Center lists the most recent datasets, maps and galleries with relevance to climate change issues; provides special features about specific datasets available in Data Basin; and provides news briefs about recent climate change publications, observations of change, climate change-related data providers, and climate change experts.

GEOS Institute. The Geos Institute uses science to help people predict and prepare for climate change impacts. This website describes the efforts of the Geos Institute and provides information on climate change adaptation and mitigation.

Great Lakes Climate Adaptation Toolkit. Freshwater Future and EcoAdapt have partnered to develop this toolkit, with funding support from the Kresge Foundation. It includes a primer on climate change and adaptation, four case studies on how community groups are incorporating climate change into their work, communications guidance, fact sheets on specific Great Lakes climate impacts, approaches to addressing climate change with community leaders, and a guide to assist with vulnerability assessments.

Great Lakes Climate Partnership Resources. Developed through a year-long partnership between NOAA's Great Lakes Regional Collaboration Team and The Nature Conservancy, these climate change adaptation resources include a **video**, **guide**, outreach and engagement **case study**, and online **climate tools** designed to empower coastal communities to engage in planning and decision making that reflect adaptation to a changing climate.

Great Lakes Integrated Sciences and Assessments Center (GLISA). Funded by NOAA, GLISA is a collaboration of the University of Michigan, Michigan State University, and The Ohio State University with the goals of 1) contributing to the long-term sustainability of the region in the face of climate change, and 2) improving the utility of scientific knowledge to decision making. Funding is available annually for climate research projects.

Great Lakes Restoration Initiative (GLRI). With Congressional funding, the U.S. EPA offers grants and cooperative agreements through the GLRI for projects to protect and restore the Great Lakes, including climate change research.

Intergovernmental Panel on Climate Change (IPCC). IPCC is the leading international body for the assessment of climate change. Online information includes current research, public policy, and education resources.

Integrating Climate Change into Invasive Species Risk Assessment/Risk Management. This 2008 workshop report from the Government of Canada, Policy Research Initiative outlines approaches for integrating climate change considerations into invasive species risk assessment and management. Topics include when to consider climate change, approaches and considerations, managing risk, and challenges and barriers.

Iterative Risk-Management Framework. The IPCC describes this overall process for making decisions regarding climate change in its Fourth Assessment Report.

Lake Superior and Climate Change Video Series (Part 1 Part 2 Part 3). In this three-part video series, scientists at the Large Lakes Observatory in Duluth, MN, explore the implications of climate change and other human activities for Lake Superior.

LANDIS-II Forest Landscape Model. LANDIS-II simulates forest succession, disturbances (including fire, wind, harvesting, and insects), climate change, and seed dispersal across large landscapes. LANDIS-II tracks the spatial distribution of discrete tree and shrub species and has flexible spatial and temporal resolutions.

MC1 Dynamic Global Vegetation Model. MC1 is a dynamic global vegetation model that uses monthly climate data and soil information (e.g., bulk density, texture, depth) to project vegetation distribution, carbon stocks and fluxes, hydrological flows, and wildfire occurrences and impacts.

Michigan Climate Coalition. The Michigan Climate Coalition (MCC) seeks to foster synergy through information, communication and action, in order to assist Michigan in responding to climate change. The website includes information from working groups on forests and wildlife.

Michigan Coastal Management Program (MCMP). Section 309 funding will be available through a competitive grant process in 2012-2016 for research to identify specific climate change impacts to Great Lakes coastal wetlands; to incorporate preservation, restoration, and climate change adaptation measures for coastal wetlands into Michigan's climate change activities; and to provide technical assistance with incorporating climate change adaptation measures for coastal wetlands in local green infrastructure plans, land use plans, and zoning ordinances.

NOAA Coastal Services Center Digital Coast. This website provides data, tools, and training to help coastal managers respond to climate change and other management challenges.

NOAA Earth System Research Laboratory. This tool, provided by the U.S. Climate Division Dataset Mapping Page, generates regional maps displaying climate data.

Northern Institute of Applied Climate Science (NIACS). The NIACS, part of the U.S. Forest Service, provides climate change tools and information for forest land managers and others to address climate change impacts. NIACS staff conduct workshops, facilitate working groups of stakeholders, use up-to-date climate science to inform local conditions, and provide adaptation recommendations.

Ohio State University Climate Change Outreach Team. The Climate Change Outreach Team hosts a webinar series to discuss climate change issues in the Great Lakes.

Ontario Ministry of Natural Resources – Climate Change. The climate change section of the Ontario Ministry of Natural Resources website includes an overview of climate change impacts, mitigation, and adaptation.

Restoring the Great Lakes' Coastal Future: Technical Guidance for the Design and Implementation of Climate-Smart Coastal Restoration Projects in the Great Lakes Region. The National Wildlife Federation and EcoAdapt are working with the NOAA to reduce the vulnerability of the Great Lakes area by developing methods to ensure that coastal planning and restoration projects are "climate-smart." This document provides key recommendations to enhance the durability of Great Lakes restoration efforts.

TNC Climate Wizard. This tool illustrates various IPCC climate change scenarios in the U.S. from 16 different GCMs. Users can view averages and changes in temperature and precipitation in the past 50 years and projections into the future.

Upper Midwest/Great Lakes Landscape Conservation Cooperative. The Landscape Conservation Cooperative provides a venue for a community of interests to explore how and where to sustain landscapes for natural and cultural resources. Funding is available for projects that support conservation delivery across the cooperative's geographic boundary, including projects that explore the potential impacts of climate change.

U.S. EPA Climate Change Program. U.S. EPA's website provides information on climate change for communities, individuals, businesses, states, localities, and governments. Topics include climate change indicators, climate economics, science, regulatory initiatives, GHG emissions, U.S. climate policy, health and environmental effects, and what you can do.

U.S. Global Change Research Program's Assessment Report on Climate Change Impacts in the U.S. – Midwest Chapter. The U.S. Global Change Research Program coordinates and integrates federal research on changes in the global environment and their implications for society. The Midwest chapter includes information on climate change impacts on the Lake Superior basin.

U.S. National Park Service Apostle Islands National Lakeshore Climate Change and Sustainability. The U.S. National Park Service's Climate Change Response Program is coordinated around four areas: Adaptation, Mitigation, Science and Education. This website describes the efforts at Apostle Islands National Lakeshore to integrate all four areas into park planning, management, operations, and staff culture.

Wisconsin Coastal Management Program. Grants are available for coastal wetland protection and habitat restoration, nonpoint source pollution control, coastal resource and community planning, Great Lakes education, public access and historic preservation. All Wisconsin counties adjacent to Lake Superior are eligible.

Wisconsin Initiative on Climate Change Impacts (WICCI). WICCI is a state initiative to develop a climate change adaptation strategy in Wisconsin.

Appendix B. Climate Strategies and Action Plans Relevant to the Lake Superior Basin

State/Agency	Action Plan/ Strategy	Description	Focus
FIRST NATIONS/TRIBES			
MICHIGAN			
Michigan Department of Environmental Quality (2009)	Michigan Climate Action Council Climate Action Plan	Presents a GHG emissions inventory and forecast, and outlines policy recommendations for reducing GHG emissions by sector (energy supply, residential, commercial, industrial, transportation, land use, agriculture, forestry, waste management).	Mitigation in Michigan
Michigan Coastal Management Program (MCMP)	Climate Change Adaptation in Coastal Wetland Management Strategy	This strategy will support the identification of research-based adaptation actions for Great Lakes coastal wetlands and the incorporation of these adaptation actions into state and local resource management plans.	Adaptation for coastal wetlands in Michigan
Michigan Department of Community Health (Cameron et al., 2011)	Michigan Climate and Health Adaptation Plan (MI-CHAP): 2010-2015 Strategic Plan	This plan seeks to: (1) integrate adaption to climate change into public health practice, (2) provide resources to assist public health agencies in responding to the impacts of climate change, and (3) incorporate the needs of vulnerable populations in addressing the health impacts of climate change.	Adaptation for public health in Michigan
Michigan Department of Natural Resources and Environment	Memorandum of Understanding (MOU) with the Wisconsin Department of Natural Resources to establish and implement a partnership for climate change adaptation	This MOU provided a framework to establish common goals between the Michigan Department of Natural Resources and Environment and the Wisconsin Department of Natural Resources to jointly pursue research, planning, and implementation focused on climate change adaptation and mitigation.	Adaptation and mitigation in Michigan and Wisconsin
MINNESOTA			
Minnesota Pollution Control Agency (Ciborowski and Fenske, 2003)	Minnesota Climate Change Action Plan: A Framework for Climate Change Action	Presents estimates and forecasts of GHG emissions, and a carbon sequestration inventory. Outlines recommended actions to reduce GHG emissions and considers existing state programs that could assist in controlling GHG emissions.	Mitigation in Minnesota
Minnesota Climate Change Advisory Group (MCCAG) (2008)	Final Report: A Report to the Minnesota Legislature	Presents an inventory of historical (by sector for 2005) and forecasted GHG emissions (through 2020). Recommends actions to reduce GHG emissions by sector (residential, commercial, industrial, energy supply, transportation, land	Mitigation in Minnesota

State/Agency	Action Plan/ Strategy	Description	Focus
		use, agriculture, forestry, waste management). Considers the costs and benefits of recommended options.	
Minnesota Department of Natural Resources, Wildlife Climate Change Working Group (Carstensen et al., 2008)	Climate Change: Preliminary Assessment for the Section of Wildlife of the Minnesota Department of Natural Resources	Describes expected climate change projections for Minnesota, effects of climate change on wildlife and landscapes in Minnesota. Recommends climate change adaptation and mitigation actions for wildlife in Minnesota.	Mitigation and adaptation for wildlife in Minnesota
ONTARIO			
Ontario Ministry of Natural Resources (2006)	Climate Change and MNR: A Program-Level Strategy and Action Plan	Describes the MNR's strategies to support the Ontario government's commitment to address the impacts associated with climate change. The strategies are organized around three themes based on the need to understand climate change, mitigate the impacts of rapid climate change, and help Ontario citizens adapt to climate change.	Mitigation and Adaptation in Ontario (including ecosystems and natural resources)
Ontario Ministry of the Environment (2008, 2009, 2010)	1) Climate Change Action Plan: Creating Our Sustainable Future. Annual Report 2007-2008 2) Climate Change Action Plan: Annual Report 2008-2009 3) Climate Progress: Ontario's Plan for a Cleaner, More Sustainable Future. Annual Report 2009-2010	Three annual reports of progress on Ontario's commitment to reduce total GHG emissions in the province. Describes Ontario's investments in renewable energy, energy efficiency, and similar initiatives.	Mitigation in Ontario
Expert Panel on Climate Change Adaptation (2009)	Adapting to Climate Change in Ontario	Presents the expert panel's strategic goals and recommendations to inform the development of a climate change adaptation strategy and action plan for Ontario.	Adaptation in Ontario (including the environment)
Ontario Ministry of the Environment (2011a)	Climate Ready: Ontario's Adaptation Strategy and Action Plan 2011-2014	Establishes five broad goals and 37 actions to help prepare Ontario for expected changes in climate from 2011 to 2014.	Adaptation in Ontario (including ecosystems)
Ontario Ministry of the Environment (2011b)	Climate Action: Adapting to Change, Protecting Our Future	Describes Ontario's changing climate and efforts to respond with adaptation and mitigation actions.	Mitigation and adaptation in Ontario
Ontario Biodiversity Council, 2011	Ontario's Biodiversity Strategy, 2011: Renewing Our	Provides a renewed commitment to safeguard Ontario's variety of species and ecosystems and proposes an ambitious	Discusses climate change as a threat

State/Agency	Action Plan/ Strategy	Description	Focus
	Commitment to Protecting What Sustains Us	but practical conservation agenda.	to biodiversity conservation in Ontario
WISCONSIN			
Wisconsin Department of Natural Resources and Public Service Commission of Wisconsin (2008)	Wisconsin's Strategy for Reducing Global Warming	Discusses Wisconsin's share of world GHG emissions and recommends short- and long-term goals for reducing GHG emissions in the state.	Mitigation in Wisconsin
Wisconsin Initiative on Climate Change Impacts (WICCI) (2011)	Wisconsin's Changing Climate: Impacts and Adaptation	Summarizes expected climate changes in Wisconsin (by mid-century) and expected impacts on water resources, natural habitats, agriculture, coastal regions, society, and the built environment. Synthesizes the findings of 15 working groups who contributed content for the report.	Adaptation in Wisconsin (including water resources and natural habitats)
Northern Institute of Applied Climate Science, U.S. Department of Agriculture (Swanston and Janowiak, 2012)	Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers	Supports partnerships and collaboration, provides scientific information, and presents a wide selection of adaption strategies and approaches that are relevant to forest ecosystems in northern Wisconsin.	Adaptation in northern Wisconsin forests
Wisconsin Department of Natural Resources	Memorandum of Understanding (MOU) with the Michigan Department of Natural Resources and Environment to establish and implement a partnership for climate change adaptation	This MOU provided a framework to establish common goals between the Michigan Department of Natural Resources and Environment and the Wisconsin Department of Natural Resources to jointly pursue research, planning, and implementation focused on climate change adaptation and mitigation.	Adaptation and mitigation in Wisconsin and Michigan
CANADA			
Government of Canada (Lemmen et al., 2008)	From Impacts to Adaptation: Canada in a Changing Climate	Describes risks and opportunities presented by climate change for each Canadian region. Chapter 6 presents information for Ontario and its subregions in the South, Central, and North, including subregional perspectives on climate sensitivities, impacts, and vulnerabilities.	Mitigation and Adaptation examples focusing on human and managed systems
UNITED STATES			

State/Agency	Action Plan/ Strategy	Description	Focus
U.S. Fish and Wildlife Service (2012)	National Fish, Wildlife, and Plants Climate Adaptation Strategy (draft)	This strategy will provide a unified approach from federal, state, and tribal partners to reduce the negative effects of climate change on fish, wildlife, plants, and the natural systems on which they depend.	Adaptation of fish, wildlife, and plants in the U.S.
National Ocean Council (2012)	National Ocean Policy Implementation Plan	This plan includes actions that address the "Resiliency and Adaptation to Climate Change and Ocean Acidification" priority objective, one of nine priority objectives identified by the National Ocean Policy.	Adaptation of oceans, coasts, and Great Lakes in the U.S.
Interagency Climate Change Adaptation Task Force (2011)	Final National Action Plan: Priorities for Managing Freshwater Resources in a Changing Climate	Describes challenges presented by climate change in the management of the Nation's freshwater resources and recommends actions for federal agencies to take over the next several years.	Adaptation of U.S. freshwater resources (including protection of water quality and aquatic ecosystems)
U. S. National Park Service (2011a)	General Management Plan/ Wilderness Management Plan for Apostle Islands National Lakeshore	Long-term management plan for the park that focuses on sustainability of facilities, services, and park operations in light of climate change and other challenges.	Climate change impacts affecting sustainable operations of park
U.S. National Park Service (2008a)	Climate Friendly Parks: Apostle Islands National Lakeshore Action Plan	Quantifies carbon footprint of the park and establishes goals and strategies for climate change mitigation, adaptation, and communication.	Mitigation, adaptation, and communication at Apostle Islands National Lakeshore
National Park Service (2008b)	Climate Friendly Parks: Pictured Rocks Lakeshore Action Plan	Quantifies carbon footprint of the park and establishes goals and strategies for climate change mitigation, adaptation, and communication.	Mitigation, adaptation, and communication at Pictured Rocks National Lakeshore
U.S. National Park Service (2010)	National Park Service Climate Change Response Strategy	Establishes goals and objectives for addressing climate change within the National Park Service through four components: science, adaptation, mitigation, and communication.	Adaptation in U.S. National Parks (including ecosystems)
U.S. Forest Service (2010)	A Climate Change Response Framework for the Chequamegon-Nicolet National Forest	Brings together the U.S. Forest Service and Northern Institute of Applied Carbon Science to address the complexities of climate change by assessing the science, working with partners, and providing guidance to better adapt ecosystems, mitigate carbon emissions, and incorporate science	Adaptation, mitigation, and science and monitoring at Chequamegon-

State/Agency	Action Plan/ Strategy	Description	Focus
		and monitoring information into forest management activities.	Nicolet National Forest
U.S. Forest Service (Solomon et al., 2009)	Global Change Research Strategy	Presents adaptation and mitigation approaches to sustain healthy ecosystems through research to: enhance ecosystem health and sustainability; increase carbon sequestration; provide decision support tools; and provide infrastructure, scientific collaboration, and science delivery (Solomon et al., 2009)	Adaptation and mitigation in U.S. forests and grasslands

Appendix C. Climate Change Adaptation Programs in the Lake Superior Basin

State/Provincial and First Nation/Tribal Programs in the Lake Superior Basin

Program Name	Description	Focus and Scope
MICHIGAN		
Michigan Climate Coalition (MCC)	Assists Michigan in responding to climate change through networking and collaboration, communication and translation, and action and filling in gaps.	Information gathering, outreach, research, and adaptation in Michigan
Pileus Project	The goal of the Pileus Project is to provide climate information to decision makers in the Great Lakes region, with a focus on agriculture and tourism. The core research team is located at Michigan State University.	Climate change decision-making related to agriculture and tourism in the Great Lakes region
MINNESOTA		
Minnesota Climate Change Advisory Group (MCCAG)	Governor-appointed group comprised of a diverse group of stakeholders. To fulfill its charge, the MCCAG developed: 1) an inventory and forecast of GHG emissions in Minnesota from 1990 to 2020, 2) a set of policy recommendations to reduce GHG emissions, and 3) recommended GHG reduction goals and targets.	Mitigation in Minnesota
Wildlife Climate Change Working Group, Minnesota Department of Natural Resources	Members of the Division of Fish and Wildlife; prepared *Climate Change: Preliminary Assessment for the Section of Wildlife of the Minnesota Department of Natural Resources* (Carstensen et al., 2008), which recommends climate change adaptation and mitigation actions for wildlife in Minnesota.	Mitigation and adaptation for wildlife in Minnesota
Climate Change Extension Educator for Western Lake Superior Communities	Sponsored by the Minnesota and Wisconsin Sea Grants, the climate change extension educator provides science-based information to Lake Superior communities in Minnesota and Wisconsin that are grappling with more intense weather events and deliberating over how a changing climate might affect their economies and environments. She also serves as a liaison between climate scientists and citizens of the western Lake Superior basin.	Education and adaptation in the western Lake Superior basin
ONTARIO		
Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR)	Provides climate adaptation outreach and education to enable communities to address local vulnerabilities, risks, and opportunities.	Outreach and education in Ontario
Coastal Zone Climate Change and Adaptation Project	Project organized by federal, provincial, local, and private partners to identify coastal features and processes of the Great Lakes that are likely to be affected by climate change, through evaluation of various climate change scenarios, and to create a list of potential adaptation options that can be used by land owners and managers to reduce vulnerability to climate change. Produced a report titled, "Coastal Zone and Climate Change on the Great Lakes" (Environment	Adaptation options for coastal communities in Ontario

Program Name	Description	Focus and Scope
	Canada, 2005).	
Ontario Regional Adaptation Collaborative	Three-year federal/provincial program to help communities adapt to climate change at the local level. Part of a federal program across Canada designed to share information across regions nationwide. The Ontario Ministry of the Environment is leading a series of projects addressing climate change impacts in Ontario, such as decreasing fresh water supplies; increasing droughts, floods and coastal erosion; and changing forestry, fisheries and agricultural resources (Ontario Ministry of the Environment, 2011b).	Adaptation in Ontario, with information-sharing across Canada
WISCONSIN		
Wisconsin Initiative on Climate Change Impacts (WICCI)	Assesses and anticipates climate change impacts on Wisconsin's natural resources, ecosystems and regions; evaluates potential effects on industry, agriculture, tourism and other human activities; and develops and recommends adaptation strategies that can be implemented by various stakeholders. WICCI connects university-based climate modelers with managers and experts in the field to assess impacts at focused and relevant measures of time and space.	Adaptation in Wisconsin
Climate Change Response Framework Project	Collaborative project in northern Wisconsin to gather information, perspectives, and expertise from a broad array of partners and provide strategies and approaches for responding to climate impacts and developing forest adaptation plans.	Adaptation and mitigation for forests in northern Wisconsin
Climate Change Extension Educator for Western Lake Superior Communities	Sponsored by the Minnesota and Wisconsin Sea Grants, the climate change extension educator provides science-based information to Lake Superior communities in Minnesota and Wisconsin that are grappling with more intense weather events and deliberating over how a changing climate might affect their economies and environments. She also serves as a liaison between climate scientists and citizens of the western Lake Superior basin.	Education and adaptation in the western Lake Superior basin

Federal Climate Programs in the Lake Superior Basin

Program Name	Description	Focus and Scope
CANADA		
Aboriginal Affairs and Northern Development Canada Climate Change Adaptation Program	Government program that provides support to communities in planning, risk assessment, priority setting, and implementation of adaptation.	Adaptation in Aboriginal and northern communities
Climate Change Impacts and Adaptation Division	A division of Natural Resources Canada that facilitates sharing of knowledge, tools, and mechanisms as a means of integrating climate change adaptation into policy and projects across government and industry.	Adaptation, communication, decision support in Canada
Regional Adaptation Collaboratives Program	Federal program aimed at increasing collaboration between government, private sector, and community organizations across Canada on complicated climate change threats and adaptation policy.	Adaptation, communication, and decision support in Canada

Program Name	Description	Focus and Scope
	UNITED STATES	
U.S. Global Change Research Program (USGCRP)	Mandated by Congress, the USGCRP coordinates and integrates federal research on changes in the global environment and their implications for society. The program is required to conduct an assessment of the impacts of global change in the U.S. every four years (http://www.globalchange.gov/).	Research, education, communication, and decision support in the U.S.
U.S. Climate Change Science Program (CCSP)	Part of the USGCRP, the CCSP, comprised of various federal agencies, integrates federal research on climate and global change through published reports on the impacts of climate change and approaches to adaptation or mitigation.	Adaption and mitigation in the U.S.
U.S. Climate Change Technology Program (CCTP)	Part of the USGCRP, the CCTP is a multi-agency research and development program for technologies that promote adaption and mitigation of climate change (http://www.climatetechnology.gov/).	Adaption and mitigation in the U.S.
Great Lakes Regional Assessment	A group of stakeholders from the Great Lakes region, coordinated by the USGCRP, who provide input, guidance, and support for climate change issues in the region. The team hosted a series of workshops from 1998 to 2002 and in 2000 prepared a report that summarizes the team's findings with respect to climate changes, and describes the impacts, challenges, and opportunities for the Great Lakes region, focusing on the years 2030 and 2090 (Sousounis and Bisanz, 2000).	Adaption in the Great Lakes region
Interagency Climate Change Adaptation Task Force	Comprised of more than 20 federal agencies and executive branch offices co-chaired by NOAA, the White House Council on Environmental Quality, and the Office of Science and Technology Policy. Prepared a progress report in 2010 outlining recommended actions in support of a national climate change adaptation strategy. In October 2011, the task force released a final national action plan that proposed priorities for managing freshwater resources in a changing climate (see Appendix B).	Adaption in the U.S.
National Park Service Climate Change Response Program (U.S. National Park Service, 2010)	Actions are structured around four strategy components: science, adaptation, mitigation, and communication. Apostle Islands National Lakeshore has instituted an educational program that includes visitor displays illustrating the impacts of climate change on the park and on the local Ojibwe population. Through a cooperative agreement with a nonprofit organization, Pictured Rocks National Lakeshore ensures local awareness of climate change and actions to address it (Saunders et al., 2011).	Outreach, adaptation, mitigation, and research at U.S. National Parks
Climate Friendly Parks Program	A joint partnership between U.S. EPA and the National Park Service. The program is part of an integrated National Park Service approach to address climate change by implementing sustainable practices in park operations, including the in the Lake Superior basin. Apostle Islands National Lakeshore and Pictured Rocks National Lakeshore have completed all of the program's required milestones to be recognized as a "Climate Friendly Park." The milestones include conducting a Climate Friendly Parks Workshop to develop park-based solutions to climate change, preparing an inventory of GHG emissions, and developing a Climate Action Plan to reduce the park's GHG emissions (U.S. National Park Service, 2011b).	Mitigation in U.S. National Parks
U.S. Forest Service's Global Change	Supports the needs of U.S. National Forest System managers and others (Solomon et al., 2009). Instructs forest managers in land management practices that enhance ecosystem	Adaptation and mitigation in U.S.

Program Name	Description	Focus and Scope
Research Strategy	adaptation to climate change and sequester carbon. Adaptation approaches focus on maintaining ecosystem health and the services that ecosystems provide, such as a water supply and habitat for wildlife.	National Forests and other forests
Great Lakes Climate Change Science and Education Systemic Network (GLCCSESN)	Funded by the National Science Foundation, the GLCCSESN is linking the education, learning science, and climate science communities with a comprehensive, regional focus. The GLCCSESN is developing a strategic plan to guide collaboration among its partners for implementation of educational and climate change science efforts.	Education on climate change science in the Great Lakes region
NOAA Climate Program Office	Manages NOAA's competitive research program on climate change and supports NOAA's contributions to the USGCRP and the U.S. Interagency Climate Change Adaptation Task Force.	Research and adaptation in the U.S.

Appendix D. Workshops, Meetings, and Conferences Relevant to Climate Change Adaptation in the Lake Superior Basin

Date/Location	Title	Description	Host/Sponsor
October 12-12, 2012 Duluth, Minnesota	Adapting Your Work to Climate Change Fall Symposium	The symposium is designed for all types of community groups to learn how to incorporate climate change impacts into their existing work, connect with available climate change resources, and network with others interested in making their work more climate savvy.	Freshwater Future and EcoAdapt
March 13-15, 2012	Climate Adaptation in the Northwoods: Information, Tools, and Collaboration	The workshop brought together a variety of forest and wildlife managers, forest planners and administrators, ecologists, conservation practitioners, and outreach specialists for a region-wide meeting to consider ways to successfully respond to climate change. Participants explored case studies from ongoing climate change adaptation efforts, shared tools and approaches for forest management, discussed goals and strategies, and engaged in a forum to interact with a growing network for northern forest climate adaptation.	The Nature Conservancy and the U.S. Forest Service
November 7-25, 2011	Online Workshop on Great Lakes Climate Change for Informal Educators (http://www.coexploration.org/CCEP-GL/)	This workshop provided a wide variety of resources on climate change science and education, as well as interactive and facilitated online reflective conversations about climate change issues in the Great Lakes. It was targeted especially to middle school and high school teachers and informal institution educators.	NSF-funded Great Lakes Climate Change Science and Education Systemic Network (GLCCSESN) team
November 3, 2011 Ann Arbor, MI	GLISA Half-Day Symposium on Climate Change and Variability in the Great Lakes Region (http://glisa.umich.edu/about/events/symposium_2011.php)	This symposium introduced the Great Lakes community to GLISA's current work and research on climate variability and change in the region. Speakers from the GLISA Core Team discussed its Climate Data Programs, Analysis of Regional Reports, and Stakeholder Network Analysis. Researchers funded through the GLISA annual Grants Competition summarized their projects and initial findings, and Kathy Jacobs of the National Climate Assessment gave the keynote address.	Great Lakes Integrated Sciences and Assessments (GLISA)
September 22, 2011 Duluth, Minnesota	Planning for Climate Impacts in the Western Lake Superior Region (http://www.seagrant.umn.edu/news/2011/09/22)	This collaborative workshop aimed to build climate planning capacity by presenting the latest climate science, allowing participants to discuss climate issues, providing information about climate planning processes and strategies, and giving examples of available planning tools and resources. The workshop also offered an introduction to climate vulnerability assessment. The workshop addressed climate issues affecting land use, public health, stormwater, emergency preparedness, and natural resource management issues in the western Lake Superior region.	Lake Superior National Estuarine Research Reserve and NOAA's Ohio Coastal Training Program, along with local and regional partners
September 12-14, 2011	Coastal Habitat Conservation in a Changing	This workshop identified and discussed tools and strategies to assess vulnerability and develop actions for climate smart conservation of	NOAA Climate Program Office,

Date/Location	Title	Description	Host/Sponsor
Ann Arbor, MI	Climate: Strategies and Tools for the Great Lakes Region	freshwater coastal habitats in the U.S. Great Lakes region (e.g., MI, WI, MN, IN, IL, OH, PA, NY).	Office of Habitat Conservation, and Great Lakes Regional Collaboration Team
August 30 – September 2, 2011 Traverse City, MI	Michigan Wetlands Association Annual Conference (http://www.miwetlands.org/)	This conference featured recent changes to Michigan's wetland regulatory program, wetland monitoring and assessment, other current issues in wetland science and policy, and a special symposium on wetland management as a response to climate change.	Michigan Wetlands Association
August 23-25, 2011 Keshena, Wisconsin	Great Lakes Tribal Climate Change Summit (http://tribalp2.org/events/conferences.php)	This summit engaged Great Lakes Tribal Nations on climate change indicators and resiliency strategies. The purpose of the summit was to share ongoing research projects, provide information related to carbon sequestration, provide a forum to share climate change projections and experiences, and begin discussing a climate change research agenda for Great Lake Tribal Nations.	College of Menominee Nation Sustainable Development Institute
July 17-21, 2011 Chicago, Illinois	Coastal Zone 2011 Conference (http://www.doi.gov/initiatives/CZ11/index.htm)	This conference provided a forum for ocean and coastal management professionals to discuss issues such as the impacts of coastal development and new threats, including those related to invasive species, global climate change, and other human-induced hazards that require new approaches to ocean and coastal resource management. One theme of the 2011 conference was "Planning for Resilient Coasts, Great Lakes, and Ecosystems." The international symposium has been held biennially since 1978.	The Nature Conservancy, U.S. Department of Interior, Illinois Department of Natural Resources, NOAA, U.S. Army Corps of Engineers, and U.S. EPA
February-March 2011 Kingston, London, and Hamilton, Ontario	Moving Forward on Adaptation: the Climate Change Adaptation Workshop Series (http://www.climateontario.ca/w_CA.php)	Three 1-day capacity building workshops were held to help Ontario Conservation Authorities (CA) address the challenges associated with climate change and to move forward on adaptation. The focus was on adaptation, vulnerability assessments, and climate impacts on water resources in Ontario. For CA staff and directors, these workshops were organized to: raise awareness of climate change and its implications to CA business; provide an update on provincial perspectives and initiatives; provide opportunity for CAs to share current CA climate change initiatives; and discuss challenges and approaches for incorporating adaptation and mitigation into CA programs.	OCCIAR, Conservation Ontario
October 5-7, 2010 Duluth, Minnesota	National Park Service Climate Change Scenarios Training Program: Great Lakes and Atlantic Coast	Thirty workshop participants applied the Scenario Planning framework to two case studies in the Great Lakes and Atlantic Coast bio-regions. Participants used major climate drivers, such as warming temperatures, changing precipitation patterns, and sea level rise to identify highly	U.S. National Park Service

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	Workshop	consequential and uncertain impacts like altered vegetation patterns, increased temperature and salinity in wetland, coastal, and shoreline environments to create narratives that can guide management options under several possible futures.	
July 15, 2010 Chicago, Illinois	Public Meeting of the U.S. Interagency Climate Change Adaptation Task Force (http://www.tvworldwide.com/events/ICCATF/100715/)	This meeting provided an opportunity for senior members of the Obama Administration to exchange climate change information with local and regional representatives, address questions and concerns about climate change impacts, and describe U.S. federal climate change adaptation planning efforts underway. The focus was on climate change adaptation in the Great Lakes region. Speakers discussed the range of climate change impacts expected for the Great Lakes region and the growing need for adaptation strategies to ensure healthy economies and ecosystems.	U.S. EPA and the Department of Housing and Urban Development
April 27-28, 2010 Madison, WI	Science Applications and Needs Workshop	As part of the Climate Change Response Framework Project in northern Wisconsin, the workshop sought to identify management approaches that can enhance the ability of ecosystems in northern Wisconsin to cope with climate change and consider how National Forests and other lands might be used to test new approaches.	U.S. Forest Service, Northern Institute of Applied Climate Science
February 24-25, 2010 Rhinelander, WI	Shared Landscapes Initiative Workshop	As part of the Climate Change Response Framework Project in northern Wisconsin, the workshop sought to increase awareness and discussion of the potential ecological and land management pressures associated with climate change in northern Wisconsin.	U.S. Forest Service, Northern Institute of Applied Climate Science
July 29-31, 2008 Ann Arbor, Michigan	Impact of Climate Change on the Great Lakes Ecosystem: A NOAA Science Needs Assessment Workshop to Meet Emerging Challenges (http://www.glerl.noaa.gov/ftp/publications/tech_reports/glerl-147/tm-147.pdf)	The purpose of this workshop was to identify and prioritize research needs that would drive the development of a NOAA research strategy to address the impact of climate change on Great Lakes coastal ecosystems.	NOAA, Cooperative Institute for Limnology and Ecosystems Research, and the Great Lakes Sea Grant Network
June 27, 2008 Flint, Michigan	Preparing for Climate Change in the Great Lakes Region	Workshop objectives were to identify policy changes that will enable Great Lakes communities to adapt to climate change and protect major ecosystems and to identify strategies for implementing those policy changes. Workshop participants identified guiding principles, priority issues, focus areas, and implementation approaches to guide climate change adaptation efforts. Participants recommended focusing efforts on water resource management issues, as they will have a significant	Mott Foundation, Joyce Foundation, Kresge Foundation, Great Lakes Fishery Trust, and Michigan Sea Grant

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		impact on restoring and promoting ecosystem resiliency. A summary report is available at http://www.miseagrant.umich.edu/downloads/climate/Climate_Workshop_Report.pdf.	
October 29-31, 2007 Duluth, Minnesota	Making a Great Lake Superior (http://www.seagrant.umn.edu/superior2007/)	Over 440 scientists, government officials, natural resource managers, and educators from over 70 towns and cities across the U.S. and Canada participated in this conference. The conference presentations focused on 12 priorities for Lake Superior, including fisheries and aquatic ecology, habitat conservation and species management, invasive species, and toxic pollutants. There was a separate session on climate change impacts on Lake Superior. Presentation topics included developing vulnerability and adaptation strategies, specific climate change impacts on Lake Superior, and climate change education.	Organized by U.S. EPA, Lake Superior Binational Program, and Great Lakes Sea Grant Network with numerous sponsors
July 18-19, 2007 Munising, Michigan	Pictured Rocks National Lakeshore Climate Friendly Park Workshop	Public workshop to develop a Climate Friendly Parks Action Plan for Pictured Rocks National Lakeshore.	U.S. National Park Service and U.S. EPA
July 16-17, 2007 Ashland, Wisconsin	Apostle Islands National Lakeshore Climate Friendly Park Workshop	Public workshop to develop a Climate Friendly Parks Action Plan for Apostle Islands National Lakeshore.	U.S. National Park Service and U.S. EPA
March 13-September 24, 2007 Wisconsin	Climate Change in the Great Lakes Region: Starting a Public Discussion (http://seagrant.wisc.edu/climatechange/HOME/tabid/36/Default.aspx)	This seminar series explored what climate change will mean for the Great Lakes region, with a focus on Wisconsin. Experts presented the current state of knowledge on what is known, what is predicted, and what can be done to adapt to a changing climate. The presentations highlighted how climate change could affect property, water resources, fisheries, and public health in the Great Lakes basin.	University of Wisconsin Sea Grant Institute, the Wisconsin Coastal Management Program, and NOAA