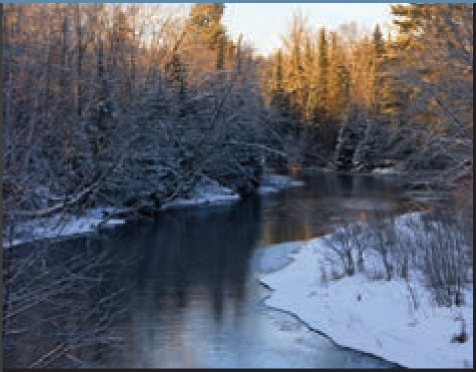
CLIMATE CHANGE IN THE MIDWEST

A Synthesis Report for the National Climate Assessment



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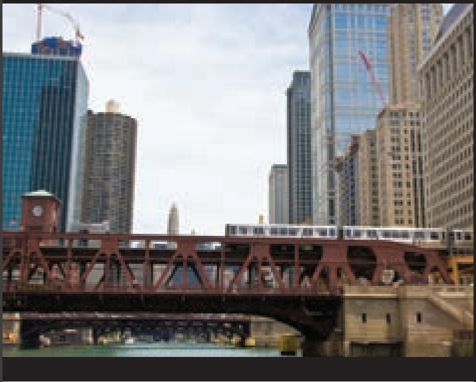

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About This Series

This report is published as one of a series of technical inputs to the Third National Climate Assessment (NCA) report. The NCA is being conducted under the auspices of the Global Change Research Act of 1990, which requires a report to the President and Congress every four years on the status of climate change science and impacts. The NCA informs the nation about already observed changes, the current status of the climate, and anticipated trends for the future. The NCA report process integrates scientific information from multiple sources and sectors to highlight key findings and significant gaps in our knowledge. Findings from the NCA provide input to federal science priorities and are used by U.S. citizens, communities and businesses as they create more sustainable and environmentally sound plans for the nation's future.

In fall of 2011, the NCA requested technical input from a broad range of experts in academia, private industry, state and local governments, non-governmental organizations, professional societies, and impacted communities, with the intent of producing a better informed and more useful report. In particular, the eight NCA regions, as well as the Coastal and the Ocean biogeographical regions, were asked to contribute technical input reports highlighting past climate trends, projected climate change, and impacts to specific sectors in their regions. Each region established its own process for developing this technical input. The lead authors for related chapters in the Third NCA report, which will include a much shorter synthesis of climate change for each region, are using these technical input reports as important source material. By publishing this series of regional technical input reports, Island Press hopes to make this rich collection of information more widely available.

This series includes the following reports:

Climate Change and Pacific Islands: Indicators and Impacts
Coastal Impacts, Adaptation, and Vulnerabilities
Great Plains Regional Technical Input Report
Climate Change in the Midwest: A Synthesis Report for the National Climate Assessment
Climate Change in the Northeast: A Sourcebook
Climate Change in the Northwest: Implications for Landscapes, Waters, and Communities
Oceans and Marine Resources in a Changing Climate
Climate of the Southeast United States: Variability, Change, Impacts, and Vulnerability
Assessment of Climate Change in the Southwest United States
Climate Change and Infrastructure, Urban Systems, and Vulnerabilities: Technical Report for the US Department of Energy in Support of the National Climate Assessment
Climate Change and Energy Supply and Use: Technical Report for the US Department of Energy in Support of the National Climate Assessment

Electronic copies of all reports can be accessed on the Climate Adaptation Knowledge Exchange (CAKE) website at *www.cakex.org/NCAreports*. Printed copies are available for sale on the Island Press website at *www.islandpress.org/NCAreports.*

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Executive Summary

The diverse landscapes of the U.S. Midwest, and the natural processes, livelihoods, and infrastructure associated with them, are vulnerable to climate change. This report, prepared as a contribution to the Third National Climate Assessment, addresses the potential impacts of climate change on natural systems, human health, and several important economic sectors within the Midwest. Key findings of the report include the following:

- Annual mean temperature in the Midwest has warmed since approximately 1900, with annual precipitation generally increasing from the mid 1930s to present. Increases in both the number of wet days and the frequency of heavy precipitation events contribute to the larger precipitation totals. Climate projections developed from global climate models (GCMs) consistently project warmer temperatures for the region by mid-to-late century. Although the majority of climate projections suggest increased precipitation during winter, there is little agreement on the sign of the projected change for other times of the year. Regardless of season, intensification of high magnitude precipitation events is anticipated.
- During the period 1948-1999, net basin supply within the Lake Superior basin declined in spring but increased in autumn, whereas regional streamflow has increased since approximately 1940. Projections of future Great Lakes water levels and streamflow that have been made over most of the last 25 years, where temperature is used as a proxy for potential evapotranspiration, suggest substantial reductions. However, recent projections that simulate evapotranspiration using an energy-based approach are inconsistent in terms of the sign (positive or negative) of future streamflow and lake level changes.
- Changes in Great Lakes water levels, regardless of the sign of the projected change, will have a large impact on hydrogeomorphologic features such as beaches and dunes, and will create vulnerabilities for coastal ecosystems, infrastructure, and communities. Lake level fluctuations may disrupt Great Lakes commercial shipping and result in increased channel maintenance costs at Great Lakes ports.
- Great Lakes surface water temperatures have increased over the past few decades. Continued warming will impact the timing and extent of thermal stratification, winter ice cover, and the availability of dissolved oxygen
- The region's ecosystems are highly vulnerable to the direct impacts of climate change and to climate-related exacerbation of current stressors such as invasive species, pollution, and pests and pathogens. The capacity of many species to adapt is limited by historical and on-going land conversion and fragmentation of habitats. An acceleration in the rate of species declines and extirpations is anticipated, as adjustments to temperature change would necessitate rapid and perhaps unrealistic movement of plant and animal species if they are to maintain pace with expected shifts in habitat ranges.

- Traditional and modern cultural connections to forest systems likely will be altered by climate change. Changes in the presence and availability of culturally-important species, such as white cedar and paper birch, are anticipated. Additionally, changes in contemporary and iconic forms of forest-based recreation can be expected. Forest ecosystems also may be less likely to provide a consistent supply of some forest products, especially if the dominant species in those ecosystems are at the southern edges of their ranges.
- Changes in the variability, timing and amount of growing season precipitation will have a substantial impact on future crop yields and the number of workable field days, and an increased likelihood of extreme heat events will impact Midwestern meat, milk, and egg production. Perennial crops may be at a greater risk of freeze damage, as flower buds lose hardiness and become sensitive to damaging cold temperatures earlier in spring.
- Flooding along the region's major rivers, including the Mississippi River, has serious consequences for riverine communities and on transportation. The risk of levee failure during a major riverine flood is a significant regional hazard, as many of the nearly 4,000 linear miles of levees in the region are in poor condition.
- Winter sports, especially those activities that depend on natural snow and ice (e.g., cross country skiing, ice fishing, snowmobiling), will likely be negatively impacted by climate change. Warmer springs and falls will increase the attractiveness of the Midwest for activities such as camping, boating, and golf.
- The region has a number of climate-sensitive diseases or health conditions, and, on balance, adverse health ramifications are anticipated to outweigh beneficial health outcomes. Greater frequency of heat waves, decreased air quality, and greater risk of waterborne disease, especially given the aging municipal water systems in the region, are of concern.
- National and state climate change policies, such as the Clear Air Act, have had a large influence on planning and investment decisions within the region's energy sector, and continued impacts of these policies on the provision and cost of energy services are anticipated.

The challenge for the Midwest will be to design and implement creative and effective adaptation strategies to reduce the region's vulnerability to climate change, while capitalizing on potential co-benefits of mitigation policies.

Chapter 1

An Introduction to the Synthesis Report

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1.1 About this Report

The Global Change Research Act of 1990 mandates that national assessments of climate change be prepared for the U.S. at regular intervals. The Third National Climate Assessment (NCA) was initiated in 2011, with the National Climate Assessment Development and Advisory Committee (NCADAC), a federal advisory committee, charged with developing the NCA report. The Third NCA report is organized by sectors and by regions.

Technical input teams were established to help support the development of the Third NCA report. Each team prepared an in-depth technical compilation of literature relevant to a particular sector or region.

This report represents the efforts of the Midwest Technical Input Team (MTIT), and summarizes and highlights the key vulnerabilities and potential impacts of climate change on critical sectors and processes within the U.S. Midwest. The MTIT was coordinated by the NOAA-funded Great Lakes Integrated Sciences and Assessments (GLISA) Center and the USDA Agricultural Research Service (USDA-ARS). The initial technical report, submitted to the NCA on 1 March 2012, consisted of a series of whitepapers commissioned from experts within the Midwest. The whitepaper authors were given considerable flexibility in the organization of their whitepapers, in recognition of the diversity of concerns and the availability of relevant literature for the different sectors. Authors were also given considerable latitude in the degree and manner in which they provided confidence characterizations of potential future changes. Following this initial submission, the whitepapers were externally reviewed with at least two ad hoc reviews obtained for each whitepaper. In addition, the Environmental Protection Agency (EPA) Region 5 Office provided an agency review of the whitepapers most relevant to their mission. Whitepaper authors responded to the comments of both the ad hoc and agency reviewers, and the revised manuscripts were further reviewed by an editorial board.

Below we provide a brief regional context for the chapters that follow, and describe the organization of the synthesis report. This report will hopefully serve as a useful resource for Midwestern stakeholders and decision-makers.

1.2 A Regional Context

The U.S. Midwest, as defined for the U.S. National Climate Assessment, includes the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin. Climate change is anticipated to have a profound influence on the physical, biological and human systems within this unique and diverse region.

The Midwest spans several steep natural gradients. Geological features transition from ancient, crystalline rocks overlain by glacial sediments in the north to a series of sedimentary rock strata covered by deep unconsolidated deposits across the central Midwest to igneous/volcanic rock deposits within the Ozark Plateau in southern Missouri (Vigil et al. 2000). Changes in elevation are relatively minor, ranging from less than 500 feet (152 meters) above sea level along the Ohio River Valley to more than 1300 feet (396 meters) in the Superior Uplands of northern Minnesota, Wisconsin, and Michigan and across sections of the Ozark Plateau in Missouri and the Appalachian Plateau in eastern Ohio. Soil types range from loess-dominated soils across most western and central sections of the region to alluvial soils near the major rivers to coarse-textured, highly heterogeneous soils in northeastern sections resulting from repeated glaciations to relatively old, highly-weathered soils in the southeast (Ruhe 1984).

Temperature decreases substantially from south-to-north, with annual mean air temperatures >55°F (13°C) in southern Missouri and Illinois and <40°F (4°C) in northern Minnesota (Kunkel et al. 2013). Because of its continental location, temperatures in the Midwest display high seasonality with warm summers and cold winters. Annual precipitation generally increases from west-to-east in Minnesota and Iowa and from north-to-south elsewhere in the region (Pryor and Takle 2009). The primary moisture source is the Gulf of Mexico, and the majority of the precipitation occurs in the warm season. The Laurentian Great Lakes of North America have a substantial influence on the weather and climate in the northeastern sections of the Midwest, with cloudier, wetter, and more moderate climate in areas downwind of the lakes than in areas upwind or away from the lakes (Scott and Huff 1996).

Native vegetation varies greatly across the region, ranging from boreal forest in far northern sections to grassland across the central and western sections to hardwood forest in the south and east to savanna and open woodlands in between (Baily 1995). The Midwest has experienced large reductions in natural land cover from pre-European settlement to the present, and much of the savanna, open woodlands, and wetland areas have been converted to agricultural use.

A substantial portion of the Great Lakes basin falls within the Midwest. The Great Lakes are the largest supply of fresh water in the world with more than 20% of the global total (Quinn 1988). Plants and animals inhabiting the Great Lakes system range from coastal and wetland species to open water plankton and pelagic fishes of sport and commercial importance (Lehman et al. 2000). The Great Lakes have a coastline and a coastal population on the same order of magnitude as many ocean coasts (Gronewold et al. 2013). Fluctuations in Great Lakes water levels have a large impact on hydrogeomorphic features (e.g., beaches and dunes), nearshore ecosystems, and coastal communities. The headwaters of the Mississippi River, the largest drainage basin in North America, lie within the Midwest. The Mississippi and its major tributaries, such as the Ohio River, have historically served as major transportation avenues. The banks of many of these rivers are now lined with levees, protecting homes, farms, factories and commercial establishments.

Although the majority of Midwest residents reside in urban areas, a larger proportion of the population lives in rural areas compared to that of the U.S. as a whole (U.S. Department of Transportation 2011; Pryor and Barthelmie 2013). Major urban centers include Chicago, Cincinnati, Cleveland, Detroit, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis. Over 5 million acres of tribal lands are also found in the Midwest, primarily in the states of Michigan, Minnesota, Missouri, and Wisconsin (U.S. Department of Interior 2014).

The Midwest region relies heavily on coal for generating electricity, although between-state differences in energy sources are evident. Petroleum and/or natural gas are as large, or larger sources of energy consumption in Minnesota, Wisconsin, Illinois, and Michigan (Pryor and Barthelmie 2013, their Figure 2.2). About one quarter of the nation's nuclear power plants are found in the Midwest (U.S. Nuclear Regulatory Commission 2014). Renewable energy comprises a modest, although significant, portion of energy usage within the region. Several Midwestern states (Iowa, Illinois, Minnesota and Indiana) are among the top ten wind energy producers in the U.S. (Pryor and Barthelmie 2013).

The two primary revenue sources for the Midwest are manufacturing and agriculture, with financial services, medicine, education, and tourism also contributing substantially to the regional economy. The abundance of iron ore in northern Minnesota and Michigan, the region's proximity to the Appalachian coal mines and other sources of energy, and access to transportation including the Great Lakes waterways contributed to the development in the late 1800s and early 1900s of manufacturing within the Midwest, particularly surrounding the Great Lakes (Sousounis and Albercook 2000). The introduction by Henry Ford of the assembly line into Detroit's nascent automobile industry further revolutionized industrial production (Gross 1996), and the Midwest remains the focus of the U.S. automobile industry. Five of the top ten states in terms of manufacturing share of total earnings fall within the Midwest. For these states (Indiana, Wisconsin, Michigan, Iowa and Ohio), manufacturing accounted for over 15 percent of 2010 total earnings compared to 10 percent nationally (U.S. Department of Commerce 2013).

Agriculture also contributes heavily to the region's economy, and the Midwest represents one of the most intense areas of agriculture in the world. Corn (maize) and soybeans are the two primary crops produced in terms of revenue and acreage (U.S. Department of Agriculture 2007), and the Midwest is often colloquially referred to as the "Corn Belt" (Hart 1986). This nomenclature, however, masks the diversity of Midwestern agriculture, which also includes the production of livestock (including dairy), vegetables, fruits, tree nuts, berries, and nursery and greenhouse plants. Agriculture is also the major land use within the Midwest (Niyogi and Mishra 2013). Most of the cropland in the Midwest is non-irrigated, although the number of irrigated acres has been steadily increasing (Schaible and Aillery 2012).

Tourism tax receipts range from approximately $6 billion in Iowa and Missouri to over $27 billion in Illinois (U.S. Travel Association 2012). Recreational activities within the region are diverse. There are 10 National Forests, 3 National Parks, 4 National Lakeshores, 64 National Wildlife Refuges, and hundreds of state and county parks within the Midwest that attract visitors interested in hunting, fishing, camping, wildlife watching, and exploring trails. Winter recreation is also popular with numerous ski resorts in the region and cross-country and snowmobiling trails (Shih et al. 2009). The Great Lakes are one of the nation's prime sport fisheries (American Sportfishing Association 2013). Golfing is also popular in the Midwest, and the region is host to a number of national golf tournaments (Stynes et al. 2000).

These and the many other systems and activities in the Midwest are sensitive to climate variations and change. The chapters that follow highlight past and projected future climate change and summarize potential vulnerabilities and impacts for several important sectors within the region, namely agriculture, ecosystems and biodiversity, forestry, coastal systems, energy, human health, outdoor recreation and tourism, transportation, and water resources.

1.3 Organization

The organization of this synthesis report is as follows:

Chapter 2, "Historical Climate and Climate Trends in the Midwest", provides a detailed description of historical climate fluctuations for the region. This chapter expands on

NOAA Technical Report NESDIS 142-3 (Kunkel et al. 2013), a summary document on regional trends and projections provided to NCA authors.

Chapter 3, “Climate Projections for the Midwest: Availability, Interpretation, and Synthesis”, describes approaches employed to develop local and regional climate projections and reviews their strengths and weaknesses. This chapter also places the climate projections included in NOAA Technical Report NESDIS 142-3 within the context of the numerous other climate projections available for the Midwest.

Chapter 4, “Agriculture in the Midwest”, surveys the impacts of historical climate fluctuations on crop and livestock production and summarizes the large literature on potential future impacts and adaptation options.

Chapter 5, “Impacts on Biodiversity and Ecosystems”, focuses on the sensitivities of species, ecosystems, and natural processes to climate fluctuations, and the possible constraints to adaptation. The chapter concludes with proposed strategies to assist species and systems adapt to climate change.

Chapter 6, “Climate Change Vulnerabilities with the Forestry Sector of the Midwestern United States” describes key vulnerabilities to the forestry sector, including confidence statements to represent the authors’ assessment of the likelihood of these vulnerabilities. The chapter also includes a brief discussion of adaptation options for each of the identified vulnerabilities.

Chapter 7, “Great Lakes Nearshore and Coastal Systems”, reviews relevant literature on the potential impacts of climate change on the physical integrity of Great Lakes nearshore and coastal systems and associated environmental and economic implications.

Chapter 8, “Climate Change and Energy”, highlights the current and potential future impact of climate change policy, in addition to climate change itself, on the supply-side (production) and the demand-side (consumption) of the Midwestern energy sector.

Chapter 9, “Health”, identifies potential human health risks in the Midwest stemming from climate change, with particular focus on urban heat waves, air pollution, water quality and waterborne diseases, and vectorborne diseases.

Chapter 10, “Outdoor Recreation and Tourism”, summarizes the importance of the travel and tourism industry to the Midwest economy and addresses its vulnerability to climate change. Potential adaptation strategies are also discussed.

Chapter 11, “Climate Change Impacts on Transportation in the Midwest,” assesses the potential impacts of climate change on regional transportation systems, including air, water, rail and surface transportation. Ongoing adaptation efforts are also highlighted.

Chapter 12, "Water Resources" places regional water resources within the context of historical climate trends and future climate projections. This chapter also explores the uncertainty surrounding future Great Lakes water levels.

"Focus: Midwest Levees" is a shorter contribution on a topic of particular concern in the Midwest. The Midwest has nearly 4,000 linear miles of levees, many of which are in poor condition. The risk of levee failure during a major riverine flood is a significant regional hazard.

Chapter 13, "Complexity and Uncertainty: Implications for Climate Change Assessments", draws on the earlier chapters and related literature to encourage assessment teams and stakeholders to consider complexity and uncertainty as integral to robust decision making related to climate change.

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Chapter 2

Historical Climate and Climate Trends in the Midwestern United States

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2.1 Introduction

The Midwestern U.S., defined here as the region stretching from Minnesota, Iowa, and Missouri eastward to Michigan and Ohio, ranks among the most important agricultural production areas of the world and contains a significant portion of the Great Lakes Basin, the largest supply of fresh water in the world with more than 20% of the global total (Quinn 1988). The current climate of the Midwest region is chiefly governed by latitude, continental location, large scale circulation patterns, and in northeastern sections by the presence of the Great Lakes. Day-to-day and week-to-week weather patterns are generally controlled by the position and configuration of the polar jet stream in the winter and transition seasons, with somewhat less influence in the summer, when the region is also influenced by frequent incursions of warm, humid air masses of tropical origin (Andresen and Winkler 2009).

The type and frequency of air masses moving through the westerlies is strongly dependent on the location of longwaves and the configuration of the jet stream across the Northern Hemisphere and the North American continent. Climate in the Midwest is a direct reflection of four primary airmass types from three different source regions: 1) northwestern Canada (continental polar), 2) Gulf of Mexico/southern U.S. (maritime tropical), 3) Hudson Bay/northeastern Canada (continental polar), and 4) northern Rockies/Pacific Northwest (maritime polar) (Shadbolt et al. 2006). Less frequently, airflow originates from the East Coast and western Atlantic and on occasion from the southwestern U.S. and northern Mexico. The relative importance of the different airflow source regions varies with season.

Migratory midlatitude extratropical cyclones are an important component of the regional climate, responsible for a significant portion of annual precipitation (Heideman and Fritsch 1988). Cyclogenesis is driven by upper-atmospheric circulation, and cyclone tracks are dictated by the amplification and propagation of Rossby waves in the midlatitudes. There are several principal areas of cyclogenesis in North America. Of particular importance for the Midwest are the Alberta and Colorado cyclogenesis regions, both of which are located on the leeward (downwind) side of the Rocky Mountains (Whittaker and Horn 1981). The Midwest also experiences a number of cyclones that form along the western Gulf Coast (Trewartha and Horn 1980), while approximately 20% of cyclones form within the region itself (Isard et al. 2000). Tropical cyclones, with origins in tropical and subtropical oceans, occasionally move into the region during the late summer and fall months following landfall in the southern or eastern U.S. and may bring widespread rainfall. Fortunately, wind or other related damage from these storms in the region is rare.

There are some existing statistical links between upper tropospheric flow and seasonal weather patterns across the region with global atmospheric teleconnection indices, but in general they are not as strong as in other regions of the U.S. (Hansen et al. 2001). For the El Niño/Southern Oscillation (ENSO), there is a tendency for an enhanced subtropical jet stream during negative phase (El Niño) winters across the southern U.S., while the main polar branch of the jet stream retreats to a more northward than normal position across central Canada. As a result, the Midwest tends to experience weaker winds aloft, fewer storms and milder than average temperatures (Climate Prediction Center 2005). During positive phase (La Niña) events, jet stream flow tends to be relatively meridional across North America, with either much above or below normal temperatures and wetter than normal weather across southeastern sections of the Midwest. Statistical links with ENSO in other seasons (especially the transitional fall and spring seasons) are relatively weak or non-existent, although a tendency for wetter and cooler (drier and warmer) than normal weather has been observed over at least portions of the region during the summer months during negative (positive) phase events (Carlson et al. 1996). Recent studies suggest that the ENSO-related impacts in the Midwest may be modified on interdecadal time scales (approximately 21 year time periods) by the Pacific Decadal Oscillation (Birka et al. 2010). There are also established links with Midwestern weather patterns and the North Atlantic Oscillation (NAO). A positive NAO phase represents a deeper than normal low pressure system over Iceland and a stronger high pressure system near the Azores, whereas these systems are weaker than normal during a negative NAO phase (Rogers et al. 2004). Portions of the Midwest, especially eastern sections, tend to have above average temperatures (Climate Prediction Center 2005) and above normal precipitation totals during winter and spring seasons with positive NAO phase (Kingston et al. 2006), although the link is not particularly strong (Rodionov 1994; Hurrell 1995). Leathers et al. (1991) demonstrated a link to temperature and precipitation in the U.S. to the Pacific North America pattern (PNA), mostly in the winter and nearby months. In the Midwest, both variables are generally negatively correlated with the PNA, which can be further related to changes in sea surface temperature in sections of the equatorial Pacific region. In a study of wintertime precipitation, Rodionov (1994) found negative correlation between the phase of PNA and precipitation totals. During the positive phase of PNA (with upper air ridging across western North America and troughing across the east), cyclonic activity across the region tends to be of northern origin and contains relatively less precipitation. During the negative phase, there is a greater frequency of cyclones of southern plains origin which tend to contain more Gulf of Mexico-origin moisture, resulting in greater precipitation totals across the Midwest (Isard et al. 2000). Rodionov (1994) also found that the position of the upper atmospheric trough across the eastern U.S. to be important, with a greater frequency of Colorado (central Rockies)-origin cyclones being associated with a more westerly position and a decrease with an easterly position (and a corresponding increase in Alberta (northern Rockies)-origin cyclones).

Finally, it is also important to consider the influence of smaller scale systems on the region's climate. Mesoscale convective weather systems in the form of clusters of showers and thunderstorms account for approximately 30% to 70% of the warm-season (April-September) precipitation over the Midwest region, with an even greater percentage during the June through August period (Fritsch et al. 1986). More recent studies have further identified links between precipitation spatial patterns and major land use boundaries in the region, with enhanced warm season convection along and near boundaries between agriculture- and forest-covered landscapes (e.g., Carleton et al. 2008).

2.2 Influences of the Great Lakes

The proximity of the Great Lakes has a profound influence on the weather and climate of northeastern sections of the region (Scott and Huff 1996). Overall, so-called "lake effect" influences result in a cloudier, wetter, and more moderate climate in areas downwind of the lakes (e.g. Michigan, Ohio) than in areas upwind or away from the lakes. These influences are related to three major physical changes associated with air flowing across the surface of the lakes and onto nearby land surfaces: changes in friction/surface drag, changes in heat content, and changes in moisture content (Changnon and Jones 1972). It is important to note that these modifications typically act in combination.

Arguably, the spatially most widespread lake effect-associated impact is a change in the amount and frequency of cloudiness, which in turn directly impacts insolation rates and air temperatures. In areas directly downwind of the lakes, given climatological source regions of relatively cold continental polar or arctic polar air masses in the interior sections of northern North America and the Arctic, a majority of lake-related cloudiness is associated with northwesterly wind flow across the region during the fall and winter seasons. Enhanced cloudiness results in mean daily insolation rates that are less than 75% of rates in areas upwind of the lakes at the same latitude, ranking the region statistically among the cloudiest areas of the country (Andresen and Winkler 2009). During the late spring and summer seasons when lake water temperatures are relatively cooler than air and adjacent land surfaces, the impact on cloudiness is symmetrically opposite, as the cooler water leads to relatively greater atmospheric stability, general low-level sinking motion, and to fewer clouds over and immediately downwind of the lakes.

Other modifications include moderated air temperatures, with a general reduction in temperatures in downwind areas during the spring and summer seasons and an increase during the fall and winter seasons. Combined with the enhanced cloudiness, daily and annual temperature ranges are also reduced. Changnon and Jones (1972) estimated that mean winter maximum and minimum temperatures in areas just east of the lakes are 6% and 15%, respectively, warmer than locations upwind of the lakes, while mean summer maximum and minimum temperatures on the downwind side are 3% and 2% lower than those upwind, respectively. Climatological extreme minimum temperatures in areas within 30 miles of the shores of the Great Lakes are as much as 20°F warmer than those at inland locations at the same latitude across the state. The impact is somewhat less in the summer season, with extreme maximum temperatures in coastal areas as much as 14°F cooler than those at inland locations across the state (Eichenlaub et al. 1990).

Given enough atmospheric lift and moisture, lake effect clouds may also produce precipitation. Altered precipitation patterns are among the most significant lake influences on regional climate. So-called lake effect snowfall greatly enhances the seasonal snowfall totals of areas generally within 150 miles of the downwind shores of the lakes (Norton and Bolsenga 1993). For example, Braham and Dungey (1984) estimated that 25-50% of the yearly snowfall totals on the eastern shores of Lake Michigan could be attributed to lake effect snowfall.

2.3 General Description

As noted earlier, Midwestern climate conditions are largely determined by the region's location in the center of the North American continent. The generic modified Koeppen classifications for the region range from Mesothermal humid subtropical (Cwa) across far southern sections of the region to Microthermal humid continental hot summer (Dfa) across central sections to Microthermal humid continental mild summer (Dfb) across northern sections. Average annual temperature varies by about 20°F across the region (Figure 2.1) from less than 38°F in northern Minnesota to more than 60°F in the Missouri Bootheel. Seasonally, the greatest range in temperature across the region occurs during winter (December–February) with the least during the summer months (June-August). Mean temperatures across the region typically peak in late July or early August and reach minima during late January or early February. Coldest overall temperatures tend to be observed in northern interior sections away from the lakes (Figure 2.2). Base 50°F seasonal growing degree day totals, a temperature-derived index of time spent above the 50 degree threshold, range from around 2000 in far northern Michigan and northeastern Minnesota to over 4000 in southern Missouri and Illinois.

Average annual precipitation increases from northwest to southeast across the region (Figure 2.3) ranging from about 20 inches in northwest Minnesota to 47 inches in southern Missouri and along the Ohio River. Precipitation occurs in all months and

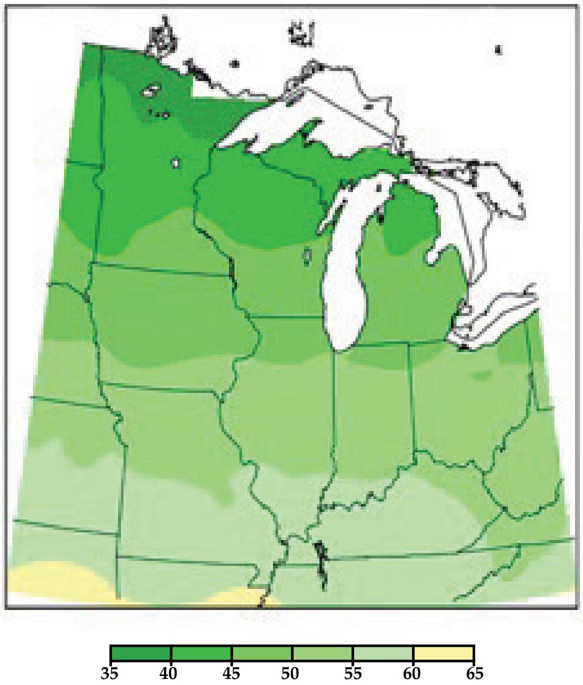


Figure 2.1. Average annual temperature (°F), 1981-2010. *Source*: Midwestern Regional Climate Center.

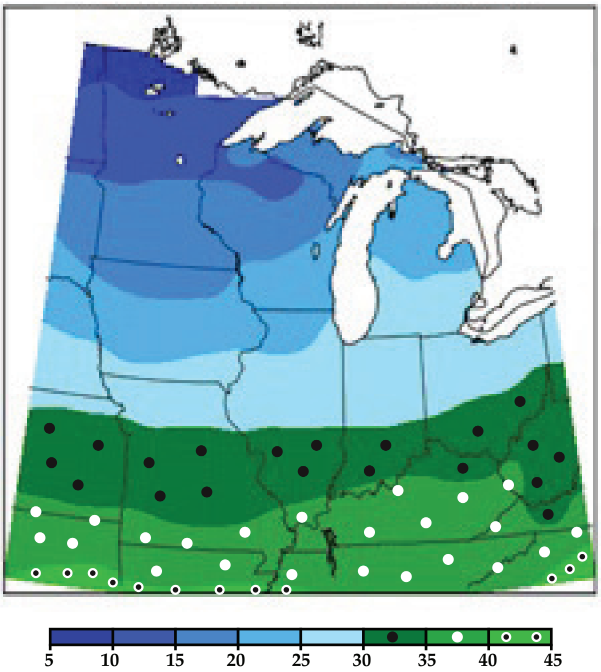


Figure 2.2. Average winter (December-February) temperature (°F), 1981-2010. *Source*: Kunkel et al. (2013).

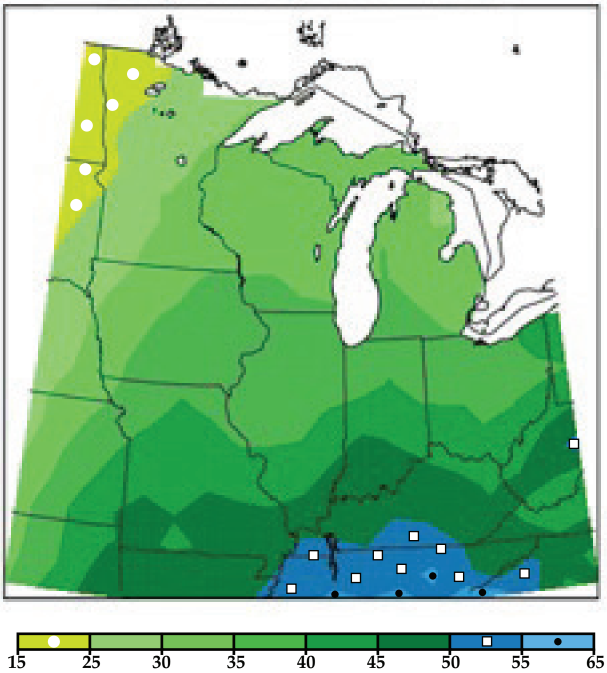


Figure 2.3. Average annual precipitation (inches), 1981-2010. *Source*: Midwestern Regional Climate Center.

seasons, but is generally greatest during the warm season and least during the winter months. The degree of seasonality increases from east to west across the region. Average summer rainfall exceeds 12 inches across most western sections, accounting for almost 50% of the annual total (Figure 2.4). Snowfall in the Midwest region is generally associated with either large, synoptic-scale weather disturbances or with the lake effect phenomenon, which may lead to highly varying snowfall totals over only short distances. Average annual snowfall varies from less than 10 inches in the far south to more than 200 inches in Michigan's Upper Peninsula, where seasonal snowfall totals and seasonal duration of snow cover are climatologically among the greatest of any location in the U.S. east of the Rocky Mountains.

2.4 Vulnerabilities

Weather and climate have major influences on human and natural systems in the Midwest, although the overall impacts are relatively less than in other sections of the U.S. (Cutter and Finch 2008). Primary economic activities in the region include agriculture, manufacturing, financial services, medicine, education, and tourism. A summary of weather and climate-related vulnerabilities follows. Portions of this section are drawn from Kunkel et al. (2013), and readers are referred to the original article for more information.

Agriculture is a major component of the Midwestern economy, with over $200B in farm gate value (NASS 2012a). The region is responsible for a significant portion of total global corn and soybean production. The Midwest is also a major producer of fruits, vegetables, dairy and beef cattle, and pigs. Weather and climate remain among

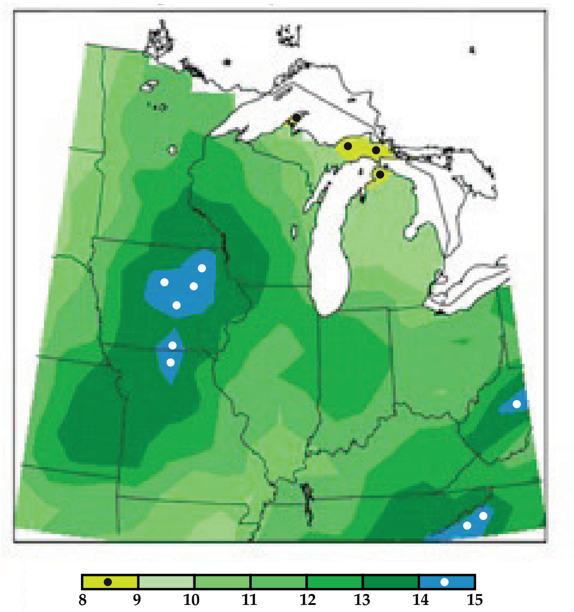


Figure 2.4. Average summer (June-August) precipitation (inches), 1981-2010. *Source*: Midwestern Regional Climate Center.

the most important uncontrollable variables involved in the region's agricultural production systems. Frequency and amount of rainfall, heat stress, pests, ozone levels, and extreme events such as heavy precipitation, flooding, drought, late spring or early fall freezes, and severe thunderstorms (high winds, hail) can seriously affect yields and/or commodity quality levels. The risks of significant losses from such events are often higher for smaller producers and for specialty crops.

The major urban centers in the region, which include Chicago, Cincinnati, Cleveland, Detroit, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis, are more sensitive to some weather and climate events due to the specific characteristics of the urban environment such as building density, land use, urban sprawl, and proximity to the Great Lakes. Extreme air and dew point temperatures can have large impacts on human health, particularly in the urban core where the urban heat island effect elevates summer afternoon temperatures and slows cooling at night. Severe storms, both winter and summer, result in major disruptions to surface and air transportation that often have impacts well beyond the region. During the winter, cities such as Chicago, Milwaukee, and Cleveland are susceptible to lake-enhanced snowfall during winter storms. Extreme rainfall causes a host of problems, including storm sewer overflow, flooding of homes and roadways, and contamination of municipal water supplies. Climate extremes combined with the urban pollution sources can create air quality conditions that are detrimental to human health.

The region serves as the nation's center for air and surface transportation; weather and climate extremes influence each form—commercial airlines, barges, trains, and trucks. Severe weather, including floods and winter storms, either stops or slows various forms of transportation for days and sometimes weeks. The Mississippi River, Ohio

River, and the Great Lakes are used intensively for barge and ship transport; high and low water levels and ice cover, all determined largely by climate conditions, affect barge and ship traffic.

Human health and safety are affected by climate conditions. Temperature extremes and storms have impacts on human health and safety, including loss of lives. Tornadoes, lightning, winter storms, and floods combined annually lead to many fatalities. Over the recent 15 year interval (1996-2010), approximately 104 weather-related deaths occurred per year across the eight Midwestern states while approximately 823 injuries occurred (National Weather Service 2014). The occurrence of vector-borne diseases is modulated by climate conditions.

With several large urban areas, as well as miles of shorelines along the Great Lakes and other lakes, tourism is a large business sector in the Midwest. Climate conditions can greatly affect the number of tourists that decide to travel to and within the Midwest. Temperature extremes and precipitation fluctuations in the spring and summer affect lake levels for fishing and other water activities, golf course maintenance, and state park visits, as well as attendance at sporting events and historical sites. In the winter, recreational activities such as skiing and snowmobiling are very susceptible to interannual fluctuations of snowfall and temperature across the region. Specific major climate vulnerabilities are summarized below.

2.4.1 REGIONAL FLOODS

Flooding is a major and important economic risk along Midwestern rivers. Some of the most costly flooding events in U.S. history have occurred along the Mississippi (1927, 1965, 1993) and the Ohio (1913, 1937, 1997) Rivers. The largest of these, the 1993 Mississippi River flood, is the second costliest flood in modern times (after Hurricane Katrina in 2005), with most of the losses occurring in the Midwest (Parrett et al. 1993). In a study across the central states of the U.S., Changnon et al. (2001) ranked Iowa first, Missouri fourth, and Illinois sixth in state losses due to flooding during the 1955-1997 period. In addition to agricultural losses and direct damage to homes and infrastructure, floods can cause regional and national disruptions to transportation. In the 1993 flood, bridges, railroads, and river transportation were all shut down for periods of weeks to months. A more recent flood event in eastern Iowa in 2008 led to massive flooding in Cedar Rapids, Iowa, when the levels on the Cedar River exceeded the previous record by more than 11 feet and led to total damages on the order of $10B (Temimi et al. 2011). In response, the city created an award-winning redevelopment plan that will help mitigate against the impacts of floods in the future (City of Cedar Rapids 2014).

Flooding along the Ohio River Valley during the winter season has been linked to upper tropospheric teleconnection patterns. La Nina (cool or negative phase) conditions in the Pacific have been shown to be significantly associated with wetter winter conditions and El Nino (warm or positive phase) with drier winters (Coleman and Rogers 2003). The Pacific-North American (PNA) teleconnection index is even more strongly linked to the Ohio River Valley winter moisture with zonal (meridional) flow being related to wet (dry) conditions. PNA mode was strongly zonal during the period leading up to the 1997 Ohio River flood as well as during the 1937 flooding event.

While many flooding events are due to persistent patterns of heavy rainfall like the ones above, another type of flooding occurs in the spring due to melting snowpacks. In the spring of 1997, record floods occurred along the Red River of the North and the Mississippi River in Minnesota and Iowa due to snowfall totals exceeding the average by 150 to 250 percent (Kunkel 2003).

2.4.2 SEVERE THUNDERSTORMS

Severe thunderstorms can be accompanied by tornadoes, hail, lightning, and strong straight-line winds, causing property and crop damage and human injuries and death. Non-tornadic thunderstorms are the most frequently-occurring weather catastrophe type (as defined by the insurance industry) based on insurance losses in this region (Changnon 2010). The mean annual numbers of severe thunderstorms generally decrease from southwest to northeast across the region, with southwestern portions included in the nation's 'Tornado Alley' region of greatest severe weather frequency. Four states in the Midwest region, Missouri, Illinois, Iowa, and Indiana, ranked among the top 10 states with greatest frequency of hail catastrophes ($1M or greater damage) during the period 1949-2006, with relative rankings of 5th, 7th, 8th, and 9th, respectively (Changnon 2008). Severe thunderstorm frequency varies by season across the region, with greatest frequency during late spring and early summer over southern sections and during mid-summer months across the far north. Most violent severe weather tends to occur during the spring.

2.4.3 SUMMER DROUGHT, HEAT, AND EXCESS RAIN

Since most agriculture in this region is rainfed, the Midwest is highly vulnerable to summer drought. As the nation's "breadbasket" and a major international food production area, droughts can have substantial economic ramifications both nationally and internationally. Large scale regional droughts were relatively common in the Midwest during the period of 1895 to 1965, but, since 1965, only the summer droughts of 1988 and 2012 have had severe impacts across the entire region. Due to the potentially large areas impacted, regional droughts may contribute to large increases in world-wide commodity and food prices.

During the summer, convective events can produce excessive rain over localized areas. These events can produce flooding along small rivers and streams as well as in urban areas where drainage is not adequate. Despite typically being short-lived, these flash flooding events can leave behind much damage. Climatologically, the fraction of annual precipitation associated with the 10 largest events of the year increases from less than 0.3 across eastern Ohio to more than 0.5 across western sections of Minnesota, Iowa, and Missouri (Pryor et al. 2009a).

2.4.4 HEAT WAVES

Major widespread heat waves occurred in the region during 1934, 1936, 1954, 1980, 1995, 1999, 2011, and 2012 (Westcott 2011). The 1995 heat wave, which lasted only four days, resulted in over 700 fatalities in Chicago, the most deadly U.S. heat wave in decades.

Maximum daily temperatures were equal to or greater than 90°F for seven consecutive days, and greater than 100°F for two days at the peak of the heat wave. Just as importantly, there was no relief at night as nighttime minimum temperatures remained above 80°F in many cases. Heat waves also cause major power outages and disrupt a number of economic activities. Climatologically, the number of days with temperatures reaching 90°F or greater in the nine largest urban areas of the region (Chicago, Cincinnati, Cleveland, Detroit, Des Moines, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis) average from 7 (Milwaukee) up to 36 (St. Louis) days each year, while the number of days over 100°F range from one1 every 2 years up to an average of 2 per year (MRCC, 2012). The factors that determine the region's climate favor occasional episodes of intense heat that are frequently accompanied by very high humidity. The heat index combines temperature and humidity to estimate how hot humans feel. Currently, southern Midwest states experience between 6 (Indiana and Iowa) and 18 (Missouri) days per year with a heat index over 95°F while northern states and states that border the Great Lakes such as Michigan and Ohio experience less than 3 days per year. Bentley and Stallins (2008) identified three predominant synoptic features associated with extreme dew point (and heat wave) events across the Midwest: 1) the development and propagation of low pressure from the high plains through the upper Great Lakes with the surface advection of low-level moisture from eastern Nebraska, Iowa, and Missouri eastward into Illinois and Indiana; 2) healthy agricultural crops and sufficient soil moisture content throughout the region; and 3) restricted low-level mixing in the boundary layer allowing near-surface moisture to become trapped. The episodic nature of these events contributes to vulnerability because the population does not become acclimated to the intense conditions as is the case in warmer regions of the country (Anderson and Bell 2011). There is evidence that adoption of simple community adaptive responses can mitigate the impacts of heat waves (Palecki et al. 2001) and that the adverse impacts of heatwaves across the region have declined in recent decades due to improved health care, increased access to air conditioning, and infrastructural adaptations (Davis et al. 2002). In response to the 1995 heat wave, the City of Chicago put together an extreme weather operations plan that included mitigation steps for the city to take during heat waves. These were implemented during a 1999 heat wave that was nearly as hot as the 1995 event, but fatalities were far less numerous. The city has also put together an ambitious Climate Action Plan that outlines both adaptation and mitigation strategies. One strategy is an aggressive "green roof" campaign, which has resulted in the installation of seven million square feet of green roofing. Green roof tops have been shown to reduce temperatures in urban areas by as much as 5.5°F, but concerns exist that they also increase surface dew point temperatures, which lead to smaller decreases in the apparent temperature (Smith and Roebber 2011).

2.4.5 WINTER STORMS

Major blizzards, snow storms, and ice storms create many problems for surface and air transportation. These in turn create numerous other impacts on the full spectrum of economic activities. Winter storms are the second-most frequent weather-related catastrophe in the region. The average annual incidence of snowstorms of 6 inches or greater snowfall in a 1-2 day period across the Midwest ranges from less than 0.5 per year along the Ohio River, to 1.0 per year across most central sections of the region, to 1.5 or more per year in northwestern Minnesota, and to more than 6 per year along the lee sides of Lakes Superior and Michigan (Changnon et al. 2006). Major snowstorms are numerically most common in December in the lake effect snowbelt regions and during January and February elsewhere across the region.

2.5. Regional Climate Trends

2.5.1 PALEOCLIMATE

Ideally, the search for climatological patterns and trends requires consistent, unbiased data from as many long term sources as possible, as the magnitude of such trends may be far less than changes experienced on an annual, daily, or even hourly basis. In general, the amount and quality of data available for climatological analysis in the Midwest region decreases quickly with time into the past. Routine instrumental observations began during the middle 19th century across much of the region, but the number and quality of those data as well as gradual changes in instrument technology complicate their use in such analyses.

There are a number of paleoclimatic records in the region based on fossil, sediment cores, tree rings, and other such evidence which illustrate large shifts in climate over geologic time scales, ranging from humid tropical conditions during the Carboniferous and Devonian eras 400-300 million Years Before Present (YPB) to frigid, glacial conditions as recently as 12,000 YBP during the end of the Pleistocene era. These major shifts are thought to be the result many factors, including tectonic drift of the continents, changes in the composition of the earth's atmosphere, periodic changes in the earth's tilt and orbit around the sun (Milankovitch cycles), and catastrophic singular events such as the impact of large meteorites and major volcanic eruptions.

More substantial paleoclimatological evidence of regional changes in climate is available since the end of the last major glacial epoch about 12,000 YBP. During early portions of the Holocene era approximately 10,000 YBP, climate in the region warmed rapidly following the end of the last major glacial epoch, resulting in a relatively mild and dry climate (versus current and recent past conditions) which lasted until about 5,000 YBP. During this period, the levels of the Great Lakes fell until the lakes became terminal or confined about 7,900 YBP (Croley and Lewis 2006), and vegetation in the region gradually transitioned from a dominance of boreal to xeric species (Webb et al. 1993). Beginning about 5,000 YBP, climate cooled and precipitation totals increased, possibly associated with a change in jet stream patterns across North America from mostly west-east or zonal to more north-south or meridional (Wright 1992). The cooler, wetter climate favored the establishment of more mesic vegetation, which is among the primary vegetation types today. Given a more meridional jet stream flow (and an increase in frequency of polar and arctic-origin airmasses into the region), there is also evidence to suggest that the frequency and amount of lake effect precipitation increased relative to previous periods at about 3,000 YBP (Delcourt et al. 2002). Finally, during the late Holocene, the region experienced a period of relatively mild temperatures from approximately 800 A.D. to 1300 A.D. (sometimes referred to as the "Medieval Warm

Period") followed by a period of relatively cool temperatures from about 1400 A.D. until the late 19th Century (the "Little Ice Age"') (Gajewski, 1988).

The mid-continent of North America was likely drier than present during the mid-Holocene, based on inferences from fossil-pollen data and estimates of past lake levels, and such conditions have often been explained by increases in the dominance (frequency and/or duration) of Pacific airmasses, zonal flow patterns, or enhanced westerlies (Schinker et al. 2006). The authors of this study also suggested that large-scale circulation patterns alone may not provide a full explanation of surface-moisture anomalies due to the dynamic interplay between surface conditions and atmospheric processes and that moisture availability (determined by atmospheric moisture flux and soil-moisture recycling) must also be considered.

2.5.2 INSTRUMENTAL RECORD

2.5.2.1 Temperature

Although there is tremendous inter-annual variability in regional temperatures, and there are multiple points in time when temperature shifts occurred, mean temperatures have increased overall since 1900 (Figure 2.5). Based on data obtained from the

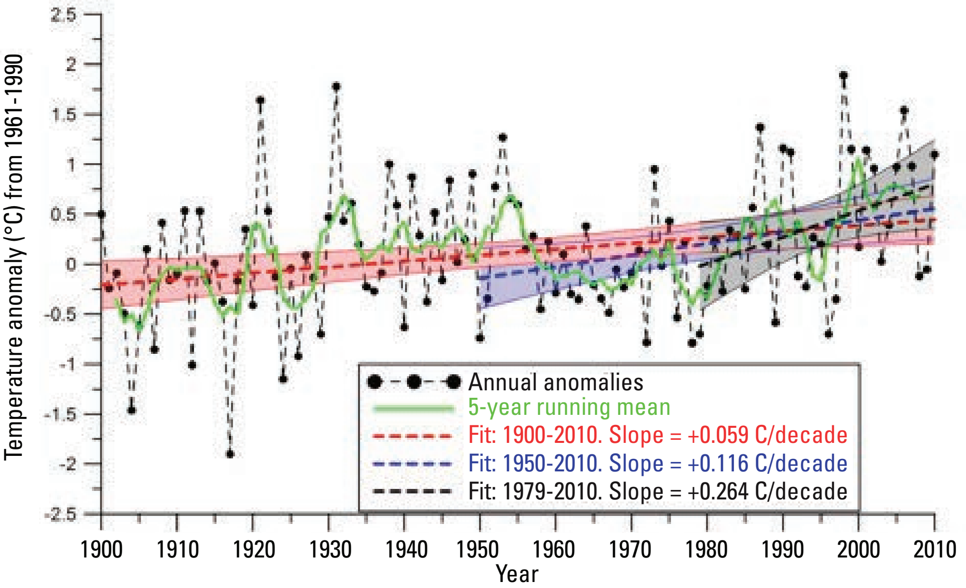


Figure 2.5. Annual temperature anomalies for the Midwest from the CRUTEM3 data set. The anomalies are relative to 1961-1990. The data have a spatial resolution of 5 x 5° thus the domain used to construct this figure is 35°N to 50°N and 95°W to 80°W. Data were downloaded from http://www .cru/uea.ac.uk/cru/data/temperature/#datdow. Also shown is a 5 year running mean and linear fits to the annual data for 1900-2010, 1950-2010 and 1979-2010. The shading represents the 95% confidence intervals on the fits. The slopes of the region-wide trend estimates are expressed in °C per decade and are shown for 3 time periods; 1900-2010, 1950-2010, and 1979-2010. *Source*: Pryor and Barthelmie (2013).

CRUTEM3 data set (Brohan et al. 2006), a homogenized data set with spatial resolution of 5° x 5°, annual mean temperature over the Midwest increased by approximately 0.059°C per decade during 1900-2010 period, 0.12°C per decade for the period 1950-2010, and 0.26°C per decade for the period 1979-2010. The trends and temporal patterns are somewhat similar to overall global trends which include an increase in mean temperature of about 0.8°C since 1850 (Trenberth et al. 2007).

2.5.2.2 Precipitation

Overall, annual precipitation across the Midwest decreased from the late 1800's through the dust bowl years of the mid 1930's, followed by a general increasing trend beginning during the late 1930s that continues to the present (Groisman and Easterling 1994; Andresen 2012), with an overall increase in precipitation during the past century. In general, annual precipitation has increased since 1895 by 2.5-5.5 inches, or a range of 5-15%. The 1930's were the driest decade on record regionally, while the recent 2-3 decades were the wettest (Lorenz at al. 2009b). The increase in precipitation since the 1930's has occurred both as a result of an increase in the number of heavy precipitation events (Kunkel et al. 2003) as well as overall increases in the number of wet days and multiple wet day events. In northeastern sections of the region, for example, the number of both single and 2-day consecutive wet day frequencies has increased more than 30% between the 1930s and the present (Grover and Sousounis 2002; Andresen 2012). Climate modeling results suggest that wetland drainage across large areas of the region over time has resulted in significant changes in the regional energy (sensible and latent heat flux) and radiation (long-wave radiation) budgets, particularly from May to October. As a result, the climate has become warmer, and convective precipitation has decreased during summer months (Kumar et al. 2010).

2.5.2.3 Seasonality of Temperature and Precipitation Changes

The increases in temperature and precipitation during the past century have not been consistent across season or time of day. Trend statistics for precipitation and mean temperature by state and season are given in Table 2.1 for the periods 1895-2010 and 1981-2010. While changes in precipitation and mean temperature have been generally consistent during both time frames across states within the region, a relatively greater proportion of the regional warming occurred during the winter and spring seasons during the 1895-2010 period, and during the summer and fall seasons during the last three decades. In some sections of the region (e.g. Illinois, Indiana, Michigan) mean summer temperatures actually decreased with time, possibly due to landscape cover type changes associated with intensified agriculture over time (Pan et al. 2004). Just as importantly, much of the warming in recent decades has been associated with warmer nighttime (i.e. minimum) temperatures (Easterling et al. 1997; Lorenz et al. 2009a). The latter results are consistent with the results of Zhang et al. (2000), who found that the largest increases in temperature across southern Canada between 1900 and 1998 had occurred in winter and early spring.

Seasonal differences were also noted for regional precipitation trends. The majority of the increase in precipitation since the 1930's has occurred during spring, summer, and

Table 2.1 Yearly trends in precipitation (inches/year) and mean temperature (°F/year) for a) 1895–2010 and b) 1981–2010 periods.

	Precipitation (inches/year)					**Temp (°F/year)**				
1895–2010	*Annual*	*Winter*	*Spring*	*Summer*	*Fall*	*Annual*	*Winter*	*Spring*	*Summer*	*Fall*
IA	0.040***	0.002	0.017***	0.020***	0.000	0.009**	0.014	0.014**	0.004	0.001
IL	0.039***	0.004	0.012	0.012*	0.010	0.004	0.005	0.011*	-0.001	-0.001
IN	0.049***	0.001	0.015*	0.020***	0.012	0.003	0.006	0.010*	-0.005	-0.001
MI	0.038***	0.003	0.004	0.016***	0.016***	0.001	0.008	0.007	-0.006	-0.008
MN	0.029***	0.003	0.008	0.008	0.010*	0.014***	0.022*	0.015**	0.008*	0.006
MO	0.027	0.005	0.010	0.010	0.015*	0.005	0.008	0.010*	0.002	-0.004
OH	0.034***	-0.002	0.011*	0.011*	0.015***	0.008***	0.011	0.014***	0.002	0.003
WI	0.022**	0.002	0.005	0.005	0.003	0.009***	0.019*	0.013*	0.002	0.002
AVG	0.035	0.002	0.010	0.010	0.010	0.007	0.012	0.012	0.001	0.000

	Precipitation (inches/year)					**Temp (°F/year)**				
1895–2010	*Annual*	*Winter*	*Spring*	*Summer*	*Fall*	*Annual*	*Winter*	*Spring*	*Summer*	*Fall*
IA	0.075	0.031	0.044	0.079	-0.081*	0.007	-0.031	-0.010	-0.006	0.062
IL	0.078	0.029	0.053	0.051	-0.053	0.036	0.014	0.046	0.020	0.052
IN	0.196*	0.073	0.066	0.069	-0.011	0.033	0.005	0.058	0.016	0.040
MI	0.000	0.040	0.033	0.006	-0.076**	0.041	0.036	0.018	0.030	0.081***
MN	0.016	0.028**	0.023	-0.025	-0.003	0.028	0.007	-0.037	0.005	0.122***
MO	0.014	-0.007	0.073	0.013	-0.065	0.038	0.020	0.035	0.045	0.043
OH	0.222**	0.084***	0.066	0.057	0.017	0.042*	0.008	0.060	0.048	0.047
WI	-0.005	0.033	0.035	0.033	-0.104***	0.037	0.030	-0.005	0.015	0.100***
AVG	0.075	0.039	0.049	0.036	-0.047	0.033	0.011	0.021	0.022	0.068

Asterisks denote significance at 0.10 (*), 0.05(**), and 0.01(***) levels respectively.

fall seasons, accounting for over 90% of the increase in the overall annual precipitation. In contrast, during the most recent three decades trends for fall precipitation were negative for all states except Ohio, while trends for almost all other seasons and states were positive. There were also relatively larger increases in winter precipitation (0.039 inches/year on average).

2.5.2.4 Growing Season

The growing season length has increased across the region during the past several decades. In an earlier study, Skaggs and Baker (1985) concluded that frost free growing season length had increased an average of 14 days between 1899 and 1992. Similarly, Robeson (2002) found the length of the growing season in Illinois to have increased by nearly one week 1906-1997, with much of the change the result of earlier last spring

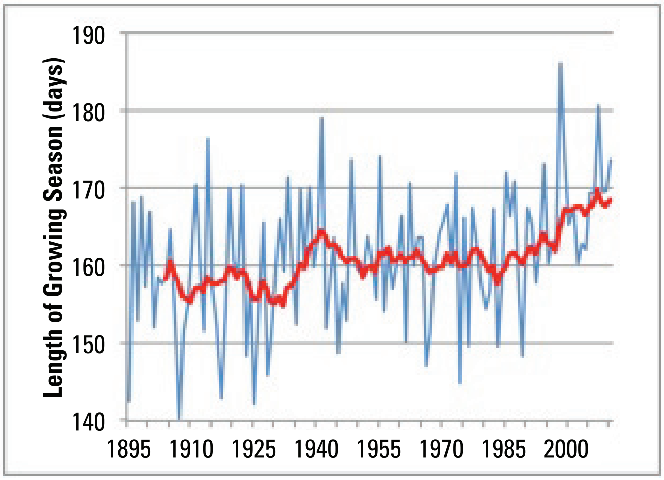


Figure 2.6. Length of the growing season, defined as the period between the last occurrence of 32° in the spring and first occurrence of 32°F in the fall. The red line is a 10-yr moving average. *Source*: Based on data from the National Climatic Data Center for the cooperative observer network and updated from Kunkel et al. (2004).

freezes. The date of the first fall freeze in the study area was virtually unchanged during the study period. These regional trends are consistent with larger, hemispheric trends (Linderholm 2006) and have been confirmed with satellite data depicting phenological changes over large areas (Zhou et al. 2001). Averaged across the eight state region over time (Figure 2.6), the frost free growing season length averaged about 155-160 days prior to the 1930s, then increased to around 160 days during the 1930s into the 1980s. Since the 1980s, it has continued to increase and now averages about a week longer than during the 1930s to 1980s period. In some contrast to the findings of Robeson (2002), the increase in length across the region is the result of both earlier last spring freezes and later first fall freezes.

Longer growing seasons allow production of longer season crop types and varieties, many of which have potentially greater yields. This has resulted in profound changes in cropping systems and mixtures across the region, especially across northern sections (Parton et al. 2007). In North Dakota, for example, the number of planted acres of corn and soybean across the state increased from 300,000 and 200,000 acres, respectively, in 1980 to 3,200,000 and 4,550,000 acres, respectively, in 2012 (NASS 2012b). Longer growing seasons have also resulted in changes to the typical crop production calendar. From 1981–2005, corn planting dates in major U.S. production areas advanced about 10 days earlier, with a concurrent lengthening of the period from planting to maturity of about 12 days and an average increase in corn yields of 0.9-2.2 bushels/acre for each additional day of earlier planting (Kucharik 2006; Kucharik 2008). While shifting climate played a major role in these changes, changes in agronomic technology such as improved cultivars and increasing capacity of agricultural implements were also found to be important (Sacks and Kucharik 2011). Not all of the impacts associated with changing seasonality have been positive. Changing seasonality has also advanced the dates at which overwintering perennial vegetation and agricultural crops break dormancy, which leaves them more vulnerable to subsequent freezing temperatures. While the last freezing temperatures of the spring season have tended to also come earlier with time across the region, the rate of change is not as rapid as the date of initial greenup, which results in

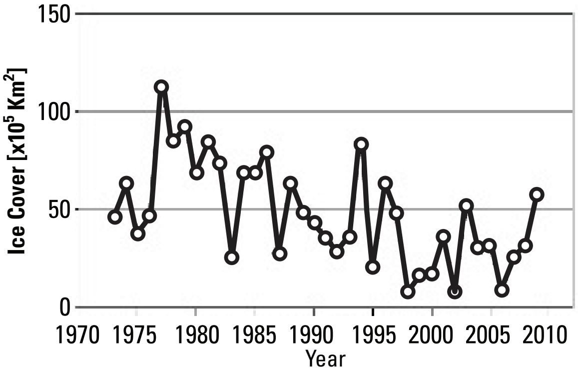


Figure 2.7. Time series of annual average ice area coverage on the Great Lakes. *Source*: Wang et al. (2010).

an overall longer period of freeze risk for many fruit crops such as cherries and apples (Winkler et al. 2013).

2.5.2.5 Ice Cover

Among the impacts resulting from the recent warmer winter temperatures is a reduction in the amount and duration of ice cover on lakes across the Midwest region including the Great Lakes. This trend is well documented in previous studies by Magnuson et al. (2000) and Magnuson (2010) which suggest an increasingly later onset of first ice cover on inland lakes in the region by 6-11 days since the middle 19th century and an increasingly earlier breakup of ice in the spring from 2-13 days during the same period. While available for a much shorter period of record, satellite imagery provides a more comprehensive estimate of ice cover changes on the Great Lakes as shown in Figure 2.7 for the period 1973–2009 (Wang et al. 2010). Average ice cover area across the Great Lakes during this period peaked during the late 1970's before decreasing by more than one half during the 1-2 decades of record. These numbers are in good agreement with the results of Duguay et al. (2006), who documented similar decreases in ice cover duration as well as trends towards earlier lake ice break up in the spring season during the period 1951-2000 in nearby areas of Canada.

2.5.2.6 Snowfall

Trends in seasonal snowfall across the Midwest during recent decades have varied by location. Average seasonal snowfall totals plotted for the thirty-year periods 1961-1990 and 1981-2010 in Figure 2.8 reveal some interesting patterns. In general, mean seasonal snowfall decreased across far southern sections of the region between the two periods, remained about the same across central sections, and increased across the north, especially in areas downwind of the Great Lakes. These trends are consistent with a reduction in the number of synoptic snowfalls and an increase in the frequency of lake effect snowfalls, possibly both linked with milder wintertime temperatures and the warmer, more open waters of the Great Lakes during the past few decades (Burnett et al. 2003). Similarly, temporal trends in the frequency of major snowstorms varied widely across the region during 1901-2000, with downward trends across southern sections and up-

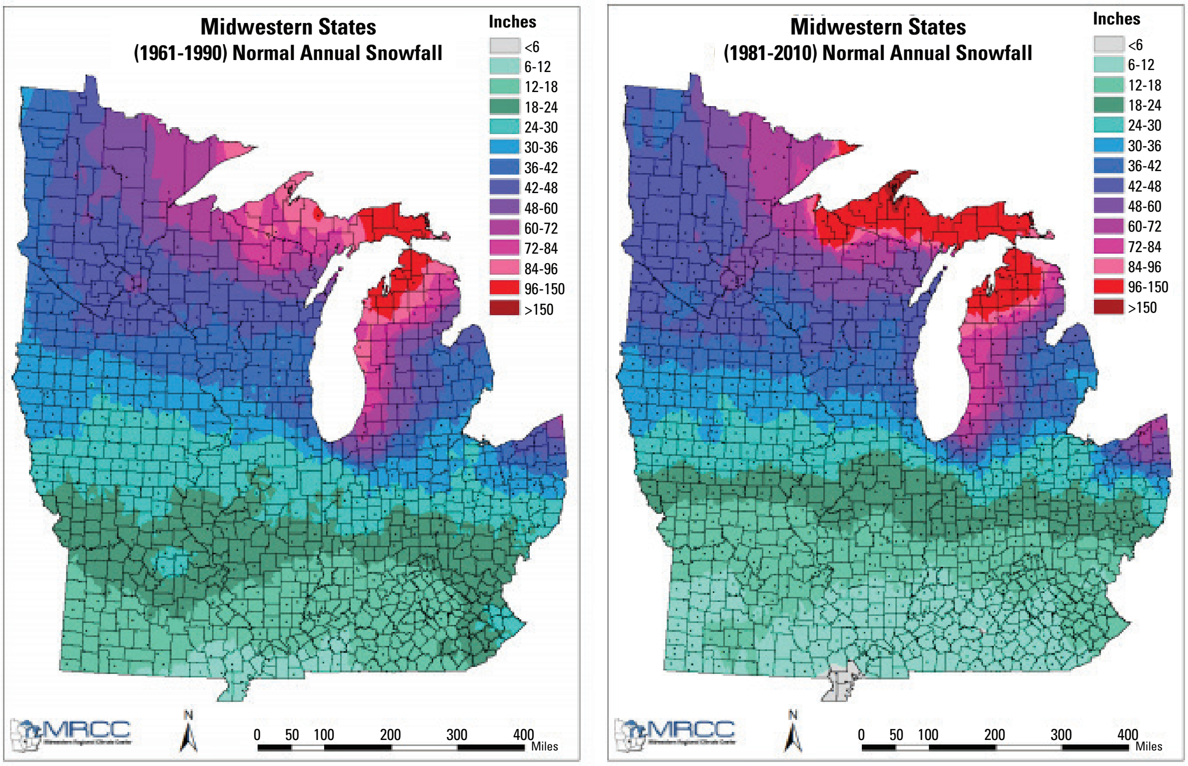


Figure 2.8. Mean seasonal snowfall (inches) across the Midwest for a) 1961-1990 (left) and b) 1981-2010 (right) periods. *Source*: Kunkel et al. (2013).

ward trends across the north (Changnon et al. 2006). In terms of snow cover, Dyer and Mote (2006) found minimal changes in North American snow depth through January, with regions of decreasing snow depths beginning in late January and continuing through March and into April, implying an earlier onset of spring melt. As noted by Andresen (2012) in sections of the Great Lakes region, there are distinct connections with snow cover and trends towards milder temperatures, with recent observations suggesting that milder winter temperatures are melting snow more quickly than in past decades even though more snow is falling.

2.5.2.7 Cloudiness

Given trends toward more annual precipitation and days with precipitation in recent decades, it is also logical to assume that cloudiness in the region has increased as well. Unfortunately, quality cloudiness and solar radiation observational records in the region are scarce. In an examination of observations obtained from U.S. military installations between 1976 and 2004, Dai et al. (2006) concluded that total cloud cover over most of the contiguous U.S. has increased during the period, including changes at Midwestern locations in the range of 1-3% per decade. While these findings are limited by the relative lack of data available for the study, they are consistent with the observed reduction in U.S. surface solar radiation from 1961 to 1990 reported by Liepert (2002) and average global decreases of 2.7% per decade noted by Stanhill and Cohen (2001). Besides the increasing frequency of precipitation, Minnis et al. (2004) attributed at least part of the recent increase in cloudiness to increases in high level cirriform cloudiness across the Midwest associated with jet aircraft contrails.

2.5.2.8 Humidity

The search for trends of humidity is complicated by the relative lack of quality observations and past changes in sensor technology. Most existing studies suggest that humidity levels across the Midwest have increased in recent decades. For example, Gaffen and Ross (1999) reported positive trends of both relative and specific humidity across the U.S., although the relative humidity trends were weaker than specific humidity trends. Dai (2006) found relatively large changes of 0.5-2.0% per decade in surface relative humidity observations from 1976 to 2004 across the central U.S. while D. Changnon et al. (2006) reported a steady increase of the frequency of high dew point days during the period 1960-2000. In a very recent study, Schoof (2013) found increases in maximum dew point temperatures during the summer season across the Midwest which partially offset flat or decreasing maximum air temperatures and a wide variance in trends of resulting apparent temperatures. A likely cause of higher dew point temperatures during the growing season is the significant increase in plant density from earlier decades, which greatly enhances the transpiration of water from the soil to the atmosphere (Changnon et al. 2003).

2.5.2.9 Wind

Similar to humidity, there is a relative paucity of long-term records of near-surface wind speeds, which when coupled with inconsistencies manifest in different data sets, the highly uneven spatial coverage of surface observing stations, and issues pertaining to local land-cover change in the proximity of the observational sites, confound accurate assessment of wind climates and the presence or absence of temporal trends. In an analysis by Pryor et al. (2009b) based on North American Regional Reanalysis (NARR) eight times per day output, 10m wind components at a resolution of ~ 32 x 32 km were extracted for 1979-2006 and analyzed to quantify mean temporal trends in a range of metrics of the wind speed distribution. In general, there was no evidence of significant changes in either the central tendency or higher percentiles of the wind speed distribution over the period of record.

2.5.2.10 Extreme Precipitation

Intense precipitation events are an important part of annual hydrology in the Midwest, with over 30% of total annual precipitation obtained in the ten wettest days of the year in most areas of the region (Pryor et al. 2009a). In the western part of the region, as much as 50% of annual accumulated precipitation falls in 10 daily events. Spatial patterns in the total amount of precipitation in the 10 greatest rainfall events per year and the temporal

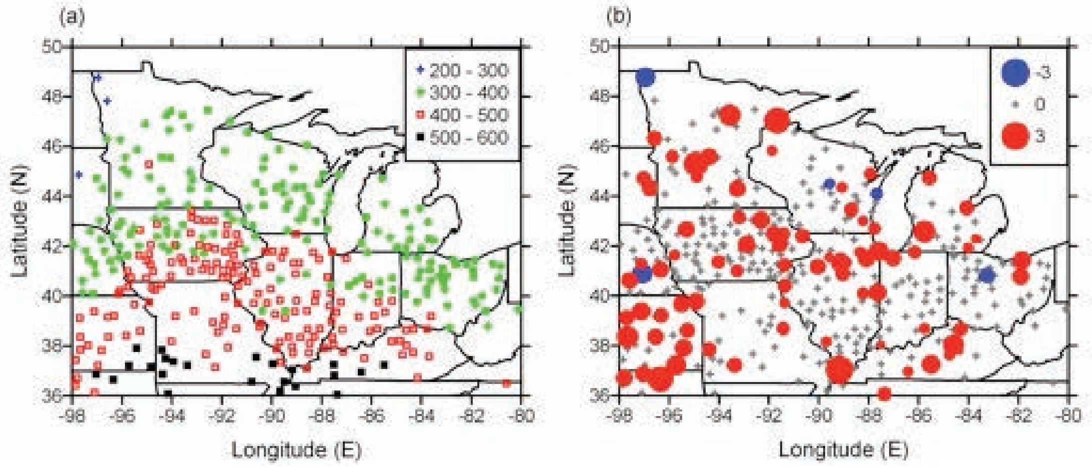


Figure 2.9. a) Mean sum of the top-10 wettest days in a year (mm) (1971-2000). b) Trend in sum of the top-10 wettest days in a year 1901-2000 expressed in a percent per decade. Red circle indicates the station showed a statistically significant increase through time; blue circle indicates a statistically significant decline. Plus symbol indicates trend was not significant (shown as 0 in the legend. The diameter of the dot scales linearly with trend magnitude. *Source*: Pryor et al. 2009c.

trends of that sum are given in Figure 2.9 (from Pryor et al. 2009c). Both metrics closely mirror those present in the total annual precipitation with the highest values in the south of the region and lowest values in the north. In general, stations that exhibit significant changes in the metrics of extreme precipitation indicate trends towards increased values. Twenty-two percent of the stations considered in the study exhibited significant increases in the total accumulated precipitation during the top-10 wettest days of the year. Over the region as a whole, the occurrence of intense precipitation events has risen substantially in recent decades. In an update of an earlier study by Kunkel (2003), the number of 24 hour, once in 5-year storms was found to have increased by about 4% per decade since the beginning of the 20th century (Figure 2.10). About 85% of the events occurred during the warm season period of May through September and approximately 90% of the annual trend was due to increases during the warm season period. Synoptically, the risk of intense rainfall events in the region tends to be associated with a westward extension and strengthening of the Bermuda subtropical high across the western Atlantic Basin (Bell and Janowiak 1995; Weaver and Nigam 2008) as well as the development of a slow moving, cut-off-low system over the Rocky Mountains and Great Plains which steadily advects low-level moisture into the Upper Mississippi region from the Gulf of Mexico (Gutowski et al. 2008). The trend towards heavier rainfall has resulted in an overall increased risk of flooding threat across the region (Markus et al. 2007), although in many urban areas the increased flood risk was found to be more strongly associated with land cover change factors than climatologic factors (Changnon et al. 1996; Scharffenberg and Fleming 2006).

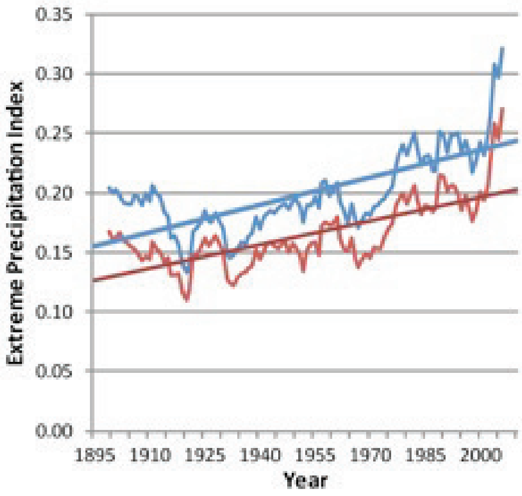


Figure 2.10. Time series of extreme precipitation index for the occurrence of 1-day, 1 in 5 year extreme precipitation events. The annual time series and linear trend (straight line) are shown in blue. A time series for the months of May through September is shown in red. Analysis is averaged for the states of IL, IN, IA, MI, MN, MO, OH, and WI. *Source*: Based on data from the National Climatic Data Center for the cooperative observer network and updated from Kunkel et al. (2003).

2.5.2.11 Extreme Temperatures

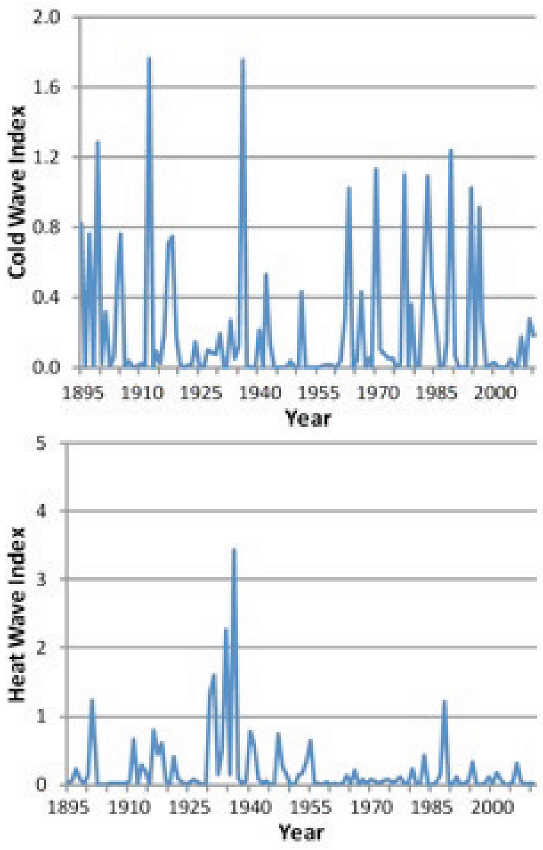
Time series plots of 4-day cold waves and heat waves in the region from 1985 through 2010 are given in Figure 2.11 after Kunkel (2003). Following relatively higher frequencies during the first few decades of the 20th century and from the late 1960's through the early 1990's, intense cold waves have been relatively uncommon, but similar to the frequency experienced from the early 1920s through 1960. The number of intense heat waves has also been relatively low in recent decades, especially relative to the 1930s Dust Bowl era in which frequencies were the highest observed during the historical period of record.

Given recent upwards trends in temperature overall, a majority of climate observing sites within the region recorded significant increases in warm extreme maximum temperature exceedences during the 1960-1996 period as well as increases in warm minimum temperatures and decreases in cold extreme maximum and minimum temperature exceedences (DeGaetano and Allen 2002).

2.5.2.12 Drought

Given an increase in precipitation across the region during the past several decades, the incidence of drought has decreased with time. In a study across central sections of the Midwest, Mishra et al. (2010) found that upward trends of precipitation and temperatures from 1916-2007 were associated with increases in total column soil moisture and runoff and decreases in frozen soil moisture. The authors also concluded that the study region has experienced reduced numbers of extreme and exceptional droughts with lesser areal extent in recent decades. A study by Andresen et al. (2009) suggests that a majority of the 10-15% increase in annual precipitation in Michigan during the past 50 years ended up as shallow aquifer recharge, which is in turn supported by observations of increasing base streamflow across the region (Johnston and Shmagin 2008). In a study of Midwestern droughts during the 1950-1990 period, Changnon et al. (1996)

Figure 2.11. Time series of an index for the occurrence of a) cold waves (left) and b) heat waves (right) defined as 4-day periods colder and warmer than the threshold for a 1 in 5 year recurrence, respectively. *Source*: Based on data from the National Climatic Data Center for the cooperative observer network and an update by Kunkel et al. (1999).



found that droughts in during the 1950-1970 period covered a relatively greater area of the Midwest region and lasted longer, while droughts during the 1971-1990 period impacted fewer basins and have been of shorter duration. The trend towards a wetter climate and decreasing drought frequency has also had a major impact on the region's agriculture industry in recent decades, with relative increases in crop yields due to less moisture stress and overall more favorable growing conditions (Andresen et al. 2001).

2.5.3 SYNOPTIC CHANGES

The links between upper tropospheric flow, synoptic circulation patterns, and climatologic trends over the region are complicated. In general, synoptic patterns characterized by large amplitude long waves in the middle and upper levels of the hemispheric circulation across the region lead to anomalously cool or warm weather, and, depending on the location of the upper air feature, to relatively wet or dry conditions resulting from the influence of cyclones or anticyclones, respectively. In contrast, a flatter, more zonal pattern across the region is characterized by more frequent, weaker cyclones and anticyclones (Angel and Isard 1998). On a hemispheric scale, Agee (1991) found a positive correlation between increased (decreased) cyclone frequency and increased (decreased) hemispheric temperatures associated with periods of warming and cooling mean temperatures between from 1900-1990 across the Northern Hemisphere. He associated the periods of warming with a flatter, relatively zonal jet stream pattern of short waves carrying more numerous yet weaker disturbances, and periods of cooling with stronger, less numerous disturbances. In the Midwest, Booth et al (2006) linked enhanced westerly upper air flow during the summer season with increases in the frequency of relatively dry Pacific-origin air masses, reductions in northward transport of Gulf of Mexico-origin moisture, and to drier than normal conditions across western sections of the region. There have also been important synoptic changes over time across the region. Grover and Sousounis (2002) suggest that upper tropospheric flow across the region during the fall season was relatively more meridional during the 1935-1956 period, and more zonal during the 1966-1995 period, which may have led to both greater frequency and total amounts of precipitation. The zonal flow was associated with greater baroclinicity across the Rocky Mountain region as well as a stronger subtropical jet and stronger low-level flow of moisture from the Gulf of Mexico. As noted earlier, other studies have linked extended droughts or wetter than normal periods in the Midwest to large scale oceanic sea surface temperature and circulation patterns in the Pacific and/or Atlantic Basins (e.g., McCabe et al. 2004).

In terms of mean pressure patterns, early studies of cyclone and anticyclone frequency and intensity across the region generally suggested a decrease in the frequency of cyclones and anticyclones during the second half of the last century (Zishka and Smith 1980; Agee 1991). More recent studies suggest more complex trends. For example, Angel (1996) found a statistically significant increase in the frequency of strong cyclones over the Great Lakes region in November and December during the 20th century. A subsequent study by Polderman and Pryor (2004) reinforced these findings, reporting an increasing frequency of cyclones originating from Colorado and the surrounding region along with a decrease in the frequency of Arctic (cold polar highs) outbreaks in the Midwest during their 1956-1999 study period. Results from the same study also linked record low lake levels of the Great Lakes with a polar jet stream displaced further south than normal, reduced winter cyclone activity, increased evaporation, and reduced ice cover on the lakes. Polderman and Pryor (2004) concluded that their results suggest that climate change is being manifested both in terms of changes in the frequency and surface manifestations of synoptic circulation patterns.

2.6 Summary

Weather and climate have major influences on human and natural systems in the Midwestern U.S. Major weather-related threats in the region include flooding, severe thunderstorms, droughts, heatwaves and coldwaves, heavy rainfall events, and winter storms. Climate across the region has varied markedly during past centuries and millennia as evidenced by a number of paleclimatological records. Major trends across the region since the beginning of the 20th century are generally spatially consistent, and are temporally somewhat similar to larger scale global and hemisphere temperature trends including warming temperatures from approximately 1900 to 1940, followed by a cooling trend from the early 1940's to the late 1970's which was in turn followed by a second warming trend that began around 1980 and has continued to the present. Much of the warming trend during the past 2-3 decades has been associated with warmer minimum temperatures during the winter and spring seasons. Another important trend regionally has been an increase of precipitation since approximately 1940, the result of increases in both the number of wet days and the number of heavy precipitation events. Seasonal snowfall totals decreased across far southern sections of the region and increased across the north, especially in areas downwind of the Great Lakes.

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Chapter 3

Climate Projections for the Midwest

Availability, Interpretation, and Synthesis

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3.1 Introduction

Climate change projections, also often referred to as climate scenarios, are widely used for assessments of the potential impacts of climate change on natural processes and human activities, including assessments conducted at the local/regional scale. A number of different approaches are used to develop climate projections, and the strengths and limitations of each method must be taken into consideration when selecting projections for use in a specific application and when interpreting, comparing, and integrating outcomes from multiple assessment studies and impact analyses.

This chapter focuses on climate projections for the National Climate Assessment Midwest region, defined as the states of Minnesota, Iowa, Missouri, Wisconsin, Michigan, Illinois, Indiana and Ohio (National Climate Assessment 2012). The goals are two-fold. First, we briefly review commonly-used approaches to develop local/regional climate projections and highlight strengths and limitations. The intent is to provide readers with a sufficient, although rudimentary, understanding of climate projections for an informed and nuanced interpretation of the substantial literature on potential climate impacts in the Midwest. Second, we summarize by climate variable potential future changes in the Midwest as synthesized from currently-available literature. This chapter expands upon NOAA Technical Report NESDIS 142-3, prepared by Kunkel et al. (2013) for the National Climate Assessment Development and Advisory Committee, in that it is more comprehensive in scope, incorporating the wide range of climate projections available for the region.

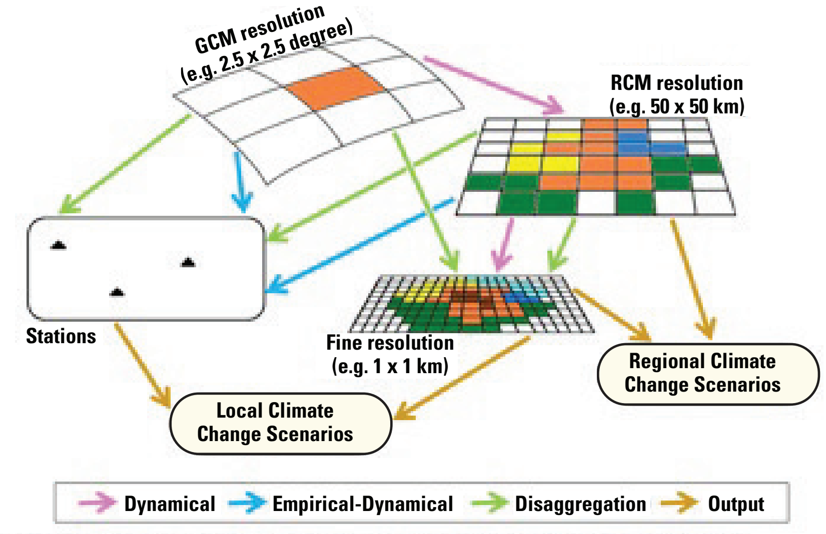


Figure 3.1. Illustration of the spatial scales of climate projections, as developed using dynamical, empirical-dynamical, and disaggregation downscaling methods applied to GCM simulations. Note that multiple downscaling steps can be applied. *Source*: Winkler et al. (2011a).

3.2 Climate Projections

3.2.1 DOWNSCALING METHODS

Most often, climate change projections are derived from simulations obtained from global climate models (GCMs). GCMs have a relatively coarse spatial resolution; for example, those used for the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) had latitude-longitude spacing that ranged from 4° by 5° to about 1.1° by 1.1°. This motivates the use of "downscaling" methods to infer higher spatial and/or temporal resolution that may be more appropriate for use in impact assessments. Downscaling procedures traditionally are classified as either "dynamical" or "statistical", although some research uses combinations of these two in "hybrid downscaling" (Li et al. 2012; Abraham et al. 2013; Pryor and Barthelmie 2014). Common downscaling methods are briefly summarized below and illustrated in Figure 3.1. Several detailed reviews of downscaling approaches are available (e.g., Mearns et al. 2003; Wilby et al. 2004; Benestad et al. 2008). The summary below is drawn primarily from Winkler et al. (2011a,b), and readers are referred to the original articles for more information including a "checklist" of considerations for evaluating alternative downscaling options (Winkler et al. 2011a).

It is not possible to argue for one downscaling approach as universally "better" than another (Christensen et al. 2007). Rather, the different approaches should be viewed as complementary, and the choice of downscaling approach(s) should be appropriate to the assessment objectives.

3.2.1.1 Dynamically-Downscaled Climate Projections

Dynamical downscaling employs numerical models, such as regional climate models (RCMs), to simulate fine-resolution climate fields, and can be particularly useful when mesoscale (a few to several hundred kilometer) circulations strongly influence the local/regional climate or when regional-scale influences such as terrain or changing land use are anticipated to have large effects on the future climate of the region (Winkler et al. 2011a). RCMs, like GCMs, are based on the fundamental equations of atmospheric dynamics and thermodynamics. For this reason dynamical downscaling is often a better choice when an assessment requires a suite (e.g., temperature, humidity, wind, and radiation) of physically consistent and spatially and temporally coherent climate variables (Hanssen-Bauer et al. 2005). Typical horizontal resolutions of RCMs for multi-decadal, continental-scale simulations are on the order 25-50 kilometers (Rummukainen 2010). Simulations with resolutions of only a few kilometers are possible using multiple nested RCMs, or when considering shorter periods or smaller domains (e.g., Liang et al. 2004; Hay et al. 2006). For comparison to observations, RCMs are driven by lateral boundary conditions obtained from reanalysis fields, in which a GCM is constrained to follow observations. The reanalysis, which very simply can be thought of as a "blend" of observations and model output, is considered to represent a "perfect" (more correctly, the best possible) GCM and thus allows the errors and biases of the RCM itself to be isolated. RCMs are also driven by coarse-scale simulations from GCMs both for historical and future periods. Comparisons of RCM results when driven by historical reanalyses with results when driven by a GCM simulation of the corresponding period help to determine errors attributable to using the GCM's depiction of current climate to force the RCM.

Resource constraints have historically tended to limit RCM simulations to relatively short periods of a few decades in length (e.g. Christensen et al. 2002; Leung et al. 2004; Plummer et al. 2006), especially when a very fine resolution is employed or when simulations are needed over a large spatial domain. Furthermore, simulations with a given RCM often have been driven by a single GCM or only a small number of GCMs. This latter limitation arose from several practical considerations: GCMs did not often store the high time resolution data needed for RCM boundary conditions; the differing output formats for different GCMs required extensive coding or data reformatting so that the data can be read by the input procedures used in the RCMs; and execution of RCMs required substantial computing time and human resources. Both short simulation periods and limited number of GCMs used in RCM studies have implications for evaluating the uncertainty surrounding projected changes. Some of these resource constraints are likely to be ameliorated with ever increasing computer power and storage capacity. Also, the protocol for the Coupled Model Intercomparison Project Phase 5 (CMIP5) includes provision for saving output from participating GCMs at sufficient time resolution for use as RCM boundary conditions so that suitable output from more GCMs is now being made available. The CMIP5 GCMs also use a standard output format which should reduce the effort needed to adapt an RCM to boundary values from different GCMs.

An example of dynamical downscaling is the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009, 2012), which has generated a uniquely detailed suite of regional-scale climate output that is being used extensively in the National Climate Assessment. Under NARCCAP, RCMs have been driven both by reanalysis fields and by GCM results. In the former the lateral boundary

Table 3.1 Available NARCCAP simulations

Regional Climate Models(RCMs)	**Global Climate Models (GCMs)**				
	GFDL	*CGCM3*	*HADCM3*	*CCSM*	*NCEP*
CRCM		X		X	X
ECP2	X		X		X
HRM3	X		X		X
MM51			X	X	X
RCM3	X	X			X
WRFG		X		X	X
Time Slices	X			X	
ECPC					X
WRFP					X

Source: http://www.narccap.ucar.edu/.

conditions are supplied by output from the NCEP-DOE reanalysis (shown as NCEP in Table 3.1), while in the latter a suite of four GCMs were used to provide the nesting. Output is available to all parties and for many variables at a daily or higher temporal resolution.

3.2.1.2 Statistically-Downscaled Climate Projections

A wide variety of empirical methods are employed in statistical downscaling. Following Winkler et al. (2011a), we categorize statistical downscaling approaches into two broad categories, namely empirical-dynamical downscaling and disaggregation downscaling. The categorization reflects differing underlying philosophies in the downscaling approach. Empirical-dynamical downscaling does not operate directly on the variable of interest as predicted by the global model, typically a surface weather variable such as temperature, precipitation or wind speed. Instead, the variable is inferred from derived relationships to large-scale variables predicted by the model, and selected to represent important dynamical and physical processes in the atmosphere. For example, precipitation can be inferred from a mid-atmospheric circulation property such as vorticity (e.g., Schoof et al. 2010). Underlying this approach is the assumption that GCMs are able to better simulate circulation and "free atmosphere" (i.e., above the boundary layer) variables compared to surface climate variables, as they are less influenced by complex surface fluxes and interactions. Thus, the circulation and free atmosphere variables represent the larger scale environment, and the empirical relationships implicitly capture the effects of local topography, geography and boundary conditions on the surface variables. Another important assumption is that the circulation and/or free atmosphere variables capture the climate change signal. Many empirical-dynamical downscaling approaches are patterned after short-range forecasting techniques such as model output statistics (MOS; Karl et al. 1990) or employ weather typing techniques to link circulation with local or regional climate.

Disaggregation methods attempt to infer fine-scale values from coarse-scale spatial or temporal fields of a particular variable, such as precipitation, although additional variables, including circulation and free atmosphere variables, may be included in the downscaling function to improve the relationship. Often the large-scale values are first adjusted for bias (error) in the GCM simulated values. To date, disaggregation downscaling has been the most common approach for developing local/regional climate projections. The relatively fewer resources needed for disaggregation downscaling methods compared to either dynamical or empirical-dynamical downscaling likely has contributed to their popularity. In particular, the "delta method" was one of the first downscaling methods employed in climate impact assessments. For this popular approach, coarse-scale GCM simulations of monthly means and accumulations of climate variables (e.g., surface temperature and precipitation) are spatially interpolated to a finer resolution grid or to station locations, the difference or ratio between the GCM projected value for a future period and for a control (historical) period is calculated, and the differences (for temperature) or ratios (for precipitation) are applied to gridded or station specific historical observed time series. One limitation of the delta method is that it does not capture future changes in variability. Temporal disaggregation is also commonly used. For example, stochastic weather generators (e.g., Wilks 1992; Katz 1996; Semenov and Barrow 1997; Dubrovsky et al. 2004, Qian et al. 2008; Semenov 2008) are often used to obtain finer temporal resolution from monthly projections. Typically, weather generators use Markov processes to simulate wet/dry days and then estimate wet day amounts, temperature and solar radiation conditional on precipitation occurrence (Wilby et al. 2004; Wilks 2010). Recent developments in weather generators include preserving the spatial and temporal correlations of the climate variables among locations (e.g., Baigorria and Jones 2010).

An assumption of both empirical-dynamical and disaggregation downscaling is that the statistical relations are stationary in time; i.e., relationships observed for the current climate will be applicable in the future. In contrast to dynamical downscaling, statistical downscaling is not as resource intensive, making it easier to build a larger ensemble (i.e., suite) of projections based on a number of GCMs and also to include multiple future time slices.

3.2.2 AVAILABLE CLIMATE CHANGE PROJECTIONS FOR THE NATIONAL CLIMATE ASSESSMENT MIDWEST REGION

The support document provided by Kunkel et al. (2013) for the National Climate Assessment focused on four sets of climate projections: 1) coarse-scale simulations from 15 GCMs obtained as part of the Climate Model and Intercomparison Project Phase 3 (CMIP3; Meehl et al. 2007), 2) time series of monthly temperature and precipitation at a 1/8° latitude/longitude resolution obtained by applying a combined bias correction and spatial disaggregation downscaling procedure known as the "BCSD method" (Maurer et al. 2002) to the CMIP3 GCM simulations, 3) daily time series of temperature and precipitation obtained from temporal disaggregation of the BCSD spatially downscaled monthly temperature and precipitation values by adjusting randomly-selected observed daily time series by the projected differences in the monthly values (i.e., the delta method), and 4) nine RCM simulations obtained from the North American Regional Climate Change Assessment Project (NARCCAP). Thus, this guidance document includes one set of non-downscaled climate projections, two sets of projections downscaled using disaggregation approaches but with different temporal resolutions, and a set of dynamically-downscaled projections.

Considerable additional resources are available for climate change assessments for the Midwest. A number of fine-resolution climate projections with global coverage have been developed by research groups worldwide that may be relevant for assessment activities in the Midwest depending on the assessment goals. Additionally, climate change projections have been developed specifically for the Midwest. Available climate projections are summarized in Table 3.2. As can be seen from the table, these projections differ in terms of downscaling procedure, resolution, time slices, the number of GCMs from which projections were derived, and the underlying greenhouse gas emissions scenarios.

3.2.3 CONSIDERATIONS WHEN USING AND/OR INTERPRETING CLIMATE PROJECTIONS

As noted above, climate projections are important components of climate impact studies; however, they must be interpreted carefully, keeping in mind the underlying assumptions and limitations and the possible sources of uncertainty. Below we highlight three issues of particular significance when interpreting and using climate projections.

3.2.3.1 Influence of Regional Topography or Circulation on Climate

Unique characteristics of a region need to be taken into consideration when interpreting local/regional climate projections. An example for the Midwest of topographic influences is the Great Lakes and the surrounding lake-modified climates. The Great Lakes are crudely represented in GCMs; for example, in the HadCM3 model used in IPCC AR4, the lakes appear as a single water body (Figure 3.2). Consequently, simple spatial

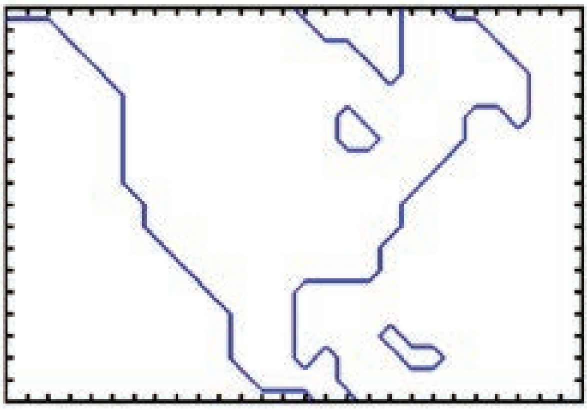


Figure 3.2. Land-sea mask for North America in the HadCM3 global climate model, one of the models used in the IPCC AR4.

Table 3.2 Available climate change projections for the Midwest

Name/ Reference	Coverage/Resolution Variables/Period	Ensemble Size	Downscaling Procedures	Availability
CMIP3 GCM archive (Meehl et al. 2007)	• Global • Spatial resolution varies by GCM • Archived at monthly time step, but finer time steps available for most models	• Over 20 GCMs (AR4 era) • 3 emissions scenarios (SRES A2, A1B, B1)	Not downscaled	Graphical summaries available in IPCC AR4 Working Group I report. Time series of monthly precipitation and mean temperature available from the Program for Climate Model Diagnosis and Interpretation (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).
CMIP5 GCM archive (Taylor et al. 2012)	• Global • Spatial resolution varies by GCM, but generally finer than for CMIP3 GCM archive • Monthly with finer, (daily, 3-hourly) time steps available for many simulations	• Over 20 GCMs (AR5 era) • 4 representative concentration pathways (RCP 2.6, RCP4.5, RCP6, RCP8.5)	Not downscaled	Time series of archived climate variables available from: http://pcmdi9.llnl.gov.
Bias Corrected and Downscaled WCRP CMIP3 Climate Projections (Maurer et al. 2007)	• Global • 1/8° lat/lon resolution • Mid century and late century time slices	• 16 GCMs (IPCC AR4 era) • 3 emissions scenarios (SRES A2, A1B, B1)	Disaggregation downscaling; BCSD method Gridded temperature and precipitations observations were upscaled to a 2° resolution and GCM projections were regridded to this resolution. Quantile mapping was used to calculate change factors which were then downscaled using an inverse distance approach and applied to the original finely gridded observed dataset.	Monthly time series available through Climate Wizard (http://www.climatewizard.org and at http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections).
TYN SC 2.0 (Mitchell et al. 2004)	• Global • 0.5° lat x0.5° lon • Mean monthly cloud cover, diurnal temperature range, precipitation, temperature, vapor pressure • 2001-2100	• 5 GCMs (IPCC TAR era) • 4 emission scenarios (SRES A1F1, A2, B2, B1)	Disaggregation downscaling. Spatial interpolation using thin plate spline scheme.	Available at http://www.cru.uea.ac.uk/cru/data/hrg.

Table 3.2 (continued)

Name/ Reference	Coverage/Resolution Variables/Period	Ensemble Size	Downscaling Procedures	Availability
WorldCLIM	• Global coverage • ~1km resolution • Climatological (30 year) mean monthly temperature and precipitation • 7 overlapping 30-year periods in 21st century	• 3 GCMs (IPCC TAR era) • 2 SRES emissions scenarios	Disaggregation downscaling (spatial interpolation).	Available at http://worldclim.org.
International Centre for Tropical Agriculture (CIAT)	• Global • 4 spatial resolutions (30 arc-seconds, 2.5 arc-minutes, 5 arc-minutes and 10 arc-minutes) • Climatological (30 year) mean monthly temperature and precipitation	• 24 IPCC AR4 models	Disaggregation downscaling (spatial interpolation).	Available at http://www.ccafs-climate.org.
10′ Future Climate Grids (Tabor and Williams 2010)	• Global • 10′ resolution • Climatological (20 year) mean monthly temperature and precipitation • Two time slices, 2041–2060 and 2081–2100	• 24 GCMs (IPCC AR4 era) • 3 emissions scenarios (SRES A1B, A2, B1)	Disaggregation downscaling. GCM simulations are debiased with respect to their mean differences from 20th-century observations. The differences were downscaled to 10′ resolution with a spline interpolation and added to mean 20th century climatologies from the CRU CL2.0 dataset.	Available at http://ccr.aos.wisc.edu/resources/data_scripts/ipcc/index.html.
NARCCAP (Mearns et al. 2012)	• North America • ~50 km • 3-hourly time step • Multiple climate variables including temperature, precipitation, humidity and wind • Two time slices, 1960-1990 and 2040-2070	• 12 simulations developed from combinations of 4 GCMs (IPCC AR4 era) and 6 RCMs • SRES A2 emissions scenario	Dynamical downscaling (RCM models).	Available at http://www.narccap.ucar.edu.
Schoof et al. 2010	• 963 stations in United States • Daily precipitation • 3 time slices (1961-2000, 2046-2065, 2081-2100)	• 10 GCMs (IPCC AR4 era) • A2 emissions scenario	Disaggregation downscaling. Statistical parameters of gamma distribution were downscaled using first-order Markov chain.	Contact author.

Table 3.2 (continued)

Name/ Reference	Coverage/Resolution Variables/Period	Ensemble Size	Downscaling Procedures	Availability
Schoof 2009	• 53 stations in the Midwest • Daily temperature • 3 time slices (1961-2000, 2046-2065, 2081-2100)	• 8 GCMs (IPCC AR4 era) • A2 emissions scenario	Empirical-dynamical downscaling. Transfer functions were developed separately for each location that related large-scale values of mid-tropospheric temperature and humidity to surface temperature (perfect prog method).	Contact author.
Hayhoe et al. 2010a	• U.S. Great Lakes region • 1/8° grid and individual weather stations • Monthly and daily temperature and precipitation	• 3 GCMs from CMIP3 archive • SRES A1F1, B1 emissions scenarios	Disaggregation downscaling using 1) the Maurer et al. 2007 approach to downscale monthly temperature and precipitation to a regular grid, and 2) asynchronous quantile regression for downscaling to individual stations and daily resolution.	Contact author. [NOTE: an updated dataset for the entire US will soon be released and available via the USGS climate projection port].
Pileus Project (Winkler et al. 2012)	• 15 locations in the Great Lakes region of North America • Daily temperature and precipitation • 2000-2099	• 4 GCMs (IPCC TAR era) • 2 emissions scenarios (A2, B2) • 8 empirical-dynamic downscaling variants based on "perfect prog" approach	Empirical-dynamical downscaling. Regression equations were developed for each location that relate large-scale circulation (the predictors) to surface climate variables (the predictands).	User tool to view summary graphics for temperature scenarios available at www.pileus.msu.edu. Precipitation scenarios available from author.
WICCI (Kucharik et al. 2010; Notaro et al. 2011; WICCI 2011)	• Wisconsin • 0.1° lat x 0.1° lon • Daily temperature and precipitation • 1960-1999, 2045-2064, 2081-2100	• 14 GCMs from CMIP3 archive • SRES A2,A1B, and B1 emissions scenarios	Disaggregation downscaling. Statistical relationships were developed between GCM fields and parameters of the probability density function for a local climate variable. The parameters were interpolated to a fine grid, and a random number generator was used to obtain daily values.	Maps of multi-model means available at http://www.wicci.wisc.edu and http://ccr.aos.wisc.edu/climate_modeling/wisconsin_climate.

interpolation of GCM output to a finer-resolution grid or a location will result in climate projections that inadequately (if at all) capture the influence of the Great Lakes on the local climate. Furthermore, dynamical downscaling using RCMs may not fully capture the effect of the lakes, as many RCMs do not include a lake module, and lake temperatures are often estimated using the average of nearshore Atlantic and Pacific temperatures.

The impacts of regionally-specific atmospheric circulation must also be considered when interpreting and using climate projections. As an example, the western portion of the Midwest region frequently experiences a southerly low-level wind maximum known as the "low-level jet," especially at night during the warm season (Walters et al. 2008). These jets contribute to the transport of moisture into the region, and downstream convergence can act to initiate or sustain convective precipitation systems that propagate across the region. The low-level jet is poorly represented in some GCMs and RCMs, introducing uncertainty into warm season precipitation projections. Furthermore, the propagating mesoscale convective precipitation systems induced by the jet are poorly represented at typical RCM grid spacings (Anderson et al. 2007) and are absent in GCMs executed at typical climate scales.

3.2.3.2 Ensembles and Multi-Model Means

One of the most robust conclusions from climate model evaluation studies is that there is no single best model for all locations, periods, or variables of interest (Pierce et al. 2009). Therefore, most climate change assessments employ an ensemble (i.e., suite) of climate projections. As pointed out by Winkler et al. (2011b), ensembles provide an estimation of what Jones (2000) refers to as the "calibrated range of uncertainty", and what Stainforth et al. (2007) refer to as the "lower bound on the maximum range of uncertainty". Ensembles usually include projections derived from a number of different GCMs and projections obtained from GCM simulations driven with different greenhouse gas emissions scenarios. More recently, projections developed from multiple simulations from the same GCM, but where selected physical parameterizations are perturbed or where initial conditions have been slightly modified to evaluate variability, are included in an ensemble (e.g., Murphy et al. 2007). Less frequently, an ensemble includes projections derived using multiple downscaling methods. A schematic illustrating the potential components of an ensemble of climate projections is shown in Figure 3.3.

Multi-model means, or in other words the average of the individual members, are frequently used to summarize an ensemble of climate projections, and indeed this is the approach used by Kunkel et al. (2013) in the National Climate Assessment support documents. The motivation for this usage comes from medium range weather forecasting, where the ensemble mean has been shown on average to be a better prediction than even the best individual member (Christensen et al. 2010). The most common method for producing the ensemble mean is to take the simple arithmetic average of all participating models. Alternative methods have been proposed in which the participating models are unequally weighted (e.g., Giorgi and Mearns 2003). However, recent research concluded "we do not find compelling evidence of an improved description of mean climate states using performance-based weights in comparison to the use of equal weights" (Christensen et al. 2010, p. 179). Transferring this concept to climate projections is hindered

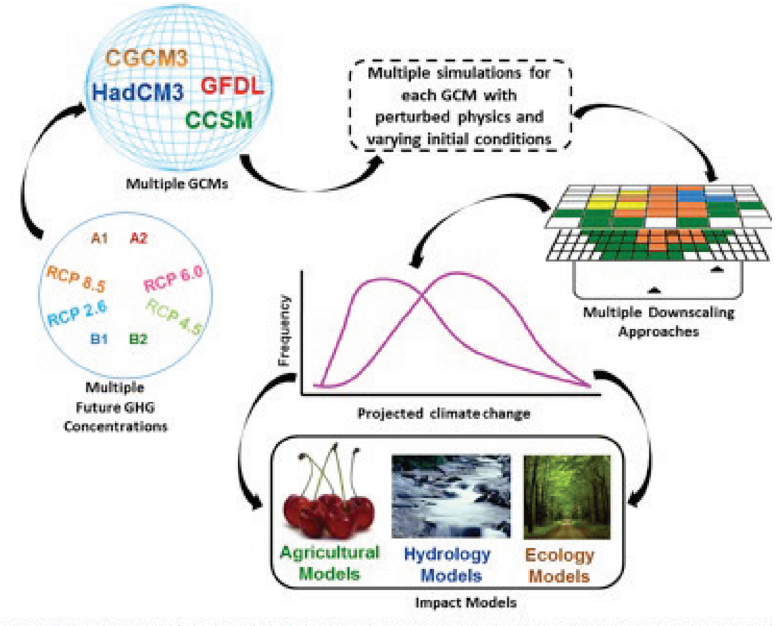


Figure 3.3. Development of an ensemble of climate projections. The dashed line indicates uncertainty sources that are infrequently considered. *Source*: Winkler et al. (2011b).

by the interdependence among the ensemble members, as GCMs and RCMs employ similar numerical schemes and parameterizations (Tebaldi and Knutti 2007). Because of this interdependence, consensus among projections should not be confused with skill or reliability (Maraun et al. 2010). Another situation where a multi-model mean may be misleading is when some members of an ensemble project a positive change in a climate variable while others project a negative change. In this case, the multi-model mean of the projected change can approach zero, even though all of the ensemble members project a substantial change but of opposite sign. The near-zero ensemble mean may be interpreted as "no change" when an arguably more informative interpretation is that the nature of the change is uncertain. Precipitation projections tend to be highly uncertain and often of opposite sign; thus, simple multi-model means may not be very informative in considering future changes in precipitation.

3.2.3.3 "Shelf Life" of Climate Projections

The National Climate Assessment organizers have requested that any new analyses for the assessment utilize climate projections developed from IPCC AR4 era GCMs. On the other hand, the available peer-reviewed literature for a particular sector or region employs climate projections from older versions of GCMs in addition to more recent simulations. In fact, there is often a substantial lag between the release of new GCM simulations and the development of downscaled climate projections, and a further lag associated with the evaluation of the downscaled projections and their use in applications. Thus, much of the literature reviewed for the National Climate Assessment will have employed simulations from earlier versions of GCMs. As pointed out by Winkler et al.

(2011b), the common assumption is that once a newer version of a GCM is available scenarios based on older versions are obsolete. Against this view it can be argued that older model runs have an advantage in that they often have been extensively compared to observations. Thus, the characteristics and limitations of older model runs are better understood than are those of newer models that have not been as thoroughly evaluated. Additionally, recent guidance from the IPCC (Knutti et al. 2010) suggests that it may be appropriate to combine GCM simulations from different "eras" in an ensemble. Concomitantly, it is appropriate to integrate outcomes from assessment studies that used climate projections developed from older versions of GCMs with those that employed scenarios developed from more recent GCM simulations.

3.2.4 EVALUATION OF CLIMATE PROJECTIONS

Evaluation is the responsibility of both the suppliers and the users of climate projections. Here we summarize recent attempts for the Midwest region to evaluate GCM projections and RCM simulations available from NARCCAP. These examples were selected to illustrate evaluation techniques and strengths and weaknesses of climate projections. Although evaluation examples are provided for only one downscaling method (i.e., dynamical downscaling), evaluation is also a necessary step for statistical downscaling. An important consideration is that the evaluation needs to be conducted in light of the potential application, and the climate variables included in an evaluation should reflect the key concerns of the application. As an example, a recent evaluation of an empirical-dynamical downscaling procedure employed a large suite of precipitation metrics selected to represent future changes in precipitation thresholds and extremes including, among others, wet day probability, mean dry spell length, wet day precipitation intensity, and the 90th percentile of wet day precipitation (Schoof et al. 2010).

3.2.4.1 GCM Simulations

Several studies have provided information on GCM performance relevant to the Midwest region. Ruiz-Barradas and Nigam (2010) examined precipitation over North America in four GCMs (CCSM3, GFDL CM2.1, HadCM3, and ECHAM5). They noted seasonal differences in regional precipitation biases, with the western U.S. generally being too wet in spring and the central U.S. being too wet in summer (except for CCSM3). They found that interannual variability of precipitation in the Great Plains region (which includes the western part of the Midwest region that is our focus) was generally similar to observed values, although the performance of each model was not necessarily consistent across seasons. The models varied in their ability to capture remote influences of sea-surface temperature on Great Plains precipitation, with CCSM3 failing to reflect the observed correlation with central Pacific sea-surface temperature. McCrary and Randall (2010) examined 20th century drought over the Great Plains in three GCMs (CCSM3, GFDL 2.0, and HadCM3). They found that all of the models produced excessive precipitation over the Great Plains. Simulated drought for the region was comparable to observations, but the models differed in the nature of their drought forcing. While drought in GFDL CM2.0 and HadCM3 corresponded with low-frequency variations in sea-surface temperature, CCSM3 showed no significant correlation between precipitation and tropical Pacific sea-surface temperature (which is broadly consistent with the findings of Ruiz-Barradas and Nigam 2010). They suggest that drought persistence in CCSM3 may be related to local feedbacks arising from that model's tight land-atmosphere coupling.

In a more comprehensive study, Wehner et al. (2011) evaluated 19 models from CMIP3 focusing on their ability to reproduce observed temperature, precipitation, and drought incidence over North America as measured by the Palmer Drought Severity Index (PDSI). Results for the North American domain as a whole showed that all models underpredicted the areal extent of drought. Although Wehner et al. (2011) did not focus specifically on the Midwest, their computations of ensemble means across all models show that over most of the Midwest temperature bias is slightly negative while precipitation bias is small. As noted elsewhere, ensemble means can hide substantial intermodel variability, and the authors noted substantial variations in performance amongst the models. Diagnoses of PDSI from projections through the 21st century following the A1B emissions scenario showed that all models produced increases in the frequency and severity of drought. An interesting finding from their study is that much of the variability amongst the model projections, which often has been taken as a measure of uncertainty, results from differences in climate sensitivities amongst the models (i.e., projected temperature change for a given change in greenhouse gas concentrations). Variations in model projections for drought were lower when the models were referenced to a given temperature change rather than a given time period.

3.2.4.2 NARCCAP Simulations

Evaluation of downscaled near-surface variables for a historical period can be used to assess the skill of the downscaling. Mearns et al. (2012) examined a variety of skill metrics for NARCCAP simulations of precipitation and temperature in current climate (1980-2004) using reanalysis fields as boundary conditions. Consistent with other studies, they found there was no single best model across all metrics. There were suggestions of an advantage for regional climate models that use spectral nudging, in which the largest spatial scales of the boundary data are used to constrain the interior of the model domain as well as the boundaries.

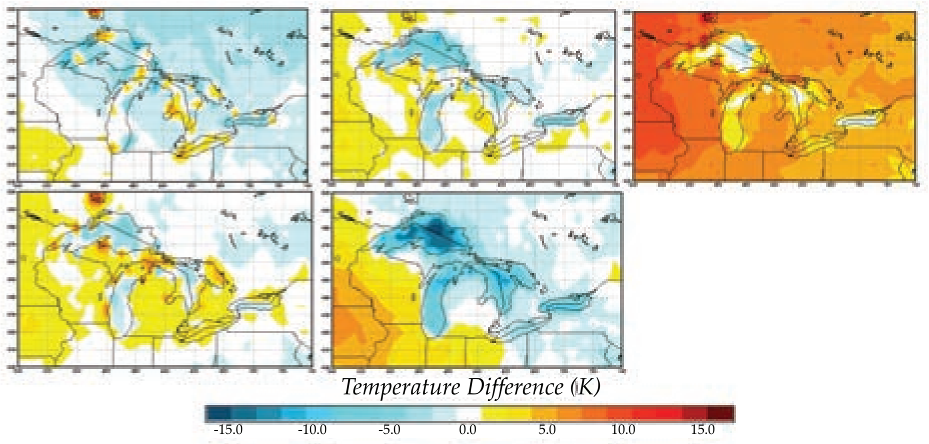
Evaluations using the NARCCAP suite to simulate multiple descriptors of wind climates over the contiguous U.S. (Pryor and Barthelmie 2011; Pryor et al. 2012b; Pryor and Barthelmie 2013a;) suggest that application of the RCMs improves the simulation of wind climates during 1979-2000 relative to the driving reanalysis and that the RCMs exhibit some skill in depicting historical wind regimes. Furthermore, evaluation of 50-year return period wind speed derived from the NARCCAP output for the historical period (1979-2000) relative to extreme wind speed estimates computed from station observed daily maximum fastest mile speeds at 35 stations across the contiguous U.S. revealed that the RCMs exhibit some skill in capturing the macro-scale variability of extreme wind speeds. Simulations of intense and extreme wind speeds by the RCMs were found, at least to some degree, to be independent of the lateral boundary conditions, instead exhibiting greater dependence on the RCM architecture. Although not employing

NARCCAP simulations, a recent analysis of dynamically-downscaled wind speeds for a nominal height of 10 meters with the lowest model level (approximately 70 meters above ground level) from the Rossby Center RCM (RCA3) run at four resolutions (ranging from 50 x 50 kilometers to 6 x 6 kilometers) found that model resolution had a larger impact on wind extremes than the central tendency (Pryor et al. 2012c).

An understanding of the spatial differences in the performance of downscaled projections, such as the dynamically-downscaled NARCCAP simulations, is critical when interpreting projected future changes. Such analyses of skill suggest considerable differences between RCMs and for different variables (e.g., Pryor et al. 2013). Cinderich (2012) compared results for the Great Lakes region from the NCEP-driven simulations for five of the RCMs in the NARCCAP suite to 32-kilometer resolution temperature and precipitation values from the North American Regional Reanalysis (NARR; Mesinger et al. 2006) for 1981-2000. Large inter-model differences are evident (Figure 3.4). January mean temperatures from the HRM3 simulation are considerably warmer than NARR temperatures across the entire Great Lakes domain, whereas for the other RCMs the January mean temperatures are warmer than NARR only in the southwestern and/or western portion of the domain. In contrast, the simulated July mean temperatures are cooler than the NARR values across much of the domain for the ECP2, MM5I, and WRFG simulations. The CCRM and NARR July mean temperatures are comparable across most of the U.S. portion of the Great Lakes region, whereas the HRCM3 mean July temperatures are warmer than NARR in the western portion of the domain. For both months, large deviations in air temperature are seen over the Great Lakes. These differences likely reflect errors in both the RCM and NARR temperature fields. In January, the RCMs, particularly ECP2, tend to overestimate mean daily precipitation compared to NARR in the northern portion of the Great Lakes region, whereas in July precipitation is underestimated in the southwestern and/or western portions of the domain (Figure 3.5).

A further evaluation of NARCCAP simulations for the Midwest focused on the differences in the distribution of daily maximum and minimum temperatures between the observations at individual stations along the eastern shore of Lake Michigan and the NCEP-driven RCM-simulated temperature at the nearest land grid point (Z. Abraham et al., personal communication). Additionally, GCM-driven RCM simulations for a historical period are compared to observed values and the simulated values from the NCEP-driven run. For brevity, histograms are shown for only one location (Eau Claire, Michigan) and one RCM (WRFG). When the annual distribution of daily maximum and minimum temperature is considered (top two histograms in Figure 3.6), the frequency distribution obtained from the NCEP-driven WRFG simulation follows closely the observed distribution. However, when the observed distributions are compared to the frequency distributions for the historical simulations driven by the GCMs (bottom histogram in Figure 3.6), larger deviations are observed, particularly a substantial cold bias for the CCSM-driven simulation. Comparison by season suggests that this cold bias is particularly large during winter. These comparisons indicate that, at least for some assessment studies, application of bias correction procedures to the NARCCAP simulations should be considered.

January



July

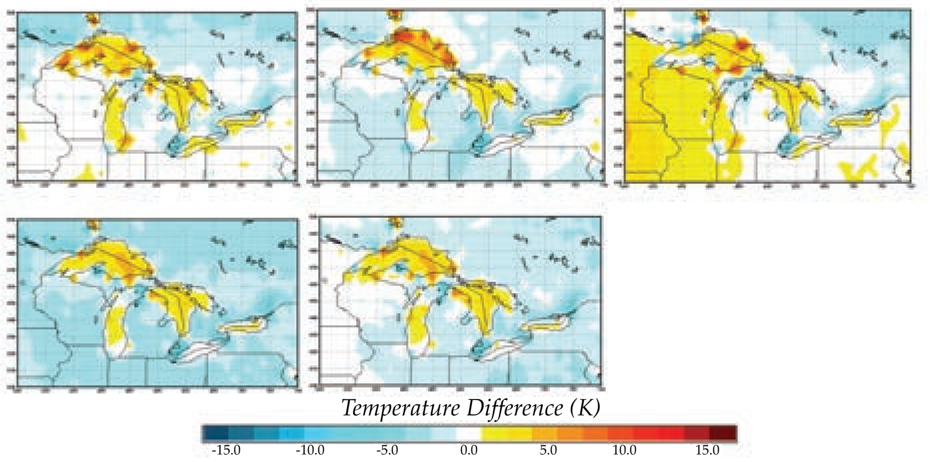
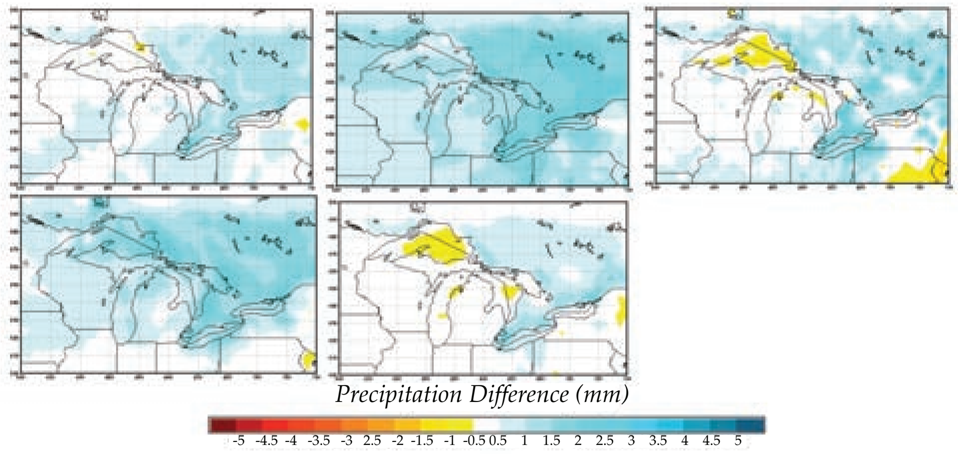


Figure 3.4. Mean surface-air temperature differences between NARR and five NARCCAP simulations for January and July. The top row (from left to right) shows the differences for the CRCM, ECP2, and HRM3 simulations and the bottom row the differences for the MM5I and WRFG simulations. *Source*: Cinderich (2012).

3.3 Projected Future Climate Change for the Midwest Region

The discussion below describes potential future change for three primary surface climate variables, namely precipitation, temperature, and wind. For each variable, we attempt to summarize and integrate the numerous climate projections available for the Midwest region, highlighting the consistency, when present, and the uncertainty surrounding the

January



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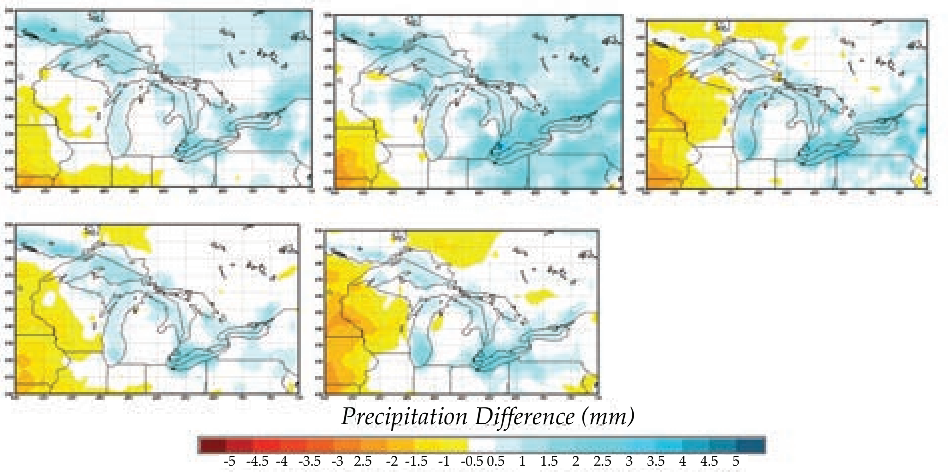

Figure 3.5. Differences in mean daily precipitation between NARR and five NARCCAP simulations for January and July. The top row (from left to right) shows the differences for the CRCM, ECP2, and HRM3 simulations and the bottom row the differences for the MM5I and WRFG simulations. *Source*: Cinderich (2012).

projections. As already noted, the available climate projections were developed from a range of GCMs utilizing a wide variety of downscaling methods.

3.3.1 PRECIPITATION

The majority of previous research on future precipitation change in the Midwest has focused on projected changes in annual and seasonal precipitation totals and on precipitation intensity.

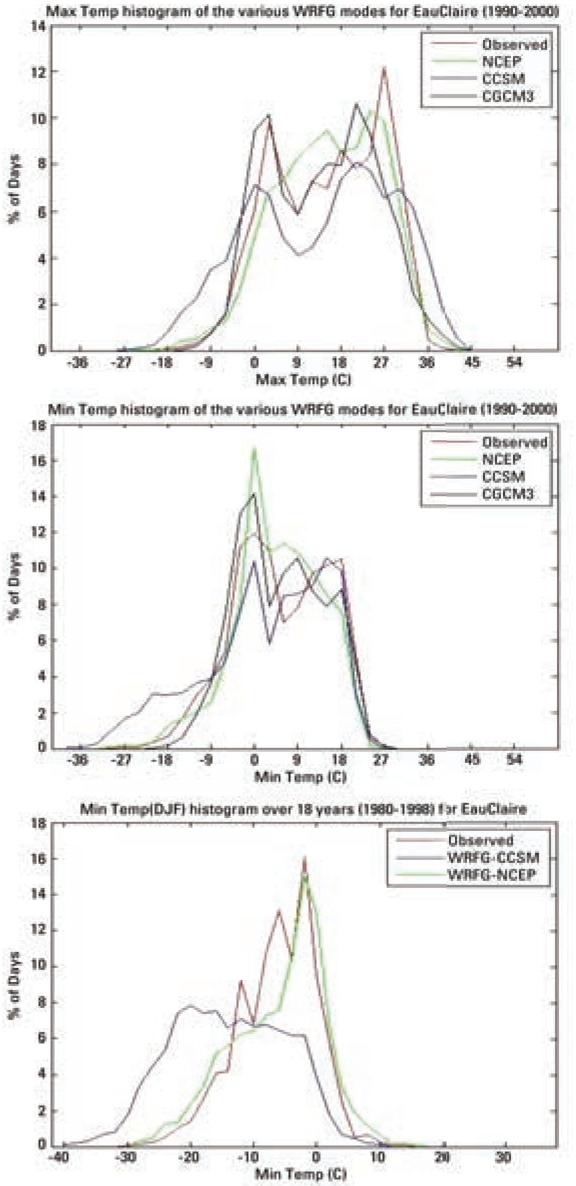

Figure 3.6. Histograms of the annual distribution of daily maximum (top panel) and minimum temperature (middle panel) for 1980-2000 a) observed at Eau Claire Michigan (red line), b) simulated by WRFG driven by NCEP reanalysis (green line), c) simulated by WRFG driven by the CCSM GCM (blue line), and d) simulated by WRFG driven by the CGCM3 GCM (black line). Bottom panel: Observed and simulated values of minimum temperature for winter (December, January, February). *Source*: Z. Abraham, P.-T. Tan, Perdinan, J. Winkler, and S. Zhong, Michigan State University, personal communication.

3.3.1.1 Annual and Seasonal Precipitation

The large degree of uncertainty surrounding precipitation projections for the Midwest has been evident since the initial U.S. National Climate Assessment completed in 2000 which employed simulations from only two IPCC Second Assessment era GCMs (i.e., CGCM1 and HadCM2). Whereas the CGCM1 scenario suggested much drier future conditions in the northwestern portion of the Midwest and annual increases of 20-40 percent elsewhere by the end of the century, the HadCM2 scenario projected increases in annual precipitation ranging from 20 to 70 percent across the Midwest by 2100 (Sousounis and

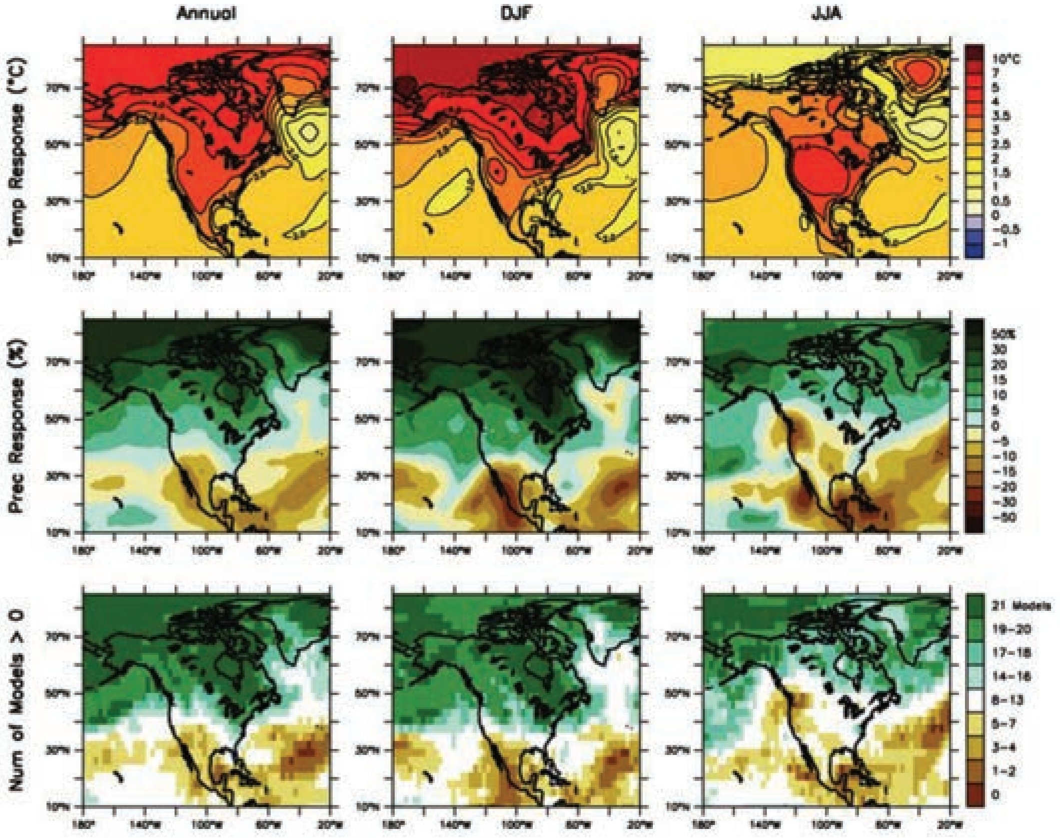

Figure 3.7. Temperature and precipitation changes over North America from the MMD-A1B simulations. Top row: annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle row: same as top, but for fractional change in precipitation. Bottom row: number of models out of 21 that project increases in precipitation. *Source*: Christensen et al. (2007).

Albercock 2000). In support of the IPCC AR4, 21 GCMs were utilized to simulate future conditions for 2080-2099 under the SRES A1B greenhouse gas emissions scenario (Christensen et al. 2007). The ensemble mean suggests an increase in annual and winter (December, January February) precipitation for most of the Midwest but little change or even a small decrease in summer (June, July, August) precipitation (Figure 3.7). The number of GCMs projecting an increase versus decrease in precipitation provides one measure of the ensemble spread. For the Lower Peninsula of Michigan and northern Ohio, Indiana, and Illinois, over 90 percent of the 21 GCMs project an increase in annual and wintertime precipitation by 2080-2099, and at least 67 percent of the models suggest increased precipitation elsewhere in the Midwest region. In contrast, approximately half of the 21 GCMs project an increase in summer precipitation in the Midwest by the end of the 21st century, with the other half suggesting a decrease or little change, again pointing out that a near-zero ensemble mean does not necessarily reflect a consensus of no change. Using the same set of GCMs, Hayhoe et al. (2010a) calculated region-wide estimates of precipitation change for the U.S. Great Lakes region under three different greenhouse gas emissions scenarios (A1FI, A2, B1). Projected changes in annual precipitation range from -2 to +10 percent for the mid-21st century, and by the end of the century only two of the 21 models project a decrease in annual precipitation with the remaining models suggesting higher annual precipitation for the U.S. Great Lakes region.

As expected, the uncertainty surrounding the GCM-projected precipitation is also evident for the projections downscaled from the GCMs. One example is the precipitation projections for Wisconsin developed by the Wisconsin Initiative for Climate Changes Impacts (WICCI). These scenarios were statistically downscaled from 14 GCMs from the CMIP3 archive (Kucharik et al. 2010; WICCI 2011). Ensemble averages suggest an approximately 25 percent increase in wintertime precipitation by the middle of the 21st century across the state, with more precipitation occurring as rain or freezing rain than currently. Similarly, ensemble averages suggest an increase in mean precipitation during early spring (i.e., March), although not in mid or late spring, with an approximately 50 percent increase by mid century in the amount of March precipitation falling as rain rather than snow. There is little agreement among the different climate scenarios regarding the sign of the projected change in summertime precipitation in Wisconsin. This is in contrast to the downscaled precipitation scenarios developed as part of the Pileus Project (Pileus Project 2007; Winkler et al. 2012) for neighboring Michigan from four IPCC Third Assessment era GCMs (CGCM2, HadCM3, ECHAM4, CCSM). These scenarios suggest drier conditions during summer (Andresen et al. 2007). The sign of the projected change for autumn precipitation in Wisconsin also varies among the WICCI climate projections, although the ensemble mean suggests an increase in precipitation especially for northern Wisconsin. Hayhoe et al. (2010a) also found considerable seasonal differences in the sign of the projected precipitation change for the U.S. Great Lakes region based on projections from three GCM simulations from the CMIP3 archive that were statistically downscaled to a 1/8° resolution. The scenarios developed by Hayhoe et al. (2010a) suggest an increase in regional precipitation in winter and spring, but not for summer and fall. Larger projected changes in winter and spring precipitation are found under higher greenhouse gas emissions, and the projected increases are greatest in the southern portion of the Great Lakes region (i.e., Illinois, Indiana, Ohio).

The projections of precipitation occurrence (the number of wet days) and precipitation intensity (the amount of precipitation on wet days) prepared by Schoof et al. (2010) for a large number of stations across the U.S. provide some additional insights on potential future changes in precipitation. These statistically-downscaled projections, developed from 10 IPCC AR4 era (CMIP3) GCMs, exhibit a high degree of variability, but results for the Midwest suggest several general tendencies: 1) a decrease in wet day probability during the cold season of around -5 percent and -8 percent for 2046-2065 and 2081-2100, respectively; 2) increased cool season (November-March) precipitation by mid and late century for over two-thirds of stations within the Midwest region, with the exception of the northwestern portion where ensemble averages suggest that cool season precipitation will decrease; 3) a decrease in the number of wet days by the end of the 21st century for summer (June, July, August) but with some inconsistencies between GCMs and stations; and 4) an almost equal number of stations within the Midwest region with projected increases and decreases in warm season precipitation in the 2046-2065 period, with the exception of the southwestern portion of the region where most stations display declining warm season precipitation.

The projections of future precipitation change obtained from the coarse-scale output from 15 GCMs from the CMIP3 archive and nine RCM simulations from the NARCCAP archive as described in the climate guidance document prepared for the National Climate Assessment (Kunkel et al. 2013) are generally consistent with the projections described above. The CMIP3 models project both increases and decreases in precipitation for mid and late-century time periods, as do the NARCCAP dynamically-downscaled projections. The ensemble means of annual precipitation for the NARCCAP simulations are largest (10-15 percent increase) in the Great Lakes region, particularly northern Wisconsin and the Upper Peninsula of Michigan, areas where earlier studies (e.g., Christensen et al. 2007) indicate greater consistency in the sign of the projected change. Consistent with the earlier results of Schoof et al. (2010), ensemble mean changes are smallest for the southwestern corner of the Midwest region, an area for which GCM projections display considerable uncertainty in the sign of the projected change (Figure 3.7). A similar but stronger southwest to northeast gradient is seen for the multi-model mean of precipitation change for the 15 CMIP3 models, with average projected changes for the end of the century ranging from approximately a 5 percent decrease in the southwestern portion of the Midwest region to close to a 10 percent increase in the northern portion.

The summaries provided in Kunkel et al. (2013) highlight seasonal differences in projected future changes in precipitation. Ensemble means for the NARCCAP projections suggest a substantial decrease in precipitation during summer in the extreme southwestern portion of the Midwest. Ensemble mean values are close to zero across the remainder of the Midwest region, very likely reflecting inconsistent signs in the projected summertime precipitation among the NARCCAP RCM simulations. The largest projected changes, as indicated by the ensemble means, occur in winter; the multi-model average suggests a precipitation increase of greater than 10 percent over much of the Midwest. The spatial distribution of the NARCCAP multi-model mean change for spring and fall suggests a northwest to southeast gradient with projected changes in fall and spring precipitation of over 10 percent increase in the northwestern portion of the Midwest and little change (again likely a reflection of inconsistent sign of the projected change) in the eastern and southeastern portions of the Midwest. This spatial pattern had not previously been seen in downscaled projections of spring and fall precipitation change.

3.3.1.2 Precipitation Intensity

Assuming warmer temperatures and consequent higher evaporation, available atmospheric moisture is likely to increase in the future, and one would expect precipitation intensity to increase as well. However, projecting future precipitation intensity is challenging, as the probability density function of daily precipitation rates needs to be well simulated in order to have confidence in the projected changes. This is not typically the case (see earlier discussion of evaluation of climate projections). A further complication is that the choice of probability density function for evaluating future changes may influence the interpretation. For example, Gutowski et al. (2007) note that while a gamma distribution can provide a useful general description of precipitation intensity and its change under future climates, other approaches may be more appropriate when considering precipitation extremes. Nevertheless, a small number of analyses have explicitly attempted to evaluate how precipitation intensity may change in the Midwest.

The aforementioned WICCI scenarios suggest that two to three additional heavy precipitation events, defined as a daily precipitation rate of two or more inches, can be expected per decade in Wisconsin by the mid-21st century. This would correspond to a 25 percent increase in the frequency of heavy precipitation. Kunkel et al. (2013) reported that the multi-model mean change in the number of days with precipitation greater than one inch from the NARCCAP simulations varies from little or no change in the southeastern and eastern portion of the Midwest region to an over 30 percent increase in the northern portion of the region by mid century. The percentage increases in frequency are projected to be larger for more extreme precipitation events (e.g., precipitation rates greater than one inch, two inches, three inches, and four inches). Amplification of large magnitude events was also reported in a separate analysis of the NARCCAP simulations that focused on the wettest pentad and top-10 wettest days of the year (Pryor et al. 2013). Schoof et al. (2010) found that, based on downscaled climate projections from ten GCMs, intense precipitation events in the Midwest are likely to either continue at their current frequency or increase in frequency, regardless of the sign of the change in total precipitation. Furthermore, the magnitude of the 90th percentile precipitation rate is projected to increase by mid and late century. They interpreted this finding as indicative of a positive shift in the central tendency and widening of the probability distribution for wet day precipitation intensities. The projected increase in frequency of heavy precipitation is broadly consistent with observed trends in the late 20th century as described by Groisman et al. (2012). They suggest that both global climate change and intensification of agricultural land use may have influenced this trend, and recommend experiments using regional climate models to quantify the relative roles of these influences.

3.3.2 TEMPERATURE

Below we highlight projected changes in annual and seasonal mean temperatures, commonly employed temperature indices (e.g., growing degree days), and temperature thresholds and extremes.

3.3.2.1 Annual and Seasonal Temperature

Although climate projections consistently indicate that annual and seasonal temperatures will increase by mid century and later, the degree of warming can differ substantially. Starting with the ensemble means from the 21 GCM simulations reported in the IPCC AR4 (Christensen et al. 2007), annual mean temperatures over the Midwest are expected to increase by approximately 5.5°F (3°C) by 2080-2099 under the A1B emissions scenario (Figure 3.7). The ensemble means suggest a larger increase in summer (June, July, August), ranging from approximately 8°F (4.5°C) over the western portion of the Midwest and 7°F (4.0°C) over the eastern portion, and in winter (December, January, February) a generally southwest to northeast gradient is projected with a mean increase of more than 6°F (approximately 3.5°C) in the southwestern portion of the Midwest and over 9°F (5°C) in the northeast. Based on the direct (not downscaled) analysis of the output from 21 CMIP3 GCMs, Hayhoe et al. (2010a) report an average increase in mean annual temperature by mid century of approximately 3.5°F (2°C) under lower emissions and approximately 5.5°F (3°C) under high emissions, and an increase by the end of the century of 5.5°F (3°C) under lower greenhouse emissions and 9°F (5°C) under higher emission. Kunkel et al. (2013) employed the same suite of 21 CMIP3 models, and found multi-model mean projected changes in annual mean temperature by the end of the 21st century ranging from approximately 9.5°F (5.3°C) in northwestern portion of the Midwest region to 7.5°F (4.2°C) in the southeastern portion for the A2 emissions scenario by the end of the century. A distinct northwest to southeast gradient in the multi-model mean projections of the change in annual mean temperature is also observed under the B1 emissions scenario and for a mid century time slice.

Downscaled climate projections in general project somewhat higher changes in annual and seasonal mean temperature than the global model output. The WICCI climate scenarios, downscaled from IPCC AR4 era GCM simulations under the A1B emissions scenario and averaged across all ensemble members, suggest increases in annual mean temperature of 4-9°F (2-5°C) in Wisconsin by the middle of the century (WICCI 2011). The WICCI scenarios project the largest warming to occur in northern Wisconsin and the least warming along Lake Michigan. Seasonal differences in the rate of warming are also seen from this set of climate projections. Projected warming is least in summer, ranging from 3-8°F (2-4°C) with larger changes projected for northern Wisconsin. In winter mean temperatures are projected to warm 5-11°F (3-6°C) by mid 21st century with the largest increases found in northwestern Wisconsin. Spring and autumn mean temperatures in Wisconsin are projected to increase at mid century by 3-9°F (2-5°C) and 4-10°F (2-6°C), respectively, with the largest increases in northern Wisconsin.

Compared to the WICCI projections, the downscaled projections developed by Hayhoe et al. (2010a) for the U.S. Great Lakes region from three CMIP3 models suggest greater complexity in the seasonal variations in projected changes. For an early period defined as 2010-2039, Hayhoe et al. (2010a) report larger projected changes in winter compared to spring and summer, but by mid century they found that the seasonality reversed with larger changes projected in summer compared to winter and spring. In terms of spatial variation, the Hayhoe et al. downscaled scenarios suggest larger increases in summer mean temperature in the southern portion of the region (e.g., Indiana, Illinois), whereas projected changes in mean winter temperature are largest in the northern portion (e.g., Wisconsin and Minnesota). Kunkel et al. (2013) found a similar spatial pattern in the distribution of projected temperature change by mid century in winter versus summer from the NARCCAP dynamically-downscaled projections for the Midwest. Additionally, the NARCCAP projections suggest relatively uniform projected changes in spring and autumn mean temperature across the Midwest by mid century.

3.3.2.2 Temperature Thresholds and Indices

Although the terms are sometimes used interchangeably, we make a distinction between a temperature "threshold" and a temperature "extreme". A temperature threshold refers to the exceedance of a specified temperature value, selected for its relevance to a natural or human activity or process. In contrast, a temperature extreme is defined in reference of the frequency distribution of temperature and refers to the magnitude of the temperature values at specified probability levels (e.g., the 95th percentile). We confine the discussion below to temperature thresholds, as they have been the focus of most analyses of climate projections for the Midwest. We also discuss in this subsection commonly-used temperature indices, such degree days which are a measure of heat accumulation from a specified base value.

Not surprisingly, the frequency of freezing (≤32°F, ≤0°C) temperatures is expected to decrease in the future. The Pileus Project projections for 15 locations in Michigan and surrounding states, when averaged across all ensemble members, suggest that by mid century approximately 15 fewer days will experience minimum temperatures below freezing, whereas by the end of the century a decrease of more than 30 days is projected (Pileus Project 2007). Ensemble means for the NARCCAP simulations, when averaged over the entire Midwest region, suggest that by mid century 22 fewer days per year will report minimum temperatures below ≤32°F (≤0°C) (Kunkel et al. 2013), although spatial and inter-model variations are apparent.

Changes in the frequency of heat waves are of particular concern due to potential impacts on human health and mortality. The Pileus Project scenarios suggest for Michigan and surrounding areas that the number of days with temperatures ≥95°F (≥35°C), averaged across the ensemble members, will increase by 5 days by mid century and 19 days by the end of the 21st century (Pileus Project 2007). For the neighboring state of Wisconsin, the WICCI scenarios project an average increase by mid century in the frequency of maximum temperatures greater than 90°F (32°C) from approximately 26 days in the southern portion of the state to 12 days in the northern portion (WICCI 2011). Multi-model means from the NARCCAP simulation suite point to considerable spatial variability across the Midwest region, with an approximately 25 day average increase in the frequency of maximum temperatures ≥95°F (≥35°C) in the southern portion of the Midwest region and fewer than 5 days in the northern portion by mid century (Kunkel et al. 2013). The NARCCAP multi-model mean (i.e., a 5 day increase) for the northern Midwest is in good agreement with the mean projected value from the Pileus Project scenarios for the mid century time frame (Pileus Project 2007). Additional analysis of the NARCCAP simulations points to a potential increase in the length of heat waves in some parts of the Midwest. The multi-model means suggest that the annual maximum number of consecutive days per year with maximum temperature ≥95°F (≥35°C) will increase by 15 days in the extreme southern portion of the Midwest, although little change is expected across a broad swath of the northern Midwest. The downscaled scenarios developed by Hayhoe et al. (2010a,b) from three GCM simulations also suggest an increased risk of extreme heat waves. By the end of the century, the frequency of heat waves similar to the 1995 heat wave event responsible for nearly 800 deaths in Chicago (Kunkel et al. 1996) is projected to range from every other year (low greenhouse gas emissions) to three times per year (high greenhouse gas emissions). Furthermore, heat waves similar to the devastating European heat wave of 2003 could occur in the Chicago metropolitan area, with at least one such event projected before mid century and 5 to 25 events projected to occur by the end of the century, depending on the greenhouse gas emissions scenario (Hayhoe et al. 2010b).

The ensemble mean of the Pileus Project scenarios suggests that the median date of last spring freeze in Michigan could occur approximately a week earlier than present by mid century and two weeks earlier by late century, with similar changes, although toward a later date, in the median time of occurrence of first fall freeze (Pileus Project 2007). These changes in freeze dates should lead to an increase in the length of the frost-free season. The multi-model means of the NARCCAP simulations suggest a fairly uniform increase across the Midwest of approximately 20-25 days in the length of the frost-free season by mid century (Kunkel et al. 2013). The projected changes based on the Pileus Project scenarios are somewhat smaller with an increase for Michigan of approximately 15 days projected for mid century and 29 days for late century, although substantial differences are evident between the ensemble members.

Warmer temperatures can be expected to reduce heating requirements but increase cooling requirements, and the climate projections available for the Midwest region support this interpretation. The NARCCAP multi-model means, when averaged across the region, suggest a 15 percent decrease in heating degree days by mid century (Kunkel et al. 2013). When viewed spatially, greater reductions are seen in the northern portion of the region although the north-south gradient is relatively weak. The magnitudes of the projected changes in cooling degree days are anticipated to be larger than the absolute changes in heating degree days. The NARCCAP multi-model means suggest a 66 percent increase in cooling degree days, when averaged across the Midwest region. However, a strong south to north gradient is projected with considerably larger increases in cooling degree days in the southern portion of the region. The Pileus Project scenarios (Pileus Project 2007) suggest a somewhat smaller increase of cooling degree days compared to the NARCCAP simulations. The ensemble mean for the Pileus Project scenarios suggests an approximate increase of 200 cooling degree days in the Lower Peninsula of Michigan compared to an increase of 400 CDDs in the same region projected by the NARCCAP simulations.

Finally, growing degree day (GDD) accumulations in the Midwest are projected to increase. The areally-averaged NARCCAP multi-model mean suggests a 32 percent increase for the Midwest in base 50°F (10°C) GDDs by mid century (Kunkel et al. 2013), whereas the Pileus Project scenarios project an average increase for Michigan of 14 percent for base 41°F (5°C) GDDs and 19 percent increase for base 50°F (10°C) GDDs by mid century (Pileus Project 2007). Larger average increases of 33 percent and 45 percent are anticipated in Michigan for base 41°F (5°C) GDDs and base 50°F (10°C) GDDs, respectively, by the end of the century.

3.3.2.3 Freeze Risk

One cannot assume that warmer temperatures will bring more favorable conditions for plants such as perennials that currently are vulnerable to springtime freeze damage. Early spring warm-ups may result in greater freeze risk if plants are at a more advanced stage of development at the time of last spring freeze. On the other hand, if the date of last spring freeze advances to a much earlier date in synchrony with plant development, spring freeze risk may not change or even decrease. Considerable uncertainty exists regarding the future susceptibility of perennial plants in the Midwest to below freezing temperatures when preceding crop development is considered. Winkler et al. (2013), using a suite of climate projections for 15 locations in Michigan and surrounding states that were developed by applying several empirical-dynamical downscaling methods to four IPCC Third Assessment era GCMs, found that approximately half of the scenarios project for the mid and late century little change in GDD accumulation (used as a measure of plant development) at the time of last spring freeze, whereas the other half project greater crop development at the time of freezing temperatures. Similarly, an approximately equal number of scenarios suggest an increase versus a decrease in the median GDD accumulation outside the frost free period (i.e., the growing season).

3.3.2.4 Apparent Temperature

In the Midwest, high summer temperatures are often accompanied by elevated near-surface humidity, which increases human heat stress through reduction of evaporative cooling from the skin. The combined effect of temperature and humidity on human heat stress is often quantified using “apparent temperature”. While historical tendencies in air temperature over the Midwest have been of comparatively modest magnitude, apparent temperatures have exhibited marked increases, driven in large part by increases in atmospheric moisture (Rogers et al. 2009). Projections for future apparent temperature regimes across the Midwest derived using disaggregation downscaling of 10 GCMs under three greenhouse gas emissions scenarios all suggest an increase in the magnitude of apparent temperature, with a substantial fraction of the increase deriving from increased humidity (Schoof 2013). This is also consistent with projections from the NARCCAP RCMs (Pryor et al. 2013). Thus the probability of heat stress events is projected to increase across the Midwest in the coming decades relative to the historical period. This interpretation is complicated, however, by the few attempts to downscale coarse-scale humidity projections for the Midwest region.

3.3.3 WIND

Recent analyses of RCM output from the NARCCAP suite have focused on possible climate change signals across a range of wind climate descriptors including the mean, 50th percentile, 90th percentile, 95th percentile, 20 and 50 year return period wind speeds and wind energy density (i.e., wind resource) (Pryor and Barthelmie 2011; Pryor et al. 2012b). Some of these analyses assessed whether there was consistency in the change of the different parameters in the middle of the current century versus the end of the twentieth century. The results generally display only a weak consistency on the climate change signal in any of the descriptors. However, approximately 22 percent of grid cells show a lower 90th percentile wind speed in all of the RCM simulations. In keeping with results of analyses that indicate the RCMs generally develop extreme wind climates that are to some degree independent of the lateral boundary conditions, extreme wind speeds are generally not characterized by a consistent change on the basis of the eight

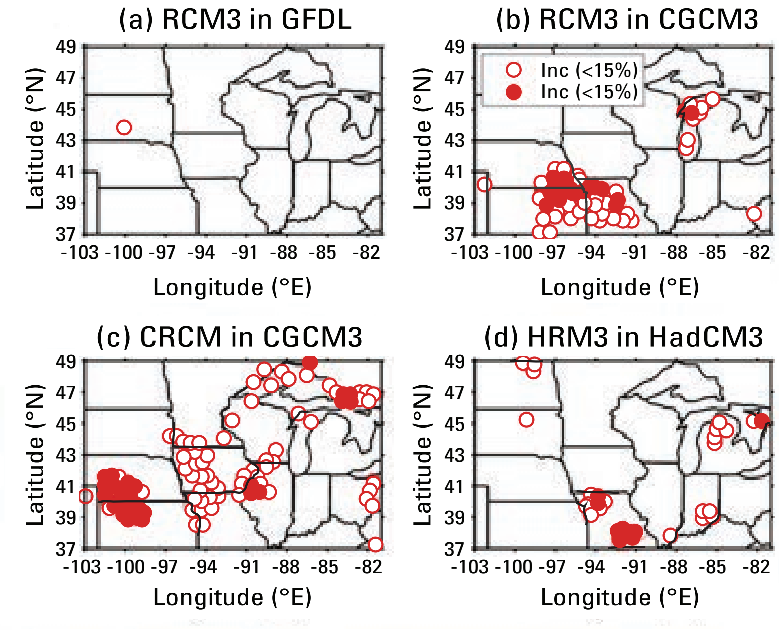

Figure 3.8. Difference in the fifty-year return period sustained wind speed (U_{50yr}) over the Midwestern US for 2041–2062 vs. 1979–2000. The frames show the different AOGCM-RCM combinations. The magnitude of change is only shown for grid cells where the value for the future period lies beyond the 95 percent confidence intervals on the control period. Note; none of the grid cells behind the legend in frame (b) exhibited significant changes. *Source*: Pryor and Barthelmie (2013b).

sets of simulations considered. Only 1 percent of grid cells over the contiguous USA indicate a consistent signal of either higher or lower values for the 20- or 50-year return period wind speed in the future. Changes in 50-year return period wind speeds over the Midwest from four of the NARCCAP simulations are shown in Figure 3.8. As for the entire NARCCAP domain, relatively few grid cells within any of the GCM-RCM combinations exhibit substantially higher or lower values for the extreme wind speed in the future. However, it is important to note that the wind climate exhibits large inherent variability at a range of time scales from minutes to decades. Analyses of a single future period of only 22 years duration precludes general inferences regarding trends in any aspect of the wind climate. Earlier research over Europe has shown that in the near-term, inter-annual and inter-decadal variability dominate over any temporal trend and that, based on results of dynamical downscaling, intense and extreme winds are unlikely to evolve out of the historical envelope of variability until the end of the current century (Pryor et al. 2012a).

3.4 Level of Confidence

The expert judgment of the authors with respect to the level of confidence that can be placed on future climate projections for the Midwest region is:

- There is no single best climate model or downscaling approach.
- There is greater confidence in projected temperature change than precipitation change.
- In spite of confidence in future warmer temperatures, change in freeze risk remains uncertain.

- The degree of uncertainty surrounding precipitation change remains high, although annual precipitation and precipitation during the cool season are expected to increase, particularly for the eastern portion of the Midwest region.
- There is little confidence in the sign (positive or negative) of change in mean precipitation for the warm season. There is somewhat greater confidence in projections of increases in the frequency and intensity of extreme warm season precipitation events.
- The use of a multi-model mean of a projected change may be misleading, particularly for projected changes in precipitation.
- Wind climates, including high impact wind events, remain challenging to simulate with the validity necessary to make assertions regarding the likelihood of change.

3.5 Summary

In this chapter we introduce readers to key considerations when using and interpreting climate projections with a specific focus on the U.S. Midwest region. Climate models and climate downscaling techniques are evolving, and model skill with respect to representing features of the current and historical climate is improving. Nevertheless, as documented herein, uncertainties remain, particularly with respect to the ability to project changes in high impact, low probability events, and confidence in future projections is generally higher for thermal regimes than for hydroclimates or wind climates.

Climate projections from multiple sources display close agreement regarding future changes for the Midwest in annual and seasonal mean temperature, the frequency of temperature thresholds including heat wave occurrences, and the magnitude of temperature indices such as degree day accumulations. Comparison and integration of the downscaled temperature projections also illuminate relatively consistent spatial patterns in projected future temperature change across the Midwest. In contrast, projections of future precipitation change remain highly uncertain for the Midwest. The majority of climate projections are in agreement regarding the sign of the projected change for only the winter season. Precipitation intensity is generally projected to increase by the mid and late century, although error in the downscaled simulations of the frequency distribution of daily and sub-daily precipitation for the current climate complicates interpretation of future changes in intensity. Given the importance of extreme hydroclimatic conditions to the region, improved simulation of precipitation is a high priority. Wind climates, particularly wind extremes, represent a major vulnerability to the Midwest. Some wind extremes occur at scales below those captured by global and regional climate models or involve processes that are not well understood, but the current suite of climate projections suggests little change in wind resources or wind extremes to the middle of the current century.

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Chapter 4

Agriculture in the Midwest

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4.1 Introduction

Agriculture in the Midwest (Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) represents one of the most intense areas of agriculture in the world. This area is not only critically important for the U.S. economy but also for world exports of grain and meat. In the 2007 Census of Agriculture these states had a market value of crop and livestock products sold of $84,502,675,000 (USDA 2007). Within the U.S., Illinois, Iowa, and Minnesota ranked 2nd, 3rd, and 4th in the value of crops sold; Iowa ranked 3rd in the value of livestock, poultry and their products; and Wisconsin ranked 7th in the value of livestock, poultry and their products sold. The economic value of agriculture in the Midwest encompasses corn, soybean, livestock, vegetables, fruits, tree nuts, berries, nursery and greenhouse plants. The economic value of the crop and livestock commodities in these states continues to increase because of rising prices.

Midwestern states are considered to be the Corn Belt; however, there is a diversity of agricultural production beyond corn and soybean. Area in corn for the Midwest in 2007 was 21,678,694 hectares followed by soybean with 16,169,269 hectares. The diversity of agricultural production is shown in Table 4.1 for the amount of the commodity produced and the state rank based on the 2007 Census of Agriculture (USDA 2007).

The impact of climate on agricultural production in the Midwest varies among years particularly in grain, vegetable, and fruit production. Fortunately, there are extensive records of agricultural production across the Midwest which allow for a detailed examination of the variation among years, the relationship to changes in the weather in each growing season, and the changing climate over a long time period in the Midwest. Variation among the years for corn grain can be seen in the records since 1866 for Iowa and Michigan production (Figure 4.1), soybean for Illinois and Indiana (Figure 4.2), sweet corn in Minnesota and Wisconsin (Figure 4.3), and potato in Michigan and Wisconsin (Figure 4.4).

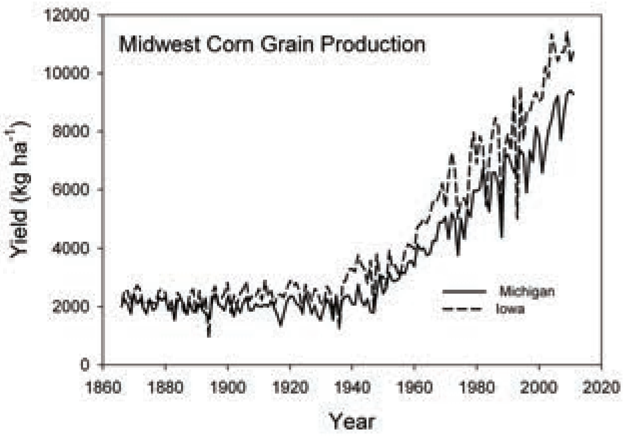

Figure 4.1. Annual corn grain yields for Iowa and Michigan from 1866 through 2011. *Source*: USDA-NASS.

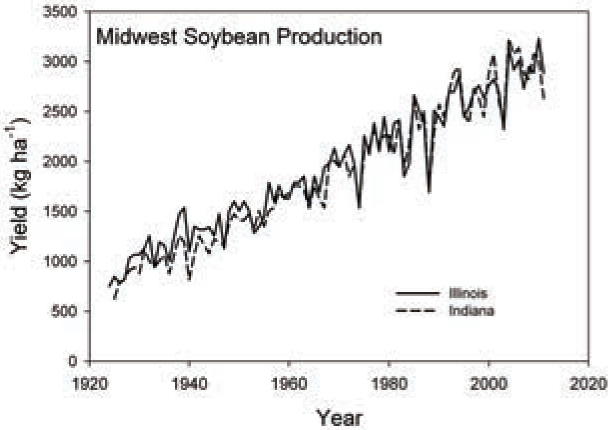

Figure 4.2. Annual soybean grain yields for Illinois and Indiana from 1924 through 2011. *Source*: USDA-NASS.

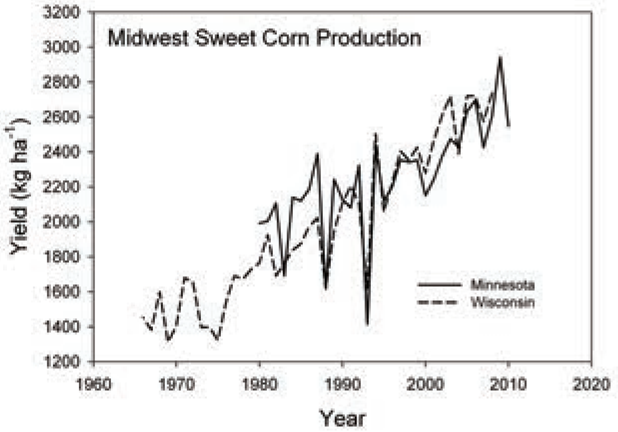

Figure 4.3. Annual sweet corn production from 1968 through 2010 for Minnesota and Wisconsin. *Source*: USDA-NASS.

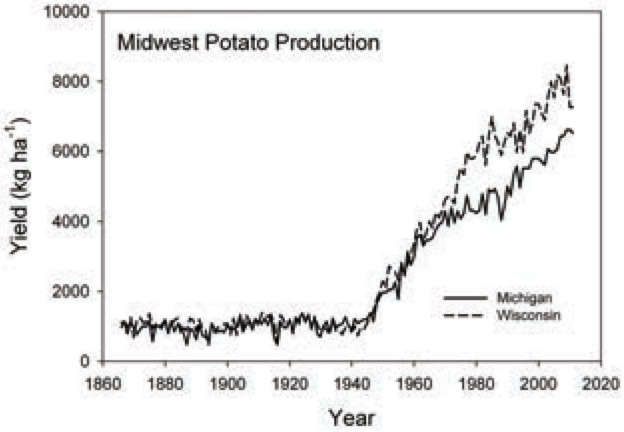

Figure 4.4. Annual potato production for Michigan and Wisconsin from 1866 through 2011. *Source*: USDA-NASS.

Table 4.1 Commodities produced and state rank for the Midwest region of the United States. Data from Census of Agriculture 2007, USDA-NASS (www.nass.usda.gov)

	Illinois		**Indiana**		**Iowa**		**Michigan**		**Minnesota**		**Missouri**		**Ohio**		**Wisconsin**	
Commodity	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank	Amount	Rank
Livestock (millions of animals)																
Layers	5.3	18	24.2	3	53.8	1	9.0	14	10.6	11	7.2	16	20.1	2	4.9	19
Hogs and pigs	4.3	4	3.7	5	19.3	1	1.0	14	7.6	3	3.1	6	1.8	10	1.1	
Pullets	0.9	28	6.9	5	11.4	1	2.0	16	3.2	1	2.6	14	6.8	6	1.2	22
Turkeys	0.8	19	6.0	7	4.0	9	2.0	16	18.3	1	8.6	4	2.0	14	3.7	10
Cattle and calves	1.2	26	0.6		3.9	7	1.0	30	1.5		4.3	6	0.8		3.4	9
Broilers	0.3		5.5	23	10.2		4.0		8.6	2	45.7	4	10.0	20	7.1	22
Milk and other dairy products from cows ($100,000)																
	340.3	20	583.2	14	689.7	12	1,285.6	7	1,475.9	6	302	24	861.3	11	4,573.3	2
Crop Production (1000 Hectares)																
Corn for grain	5,300.0	2	2,574.9	5	5,614.1	1	951.3	11	3,157.1	4	1,368	9	1,459.4	8	1,315.6	10
Soybean	3,356.5	2	1,936.0	4	3,485.6	1	694.3	12	2,539.0	3	1,891	5	1,714.4	6	551.6	15
Forage	240.1	32	221.3	33	455.5	23	469.6	21	964.7	15	1,577	4	468.0	22	1,132.1	7
Corn for silage	30.4		42.9	17	89.3	8	120.3	7	175.4		28		74.0	11	296.5	1
Oats for grain	1				27.0	7										
Wheat for grain	360.8	12	146.7	19	11.9		211.7	17	691.4	10	356	14	296.3	15	113.5	
Sorghum for grain	31.0	11														
Sugarbeets for sugar									196.5	1						
Vegetables											12				120.3	4
Cotton											153					

[1] Cells with no values entered represent a very small land area and production of the specific commodity

4.2 Historical Impacts on Crop Production

Climate impacts on crop production are detectable throughout the history of observations in the U.S. There is another trend which is noteworthy in these observations which is related to the rapid and steady increase in annual production for crops beginning after the mid-1940's with the introduction of commercial fertilizers and enhanced genetic materials. However, the introduction of improved agronomic practices has not alleviated the effect from years with large impacts caused by unfavorable weather during the growing season. Soybean production has shown a steady increase since records began for the Midwest in 1924, and there are years with large reductions in yield which are related to extremes due to drought (1988) or flooding (1993). In the grain crops, exposure to extremes, e.g., drought in 1988, created a 30% reduction in yield, and the floods of 1993 caused a 44% reduction in the potential sweet corn yield for that year as defined by Hatfield (2010). Water availability is the dominant climatic factor causing yield variation among years. The effects of weather within a growing season on crop yield are not isolated to a local region and are often observed across large areas of the Midwest, as evidenced by the spatial extent of the billion dollar events affecting agriculture (NOAA 2012). For example, the drought of 2012 affected agriculture across 23 states and reduced crop and animal production. However, yield decreases in most years average between 15-20% from the potential yield due to short-term exposure to stresses (Hatfield 2010). These stresses can be characterized as periods in which soil water is not available to meet the atmospheric demand or the temperatures are not in the optimal range for growth. Examination of the yield trends shown in Figs. 4.1, 4.2, 4.3, and 4.4 reveal that only a small fraction of the years in the yield record do not exhibit some degree of stress imposed by weather on crop growth or yield.

4.3 Sensitivity to Temperature

Temperature effects on plant growth have been extensively studied, and future impacts of climate change may be more related to changes in temperature compared to other climatic factors. Each of the crops grown in the Midwest has a specific temperature range characterized by a lower and upper limit at which growth ceases and an optimum temperature at which growth proceeds at a rate for maximum size of the plant. These temperature limits have been recently defined for several species relative to climate change by Hatfield et al. (2011). The effects of temperature as a climate change parameter have been recently evaluated by several different groups who suggest that temperature stresses may be extremely significant in terms of affecting crop growth and yield. Lobell et al. (2011) observed that the changes in temperature which have already occurred from 1980 to 2008 have reduced crop productivity. They concluded that corn (*Zea mays* L.) yields declined 3.8% and wheat (*Triticum aestivum* L.) declined 5.5% compared to the yields without climate trends. An important conclusion from this research was the observation that climate trends have a significant enough effect to offset the yield gains from technology and CO_2 increases. Kucharik and Serbin (2008) reported that projected corn and soybean (*Glycine max* (L.) Merr.) yields for Wisconsin would be significantly impacted because of rising temperatures. Analyses such as these and the results reported by Hatfield (2010) reveal that climate has already affected crop production. The recent study by Schlenker and Roberts (2009) discussed the potential nonlinear effects of warming temperatures on crop yields in the United States and showed there would be large impacts on productivity because of plants being exposed to conditions which are outside the thermal boundaries for optimal growth. A challenge for research is to begin the process of quantifying the temperature response of plants.

One of the changes in the climate which has a negative impact on plant growth and yield is the increase in the nighttime temperatures. The effect of minimum temperatures on plant growth has been observed in the small grains, e.g., wheat and rice (*Oryza sativa* L.). When temperatures increased above 14°C there was a decreased photosynthesis after 14 days of stress causing wheat grain yields to decrease linearly with increasing nighttime temperatures from 14 to 23°C, which in turn leads to lower harvest indices (Prasad et al. 2008). In their studies, when nighttime temperatures increased above 20°C there was a decrease in spikelet fertility, grains per spike, and grain size. Temperature effects on pollination and kernel set in corn may be one of the critical responses related to climate change. Pollen viability decreases when plants are exposed to temperatures above 35°C (Herrero and Johnson 1980; Schoper et al. 1987; Dupuis and Dumas 1990). Pollen viability (prior to silk reception) is a function of pollen moisture content and strongly dependent on vapor pressure deficit (Fonseca and Westgate 2005). Although there is limited data on sensitivity of kernel set in maize to elevated temperature, there is evidence suggesting the thermal environment during endosperm cell division phase (8 to 10 days post-anthesis) is critical (Jones et al. 1984). Temperatures of 35°C compared to 30°C during the endosperm division phase reduced subsequent kernel growth rate (potential) and final kernel size, even after the plants were returned to 30°C (Jones et al. 1984). When corn plants are exposed to temperatures above 30°C, cell division was affected which reduced the strength of the grain sink and ultimately yield (Commuri and Jones 2001). Leaf photosynthesis rate has a high temperature optimum of 33 to 38°C with a reduction in photosynthesis rate when corn plants are above 38°C (Crafts-Brandner and Salvucci 2002). In a controlled environment study on sweet corn (*Zea mays* L. var. *rugosa*), Ben-Asher et al. (2008) found the highest photosynthetic rates occurred at temperatures of 25/20°C while at 40/35°C (light/dark) photosynthetic rates were 50-60% lower. They concluded from these observations that photosynthetic rate declined for each 1°C increase in temperature above 30°C. The expectation is that corn grain plants would show a similar response. In soybean, there is a temperature effect and a comparison of growth at 38/30°C versus 30/22°C (day/night) temperatures, revealed elevated temperatures reduced pollen production by 34%, pollen germination by 56%, and pollen tube elongation by 33% (Salem et al. 2007). Exposure to air temperatures above 23°C caused a progressive reduction in seed size (single seed growth rate) with a reduction in fertility above 30°C leading to a reduced seed harvest index at temperatures above 23°C (Baker et al. 1989).

4.4 Potential Future Impacts

The chances for continued impacts for climate change are increasing according to a recent study by Rahmstorf and Coumou (2011) in which they attributed the extreme heat events in Russia during 2010 to climate change and concluded these extremes would not have occurred without climate change. They projected an increase in extremes to occur around the world as a result of climate change. The expectation for a changing climate both in means and extremes will cause impacts on agriculture.

4.4.1 TEMPERATURE

Increases in high temperatures are not the only effect on crops. Although there has been a warming trend in temperatures, the freeze-free season has only lengthened slightly (Hatfield et al. 2008; Hatfield et al. 2011, Walthall et al. 2012). As perennial plants produce flower buds earlier in the spring due to warmer temperatures, they could be exposed to relatively normal freezing conditions later in the season that destroy the crop. Fruit and berry crops across the Midwest will be subjected to more extreme conditions and negatively impact growth and production. While there is evidence of changing climate, the overall impacts on perennial crops becomes more uncertain because of the uncertainty in chilling requirements. Winkler et al. (2013) summarized the effects of climate change on perennial crops as being from the fulfillment of the winter chill requirements, risk of springtime freezes, disruption of pollination, heat stress due to extreme temperature events and increased disease and insect pressures.

4.4.2 CO_2 CONCENTRATION AND EVAPOTRANSPIRATION

Changes in CO_2, temperature, and precipitation will impact agriculture in the Midwest. For plant types that respond well to CO_2 enrichment (C_3 plants), CO_2 may exert a positive influence on growth until temperatures warm more significantly. The positive effect on grain yield, however, has not been as large (Hatfield et al. 2011). An analysis by Bernacchi et al. (2007) using soybean grown in a free air carbon dioxide enrichment (FACE) system at 550 compared to 375 μmol mol^{-1} showed a 9 to 16% decrease in evapotranspiration (ET) with the range of differences over the three years caused by seasonal differences among years. There has been evidence that the reduction in ET caused by increasing CO_2 will diminish with increasing temperatures; however, this has not been evaluated in Midwestern crops.

4.4.3 PRECIPITATION

Changes in the seasonal timing of precipitation will be more evident than changes in precipitation totals (Iowa Climate Change Impacts Committee 2011). There is evidence of an increase in spring precipitation across the Midwest and an increase in the intensity of storm events, though climate model projections for precipitation changes don’t exhibit the same degree of confidence compared to the observations across the Midwest. The shifts in precipitation will affect field preparation time in the spring. An analysis of workable field days for April through mid-May in Iowa has shown a decrease from 22.65 days in the period from 1976 through 1994 compared to 19.12 days in 1995 through 2010 (Walthall et al. 2012). This is a major change in the days available during the spring for field work. There is an increased risk for both field work and soil erosion because of these shifts in precipitation. There has been little attention directed toward the workable days in the fall during harvest periods and the potential impact on grain, fruit, or berry quality. Impacts of increased precipitation and intense events are associated with increased erosion and water quality impacts (nutrients and pesticides). It is expected that these impacts will increase with increased spring precipitation because of the lack of ground cover with vegetation.

4.4.4 WATER QUALITY

Water quality impacts relative to a changing climate have not been thoroughly investigated, but many impacts are related to soil water excesses. Shifts in precipitation patterns to more spring precipitation coupled with more intense storms creates the potential for increased water quality (sediment, nitrate-N, and phosphorus). In an analysis of the Raccoon River watershed in Iowa, Lucey and Goolsby (1993) observed nitrate-N concentrations were related to streamflow in the river. Hatfield et al. (2009) showed that annual variations in nitrate-N loads are related to the annual precipitation amounts because the primary path into the stream and river network was leaching through subsurface drains. The Midwest is an extensively subsurface drained area and these drains would carry nitrate-N from the fields and across the Midwest with the current cropping patterns which do not have significant amounts of water use during the early spring because the precipitation amounts exceed the crop water use rates leading to a surplus of soil water in the soil profile (Hatfield et al. 2009). Increased intensity of spring precipitation has the potential for increased surface runoff and erosion in the spring across the Midwest. Potential increases in soil erosion with the increases in rainfall intensity suggest that runoff and sediment movement from agricultural landscapes will increase (Nearing 2001). Water movement from the landscape will transport sediment and nutrients into nearby water bodies, and further increases in erosion events can be expected to diminish water quality.

4.4.5 WEEDS, PESTS, AND DISEASE

Indirect impacts from climate change on crop, fruit, vegetable, and berry production will occur because of the climate change impacts on weeds, insects, and diseases. This has not been extensively evaluated across the Midwest and presents a potential risk to production. Current estimates of losses in global crop production due to pests show weeds cause the largest lost (34%), followed by insects (18%), and diseases (16%) (Oerke 2006). Further changes in temperature and precipitation patterns will induce new conditions which will affect insect populations, incidence of pathogens, and the geographic distribution of insects and diseases (Garrett et al. 2006; Walthall et al. 2012). Increasing CO_2 positively affects weed growth adding to the potential for increased competition between crops and weeds (Ziska 2010). However, information on the specific interactions between plants or animals and pests is not well understood in the context of climate change. Several weed species benefit more than crops from higher temperatures and CO_2 levels (Ziska 2001, 2003). One concern involves the northward spread of invasive weeds like privet and kudzu, which are already present in the southern states (Bradley et al. 2010). Significant effects on production may result from weed pressure caused by a positive response of weeds to increasing CO_2 (Ziska 2000, 2003a, 2003b; Ziska et al. 1999, 2005). The effects of CO_2 on increasing weed growth may lead to increased competition in fields without adequate weed management. A void of knowledge currently exists on the effect of changing climate on insects and diseases and the extent of a changing risk pattern on agricultural production. Changing climate and changing trade patterns are likely to increase both the risks posed by, and the supply of, invasive species (Bradley et al. 2012). Controlling weeds costs the U.S. more than $11 billion a year, with most of that spent on herbicides. Both herbicide use and costs are expected to increase as temperatures and CO_2 levels rise (Nikolinka et al. 2009). Also, the most widely used herbicide in the U.S., glyphosate (also known as RoundUp™ and other brand names), loses its efficacy on weeds grown at CO_2 levels projected to occur in the coming decades (Ziska et al. 1999). Higher concentrations of the chemical and more frequent sprayings thus will be needed, increasing economic and environmental costs associated with chemical use.

Recent reviews on the effects of climate change on disease prepared by Coakley et al. (1999), Anderson et al. (2004), and Garrett et al. (2006) reveal the complexities of any simple approach of relating climate change to changes in disease populations. For example, Coakley et al. (1999) concluded that climate change may be smaller than the effects due to land use patterns, pesticide use, and transgenic technologies; however, climate change effects on land use patterns have the potential to create interactions among climate, diseases, and crops. Anderson et al. (2004) in their review on emerging infectious diseases stated that the complexities of climate change and the biotic response to climate change create a situation in which the prediction of the future effects is difficult. Garrett et al. (2006) summarized the current state of knowledge on diseases and climate change as dependent upon the effect which climate has on both the host and the pathogen. One example of the complexity of the interactions between climate, host, and pathogen is aflatoxin (*Aspergillus flavus*). Russell et al. (2010) found that temperature and moisture availability are crucial for mycotoxigenic fungi and mycotoxin production and both the pre-harvest and post-harvest conditions are critical in understanding the impacts of climate change. Wu et al. (2011) found that high temperatures and drought stress affect aflatoxin production and at the same time reduce the growth of the host plants and the mycotoxin effect is further changed by the presence of insects creating a potential for a climate-mycotoxin-insect-plant interaction.

Insects are directly affected by temperature and synchronize their development and reproduction with warm periods and diapause with cold periods (Roff 1983). Porter et al. (1991) suggested that an increase in winter temperatures would result in greater survival of insects overwinter and cause an increase in populations and coupled with higher summer temperatures would increase the number of generations per year. An example of this has been observed in the European corn borer (*O. nubialis*), which produces one generation in the northern Corn Belt to more than two in the southern Corn Belt (Showers, 1983). The changes in the number of generations coupled with the shift in ranges of insects will alter the insect pressure in a given region. Parmesan et al. (1999) observed there was a northward trend in non-migratory butterflies in Europe and these changes in the range of insects would be associated with land use patterns and climate change. These observations suggest there would be an interaction among climate change, land use patterns, and insect populations.

4.4.6 STRESSES ON LIVESTOCK

Climate stresses on livestock in the Midwest are reduced because most of the species are grown in confined production facilities where there is control of the temperature and humidity and the animals are not exposed to the natural environment (Mader et al. 2007). In these systems, there may be a greater effort directed toward energy efficiency in these facilities and management to ensure a limited exposure to extreme conditions during transport of animals to processing facilities. Dairy cattle are often grown in unconfined facilities, but shelter is provided for these animals from severe weather events. Increases in temperature and humidity occurring and projected to continue to occur under climate change will impose a significant impact on production of the different species shown in Table 4.1. Exposure of livestock species to the combination of temperature and humidity factors will increase stress levels (Mader 2003, 2007; Mader et al. 2011). These effects, however, have not been extensively quantified across the Midwest. The indirect impacts of climate change on livestock will occur because of the potential for a changing climate to affect the occurrence of insects and diseases. There is an increased risk of the exposure of animals to insect and disease pressure as a result of climate change, but these relationships have not been established for the animal species of the Midwest. Another indirect impact of climate change may be through the availability of feedstock derived from crop production. Reductions in grain production would have an impact on the number of animals which could be produced.

4.5 Adaptation

Agriculture is a very fluid system and within annual crop production there is continual adaptation to adjust to the changing climate conditions. There are shifts in planting dates dictated by the precipitation amounts that occur each year. In order for producers to make large shifts in agronomic practices, e.g., maturity dates on crops, there would have to be a consistent pattern in the climate trends and events each year. Adaptation strategies for Midwest crop agriculture will have to include practices which protect the soil from erosion events while at the same time increasing the soil organic matter content through carbon sequestration via improved soil management (Hatfield et al. 2012). Adaptation strategies for livestock across the Midwest would be relatively minor because of the majority of the production systems already occurring under confined spaces with controlled environments.

Crop insurance has been used as a process to offset losses to producers due to weather events during the growing season. Given the uncertainty in the climate change it is difficult to evaluate how crop insurance payments will change in the future (Beach et al. 2010). There have been shifts in the perils which have triggered crop insurance payments for the past 20 years with a shift from drought to flooding and excess water being the major cause of insurance claims.

Adaptation of agricultural systems will occur through many different paths. Producers have readily adopted changes which entail changes in planting date and maturity selections. Other changes, such as the changing of cropping systems to increase water availability in the soil via increases in organic matter content or reductions in soil water evaporation, may be more difficult to implement. Adoption of improved nutrient management systems to prevent losses of nutrients either by leaching, runoff, or in the case of nitrogen fertilizers, nitrous oxide emissions, represent strategies to enhance crop performance under variable climates. Development of plant genetic resources for annual crops to increase their tolerance to stress will be a necessary component of adaptation to climate change. The potential options for crop adaptation to climate change have been described by Redden et al. (2011). There have been many proposed strategies for adaptation to climate change for annual crops; however, there may be fewer options for perennial crops. For livestock, adaptation strategies will typically involve some aspect of the housing facilities for animals and may entail a greater cost of implementation than in cropping systems.

4.6 Risk Assessment

Exposure to extreme events for both temperature and precipitation can cause reductions in plant production and yield. There is evidence in the observed yield history for crops grown in the Midwest that extremes can have significant impacts on production levels; however, there are impacts on yields from variability in weather during the growing season caused by short-term weather impacts, e.g., less than normal rainfall but not enough deficiency to trigger drought. With the likelihood of an increase in the occurrence of extreme events across the Midwest, we could expect a greater variation in production amounts. It is also interesting to note in these records that not all extreme events impact the entire Midwest. Some events (flooding or drought) are more localized and affect the production within a state or are even isolated to a few counties. Development of a risk assessment for climate impacts on agriculture will require the application of crop simulation models into which climate scenarios can be incorporated to evaluate potential adaptation strategies. There is an effort to begin to intercompare and improve crop models for the purpose of providing better simulations of crop production around the world. This effort is known as the Agriculture Model Intercomparison and Improvement project (AgMIP, www.agmip.org). Efforts are underway to provide intercomparisons for corn, soybean, wheat, rice, sugarcane, peanut, and millet using models developed by the international community and evaluated against data sets from different locations around the world. This approach would allow for an assessment of the potential impacts of climate on future production levels but also allow for the evaluation of the efficacy of various adaptation strategies.

4.7 Summary

Agriculture is directly and indirectly affected by changes in climate as evidenced by the temporal changes in crop and animal productivity. The direct effects are temperature and precipitation and particularly the patterns and extremes of these two variables during the growing season. Temperature directly affects the rate of plant development and also the rate of water use by the crop and in years with below normal precipitation can easily lead to water stress conditions. Across the Midwest, the availability of soil water through precipitation is one of the major factors affecting crop production. Climate change will cause conditions in which the seasonal patterns of temperature and precipitation will become more variable leading to even greater variation in production. Animal production will be affected by the changing climate because of the increased likelihood of extreme events disrupting normal metabolic patterns creating conditions which impact meat, milk, and egg production. The changes in climate will also impact insect, disease and weed dynamics, and these factors will increase in intensity and create the potential for greater losses from these factors.

The challenge for agriculture will be to implement adaptation strategies which will alleviate some of the exposure to climate events causing a loss in production. These will have to be evaluated in the context of a risk assessment framework to determine the likelihood of the impact of climate on agricultural production and the cost of the adaptation strategy compared to the loss in production. Economic analysis of the costs of climate change on agricultural production will be one of the primary factors considered before implementation of new practices occur. Agriculture has been successful in adapting the changes as evidenced by the continual increases in productivity and the challenge will be to continue to develop and refine effective adaptation strategies.

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Chapter 5

Impacts on Biodiversity and Ecosystems

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5.1 Introduction

At a global scale, rapid changes in climate are expected to lead to increases in extinction risk across all types of life forms, and to reductions in the ability of natural systems to provide key services upon which human societies depend (Thomas et al. 2004; Field et al. 2007; Brook et al. 2008; Maclean and Wilson 2011; Bellard et al. 2012). The rate at which changes in temperature and other climate factors are occurring in the Midwest suggests that many, if not most, wild species and natural systems will experience climate change as a major stressor. Like other regions at moderate to high latitudes, both observed rates of temperature change, and climate change projections for the Midwest region are higher than projections for the global average (e.g., as illustrated in Girvetz et al. 2009). This region is also quite flat, so shifting up in altitude is typically not an option as a response to increasing temperatures. As a result, moving to a place with lower temperatures typically means shifting across long distances, suggesting that if species are not highly mobile, they are unlikely to be able to disperse fast enough to "track" preferred climatic conditions. For many species, including some that are able to show flexible responses within a limited range of temperature increases, genetic changes are likely to occur too slowly for natural selection to keep pace with the rapid warming in the environment. As species "fall behind" in terms of adapting to changing conditions, we are highly likely to see more examples of reductions in fitness, population declines, and eventual extinctions (Parmesan 2006; Foden et al. 2008). In addition, species that are able to adapt quickly to new conditions may put additional pressures (e.g., as competitors, predators, or parasites) on those that are not able to move or adapt, further accelerating the process of species loss (Parmesan 2006; Brook et al. 2008).

The high degree to which terrestrial and aquatic systems in the Midwest region have been altered by human actions makes it clear that as we frame our understanding of what species and ecosystem services are at risk, we need to think beyond high profile examples of the observed responses of species and natural systems. Given the current low proportion of natural land cover in the southern part of the Midwest region, the dominance of non-native invasive species in our aquatic systems, and impacts from pollution and barriers to movement, species lost from natural areas may only rarely be replaced with "native" species moving north. Thus, though the species and systems of the Midwest region may not stand out as being highly vulnerable to climate change when compared to those threatened by loss of polar ice cover or sea level rise, the long-term viability of our species and systems may be at high relative risk due to climate-driven enhancement of existing stressors – the same stressors that have been the focus of decades of conservation and management efforts.

5.2 Linking Climate Impacts to Species and System Sensitivities

Observed changes, along with ecological theory, allow us to develop "rules of thumb" for how species are likely to respond to the most direct aspects of climate change (e.g., changes in air or water temperature). In addition, experimental studies and predictive models may provide clues as to how several climate factors (temperature, precipitation patterns) may interact, and we can weave these tools together with observations from both current and past climate changes to improve our understanding of vulnerability (Dawson et al. 2011). While these data and tools are useful, it is important to recognize that because many climate factors, species, and ecological processes are likely to be changing simultaneously, species and systems may show very complex responses. This complexity is likely to lead to surprises, and makes it hard to categorize relative risk, and to define meaningful management approaches to reduce risk. Assessing the relative vulnerability of species becomes even more uncertain when we try to put climate change-related risks in the context of all of the other stressors that wild species and ecosystems currently face, such as habitat loss, invasion by non-native species, changes in hydrology, and pollution. To be comprehensive in our risk assessment, we also need to try to anticipate the changes species and systems will face in the future, including actions that societies take in response to changes in climate. Many researchers describe climate change as exacerbating current threats (e.g., Brook et al. 2008), a role that is likely to increase in importance and complexity as the rate of change continues to accelerate.

Understanding how climate change will impact species, systems, and ecological services is further complicated by the fact that several aspects of climate change involve feedback loops, or can impact species through multiple pathways. For example, surfaces waters of the upper Great Lakes (Lakes Michigan, Huron, and Superior) are showing summer temperature increases that exceed regional temperature increases on land, in part due to positive feedbacks on the warming rate due to reductions in ice cover. Overall, the Great Lakes have shown a 71% reduction in average ice cover from 1973-2010 (Wang et al. 2011). Specifically, ice reflects energy from the sun and insulates the water from the warming air, but melts more quickly when the air is warmer; this loss of ice cover accelerates the rate of surface water warming (Austin and Colman 2007, 2008; Dobiesz and Lester 2009). Warmer waters can stress species because the increase in temperature reduces the oxygen holding capacity of water, and because at higher temperatures, the respiration rate of organisms, which determines how much oxygen is needed, is higher. These increases in temperature are triggering a whole range of system-wide impacts, including increases in wind speeds and current strengths, and increases in the duration of the stratified period (Austin and Colman 2007, 2008; Desai et al. 2009; Dobiesz and Lester 2009). Predicting ecological responses to rapid changes would be challenging under any circumstances, but the fact that food webs and the flow of energy in Great Lakes systems are continually shifting as a result of human-facilitated invasions by exotic species (Vander Zanden et al. 2010) makes understanding changes in these critical systems a particular challenge.

As with changes in temperature, there is little doubt that changes in precipitation have great potential to impact species, systems, and ecosystem services. However, at this time, it is much harder to make the case that changes in the amount and timing of precipitation that have occurred in the recent past, or may be observed, are consistent with what is expected due to climate change. This is because long-term patterns of precipitation across space have tended to be more variable than temperature, and are associated with many short and long term cycles. In other words, while we know that too much or too little precipitation can lead to mortality or reduced fitness, it is often hard to detect a climate change signal within the "noise" of historic variation, and thus attribute observed changes in species that may result from precipitation changes to climate change as a key driver. Similarly, projections for precipitation amount and seasonal patterns tend to vary strongly across the suite of General Circulation Models (GCMs) used to evaluate possible future conditions (Winkler et al. 2014). With respect to extreme precipitation events rather than mean values, however, there is general agreement that the frequency of extreme precipitation events (intense storms) is likely to increase, though some projections suggest this trend will vary from little change to substantial increases across the Midwest Region (Winkler et al. 2014). Agreement increases as analyses are focused on storms defined by higher and higher thresholds; for example, recent climate change projections for the Midwest suggest increases in the frequency of days with storm events with greater than 1 inch of precipitation, with the highest increases suggested for the frequency of the highest volume storms (Kunkel et al. 2013). In general, these trends agree with observed patterns of increases in peak storm events over the second half of the last century for the upper Midwest (CCSP 2009; Groisman et al. 2004, 2012). Further, even while future precipitation patterns are uncertain, we can be confident that precipitation falling in a warmer climate will evaporate or be transpired by plants more quickly, leading to higher potential for moisture stress even if a given suite of future projections does not suggest an overall decrease in the amount of precipitation.

When considering how to rank vulnerabilities and prioritize our efforts to protect and restore key systems in the Midwest and Great Lakes region, it is particularly important to understand the interaction between climate change and changes in land cover. Land cover plays a very important role in determining the water and energy balance of a system, in that vegetation cover slows water down, removes water from the system through evapotranspiration, and influences local temperature due to variations in albedo (reflectance) and by shading the ground surface. When vegetation is removed or undergoes a major change in composition or structure, such as when forest is converted to agriculture, all of these relationships have the potential to change in ways that increase runoff and promote flooding (Mao and Cherkauer 2009; Mishra et al. 2010a). The impacts of changes in landcover on aquatic systems can be quite strong. This is especially true in landscapes with high proportions of agriculture or urban land uses, which act as sources of pollutants and fertilizers when large volumes of water flow across them into rivers and Great Lakes coastal areas. In formerly forested watersheds, reductions in the tree cover around streams have likely been leading to increases in stream temperatures as well. Further, the region has lost capacity to store water as a result of dramatic, large-scale draining and filling of wetland ecosystems. In the northern half of the region (Michigan, Minnesota, and Wisconsin), estimates of conversion rates from circa 1780 surveys in comparison to 1980s Wetland Inventory Maps range from 42-50 percent, while in the southern portion of the Midwest (Illinois, Indiana, Iowa, and Ohio) losses are estimated at between 85-90 percent (Mitsch and Gosselink 2007, their Appendix A). These diverse systems often occurred on areas with fertile soils that were drained for agriculture, although major cities like Chicago were also built upon drained wetlands. Thus, for the Midwest, changes to the timing, form (snow or rain), and amount of precipitation are acting on a system that is already highly altered in ways that tend to promote lower evapotranspiration and higher rates of surface runoff that lead to flooding. Although wetland systems can sometimes be restored, protection is crucial. Even when we invest in restoring these critical systems, it is typical for important services and structural components to lag behind conditions in less disturbed wetlands, even after a decade or two of restoration efforts (Moreno-Mateos et al. 2012).

5.3 Observed Responses to Temperature

A majority of wild species show predictable changes in responses to increasing temperatures, and the role of temperature in shaping species life histories is strong. In other words, temperature regime is a key element to which species have adapted over long (evolutionary) time periods. The potential effects of temperature changes are most apparent for ectothermic ("cold-blooded") animals such as insects, reptiles, and fish, for which body temperature, the key determinant of metabolic rate, strongly tracks the environmental temperature. For most ectotherms, changes in internal temperature are associated with exponential increases in the rate of metabolic reactions that underlie body maintenance and growth (Deutsch et al. 2008; Zuo et al. 2011). Rates of key processes increase to an optimal threshold, after which they rapidly decline as organisms get closer to maximum temperature thresholds (Deutsch et al. 2008; Kearney et al. 2009).

At lower environmental temperatures, disruption in the availability of energy influences a wide array of physiological and behavioral traits, such as activity patterns and rates of growth and reproduction. In a warming Midwest region, research suggests that ectotherms like insects and reptiles will have longer active periods (prior to becoming dormant for the winter) and overall may experience higher fitness (Deutsch et al. 2008). However, metabolic costs will increase, especially for species that cannot avoid higher temperatures through behavioral changes or movements, for example by moving to cooler microhabitats, or avoiding activity in the hottest parts of the day (Kearney et al. 2009). An increase in metabolic rate leads to a cascade of changes, including higher food requirements. In "whole lake" warming experiments, Biro et al. (2007) found an increase in the time spent searching for food was one mechanism leading to increased mortality of young rainbow trout (*Oncorhynchus mykiss*); in warmer conditions they found higher rates of mortality that they attributed to predation. Homeothermic ("warm-blooded") animals—birds and mammals—maintain a relatively constant body temperature but still can experience heat-related stress as temperatures continue to increase, especially when they inhabit areas where they are already close to thermal tolerance limits. For example, moose (*Alces alces*), which are at their southern range limit in the northern edge of the Midwest region, are highly sensitive to increases in temperature, and have shown declines in survival that are correlated with recent warming trends (Lenarz et al. 2009, 2010). As with ectotherms, there is some evidence that species that can moderate their exposure to climatic extremes through "sleep or hide" types of responses (hibernation or torpor during cold periods, use of burrows or other shelters during the hottest part of the day) may be at reduced risk relative to other species with otherwise similar characteristics (Liow et al. 2009).

Plants also have temperature tolerances, though sensitivity to high temperatures is also strongly linked to water availability (i.e., moisture stress). The seeds of some plants also require a period of cold temperatures so that they can germinate, suggesting that if that period is shortened as a result of warming minimum temperatures, fitness of some plants may be reduced. Similarly, some plants require a chilling period prior to budburst, and changes in climate may alter the pattern of bud and leaf development (Morin et al. 2009).

Although an increasingly wide array of responses of species and systems to temperature-related stresses have been classified (e.g., Root et al. 2003; Parmesan 2006; Geyer et al. 2011; Maclean and Wilson 2011) for the purposes of this review, responses are grouped into five basic types: 1) spatial shifts in range boundaries (e.g., moving north in the Midwest region); 2) spatial shifts in the density of individual animals or plants within various subsections of a species' range; 3), changes in phenology (the timing of events), such as when leaves emerge in spring, or when birds lay their eggs; 4) mismatches in the phenology of interacting species; and (5) changes in morphology and genetics. These categories are not mutually exclusive, as, for example, a change in the timing of bird migration can represent both a phenological shift and a shift in gene frequencies (genetics).

5.4 Changes in Species Ranges and Relative Abundances

Shifts in where species occur can result from several different mechanisms. For many species, changes in climate conditions will enhance a given species' survival rate, growth rate, and/or reproductive rate in some parts of the species' range, and reduce one or more of these rates in other locations. Thus, even without dispersal (movement away from previously occupied habitats), these changes can lead to shifts in the subset of areas within a range where species are common, rare, or absent, and eventual changes in range. Changes in vital rates like survival can be linked back to the physiological constraints of balancing energy reserves under specific climatic conditions, as individuals in highly suitable climatic conditions will often have higher reproduction, survival, or both, than individuals in habitats that are more "costly" (e.g., higher cost of foraging due to heat or cold stress, higher metabolic rate due to higher water temperature for aquatic species).

Movements in mobile species can be direct responses to temperature, such as fish seeking out deeper, colder water, or can be the result of natural selection acting on more random movements by populations of individuals, as those that become established in areas with more suitable climates are more likely to survive and reproduce. Similarly, for species like plants, which are rooted in one location, shifts in range occur as a result of a life stage like seeds being dispersed (e.g., by wind or birds) and becoming established in new areas that are now presumably more suitable than they had been in the past.

For species to "track" changes in temperature by shifting ranges, they need to be mobile in some stage of their life history and have a suitable path to follow (e.g., "permeable" landcover, a freshwater system that is free of barriers and contains suitable habitat). As a general rule, range shifts in response to warming temperatures result in species moving to higher latitudes or altitudes, although factors like topography, distance to water bodies, and shading by tall vegetation influence regional and local temperatures, and can contribute to variations in the spatial pattern of how species respond (Ashcroft et al. 2009, Dobrowski 2011, Klausmeyer et al. 2011). Areas that are consistently cooler than other locations due to persistent factors (altitude, aspect, proximity to water) can act as climatic "refugia," in that they can support species that otherwise would be lost from an area. In the Midwest region, the most notable influence on regional climate is the "lake effect" in areas around the Great Lakes, which acts to modify both high and low temperatures in coastal areas and on Great Lakes islands (Scott and Huff 1996). Similarly, in the Midwest it is possible to have streams within the same watershed that vary enough in temperature to support different fish assemblages (e.g., cold water, cool water, or warm water fish) due to local variation in geography and variation in the extent to which the stream is supplied by cold groundwater (Ficke et al. 2007; Chu et al. 2008; Lyons et al. 2010).

Landscapes in the Midwest are typically fairly flat, so shifting up in altitude is typically not an option as a response to increasing temperatures. For terrestrial species, in the absence of some form of climatic refugia, moving to a place with lower temperatures typically means shifting across long distances. The combination of higher latitudes and relatively flat topography that characterizes Midwestern states suggests that species "tracking" changes in temperature by shifting their ranges will require more rapid movement in this region than in other geographies where rates of temperature increase are lower, and/or where they could shift up in altitude to reach cooler habitats (Guralnick 2007; Jump et al. 2009; Loarie et al. 2009; Chen et al. 2011). In effect, the lack of topographic diversity in most parts of the Midwest can be thought of as increasing a species' exposure to climate change, or as a factor that reduces extrinsic adaptive capacity (i.e., the component of a species' potential to adapt to changing conditions that is linked to its current environment, rather than intrinsic factors like traits or genetic diversity). For example, to reach terrestrial areas that are 1°C cooler, a species in mountainous terrain could shift approximately 167 meters (m) in altitude, while achieving the same shift in flat terrain would mean a shift of roughly 145 km to the north (Jump et al. 2009).

A recent global study suggests that, in most of the Midwest, tracking changes in temperature in the second half of the century (2050-2100, A1B emissions scenario) will require terrestrial species to move over 1 km/year; in comparison, the global average estimate of the "velocity" of dispersal needed to track changes in terrestrial systems was less than half that rate, at 0.42/km year (Loarie et al. 2009). Similar estimates were attained in modeling work that focuses on estimating the "temperature maintaining distance" for small mammals in northern Indiana; Francl et al. (2010) suggest that to track changes in average January temperature that occurred during the mid 20th century, species would have needed to move north at between 0.4 and 2.1 km/year, with that estimate increasing in projections for this century. Rates of 1 km/year and higher are currently being achieved in some locations by some taxa (Chen et al. 2011), but such rates are likely to be unattainable for many species, especially in highly-modified landscapes where natural habitats are rare, or in aquatic systems with limited connectivity. If emissions exceed the A1B scenario projections and are closer to A2, tracking change in the Midwest will require even faster movements (e.g., several km/year or more, Loarie et al. 2009, their supplemental figure S17).

Recent work by Schloss et al. (2012) evaluating mammal vulnerability incorporates both temperature and precipitation changes, which reduces the extent to which the Midwest stands out among other locations in North America and the western Hemisphere in terms of the velocity of change (see their Figure 2), but highlights that even this mobile group has some highly vulnerable members. Specifically, their work incorporating dispersal ability into range change projections for the western hemisphere suggests that on average about 9% of mammals at a given location are likely to be unable to keep pace with climate change, with many locations in the Midwest modeled to have higher vulnerabilities, up to about 39% (Schloss et al. 2012, their Figure 1). Schloss et al.'s (2012) work provides estimates of dispersal velocities for several hundred mammals, and shows the variety of rates possible within one taxonomic group. In the Midwest, values range from fast dispersers like the gray wolf (*Canis lupus*), which they estimate can move about 40 km/year, to much smaller animals for which dispersal events are short and rare, like northern short-tailed shrews (*Blarina brevicauda*) with an estimated movement rate of 0.40 km/year (Schloss et al. 2012, their Supplement dataset S1).

From a vulnerability standpoint, species that can move rapidly (e.g., birds, large mammals) are typically seen as more likely to be able to keep up with climate change than other species with lower dispersal capacities (e.g., amphibians, most plants, sessile aquatic invertebrates, insects that are poor dispersers). However, it is important to remember that suitable climatic conditions are necessary but not sufficient; persistence in new habitats also depends on how well new areas meet an organism's needs for food and shelter, and habitat for movement needs to be available between current and future ranges. Schloss et al.'s (2012) assessment of mammal vulnerability integrates land use as well as the projected velocity of change in both temperature and precipitation, which for the Midwest highlights the importance of land conversion as a barrier to species movements (Schloss et al. 2012, their Figure 5). Further, even mobile species that depend on food sources or habitat components that shift at slower rates will be vulnerable if the species that they depend on decline in abundance. In addition to moving north within river systems or large lakes, as noted above, some aquatic species also may be able to move into deeper, cooler waters within the same water body, although these deeper habitats may not have all of the other resources that a given species requires. Dependence on stream habitats may suggest high vulnerability for many species, as even in aquatic systems that appear to have high connectivity (e.g., few barriers to movement due to structures or pollution), many taxa (like stream insects) can be limited in their movements by habitats or hydrologic conditions (Strayer 2006) that they cannot use or travel through. Further, even highly connected rivers and streams may show little variation in water temperature if they are oriented in an east-west rather than north-south direction.

Examples of species showing range and abundance changes in and near the Midwest region are beginning to accumulate, with the best documented examples coming from researchers conducting long-term research on topics such as community composition and population dynamics. The forest-focused review by Handler et al. (2014) includes summaries of work examining both observed and projected change in tree species ranges; most trees are expected to shift more slowly than optimal given the changes in climate. For birds, which are clearly very mobile, several recent papers document range shifts. In general, species ranges have shifted to the north, which typically corresponds with patterns of warming, though some studies find smaller numbers of species shifting in other directions (Zuckerberg et al. 2009, New York state; Hitch and Leberg 2007, breeding ranges in North America; LaSorte and Thompson 2007, winter ranges in North America). Work by Myers and colleagues (2009) on mammals in Michigan documents rapid changes in ranges for several common species, including northern range edge shifts of over 225 kilometers since 1980 for white-footed mice (*Peromyscus leucopus*). Similar rates of movement appear to have been occurring for southern flying squirrels (*Glaucomys volans*), although the authors suggest that small, hard to detect populations may also have been rapidly expanding and contributing to the shift in range (Myers et al. 2009). The movement of white-footed mice is of concern from a public health perspective, as these mice are key hosts for the ticks that carry Lyme disease (Ostfeld 2009). Bowman et al. (2005) also documented rapid northern shifts of southern flying squirrels in Ontario over a series of years with relatively warm winters and higher food availability (tree mast). They document a 200 km northward shift over 9 years (1994-2003), but the range contracted to its historical limit following a very cold winter in 2004 that was associated with mast failure. The same research team documented a relative reduction in genetic diversity within squirrels trapped at the northern edge of this range expansion, providing evidence that even for species that can shift quickly, there may be fitness consequences associated with these rapid responses (Garroway et al. 2011).

Species are also showing changes in abundance within current ranges. Studies on moose (*Alces alces andersoni*) provide an indication of the complexity of the sensitive relationship between a species' population numbers and environmental temperature. Two separate research teams focused on understanding factors such as birth rates, parasite loads, and survival of moose in northwestern Minnesota (Murray et al. 2006) and on Isle Royale in Lake Superior (Vucetich and Peterson 2004; Wilmers et al. 2006) found that warming temperatures are contributing to local population declines through increases in heat stress-related effects. Modeling work by the northwestern Minnesota team suggests that, given the observed relationships between vital rates (birth rates, survival) and temperature, moose populations will not persist over the next 50 years (Murray et al. 2006). Population monitoring and modeling also suggest that a third population of moose in northeastern Minnesota is declining, though at a slower rate (Lenarz et al. 2009, 2010).

As suggested by the examples above, documenting changes in species viability and ranges represents a major challenge, especially for wide ranging or hard to detect species. As a result, many researchers have used predictive modeling tools to try to understand current and future impacts on species distributions. Due to their strong dependence on relatively narrow temperature regimes, freshwater fish have been the subject of many research studies examining the impacts of temperature change on distributions. Early work suggested major impacts, such as a 50% reduction in North America's cold and cool water fish with a temperature increase of 4°C (Eaton and Scheller 1996); this study highlighted the Midwest as a region with particularly high impacts. Recent work in the Midwest region has added complexity and additional factors (presence of invasive species, changes in land use) to the modeling approaches used in the past, but continues to suggest high potential for major reductions in fish diversity due to temperature increases. Lyons et al. (2010) conducted a modeling study of potential changes in the distribution of 50 common stream fish species in Wisconsin. The species they included in their study can be grouped by their water temperature preferences: 19 of the 50 are defined as cold- or cool-water species, and 31 species are found in warmer streams. In this multifactor model, all of the cold- and cool-water species and four of the warm water species (23 of the 50) are projected to decline over the next fifty years. Of the 27 species that are adapted to warmer water, four are projected to show little change in population, while the other 23 are expected to increase in population. Under the highest warming scenario they tested (5°C increase in air temperature, 4°C increase in stream temperature), three of the cold water species were predicted to go extinct in the state (Lyons et al. 2010). In similar work focused on cisco (*Coregonus artedii*) in Wisconsin, a species of conservation concern that is found primarily in larger, deeper, cooler lakes, Sharma et al. (2011) looked at 78 different climate change projections (B2, A1, and A2 scenarios) and estimated that 25-70% of populations in the state will be extirpated by 2100. As the complexity of the models used to project changes in fish distributions has increased to include habitat and land use variables, we have gained insight into how we might slow the rate of species losses (e.g., Jones et al. 2006; Steen et al. 2010). For example, modeling work that considered changes in land cover and temperature increases on nine game fish in the Muskegon River watershed of Michigan projected population declines for cold-water fish, but suggested that some of these changes could be slowed through increasing forest cover near stream habitats to help reduce stream temperatures (Steen et al. 2010).

When species are mobile and suitable habitat is present in the right location, range shifts may represent a viable response to changing conditions. However, range and abundance changes are of concern for several reasons. First, species that are not able to disperse will be stressed by climatic conditions that are becoming less and less favorable, and the added impacts of species moving in from warmer areas that are less challenged by the same climatic conditions. The species moving in may directly compete for key resources and also may contribute to the decline of resident species by spreading diseases and parasites. Second, range shifts by species that act as forest or crop pests, or that are detrimental to public health (i.e., carry diseases, create toxic algal blooms) are key concerns in the Midwest, and are important subjects of observational and model-based research studies (e.g., Hong et al. 2006; Jactel et al. 2011). In particular, many invasive, non-native pests are likely to be more successful at surviving in our region as minimum winter temperatures continue to rise (Bierwagen et al. 2008; Vander Zanden et al. 2010). Third, we are concerned about range and abundance shifts because species movements will often be independent of shifts of other species. We expect species to shift independently because the set of constraints that describe the habitat and ecological niche for each species (factors like temperature, food availability, soil types, and stream flow characteristics) is unique (Parmesan 2006). In effect, we expect to see the "tearing apart" of sets of species that typically interact, and many of these interactions may be critical to the survival one or more of the interacting species (Root and Schneider 2006).

5.5 Changes in Phenology

In many species and systems, seasonal changes in temperature act as cues that trigger transitions in the seasonal cycles, such as metamorphosis (e.g., transition from egg to larvae), the development of new leaves, or the initiation of phytoplankton blooms that transfer energy from these primary producers through aquatic food webs. In addition to triggering changes in timing, known as changes in "phenology", warming trends can impact species indirectly by influencing other key seasonal events that trigger changes in their seasonal cycles, such as shifting the timing of snowmelt, flooding, or lake stratification. Further, timing issues become important in the context of ephemeral (temporary) habitats, like small streams or wetlands that dry out in the summer. When increasing temperatures promote faster drying, this can put species like amphibians and aquatic invertebrates at risk if habitats dry before they have completed aquatic life stages (Brooks 2009).

Several early phenology studies that were highly influential in raising awareness that species were responding to changes in climate focused on, or included, study sites in or near the Midwest. These included evidence of 10 to 13 day advances in frog calling dates (an indicator of timing of breeding) in western New York in response to a 1 to 2.3°C increases in temperature in key months (Gibbs and Breish 2001), advances in the timing of many spring events (bird arrivals, plant blooming) on a Wisconsin farm in the 1980s and 1990s relative to observations taken by Aldo Leopold in the 1930s and 1940s (Bradley et al. 1999), and a nine day advance in the laying date of tree swallows (*Tachycineta bicolor*) across the continental U.S. over 32 years (1959-1991; Dunn and Winkler 1999). Phenology changes can also be linked to indirect climate change impacts, such as timing of seasonal disappearance of ice (ice-out) in spawning streams. Recent work by Schneider et al. (2010) suggests that both ice-out and walleye (*Sander vitreus*) spawning are occurring earlier in Minnesota.

In most cases, the implications of change in phenology on fitness are unclear, but as we build longer term datasets in the Midwest, it is likely that patterns will continue to emerge. For example, a recent paper documenting long-term (approximately 100 years) changes in phenology and abundance of 429 plant species in Concord, Massachusetts (many of which are also found in this region) showed that although there has been an overall shift of 7 days in flowering phenology associated with a 2.4°C temperature increase in the study area, some plant families are showing less of a response to temperature than others (Willis et al. 2008). In many cases this failure to shift flowering time in response to changes in seasonal temperature was associated with strong declines in abundance (Willis et al. 2008).

Two teams of researchers have documented climate-related changes over the past two decades in nesting patterns in freshwater turtles in Illinois (painted turtles *Chrysemys picta*, Schwanz and Janzen 2008; red-eared sliders *Chrysemys picta elegans*, Tucker et al. 2008). Their work shows how complex predicting responses to climate can be. Like many reptiles, these turtles exhibit temperature-dependent sex determination, which means that the temperature at which the eggs are incubated determines the sex ratio of the eggs within the clutch. However, the relationship between air temperature and sex ratio is not simple, because vegetation cover can influence the nest temperature, and nests that are created early in the season may be in soils that are still cooler than ambient air (Tucker et al. 2008; Schwanz and Janzen 2008; Schwanz et al. 2010). In the study by Schwanz and Janzen (2008), initiation of nests has become earlier over time, with advances linked most strongly to years with warm winters; second and third clutches of eggs in the same season have also become more common. Tucker et al.'s (2008) study site has experienced a more consistent warming trend and responses appear stronger. These include significantly earlier first nesting dates (2.23 days earlier per year) and a lengthening of the nesting season by 1.2 days per year between 1995-2006. As a result of these changes, especially the additional clutches per year, the total number of offspring in the Tucker et al. (2008) study increased, with one surprising twist. Warmer temperatures produce more females in this species, but in recent years, the trend has been towards more males. The authors suggest that shifts towards earlier first clutches, plus a higher frequency of late season clutches, has meant more eggs developing under cooler soil conditions.

The term "phenology mismatches" describes situations where species that interact in some important way respond differently to a temperature change. The potential importance of mismatches may be easiest to imagine in systems where attainment of a threshold temperature cues the emergence of leaves of a dominant tree or grass, or algal growth. In such a system, a shift in the timing of spring warming that alters when these plants grow or bloom could represent a key change in the foundation of the food web that determines energy flows throughout that entire ecological system. If other species in the same system do not shift in the same direction and at a similar rate, they may be at a strong disadvantage in terms of their ability to survive and reproduce relative to other species.

Although a wide variety of species are likely vulnerable to phenological mismatches, it is rare to have direct evidence that species are experiencing declining fitness through this mechanism. However, it is not very hard to pull together information to make the case that these types of changes should be of concern. For example, the northern Great Lakes region and the Mississippi River corridor stand out within North America as regions that support vast numbers of birds during spring and fall migration. One group, songbirds, depends upon a ready source of insect prey, both along their migration routes, and in their breeding habitats. Studies in Europe have documented advances in insect emergence relative to bird arrivals at breeding habitats, and suggest that these timing mismatches are leading to reduced breeding success (Visser et al. 2006; Both et al. 2009). In the U.S., Marra et al. (2005) compared the median capture dates of 15 long distance migrants from bird monitoring stations in coastal Louisiana and two stations in the Great Lakes region, Long Point Bird Observatory (on the north shore of Lake Erie) and Powdermill (western Pennsylvania). They also compared the duration of time between the median arrivals for the same species at the southern and northern sites. They found that median capture dates were earlier in years with warmer spring temperatures (mean April/May temperature) for almost all of their focal species, at a rate of roughly 1 day earlier per each 1°C increase in temperature. However, they note that in indicator plants (lilac, *Syringa vulgaris*), budburst occurred 3 days earlier for the same temperature increment, a similar rate to the average reported for plants in the Willis et al. (2008) study described above. Similarly, Strode (2003) suggests that North American wood warblers are not advancing in phenology as fast as key prey are likely to be responding to increased temperatures (e.g., the eastern spruce budworm, *Choristoneura fumiferana*). Earlier arrivals were at least in part achieved through faster migration (as opposed to earlier departure dates), as the duration of migration between the southern and northern locations decreased by 0.8 days with every 1°C increase (average of 22 days, Marra et al. 2005).

One message from this body of work is that patterns in phenology will vary both in time and space, and that our ability to predict changes in timing, and potential mismatches, is very uncertain. For example, recent work from Minnesota and South Dakota shows that many species migrating through the prairies are arriving significantly earlier, especially those that are typically earliest and tend to feed on aquatic insects (Swanson and Palmer 2009). While patterns emerged in terms of which species are arriving earlier, the strength of trends for the same species varied across the two states. Interestingly, strong changes were detected even though temperatures in spring for the region have not shown much change, although winter temperatures have significantly increased (Swanson and Palmer 2009).

5.6 Changes in Genetics and Morphology

Most studies documenting responses to climate change focus on readily-observable characteristics such as phenological shifts; however, increasing numbers of studies are showing that changes in other characteristics, such as morphology (body shape or size), behavior, and underlying gene frequencies, can be linked to rapidly warming temperatures. As with other areas of response to climate, well-documented patterns that are not necessarily directly climate-related lead us to expect genetic impacts, such as well-documented patterns of reduced genetic diversity in populations at the "leading edge" of directional range expansions (Excoffier et al. 2009; Sexton et al. 2009; see also the Garroway et al. 2011 northern flying squirrel example cited above). Demonstrating changes in gene frequencies in response to climate change is a major challenge, as it requires these frequencies to have been measured in many generations. As a result, most examples are studies of short-lived insects like fruit flies (*Drosophila* species) using comparative approaches. Work on fruit flies around the world has demonstrated shifts in how chromosomes are arranged that correlate with geographic patterns, i.e., populations in the north shift toward showing patterns like those to the south as climate warms

(Levitan 2003; Balanyá et al. 2006; Etges and Levitan 2008). These changes tend to be discussed in terms of "heat tolerance," yet the actual benefit of these changes in terms of enhanced viability have not yet been established (Gienapp et al. 2008).

Strong evidence of similar genetic changes in vertebrates in response to climate change is very rare (Gienapp et al. 2008), but one notable exception comes from long-term research focused on red squirrels (*Tamiasciurus hudsonicus*) in western Canada. Work by Réale et al. (2003) demonstrated that shifts toward earlier breeding phenology in response to climate-induced changes in food supply are the result of both phenotypic plasticity (87 percent of the change) and an evolutionary response (13 percent). Recent work by Pergams and Lacy (2008) documented rapid genetic and morphological changes in Chicago-area mice (*Peromyscus leucopus*), though the mechanism for this change likely includes a complex set of environmental factors in addition to recent climate change.

Although results suggest that some species may be able to respond quickly to changes, many others may lack the genetic variation that might allow selection, and thus adaptation, to occur. In other cases, as has been demonstrated for a Minnesota population of a native prairie plant (*Chamaecrista fasciculata*), adaptive responses can be slowed even when variation is present due to linkages between traits that are "antagonistic", such that one trait confers benefits in a new climate and another does not (Etterson and Shaw 2001).

5.7 Changes in Key Disturbance Factors and Processes

In addition to the many direct and indirect influences of climatic factors on species and ecological systems described above, climate change can also alter key processes that influence the viability of species and characteristics of systems. For terrestrial systems in the Midwest region, processes with a strong link to climate include fire frequency and intensity, flooding frequency and volume, drought, and, with possibly less certainty, wind and ice storms. These disturbances and some interactions (i.e., moisture stress tends to correlate with increased damage when trees are attacked by insect pests or disease outbreaks) are described for forest systems in Handler et al. (2014). Some systems are likely to benefit from changes in disturbance regime, and may be easier to restore or maintain on the landscape as a result of these changes. For example, prairie ecosystems (which have been drastically reduced in extent in the central U.S.), along with several species of oak and pine, are favored by drier conditions and frequent fires.

Changes in temperature, both direct and through the ice and wind-related mechanisms described above in the impacts section, have the potential to profoundly change how large lakes in our region function (see also the review by Mackey 2014). Specifically, these climate change factors may drive changes in the timing or duration of stratification (the separation of lakes into distinct horizontal layers). The differences in temperature, light availability, and other factors that occur as a result of stratification provide a diversity of habitats within stratified lakes, which allows species with a wide variety of temperature and other habitat requirements to persist. The timing of stratification, as well as the timing of the fall "turnover", when the oxygen-rich surface waters cool and increase in density and finally sink down and mix with the others, can be a critical factor influencing the viability of lake species, especially cold-water fish (Magnuson et al.

1997). Given that changes in water temperatures for the upper Great Lakes are projected to continue to match or exceed the air temperature increases, we should expect to see longer stratified periods and increased risk of oxygen deficits below the thermocline in late summer (Magnuson et al. 1997; Jones et al. 2006; Dobiesz and Lester 2009). Increases in the duration of the stratified period of over two weeks have already being observed for Lake Superior (Austin and Colman 2008), and projections for the end of this century suggest that we could see lakes stratify for an additional one and a half months (Lake Erie for a lower emissions scenario and thus less climate change) to three months (Lake Superior under the assumption of higher future emissions; Trumpickas et al. 2009). Stratification is less likely in lakes, lake basins, or bays that are shallower and located at lower latitudes. However, some shallow water bodies will exhibit oxygen-poor "dead zones" because shallow water warms more rapidly. Warmer water holds less oxygen and also triggers an increase in respiration rates (and oxygen needs) for ectothermic aquatic species. As warming continues, we should expect more and more areas to develop "dead zones" and for others to transition from stratifying in summer to not stratifying at all due to increases in water temperature, with a resultant loss of species that depend on habitats characterized by colder water.

5.8 Linking Observations to Future Changes

Thus far, the weight of evidence suggests that the most appropriate expectation for how species may respond to climate change is to anticipate more of the types of changes we have already seen -- i.e., changes in ranges (evading the change) and changes in phenology and behavior that allow species to persist in the same range. Not all changes in observed characteristics (phenotypes) that allow a species to persist in the same place require a change at the genetic level, as many species are able to show flexible or "plastic" responses to temperature or water availability as conditions vary across years. Thus, when conditions change in a given location, we can expect to see both flexible changes in some species (phenotypic plasticity), and, if diversity is present and individuals that best tolerate the new conditions produce more offspring, heritable changes (i.e., evolution – a change in how common given genes are within the population). In general, phenotypic plasticity can be thought of as a "short-term" solution, as the limits to these responses will eventually be exceeded as a population experiences a long-term increase or decrease in an environmental factor (Gienapp et al. 2008). Thinking about both mechanisms for change highlights a caution for our ability to manage over the long term. That is, many species that appear to be tracking changes in climate, or thriving even as factors change, may show sudden declines in viability once the temperature shift exceeds some critical threshold beyond which their "flexible" response is not enough.

The potential for evolution in response to climate change is constrained by the degree to which genetic variation for particular traits is present in a given population. For example, traits that contribute to increased heat- or drought-tolerance must be present in a population for natural selection to favor the individuals that have those traits, and eventually lead to an overall change in the proportion of individuals with that "adaptive" trait in later generations. For many of the Midwest's species of greatest conservation concern, we already suspect that population declines, habitat fragmentation, and other stressors have reduced the level of genetic variation such that there is little variation left upon which natural selection can act. It is, however, exceedingly rare to actually have data on genetics over time that can be used to confirm or refute this suspicion. Similarly, evidence for genetic responses to climate change is extremely rare, as it requires genetic data to have been sampled over time (Balanyá et al. 2006). As of yet, while there are many examples of changes in species in response to climate change, there are no documented examples of genetic shifts in thermal tolerances that appear to allow species to remain viable in the same location following a change that would have otherwise led to reduced survival or reproduction (Parmesan 2006; Bradshaw and Holzapfel 2008; Gienapp et al. 2008).

5.9 Assessing Vulnerabilities

The vulnerability of a species, system, or ecological service can be described as a function of three factors: 1) exposure to some form of change in climate (e.g., temperature increase, change in timing of flooding); 2) sensitivity to the change, and 3) adaptive capacity, or the potential for that species, system, or process to respond, move, or even transform in a way that allows persistence or maintenance of key functions as conditions rapidly change (Schneider et al. 2007; Foden et al. 2008; Williams et al. 2008; Klausmeyer et al. 2011). While these categories are helpful for framing discussions, the concepts of sensitivity and adaptive capacity can be hard to disentangle in environments with a strong human influence. For example, a species or system may be much more sensitive to changes in hydrology (timing and amount of water availability) if invasive species, or water infrastructure, have already changed the way water moves through the system. For this reason, it is often helpful to think of both sensitivity and adaptive capacity in terms of intrinsic and extrinsic characteristics.

Intrinsic aspects of sensitivity include physiological tolerances for temperature or drought, while related intrinsic components of adaptive capacity include genetic diversity of a population (potential that some individuals have traits that lead to higher tolerances), and traits that allow movement or flexible timing for key life events. Following the temperature tolerance example, an animal may be more sensitive to increases in temperature if it is already stressed by some other factor, such as exposure to pollution or water with low levels of dissolved oxygen. Extrinsic elements of adaptive capacity include the geographic context in which the exposure to climate change takes place – for example, fish in deeper rivers or lakes are more likely to be able to persist as temperatures warm, because they can move into deeper water. Similarly, species that are likely to respond to changes in climate by shifting their range have higher intrinsic capacity to do so if they can swim, fly, or run, and higher extrinsic adaptive capacity to do so if they are currently found in a landscape or aquatic system that is connected to cooler habitats. From a management and conservation standpoint, we are typically trying to move "levers" that reduce the impact of extrinsic factors. Can we implement actions that address other stressors (like pollution or habitat loss) that increase sensitivity, or reduce adaptive capacity? Can we remove barriers to movement? Can we work with partners in other sectors to reduce the impacts of water management infrastructure on stream hydrology? However, in many if not most parts of the Midwest, there will be at least some species or system types for which there is little we can do to reduce the impacts of climate change, and little intrinsic potential for the species or system to adapt. For these cases, reducing the rate of change through reduction of greenhouse gas emissions is the only meaningful strategy.

Characteristics often identified as indicators of species that are at greatest risk of population decline or possibly even extinction due to climate change impacts include (Parmesan 2006; Brook et al. 2008; Foden et al. 2008; see also the list for trees in Handler et al. 2014):

- Occur at high altitude or latitude (can't shift range further up, or to the north in the Northern Hemisphere).
- Occur in isolated habitats surrounded by developed land or adjacent to natural barriers that inhibit dispersal.
- Near limits of physiological tolerance.
- Limited dispersal ability.
- Very specific habitat requirements, including ties to a particular timing of water availability.
- Highly dependent on interactions with one or a few other species (susceptible to phenology mismatches, and mismatches in rate or location of range shifts).
- Long generation time (slow potential pace of microevolution).
- Low genetic variability and/or low phenotypic plasticity. Low genetic variability may arise due to population reductions, or to a long history of occupying a relatively narrow set of climatic and habitat conditions.

In general, for the Midwest, vulnerability assessments often highlight aquatic species that depend on cold water as being among the most vulnerable, as these species often have narrow tolerance limits, and aquatic systems are often degraded and not well connected. While the high vulnerability of cold water fish (described in an earlier section) are of concern due to the ecological, recreational, and commercial values of fish, there are many other species that are likely at risk in aquatic systems as water temperatures rise and smaller streams dry up more quickly during longer, hotter summers. Through connecting patterns of geologic history, current species diversity, and potential climate impacts, we can identify other particularly vulnerable taxa. While the Great Lakes are a "young" freshwater system (i.e., species there moved in after the most recent glacial retreat, some 14,000-16,000 years ago), the southern part of the Midwest region sustains species with much longer ecological histories in the area, which leads to higher specialization and species diversity. Work by DeWalt and colleagues indicates that unglaciated areas of southern Illinois, southern and central Indiana, and southern Ohio could lose many rare aquatic insect species if changes in precipitation patterns and increasing evapotranspiration rates promote more rapid drying of small, isolated ephemeral streams (DeWalt et al. 2005; DeWalt and Grubbs 2011; DeWalt et al. 2012). Similarly, the combination of several risk factors suggests that freshwater mussel species, already highly imperiled in the Midwest, have strong potential to be highly vulnerable. Freshwater mussels are temperature sensitive, have low mobility and high habitat specificity, and have a strong dependence on the presence of one or a few host species (often fish) during their larval stage when they are obligate parasites, and these fish are also likely to be vulnerable (Strayer 2006; Pandolfo et al. 2010).

Because the suite of potential impacts is so large, and impacts are often inter-related, our "best guesses" on impacts and species vulnerability may vary considerably depending on how many risk factors are considered. For example, Jones et al. (2006) found that projections of the potential impact of climate change on Lake Erie walleye (*Sander vitreum*) based simply on water temperature change were very different from results incorporating changes in climate-sensitive factors such as water levels and light penetration. Adding more factors played out differently for different subsets of the population. For river spawning fish, adding habitat factors suggested a more optimistic outcome (fewer model runs were associated with reduced fish recruitment than when habitat factors were not included), while for lake spawning fish, adding information on possible lake level declines to the thermal tolerance information suggested a higher potential for reduced recruitment. Jones et al.'s (2006) work relied upon decades of research on this fish's habitat needs and biology, and illustrates that for well-known species like walleye, the challenge to managers and conservation practitioners may focus on characterizing a complex set of direct and indirect climate-related changes that may interact and influence species survival. For most other species, a lack of baseline information from which to even begin the process of understanding potential impacts is often the most daunting challenge.

Considering the range of climate change drivers, and diversity of impacts described for both terrestrial and aquatic systems, it seems likely that one of our most challenging systems to protect will be Great Lakes coastal ecosystems (reviewed by Mackey 2014). The region's Great Lakes coastal ecosystems have experienced dramatic changes due to accidental and intentional introductions of non-native species, and are already under stress from a wide range of factors (pollution, coastal development, reduced connectivity to streams and rivers). Due to their location at the interface between terrestrial and aquatic systems, coasts are susceptible to changes in an unusually high number of climate-driven factors as well. In particular, the potential for interactions between invasive species, increasing runoff from terrestrial systems during storms, and temperature increases in shallow waters and surface waters make understanding and responding to changes in these systems a major challenge. Yet, both the wild species and the people of our region depend on productive, clean coastal systems as the base of food chains and local economies.

5.10 Helping Species and Systems Adapt in the Midwest

5.10.1 INCREASE CONNECTIVITY AND "SOFTEN" MANAGEMENT

Within the Midwest region, the ability of species to shift locations in space is likely to vary widely, both as a result of differences in movement ability and as a function of the condition of the landscape or freshwater system (Parmesan 2006). In much of the Midwest, there are many barriers to movement, including both natural features like the Great Lakes, and vast expanses of land that may be inhospitable due to current land use (e.g., conversion to agriculture or other forms of development, Mitsch and Gosselink 2007; Handler et al. 2014). A key goal for helping species and systems adapt in our region is improving connectivity by restoring natural habitats in areas where key connections have been lost and by working to "soften" management in lands managed for multiple purposes, such that the ability of wild species to inhabit and move through those areas is increased.

By increasing connectivity in both terrestrial and aquatic systems, we have the potential to increase the capacity of biodiversity to adapt to climate change through at least three mechanisms. First, restoring connectivity at local scales (i.e., connecting neighboring forest patches or stream reaches) increases the chances that genetic diversity in an area will be maintained by allowing increased mixing of populations. Higher rates of mixing, or "gene flow," should promote future populations with a wider range of variation in key traits (e.g., heat tolerance, growth rate under drought), which in turn should increase the odds that some individuals will be able to persist and thrive under new climatic conditions. Second, restoring connectivity can improve adaptive capacity by allowing mobile species access to cooler or moister microclimates (north facing hillsides, streams with high forest cover) within the same local area so that individuals can shift into these habitats when conditions are severe. Third, again for mobile species, increasing the connectivity of habitats provides a pathway for long-term shifts in range, as species shift north in our region to "track" their most favorable temperature regime. In addition to these three species-focused mechanisms, increasing the connectivity of ecological systems promotes resilience by allowing large scale ecological processes like flooding to occur, which provides an essential mixing of energy and materials between aquatic and terrestrial systems. By restoring the connectivity and extent of natural systems like floodplains and allowing this natural process to occur in natural areas, we can also help prevent people and property from being harmed as flood frequencies increase due to increases in peak storm intensities.

For terrestrial animals, ways to increase connectivity include taking actions that enhance the likelihood that animals can move through our landscapes, such as restoring key habitats that have been lost, and working with landowners to enhance habitat values ("soften" management) on highly managed or modified lands. These types of actions should also benefit plants, which may be moved either by animals or by wind. To help fish and other aquatic species respond to increasing temperatures by shifting ranges, we need to identify barriers in streams and rivers, and, balancing the risk of allowing access by invasive species (e.g., sea lamprey), take action to remove key barriers to movement. Understanding and developing responses to potential shifts in freshwater species are a particular challenge, because there is typically less information available on the distribution of aquatic species, and conservation areas are often more strongly tied to terrestrial, rather than aquatic, species diversity (Strayer 2006; Heino et al 2009; Herbert et al. 2010). Further, for aquatic invertebrates with limited dispersal abilities, different natural habitats within streams can act as barriers, potentially preventing shifts in range in response to climate change (Strayer 2006).

5.10.2 CONTINUE TO PROACTIVELY ADDRESS THE THREAT OF INVASIVES

In the upper Midwest/Great Lakes region, we have many native species, especially plants, which are best suited to survive and compete for resources when winter conditions are harsh and growing seasons are relatively short. As winter warms and the growing season extends, plants that can grow faster and take advantage of these changes are likely to dominate, and this increase in competition is likely to increase the rate of loss of the region's native species. These more competitive species may be native, may be species from south of the region's boundary, or may be non-native invasive species that have not been able to persist after dispersing here in the past, but will be able to survive and thrive here under future conditions. Given that some native species will shift out of the region, to maintain or increase species diversity, we should plan for and even promote some uncommon or new species as conditions change. However, we need to be even more vigilant about keeping potential invasive species from outside of North America from gaining a foothold. Strategies to address these challenges include increasing support for partnerships like weed management cooperatives that focus on early detection and eradication, and increasing investment in education-focused partnerships with stakeholders that are sources of non-native plants, such as the landscaping/gardening industry. Further, we need to be careful as we select seed and plant sources for restoration activities, as using seed sources from farther south in a species' range may make sense in some situations if we want to be proactive, but may contribute to declines in rare local populations if planted in proximity to locally-produced plants (Holmstrom et al. 2010). Invasive species issues are a pervasive problem in the Midwest's aquatic systems, most notably in the Great Lakes, and they are addressed in a climate change context in Mackey et al. (2014).

5.10.3 SHIFTING SOME OF OUR CONSERVATION ATTENTION FROM SPECIES TO "STAGES"

Historically, efforts to identify key places to conserve in order to protect biodiversity have focused on mapping patterns of where species are found, and choosing to purchase or protect areas based on "diversity hot spots" suggested by these distributions. Given that many species are likely to shift distributions in response to changing conditions, and that individual species' responses to climate change will be complex and individualistic (Root and Schneider 2006; Chen et al. 2011), these maps in essence represent a snapshot, not a long term picture. As a result, it makes sense to think about protecting factors that correlate with or "drive" patterns of diversity at the scale of a region or landscape. This perspective of moving from a focus on species toward a focus on landscapes or watersheds is not new, but it takes on a greater importance and includes some additional elements (protecting climatic refugia, and saving the "stage", described below) as we update conservation and management to incorporate climate change (Groves et al. 2012).

Specifically, a key strategy for "climate smart" biodiversity conservation involves broadening our perspective from species to think about the diversity of conditions on landscapes and watersheds (Strayer 2006). As we prioritize areas for protection, consistent patterns of local-scale variation in climatic factors (e.g., north facing slopes are cooler than south-facing slopes due to difference in sun exposure, the Great Lakes modify the climate of areas near their shores) should be recognized and integrated with other consistent patterns in drivers of biodiversity (e.g., variations in soil, streambed type, or topography)(Anderson and Feree 2010; Beier and Brost 2010). While we recognize that the specific values of climate variables (i.e., high temperatures) will change, these consistent differences across sites are expected to persist, because the factors that create them (e.g., underlying topography, presence of the Great Lakes) will not change due to climate change. These consistent landscape-scale units of variation have been referred to as "stages" (in the sense of a location where actors, or species, might appear, Anderson and Feree 2010) or "land facets" (Beier and Brost 2010). If we can map these stages, we can focus land protection or conservation efforts on capturing the widest possible variety of these land or aquatic units. When these gradients are protected, we maximize the potential for heat-stressed individuals of a wide range of species to encounter cooler micro-sites without having to move long distances. Further, adapting our conservation work to include the goal of capturing the range of factors that underlie variation in species should help protect a wider range of species within taxa that are typically not represented as conservation areas are designated, such as mollusks and other aquatic invertebrates (Lydeard et al. 2004; Strayer 2006).

In the Midwest, one element of capturing the breadth of land facets or stages to conserve will involve increasing our understanding of how exposure to climate change varies across landscapes, stream networks, and within large lakes and rivers. Individuals of a species respond to the climate they experience, not average conditions (Walther et al. 2002), and what they experience varies with factors like latitude, landform, distance from a Great Lake, and water source (groundwater or surface water, Chu et al. 2008; Andersen and Feree 2010; Beier and Brost 2010; Klausmeyer et al. 2011; Magness et al. 2011). Thus, a key step toward updating our approach to conservation involves answering questions like: "What factors influence the spatial distribution of warming?" Once we have a better understanding of current variation, we can develop conservation strategies that take advantage of naturally cooler areas or climate "refugia", such as the cooling influence of the Great Lakes on nearby terrestrial systems, and do a better job of protecting the thermal regime of streams (e.g., by restoring riparian vegetation, protecting groundwater inputs, and minimizing exposure to urban runoff, Chu et al. 2008; Steen et al. 2010; Groves et al. 2012).

5.10.4 INCREASING "GREEN INFRASTRUCTURE" TO HANDLE STORMWATER

As climate change continues, we will need to be much more proactive in how we address issues related to storms and flooding. Natural systems are at risk from these changes, but can also be a key part of the solution – by increasing the proportion of forests near rivers, wetlands and other natural systems in areas prone to flooding, water can be slowed down and held, reducing the risk to both aquatic systems and to people (Kousky 2010; Kousky et al. 2011).

To reduce the problem of flooding and proactively prepare for increases in storm intensities, restoring systems like forests and wetlands in flood prone areas are essential components of adaptation strategies to benefit people and nature. This approach is supported by research showing how hydrology in the Upper Great Lakes region has changed as a result of large-scale conversion of forests into agriculture and other forms of land use with lower rates of evapotranspiration and infiltration (Mao and Cherkauer

2009; Mishra et al. 2010a; Groisman et al. 2012). Most opportunities and potential benefits to biodiversity from engaging with actions taken in other sectors are not new, but they may now rise in importance, as we expect adaptive actions to take place in these sectors.

A good example of a persistent stressor that fits this description is overflows of combined sewer and stormwater handling systems in which rainwater, sewage, and industrial wastewater are transported in the same pipe to sewage treatment plants where water is treated and discharged to a water body. At this time approximately 746 cities in the U.S. (U.S. EPA 2004, 2008) have combined sewer-stormwater systems, and many of these are in the upper Midwest. Heavy precipitation or rapid snowmelt, both of which are predicted to be enhanced in the Great Lakes region, can lead to overflow, which means direct discharge of wastewater into water bodies. Overflows are a threat to both water quality and public health, as output can include microbial pathogens, suspended solids, biochemical oxygen demand (BOD), toxic materials, nutrients, and debris (U.S. EPA 2004). In many locations, infrastructure for handling wastewater is in need of updating, and sectoral climate change vulnerability assessments emphasize the need to plan for increases in stormwater volume (U.S. EPA 2008). When updates to these systems are planned, the conservation community can play important roles in promoting the implementation of "green infrastructure" (e.g., wetland restoration, riparian buffers, rain gardens) and in ensuring risks to biodiversity are accounted for as new standards and policies for these systems are put into place.

5.10.5 PROTECT PEOPLE AND NATURE BY RESTORING FUNCTIONAL ECOSYSTEMS IN WATERSHEDS DOMINATED BY AGRICULTURE

Direct and indirect impacts of climate change have great potential to reduce the effectiveness of conservation strategies focused on protecting rivers and streams in watersheds dominated by agriculture. First, these aquatic systems will be affected by temperature changes and are highly sensitive to changes in the timing and amount of precipitation. Further, an increase in the intensity of peak storm events (Groisman et al. 2012; Kunkel et al. 2013; Winkler et al. 2014) suggests an increase in some of the most important current threats. For example, big storms, especially storms that occur when soils are saturated, lead to overland movement of sediments and pollution from agricultural fields into streams, which can drastically reduce the suitability of these systems for the region's native fish and aquatic invertebrates (Strayer 2006; Sowa et al. 2007; Herbert et al. 2010).

Responses by farmers to changes in climate also have the potential to put sensitive species and aquatic systems at greater risk. For example, increases in temperature influence what farmers can grow and may lead farmers to have crops in the field for longer periods, thereby potentially adding additional fertilizer or pesticide treatments. Temperature increases are also expected to lead to increased evaporation, which promotes drought stress and reduced stream flows (Mishra et al. 2010b) even without a decrease in precipitation. In some places, increased drought stress may promote increased investments in irrigation and increased withdrawal pressure on ground and surface water supplies. Interactions with hydrology are also important in the spring. In many watersheds, farms have very effective systems for quickly shunting spring precipitation off of fields to allow earlier planting of crops. As the intensity of storms continues to increase, we expect to see more farmers adding to their drainage infrastructure. However, drainage, and the simple conversion of land to forms that have low capacity to absorb water or reduced capacity to slow the overland flow of water, promotes flooding of all sorts of land types, including farms, residential areas, and cities. As this example suggests, thinking through possible interactions between the agricultural sector and natural resource management highlights the fact that successful adaptation will require collaborative solutions. One key strategy for reducing the risk of flooding is to work in partnership to reconnect and re-vegetate natural floodplains along streams and rivers. Natural floodplains provide the essential services of holding and absorbing flood waters, which protects people and property, while also promoting connectivity for a wide variety of species that use them as corridors through what is often an inhospitable landscape (Opperman et al. 2009; Kousky 2010; Kousky et al. 2011).

5.10.6 MOVING TOWARD SMARTER CONSERVATION

As we work to update our conservation plans and make them "climate smart", it is vitally important that we also update or approaches to management such that they become more agile and able to shift strategies quickly in the face of new information and surprises. With respect to anticipating surprises, we expect that surprises for resource managers will take at least three forms: 1) exceedance of thresholds (e.g., temperatures rise above thermal tolerance thresholds, leading to strong declines in fitness); 2) new interactions among species and/or new or synergistic impacts related to interactions with climate and other stressors (e.g., invasive species); and 3) higher frequency of extreme weather events with catastrophic impacts on focal systems (floods, ice storms, "typical" cold periods in spring that now occur after a prolonged spring warming).

Acting in a climate smart way will also require that we improve our ability to share and synthesize the information we do have, and improve our tools for acting in the face of uncertainty. We will also need to do a better job of separating scientific data from values, and work more closely with a broader range of stakeholders to craft cross-sector solutions (Hobbs et al. 2010; Groves et al. 2012). Evidence that addressing climate change helps promote larger-scale approaches to conservation can be seen in the recent emergence of many regional scale collaborations, including a recent agreement between the states of Michigan and Wisconsin to share information and work together on adaptation, and a suite of federal initiatives, including USFWS's Landscape Conservation Cooperatives, NOAA's Regional Integrated Sciences and Assessments teams, USGS's Regional Climate Hubs, and the USFS's Shared Landscape Initiative. Given all of these new opportunities, we need to be ready to pursue actions that improve conservation more broadly by improving communication, collaboration, and connectedness of efforts. Although encouraging in many respects, this growing list of entities that seek to lead on climate change through creating regional partnerships suggests that, while key agencies agree on an appropriate scale for consideration of the challenge, we face a major coordination challenge if we intend to use our limited resources efficiently.

5.11 Five key points

In summary, I highlight five key points that I see as important considerations for resource managers and decision-makers in the Midwest. Likelihoods (in parentheses) indicate my own assessment of the probability of these focal impacts, based on this literature review and discussions with other members of the assessment team. Assessing climate change impacts and vulnerabilities for the species and ecosystems across the region is a very complex challenge, and this review only begins to address this important task. However, to protect people and nature in the region, we need to act now on the information that we do have.

1) Rapid climate change over the next century will stress a majority of species in our region, and is likely to accelerate the rate of species declines and extinctions (very likely). In the Midwest, key drivers of these stresses and extinctions are likely to be interactions between climate change and current stressors, and adaptive responses will often be constrained by factors like habitat loss and lack of connectivity, invasive species, and hydrologic modifications. Direct effects of temperature increases are likely to be most critical for aquatic species that require cold to cool stream habitats.

2) Due to geographic factors (relatively flat topography and moderate to high latitudes), species in the Midwest that respond to increasing temperatures by shifting ranges will need to move particularly fast relative to species in many other parts of the continental U.S. to track projected changes (likely). Further, movements will often be limited by a lack of natural land cover, or a lack of appropriate aquatic habitats, and the presence of both natural and anthropogenic barriers on land and in aquatic systems (very likely).

3) One pro-active approach for helping a wide range of species adapt is to start by identifying large-scale patterns in projected exposure to climate change, and patterns in current factors that influence local-scale climate exposure (i.e. land that remains cooler than other areas due to proximity to the Great Lakes; streams fed by cold groundwater). When these climatic patterns are combined with maps that describe variation in key factors that correlate with differences in habitat conditions (soil type, slope and aspect, hydrologic factors), we can strive to protect a variety of conditions, or “stages”, for species to inhabit. The goal of protecting a diversity of conditions on the landscape and in aquatic systems can be pursued with more certainty in terms of defining the actions to take than one focused on protecting a particular list of species (or “actors” on the stages), as each species may respond to changes in surprising ways. In effect, this is a way to hedge our bets in favor of biodiversity: If we can protect and connect a network of lands and waters that encompass the widest possible range of abiotic factors, this range of available habitats should continue to promote a high diversity of species, and provide a complement and safety-net to traditional species- and habitat-focused approaches.

4) For freshwater and coastal species in the Midwest, it is particularly important to recognize the interaction between climate change, changes in land cover, and changes in hydrology. Land cover plays a very important role in determining the water and energy balance of a natural system. When vegetation is removed, or experiences a major change in composition or structure, these balances tend to shift in ways that increase runoff, and

promote flooding, both of which contribute to stressors that put sensitive species and habitats at risk (very likely).

5) When the natural systems that act to slow or store stormwater are protected and restored, both people and nature benefit. Pro-active partnerships can help reduce additional losses of these key systems and ecological services, thus preventing actions that further disrupt our region's hydrologic balance.

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Chapter 6

Climate Change Vulnerabilities within the Forestry Sector for the Midwestern United States

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6.1 Introduction

Forests are a defining landscape feature for much of the Midwest, from boreal forests surrounding the northern Great Lakes to oak-hickory forests blanketing the Ozarks. Savannas and open woodlands within this region mark a major transition zone between forest and grassland biomes within the U.S. Forests help sustain human communities in the region, ecologically, economically, and culturally.

Climate change is anticipated to have a pervasive influence on forests in this region over the coming decades. In recent years, a growing field of study has emerged to categorize and predict the consequences of climate-related changes in forest systems

(Schwartz et al. 2006; Parry et al. 2007; Fischlin et al. 2009; Clark et al. 2011; Glick et al. 2011; Swanston et al. 2011). Two metrics that are often used to assess the outcome of climate-related changes in natural systems are “vulnerability” and “risk.” In this paper, we define vulnerability as “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes” (IPCC 2007). Vulnerability is a function of the degree of climate change a system is exposed to, as well as the system’s sensitivity and capacity to adapt with minimal disruption (Glick et al. 2011; Swanston et al. 2011). Also, it is important to note that vulnerability can refer to a decline in vigor and productivity in addition to more severely altered community composition or ecosystem function (Swanston et al. 2011). That is to say, a species or ecosystem may be considered vulnerable to climate change by virtue of decreased well-being even it is not projected to disappear completely from the landscape.

Risk offers an additional approach to describe the potential consequences of climate change in forest ecosystems. Risk includes an estimate of the likelihood or probability of an event occurring, in combination with the consequences or severity of impacts of that event (Glick et al. 2011). This approach explicitly considers uncertainty, although clearly communicating uncertainties is necessary for describing both vulnerability and risk in the context of natural resource planning.

This chapter summarizes recent information related to the major potential vulnerabilities associated with climate change in the forestry sector, organized according to “key vulnerabilities.” For the purposes of this white paper, key vulnerabilities are those that have particular importance due to the anticipated magnitude, timing, persistence, irreversibility, distributional aspects, likelihood, and/or perceived importance. Rather than attempting to quantify these risks, this assessment focuses on the question, “What is at risk?” This paper does not attempt to make new estimations of vulnerability or risk for the forestry sector, but rather synthesizes recent information to provide a useful summary.

The Midwest Region, as defined for the purposes of the NCA, covers the states of Minnesota, Wisconsin, Michigan, Iowa, Missouri, Illinois, Indiana, and Ohio. Forest ecosystems are not organized along political boundaries, but are distributed according to patterns of climate, moisture, soils, and disturbance. Therefore, we present information

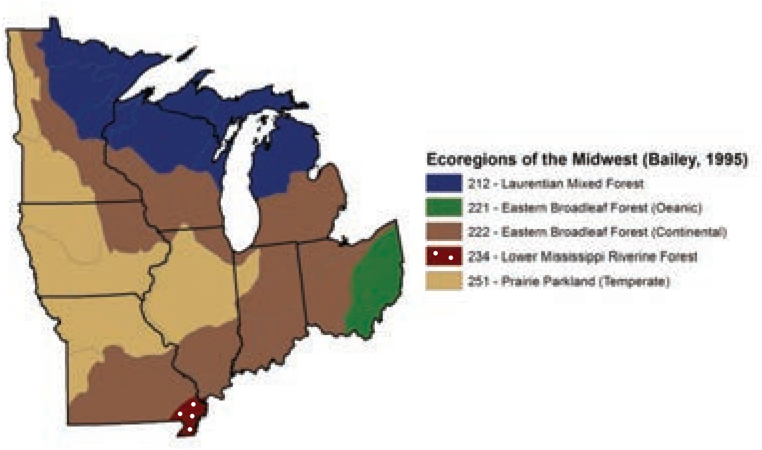


Figure 6.1. Ecoregions within the Midwest Region. *Source*: Bailey (1995).

on important climate change-related vulnerabilities according to ecological regions (ecoregions), as defined by Bailey (1995). The Midwest's eight-state footprint includes five distinct ecoregions, which are delineated according to associations of biotic and environmental factors that determine the structure and function of ecosystems.

The species, disturbance regimes, existing stressors, and potential exposure to climate change are different for each of these ecoregions. Therefore, we present key vulnerabilities that capture broad concerns across the Midwest and include ecoregion-specific information for greater depth and context where available. Because of the numerous connections between the forestry sector, other elements of the natural environment, and other sectors of human activity, there is necessarily some overlap between this paper and the companion contributions to the Midwest Technical Input Report.

6.2 Organization

For this report, we have followed guidelines related to framing key conclusions, communicating uncertainty, and ensuring information quality as presented by the NCA Development and Advisory Committee (NCA 2012). We organized this paper to enable readers to easily identify priority themes and key vulnerabilities. We draw a distinction between vulnerabilities related to forest ecosystems (forest ecosystems), and vulnerabilities related to ecosystem services derived from forests (benefits from forests). We categorize urban forests as a distinct class of forested ecosystems, because of specific risks, consequences, and vulnerabilities associated with these types of forests. The adaptation section describes general concepts and actions for responding to these vulnerabilities, but it is outside the scope of this report to make recommendations or cite specific actions.

Each key vulnerability statement is followed by our qualitative view of its likelihood of occurring, using specific language established by the Intergovernmental Panel on Climate Change (IPCC 2005; Backlund et al. 2008). Our use of these confidence statements is similar to Backlund et al. (2008); the statements reflect our judgment as authors, and we have not applied this terminology to previously published studies. Figure 6.2 presents the spectrum of confidence terms used in this paper.

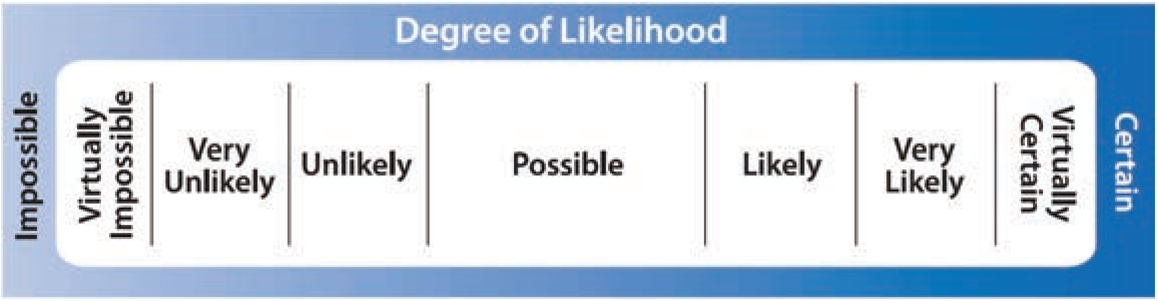


Figure 6.2. Language for describing confidence in findings. *Source*: Backlund et al. (2008).

6.3 Considerations and Caveats

The conclusions drawn in this paper are predicated upon the future projections of global and regional climate models. As discussed in Winkler et al. (2014), these climate projections must be interpreted with an understanding of the inherent uncertainties associated with making long-term projections for the complex global and regional climate system, as well as the uncertainties associated with particular aspects of climate models and downscaling procedures. Despite the uncertainties, there is widespread consensus among the scientific community that these models provide reliable projections of future climate. Although we are synthesizing research that utilizes numerous general circulation models, future emissions scenarios, and downscaling methods, we attempt to refer to the standard set of climate projections prepared for the Midwest Region for the National Climate Assessment (Kunkel et al. 2013; Winkler et al. 2014). These projections rely on a suite of climate model simulations using the B1 and A2 emissions scenarios as "low" and "high" climate futures, respectively.

The companion paper by Andresen et al. (2014) includes a discussion of historical climate during the previous 12,000 years in addition to observed trends during the 20th century. When contrasting projected future changes with historic climate records, it is important to note that both the magnitude and rate of change are influencing forest ecosystems, in addition to new interacting stressors that have not previously impacted forests in this region. Substantial change in climate has occurred throughout the Midwest Region during the past 12,000 years, but a major consideration is that in past millennia these changes were driven by natural phenomena, and resulting ecological changes occurred across a matrix that was comparatively free of human modification and development. Contemporary and future changes are occurring within a complex socioeconomic framework, such that future changes in Midwestern forests may have profound impacts on interrelated economic, social, and demographic systems. Recent published studies have concluded that climate change is already happening, and some of the observed indicators of change include severe weather patterns (Changnon 2011; Coumou and Rahmstorf 2012), lake ice timing (Magnuson et al. 2000; Johnson and Stefan 2006), tree phenology (Dragoni and Rahman 2012; Andresen et al. 2014), and wildlife distributions (Myers et al. 2009; Rempel 2011).

Our key vulnerability statements consider outcomes projected in ecosystem models in addition to empirical data gathered in recent years. All models have limitations, but they are useful tools to examine scenarios that are not possible to test directly. For example, statistical niche models such as the Climate Change Tree Atlas (Prasad et al. 2007-ongoing) rely on statistical relationships between the observed range of a species and several determining variables, including climate variables. The relationships accounted for by the model can only describe the realized range of a species, rather than the full potential range. Additionally, the contemporary relationships which determine habitat suitability for a particular species might not hold true in the future. Ecological process models like LANDIS (Scheller et al. 2007) also have inherent limitations to bear in mind, such as the inability to incorporate a full suite of disturbances and stressors into projections of forest growth and survival. Simulations from models should be treated as simplified scenarios to explore a range of outcomes, rather than concrete predictions.

The key vulnerabilities in this paper, and the confidence statements applied to each, reflect our professional consideration of these multiple formats of evidence and projections, along with their associated uncertainties and caveats.

6.4 Forest Ecosystems

6.4.1 KEY VULNERABILITIES ACROSS THE MIDWEST REGION

This section covers broad key vulnerabilities that are expected to be common to forest ecosystems across the entire Midwest Region. We have divided these region-wide vulnerabilities between "forest ecosystems" and "urban forests."

Forest ecosystems

1. Key Vulnerability: Climate change will amplify many existing stressors to forest ecosystems, such as invasive species, insect pests and pathogens, and disturbance regimes (very likely).
Forest ecosystems throughout the Midwest Region are exposed to a range of natural, introduced, and anthropogenic stressors. These include invasive flora and fauna, natural and exotic pests and diseases, altered disturbance regimes, land-use change, forest fragmentation, atmospheric pollutants, and others. Decades of research have revealed numerous individual and combined effects of many of these stressors on a variety of forest types. A more recent and rapidly growing area of this research, including experimental, observational, and modeling studies, includes the interaction of changing climate with existing stressors.

Anthropogenic changes in forest ecosystems are diverse and pervasive throughout the Midwest Region, including land conversion, fragmentation, timber harvesting, and fire suppression (Flickinger 2010; Minnesota Department of Natural Resources 2010). The Midwest has experienced large reductions in forest cover from pre-European settlement to the present, with the most dramatic declines occurring in Ohio (95% forest cover reduced to 30%) and Illinois (40% forest cover reduced to 13%) (Illinois Department of Natural Resources 2010; Ohio Department of Natural Resources 2010). Open woodlands and savannas have been lost to agricultural expansion and fire suppression, while fragmentation has reduced overall forest patch size and resulted in more edge habitats (Radeloff et al. 2005 ; Nowacki and Abrams 2008). Compared to other parts of the country, the Midwest Region stands out as one of the most concentrated areas of ecosystem conversion and alteration. A recent analysis by Swaty et al. (2011) highlighted this trend by integrating the combined effects of outright land conversion with the more subtle influences of fire suppression and forest management. Several studies from around the globe have illustrated the negative influence that habitat fragmentation will likely have on range expansion and colonization of new habitats by a variety of tree species (Honnay et al. 2002; Iverson et al. 2004a; Scheller and Mladenoff 2008). Habitat loss and fragmentation are two primary reasons that tree species may not be able to naturally colonize newly suitable habitats in the future quickly enough to keep pace with the rate of climate change.

In general, anthropogenic impacts have reduced diversity across forest ecosystems (Nowacki and Abrams 2008). Less diverse ecosystems inherently have greater susceptibility to future changes and stressors (Swanston et al. 2011). Elmqvist et al. (2003) emphasize that "response diversity," or the diversity of potential responses of a system to environmental change, is a critical component of ecosystem resilience. Response diversity is generally reduced in less diverse ecological systems. Therefore, climate change represents an even larger potential stressor for systems heavily disrupted by human activities.

Climate change is also changing the disturbance regimes that influence forest ecosystems across the U.S., including fire occurrence and severity, drought, floods, and ice storms (Dale et al. 2001). The Midwest has experienced increasing frequency and/or intensity in severe weather events in recent decades, including catastrophic storms (Changnon 2009, 2011), extreme precipitation events (Kunkel et al. 1999; Kunkel et al. 2008) and floods (Cartwright 2005; Tomer and Schilling 2009). For each decade from 1961 to 2010, the Midwest Region experienced more frequent rainfall events greater than 1 inch/day (Saunders et al. 2012). The frequency of rainfall events greater than 3 inches/day increased by 103% over this time period. States with the largest increases include Indiana (160%), Michigan (180%), and Wisconsin (203%). These high-intensity rainfall events are linked to both flash flooding and widespread floods, depending on soil saturation and stream levels at the time of the event. The total amount of precipitation in the Midwest Region increased by 23% from 1961-2010. Conversely, drought frequency declined slightly over the 20th century for the Midwest Region (Kunkel et al. 2008). Sparse long-term data on intense wind storms make it difficult to determine if these events are occurring more frequently (Peterson 2000).

While it might seem counter-intuitive given the increase in overall precipitation across the Midwest Region, moisture limitations on forest ecosystems are projected to be more common by mid-century under likely future climate scenarios. This is due to a combination of factors: extended growing seasons, increased summer temperatures, and more episodic precipitation patterns (Hanson and Weltzin 2000). Cherkauer and Sinha (2010) examined streamflow patterns based on downscaled climate projections in four states surrounding Lake Michigan and found that projected summer low flows decreased, summer high flows increased, and overall flashiness increased in summer months. When overlaid with projected increases in temperature for the region (Kunkel et al. 2013; Winkler et al. 2014), there appears to be increased potential for late-summer droughts and decreased moisture availability for forests, particularly at the end of the growing season. The consequence of moisture stress on forest ecosystems depends on a range of factors, but this disturbance can lead to substantial declines in productivity and increases in mortality. This is especially the case for seedlings, drought-intolerant species, and drought-intolerant forest types (Hanson and Weltzin 2000).

Among natural disturbances, fire has been the most manageable and fire suppression is likely to continue for most of the Midwest Region. The maximum duration of multi-day periods with temperatures >95°F is projected to increase by 85-245% across the entire Midwest Region by mid-century, according to a range of climate projections (Kunkel et al. 2013). A greater frequency of high-temperature days, in combination with dry late summer conditions, could lead to more active fire seasons across the region (Bowman et al. 2009). Increased investment in fire suppression and preparedness would likely minimize impacts to ecosystems for some time, but future decades may see much greater fire severity as seen in modeling projections (Lenihan et al. 2008) and western examples of near-term stress combined with long-term fire suppression (Peterson et al. 2005).

Dukes et al. (2009) reviewed the state of knowledge regarding climate change on insect pests, pathogens, and nuisance plant species, and on the resulting impacts on forest ecosystems throughout the eastern half of the U.S. Under the A2 emissions scenario, they forecast more insect pest damage due to increased metabolic activity in active periods and increased winter survival, although effects of climate on forest insects remain uncertain. Additionally, changes in phenology due to climate change could result in timing mismatches with beneficial insects such as pollinators (Forkner et al. 2008; Dragoni and Rahman 2012). It is more difficult to anticipate the response of forest pathogens under a warmer future due to complex modes of infection, transmission, survival, and tree response (Dukes et al. 2009). These researchers also generally expected invasive plants to "disproportionally benefit" due to more effective exploitation of changed environments and more aggressive colonization of new areas. For each of these categories of forest stressors, uncertainty limits the ability to make confident predictions.

Kling et al. (2003) also reviewed interactions between forest insect pests, atmospheric pollutants, elevated CO_2, and climate change. They suggested increased drought stress may make forests more susceptible to both fires and pests, but elevated CO_2 could speed forest succession after these disturbances. They anticipated, however, that ground-level ozone could counteract any short-term increase in forest growth due to elevated CO_2 or nitrogen deposition. Results from several Free-Air CO_2 Enrichment (FACE) experiments add insight to the potential for elevated CO_2 levels to alter the functioning of forest ecosystems – perhaps most importantly that observed responses in these field trials cannot simply be extrapolated to all forests (Norby and Zak 2011). Results from the Rhinelander FACE experiment indicate that aspen forests exposed to elevated CO_2 levels experienced an overall increase in productivity over 12 years (Zak et al. 2011). While increased ozone levels reduced plant growth in early years of the study, elevated growth of ozone-tolerant genotypes and species compensated for this decline.

The interactions between these stressors are complex, with some ecosystems potentially experiencing increases in forest health and vigor, while others are more likely to show a loss of ecological function or identity. Less diverse forests are generally considered more vulnerable to climate change if they are at all maladapted (Swanston et al. 2011), and may warrant greater scrutiny as systemic changes to stressors continue.

2. Key Vulnerability: Climate change will result in ecosystem shifts and conversions (likely).

As temperature and precipitation patterns continue to change (Andresen et al. 2014; Winkler et al. 2014), it is possible that large ecosystem shifts and conversions will accompany the changes. Ecosystems are complex assemblages of species, and so the response of individual species will strongly affect how ecosystems respond as a whole. Additionally, climate pressure on changing forests will continue within the context of forest management, possibly including active and widespread adaptation efforts. Changes in broad ecosystem types will thus vary from one place to another based on local management decisions and specific influences of site-level environmental factors.

Examination of simulated ecosystem responses to a range of climate projections can be used to assess large-scale trends that may be expected in forest systems. Lenihan et al. (2008) used the dynamic vegetation model MC1 to examine potential changes in vegetation classes at the end of the 21st century due to climate change and fire suppression.

Under future emissions scenarios comparable to Kunkel (2011) with continued fire suppression, they projected that the Midwest Region would lose most boreal (labeled subalpine) forests, with a majority of the region transitioning to a temperate deciduous forest (SF-A and SF-B, Figure 6.3). In future scenarios with more wildfire activity, the boreal forest types were similarly diminished in the Midwest Region, but they were replaced in western portions of the region by woodlands, savannas, and grasslands. Temperate deciduous forests were projected to move northward and occupy much of Indiana, Ohio, and Michigan under both high (USF-A) and low (USF-B) emissions scenarios.

Simulation results from Lenihan et al. (2008) also showed a large expansion of woodland/savanna and grassland vegetation types in the Midwest under the unsuppressed fire scenarios (USF-A and USF-B, Figure 6.3). This work is largely consistent with results

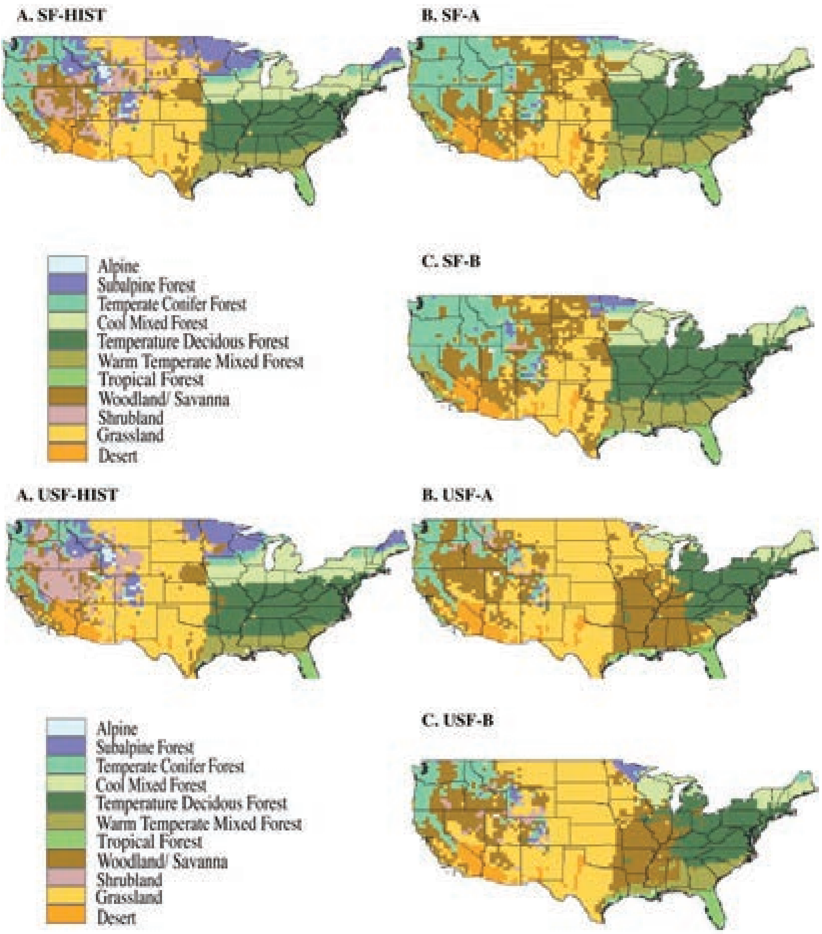


Figure 6.3. Model simulated vegetation type with suppressed fire (SF) and unsuppressed fire (USF) for 1971-2000 historical period (HIST) and 2070-2099 future period. A: SRES-A2 emissions scenario (high climate change), B: SRES-B2 emissions scenario (low climate change). *Source*: Lenihan et al. (2008).

from the systems mapping approach of Frelich and Reich (2010), which showed a broad shift from forest to savanna along the prairie-forest border in the Midwest. The systems mapping approach did not include explicit consideration of fire suppression. These studies illustrate the potential for major shifts in vegetation types even under lower emissions scenarios, but also that societal investment into management efforts such as fire suppression may have equally strong influence.

When considering the potential for ecosystem conversions, species migration is a critical issue. It is not necessarily communities that move, but instead species that move and then form new communities. Re-constructions of vegetation response to past climate change indicate that the species forming forest communities have disassembled and re-aggregated in different permutations (Davis et al. 2005). Species distribution models have also indicated that species may respond individually to future climate change, with suitable habitat expanding for some species and declining for others (Walker et al. 2002; Iverson et al. 2008b; Morin et al. 2008). For the majority of 134 tree species across the eastern U.S., the Climate Change Tree Atlas estimates that mean centers of suitable habitat will migrate between 100-600 km to the northeast under a high emissions scenario and between 50-400 km under a more mild climate change scenario (Prasad et al. 2007-ongoing). Similarly, a process-based distribution model incorporating phenological timing, reproductive success, and dispersal ability (PHENOFIT) projects a general northward expansion among 14 widespread Midwestern tree species, with local extinctions at southern range extents (Morin et al. 2008). The interacting factors of unprecedented local climates, habitat fragmentation, widespread forest management, and adaptation actions will greatly influence how species migrate, colonize, or survive in current and future habitats. Taken together, this raises the possibility that unprecedented assemblages of species could form novel ecosystems.

3. Key Vulnerability: Many tree species will have insufficient migration rates to keep pace with climate change (likely).

Analysis of forest species responses to past climatic change has highlighted the fact that contemporary rates of temperature change will make it very difficult for trees to migrate fast enough to track changes (Davis 1989; Davis et al. 2005). Studies utilizing species distribution models have projected that tree species in the eastern U.S. have a low probability of colonizing habitat beyond their existing ranges over the next 100 years (Iverson et al. 2004a). Habitat loss and forest fragmentation are two primary reasons for this expected inability to migrate, with the actual movement of tree species being substantially slower compared to the shifts in optimum latitudes based on temperature and precipitation. Iverson et al. (2004b) estimated that less than 15% of newly available habitat would be colonized over 100 years in a study of five eastern tree species, using future temperature projections similar to Kunkel (2011). The high degree of fragmentation in natural ecosystems across the Midwest means that widespread vegetation migration will be less able to occur in response to projected climate change (Honnay et al. 2002; Iverson et al. 2004a; Scheller and Mladenoff 2008).

Studies are beginning to emerge that examine whether observed tree distribution shifts match the anticipated trends. These studies largely serve as a reminder to avoid an oversimplified view of northward range shifts. Some work has found evidence of an expansion northward of northern species, with less evidence of a strong response by southern species (Woodall et al. 2009), but northward range expansions may be limited to a small percentage of species (Zhu et al. 2011). Range contractions along the southern edge of several species' distributions have also been documented (Murphy et al. 2010; Zhu et al. 2011). Based on gathered data of seedling distributions, Woodall et al. (2009) estimated that many northern tree species could possibly migrate northward at a rate of 100km per century. Other studies have estimated that suitable habitat for tree species in the Midwest Region will shift as much as 400-600km by 2100, suggesting that natural migration rates will not be suffienct to keep pace with climate change (Prasad et al. 2007-ongoing). Researchers have raised the possibility that human-facilitated migration could allow more rapid species movement (Woodall et al. 2009), but widespread assisted migration would require a concerted effort across the region.

Plants that are "left behind" by a shifting habitat will not necessarily become extirpated from a site, especially if there are no better-adapted species to out-compete them. Better-adapted species may fail to successfully migrate and establish due to several factors, such as habitat fragmentation, land-use change, or moisture patterns (Honnay et al. 2002; Iverson et al. 2004a; Scheller and Mladenoff 2008; Crimmins et al. 2011). Even without strong competitors, plants living outside their suitable habitat may decline in vigor or have lower resilience to a variety of stressors. In the long run, ecosystem shifts may take place not through climate-related mortality, but instead through poor recruitment of young trees.

Urban forests

4. Key Vulnerability: Climate change will amplify existing stressors to urban forests (very likely). Urban forests are distinct from natural or managed forest ecosystems, partly because of their structure and composition, and partly because of the many specialized benefits they provide for residents of cities and towns.

The Midwest is home to several major metropolitan areas, including Chicago, Indianapolis, Columbus, Detroit, Milwaukee, Kansas City, Cleveland, and Minneapolis. According to 2010 U.S. Census data, over 45 million people live in urban areas of the eight states in this region, almost 75% of the region's total population (U.S. Census Bureau 2011). Urban areas occupy 3.9% of the total land area in the Midwest, with an average tree cover of 33.2% (Nowak and Crane 2002). This is a higher proportion of urban tree cover than the U.S. average, and the second highest proportion among all the major regions of the country.

Forests in metropolitan areas typically occur in unnatural mixed assemblages with ornamental and understory species (Woodall et al. 2010). These forests usually have 50-80% less biomass per area than is typical in forest areas. While large numbers of different species may occur in urban settings, a few primary species represent the majority of trees. The state of Indiana illustrates this pattern, with maple and ash species making up the bulk of trees found within municipalities, while 3 of the top 11 most frequent species are non-native to the state (Indiana Department of Natural Resources 2010).

Benefits of urban forests include decreased heating and cooling demands for neighboring buildings; recreational opportunities found within urban green spaces and trails; and mental, physical, and emotional well-being of the general public (McPherson et al. 1997; Nowak and Crane 2002; Younger et al. 2008). These specialized values are important in large metropolitan areas as well as smaller communities throughout the Midwest Region.

Climate change will have direct and indirect consequences for urban forests. Climate change is expected to amplify existing stressors that urban forest communities currently face, similar to forests in natural environments (Roloff et al. 2009). Expected consequences of climate change include increased activity of insect pests and diseases, more frequent exposure to heat waves and drought, and phenological mismatches with pollinators and dispersal agents. Additional stresses faced by urban forests include increased atmospheric pollution, heat island effects, salt damage, highly variable hydrologic regimes, and frequent exposure to novel pests and diseases.

A recent study of urban forests throughout the eastern U.S. provides some interesting context for how these forests may adapt to climate change (Woodall et al. 2010). For example, greater than 10% of trees species that currently comprise urban forests in Minneapolis are found far northward of their natural ranges. This subset of the urban forest canopy may therefore be more amenable to future changes in temperature and precipitation. Researchers examined the possibility for urban forests to act as refugia for natural ecosystems or as northern dispersal centers to facilitate future migration, but ultimately concluded that these potential benefits are unlikely to be realized. This conclusion was due in large part to the physical limitations of urban forests – few candidate species for migration, low overall abundance of suitable species, and isolation from the surrounding forest matrix.

6.4.2 CONSIDERATIONS WITHIN PARTICULAR ECOREGIONS

This section presents specific considerations of climate change vulnerabilities for the particular ecoregions located within the larger Midwest Region. Where available, information has been organized according to the same key vulnerabilities mentioned above, to aid comparing ecoregional specifics to larger regional trends.

Ecological Province 212: Laurentian Mixed Forest

The recent vulnerability assessment by Swanston et al. (2011) includes a list of important vulnerabilities identified for forest ecosystems in northern Wisconsin, which may be generally applied to the ecoregion. This assessment relied on a combination of model results and expert input to compile the following list of vulnerabilities. Parenthetical confidence statements reflect the judgment of Swanston et al., based on specific language established by the Intergovernmental Panel on Climate Change (IPCC 2005).

- Risk will be greater in *low diversity ecosystems* (very likely).
- Disturbance will destabilize *static ecosystems* (very likely).
- Climate change will exacerbate problems for *species already in decline* (very likely).
- Resilience will be weakened in *fragmented ecosystems* (very likely).
- Altered hydrology will jeopardize *lowland forests* (very likely).
- Changes in habitat will disproportionately affect *boreal species* (virtually certain).

- Further reductions in habitat will impact *threatened, endangered, and rare species* (virtually certain).
- Ecosystem changes will have significant effects on *wildlife* (very likely).

Similarly, this assessment includes a list of characteristics or components that may enable certain species, communities, and ecosystems to better accommodate change (Swanston et al. 2011). More adaptive ecosystems include:

- Species that are currently increasing
- Species with a wider ecological range of tolerances
- Species with greater genetic diversity
- Species and ecosystems adapted to disturbances
- Species and ecosystems adapted to warmer, drier climates
- Species in the middle or northern extent of their range
- Diverse communities and species
- Habitats within larger, contiguous blocks

Laurentian Mixed Forest: Climate change will amplify many ***existing stressors*** *to forest ecosystems, such as invasive species, insect pests and pathogens, and disturbance regimes (very likely)*

Similar to the trend for the entire Midwest Region, future climate change may amplify existing stressors for forests in the Laurentian Mixed Forest province. A recent example of this synergistic effect is a study from northern hardwood stands recently invaded by exotic earthworms (Larson et al. 2010). Sugar maple trees were more sensitive to drought in invaded stands relative to non-invaded stands, exhibiting more reduced growth during these dry periods. Studies have also highlighted the potential for white-tailed deer (*Odocoileus virginianus*) to alter forest composition due to preferential browsing of seedlings (Salk et al. 2011). Preferential herbivory can ultimately lead to stand conversion, and is a potential multiplier of climate change influences. Gypsy moth (*Lymantria dispar*) is currently limited by cold winter temperatures across the Midwest Region, and is anticipated to expand its range northward under future climate change scenarios (Vanhanen et al. 2007).

There is already a recognized trend toward less diverse forests in the Laurentian hardwoods, though not necessarily due to changing climate. Schulte et al. (2007) compared early settlement records to contemporary conditions throughout the Laurentian Mixed Forest province and found an overall trend toward reduced forest diversity, reduced forest area, and a greater tendency toward deciduous broadleaf species. They attribute these changes primarily to human land use and persistent herbivory by white-tailed deer. Less diverse systems are generally understood to be more susceptible to increased stresses associated with future climate change (Swanston et al. 2011), which may in turn exacerbate historical trends of decreasing forest land and species diversity.

Laurentian Mixed Forest: Climate change will result in ***ecosystem shifts and conversions*** *(very likely)*

Researchers using LANDIS, a spatially interactive landscape model, across a large region in northeastern Minnesota projected declines in boreal species under both high

(A2) and low (B2) emissions scenarios (Ravenscroft et al. 2010). Management treatments that mimicked previous natural disturbance regimes maintained a wider variety of species across the landscape, especially in the low climate change scenario. Under high emissions, however, a much greater proportion of the simulated landscape was converted to non-forested habitats. In general, simulated forest systems across the landscape under both scenarios became more homogenous maple stands (*Acer* spp.) with decreasing proportions of pines (*Pinus* spp.) and hemlock (*Tsuga canadensis*).

Laurentian Mixed Forest: Many tree species will have ***insufficient migration rates*** *to keep pace with climate change (likely)*
Simulations examining forest ecosystem composition and change using LANDIS have reinforced the expectation that forest communities will not be influenced only by shifts in habitat ranges, but also by species' ability to actually migrate and establish in new areas. For the Boundary Waters Canoe Area in northern Minnesota, Xu et al. (2011) found that with increased wind and fire disturbance expected with climate change, forest composition change was influenced more by colonization of new species than competition among existing species. Additionally, LANDIS simulations in northern Wisconsin found that species migration is negatively correlated with habitat fragmentation (Scheller and Mladenoff 2008).

This is an important consideration because of the amount of fragmented forest in the region. Figure 6.4 shows the status of forest fragmentation in Minnesota, where two major factors contributing to forest fragmentation are large-scale divestiture of forest industry land and parcelization of non-industrial private forest land (Minnesota Department of Natural Resources 2010).

Parcelization is the division of larger landholdings into smaller units. The average landholding size in Minnesota has decreased from 39 acres in 1982 to 31 acres in 2003, and a similar trend is present in Wisconsin where average parcel size decreased from 41 to 30 acres during 1997 to 2006 (Minnesota Department of Natural Resources 2010, Wisconsin Department of Natural Resources 2010). While parcelization may not immediately result in direct impacts to forest ecosystems, this pattern often results in consequences for forest ecosystems as well as forest industry (Gobster and Rickenbach 2004; Haines et al. 2011). Long-term studies in northern Wisconsin have shown that parcelization is often a precursor to fragmentation and land-use change in forest ecosystems (Haines et al. 2011). Therefore, contemporary demographic and land ownership trends may make it increasingly difficult for forest species to migrate fast enough to keep pace with climate-related shifts.

Ecological Province 221 & 222: Eastern Broadleaf Forest (Oceanic & Continental)

Eastern Broadleaf Forest: Climate change will amplify many ***existing stressors*** *to forest ecosystems, such as invasive species, insect pests and pathogens, and disturbance regimes (very likely).*
Climate change is likely to cause similar stress on forests in the Eastern Broadleaf province as in the rest of the Midwest Region, including drought, forest pests and diseases, non-native species, and altered disturbance regimes. Oak decline is a major stressor

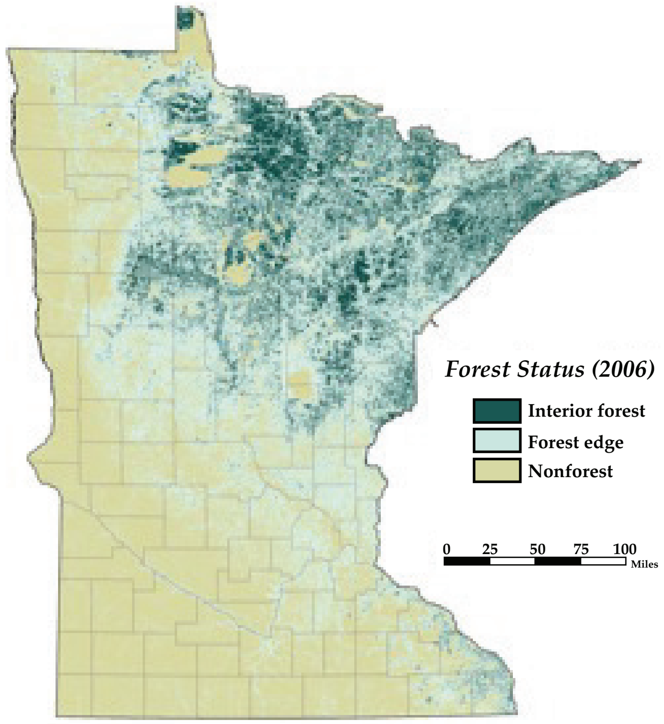


Figure 6.4. Fragmentation of forest land in Minnesota, based on the 2006 National Land Cover Database. Land cover data were classified using a 7x7 analysis window, meaning that forested areas would have to be larger than 10 acres to be considered interior forest. This method does not distinguish between forest edges caused by natural versus developed land cover. *Source*: Dacia Meneguzzo, USFS.

throughout the southern half of the Midwest Region. This condition is correlated with drought periods (Dwyer et al. 1995; Fan et al. 2006; Wang et al. 2008). Species in the red oak group (*Quercus rubra, Quercus coccinea, Quercus velutina*) are particularly susceptible to decline and make up a large proportion of upland forests in this ecoregion. Decline begins with stressed trees that are then attacked by insects and diseases. If droughts become more frequent or severe, oak decline could worsen. A buildup of fine and coarse fuels could result from increased tree mortality, increasing the risk of wildfire in the area.

Existing forests may have to compete with undesirable species under warmer future conditions. Kudzu (*Pueraria lobata*) is an invasive vine that typically transforms invaded forests in the southeastern U.S. by quickly overgrowing and smothering even mature overstory trees. Kudzu-related economic damage to managed forests and agricultural land is currently estimated at $100-500 million per year in the southeastern U.S. (Bradley et al. 2010). Kudzu's current northern distribution is limited by winter temperatures. It occurs nowhere in the Midwest Region except for the southern portion of Missouri. Modeling suggests the risk for kudzu invasion into the Continental and Oceanic Eastern Broadleaf ecoregions could be heightened under future warming (Jarnevich and Stohlgren 2009; Bradley et al. 2010). The aggregate of the models suggests a medium risk for invasion for Missouri, Indiana, Illinois, and Ohio over the next century. Studies have also projected that Chinese and European privet (*Ligustrum sinense* and *L. vulgare,* respectively), highly invasive shrubs, could expand to new territory across the Midwest Region over the next century (Bradley et al. 2010).

Eastern Broadleaf Forest: Climate change will result in ***ecosystem shifts and conversions*** *(likely).*

Forests in the Eastern Broadleaf Forest ecoregion may be at risk of losing keystone species or converting to different ecosystem types. Based on dendrochronological research, white oak (*Quercus alba*) may have reduced growth in the future at the western extent of its range (Illinois, Iowa, Missouri). This is due to a negative correlation between growth and June and July temperatures, which are projected to increase (Goldblum 2010). Decreased habitat suitability for white oak is also projected by species distribution models (Iverson et al. 2008b). A decrease in white oak could make way for other species more suited to higher summer temperatures. As mentioned above, a shift in the prairie-forest border could dramatically alter the makeup of ecosystems in the Prairie Parkland and Eastern Broadleaf ecoregions (Frelich and Reich 2010).

Fire has historically been a common disturbance agent within the Broadleaf Forest ecoregions, particularly along grassland transition zones. Fire suppression during the past century has favored shade-tolerant species like maple, while placing fire-adapted tree species like oaks and shortleaf pine at a competitive disadvantage. This trend is illustrated by the large increase in maple species across the Midwest, especially in smaller size classes (Illinios Department of Natural Resources 2010; Ohio Department of Natural Resources 2010; Raeker et al. 2010). This ongoing ecosystem conversion, in combination with existing stressors facing oaks, may make it more difficult for fire-adapted species to expand into available habitat in the future. Lenihan et al. (2008) projected that woodlands and savannas could occupy a majority of the Eastern Broadleaf Forest province in both high and low future climate scenarios in the absence of extensive fire suppression (Figure 6.3). If fire-dependent forests continue to decline, these forest types may not be available to occupy future suitable habitat in the ecoregion. This scenario could result in unanticipated conversions favoring non-forest systems or non-native species.

Lowland forest systems in this ecoregion may also be subject to conversions due to climate change. Bald cypress (*Taxodium distichum*) swamps, located in far southern Illinois, Indiana, and Missouri are highly dependent on precipitation patterns and periodic flooding, which are likely to change across the Eastern Broadleaf region based on current climate projections (Middleton 2000 ; Middleton and Wu 2008). The southern extent of the range is likely the most vulnerable, while the northern extent may serve as a refuge to more southern associated species (Middleton and McKee 2004).

Eastern Broadleaf Forest: Many tree species will have ***insufficient migration rates*** *to keep pace with climate change (likely).*

Habitat suitability for shortleaf pine (*Pinus echinata)*, which currently is at its northern extent in southern Missouri, may increase in northern Missouri, southern Illinois, and Indiana (Iverson et al. 2008b). However, habitat fragmentation and past management that favored oaks instead of pine could hamper the migration of shortleaf pine into newly suitable areas.

Bald cypress also presents an example of migration barriers that may prevent species from successfully tracking changes in temperature and precipitation. Seeds of bald cypress disperse by water, and most of the watersheds where they are located flow southward (Middleton and McKee 2004). In addition, bald cypress swamps have become increasingly fragmented in the north as they have been drained to make use for agriculture and local rivers have been dammed, making northward dispersal even more difficult (Middleton and Wu 2008).

Ecological Province 251: Prairie Parkland (Temperate)

Prairie Parkland: Many tree species will have ***insufficient migration rates*** *to keep pace with climate change (likely).*

Fragmentation and parcelization of forest ecosystems is more drastic in the Prairie Parkland than other ecoregions throughout the Midwest. For example, over 90% of forest land in Iowa is currently divided into private holdings averaging less than 17 acres (Flickinger 2010). Parcelization frequently leads to fragmentation in forest ecosystems, even though land use change may not immediately follow ownership transfers (Haines et al. 2011). Combined with extensive conversion of available land to agricultural monocultures, this ecoregion currently exists as a highly fragmented landscape for forest ecosystems. This condition raises the possibility that tree species in the Prairie Parkland ecoregion may be unable to migrate successfully to future suitable habitat, perhaps more so than other ecoregions in the Midwest.

6.5 Benefits from Forests

This section presents information on key vulnerabilities that are related to major ecosystem services provided by forest ecosystems. This information in the following sections is relevant across the Midwest Region, therefore we do not provide additional ecoregion-specific context.

6.5.1 FOREST PRODUCTS

5. Key Vulnerability: Forest ecosystems will be less able to provide a consistent supply of some forest products (likely).

One of the benefits humans derive from forests is a diverse supply of wood products. Although the importance of forest industry to the overall economy varies throughout the Midwest Region, the sector accounts for between 0.5-2.1% of total employment in a given state and 0.9% of employment across the region.

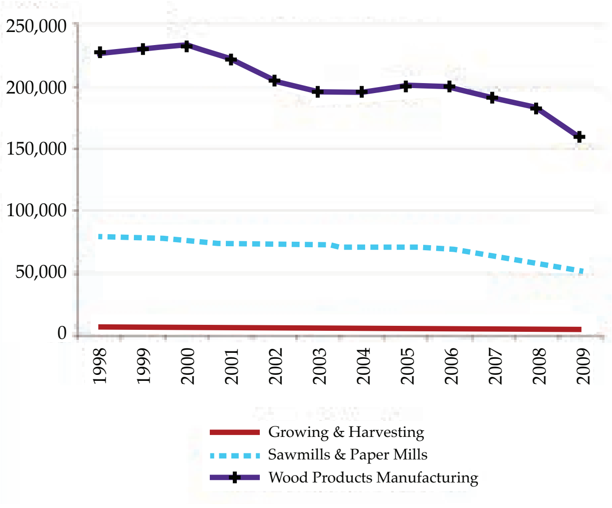
Beyond direct employment, the Midwest is an important component of the nation's forest products industry. Wisconsin is the top-ranking paper producer in the country, and Indiana is a national leader in the production of wood office furniture, kitchen cabinets, and other products (Indiana Department of Natural Resources 2010; Wisconsin Department of Natural Resources 2010). The forest products industry is the fourth largest manufacturing industry in the state of Minnesota (Minnesota Department of Natural Resources 2010). While employment related to direct growth and harvest operations has remained more or less consistent, employment in processing mills and manufacturing facilities has been declining steadily over the past decade.

Table 6.1 Total employment, timber-related employment, and economic output for the forestry sector for the entire Midwest Region and the individual states.

	Total Private Employment	Timber Employment	Economic Output of Forest Industry
Illinois	5,120,970	26,416	$2.5 billion
Indiana	2,449,980	28,069	$7.5 billion
Iowa	1,283,769	14,031	$3 billion
Michigan	3,383,615	23,478	$8 billion
Minnesota	2,417,174	25,505	$6 billion
Missouri	2,358,706	16,356	$5.7 billion
Ohio	4,460,553	31,527	$2.6 billion
Wisconsin	2,355,879	50,144	$20.5 billion
Midwest	23,830,646	215,526	$55.8 billion

Source: Employment figures are from Headwaters Economics (2011). Economic output figures are from the 2010 State Forest Resources Assessments (Flickinger 2010; Illinois Department of Natural Resources 2010; Indiana Department of Natural Resources 2010; Minnesota Department of Natural Resources 2010; Ohio Department of Natural Resources 2010; Price 2008; Raeker et al. 2010; Wisconsin Department of Natural Resources 2010).

Figure 6.5. Employment in timber-related fields, from recent census data compiled across all eight states in the Midwest NCA region. *Source*: Headwaters Economics (2011).



The ecological changes that occur as a consequence of climate change could have cascading effects throughout the forest products industry, from altered timber supply to the management practices that may be employed (Irland et al. 2001). These effects depend not only on ecological responses to the changing climate, but also on socioeconomic factors that will undoubtedly continue to change over the coming century. Major socioeconomic factors include national and regional economic policies, demand for wood products, and competing values for forest land (Irland et al. 2001). It is possible that the net effect of climate change to the forest products industry in the Midwest will be positive, if the industry can adapt effectively.

An example of how climate change may influence the forest products industry throughout the Midwest can be seen in white oak, which occurs across the grassland and broadleaf forest ecoregions. White oak is an important tree species, economically and ecologically. As recently as 2005, oak species accounted for 36% of annual harvest in Illinois, and white oak in particular was a favored harvest species (Illinios Department of Natural Resources 2010). Oak species are also the primary harvest species in the Ohio portion of the Oceanic Eastern Broadleaf ecoregion (Ohio Department of Natural Resources 2010). The ongoing decrease in oak species is likely a result of several factors, ranging from fire suppression to drought to pests and diseases, as mentioned above. Climate change may amplify the rate of this decrease. The species does show variation in sensitivity to climate parameters across its entire range, highlighting the fact that relationships may differ geographically for widely distributed species (Goldblum 2010).

Future models considering climate change also project that other commercial species like aspen, sugar maple, black cherry, and hickory may see substantial changes in distribution and abundance (Iverson et al. 2008b). Large potential shifts in commercial species availability may pose risks for the forest products sector if the shifts are rapid and the industry is unprepared. These trends will be important to examine for other economically important species, and the forest industry will benefit from awareness of regional differences as well as potential opportunities as new merchantable species gain suitable habitat in the region.

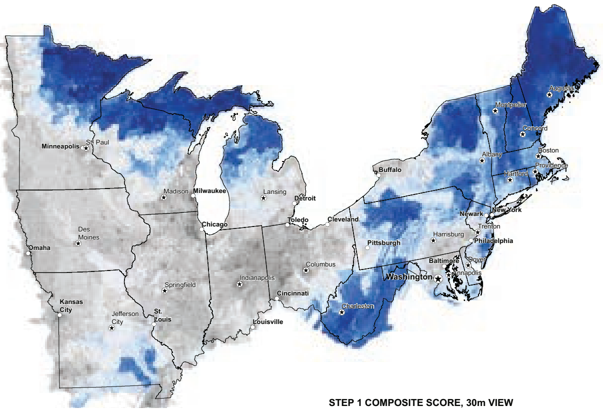
6.5.2 WATER RESOURCES

6. Key Vulnerability: Climate change impacts on forests will impair the ability of many forested watersheds to produce reliable supplies of clean water (possible).

Forested watersheds play a vital role in providing clean water supplies. Forests reduce surface runoff, soil erosion, water temperatures, and pollutant levels as water moves through the ecosystem (Furniss et al. 2010). For these reasons, maintaining forest cover can be a key aspect of “source water protection” for municipal watersheds. Drinking water often arises from forested landscapes, and the proportion of forest cover in source watersheds is inversely related to the cost of water treatment (Ernst et al. 2004). Protecting drinking water sources from contamination remains a much cheaper and effective option than disinfection and filtration of water supplies. As noted in the Indiana Statewide Forest Assessment, forest cover alone cannot ensure water quality, because other factors like storm water management, point-source pollution, and agricultural practices often have large influences (Indiana Department of Natural Resources 2010). Responsible stewardship of forest land is still a critical determinant of overall watershed health, however.

All eight states in the Midwest Region have experienced sharp declines in the ratio of forest acres per person over the past century, with Illinois, Indiana, Iowa and Ohio all having less than one forest acre per person (Barnes et al. 2009). Public surface water supplies are common in all states throughout the Midwest, with the exception of Wisconsin. In Iowa, forests account for only 14% of the land cover in surface water protection zones for municipalities that rely on surface drinking water supplies (Flickinger 2010). The

Figure 6.6. Index of the Ability to Produce Clean Water, from Barnes et al. (2009). Dark blue areas have higher scores and a greater ability to produce clean water. *Source*: Barnes et al. (2009).



Missouri Department of Natural Resources estimates only 55% of the potentially forested riparian buffers are currently forested across the state (Raeker et al. 2010). If these rates continue to decline, municipal water supplies will be further stressed to provide clean water.

Barnes et al. (2009) developed an index to characterize a watershed's ability to produce clean water by combining six layers of spatial data: road density; soil erodibility; housing density; and the percentages of forest land, agricultural land, and riparian forest cover. Much of the Laurentian Forest Province scored very high according to this assessment, although other ecoregions within the Midwest had low to mid-range scores.

As outlined above, interacting effects of climate change, habitat fragmentation, disturbance, and forest stressors may result in reduced forest cover throughout the Midwest Region. This could occur through a variety of pathways, including ecosystem shifts and migration of the prairie-forest border, or situations where existing forest species experience declines and new migrants are unable to fully colonize the available habitat. The impacts of climate change on the extent and condition of forest ecosystems across the Midwest Region will alter the ability of these watersheds to produce clean water, which in turn will dictate how municipalities across the region provide water to the human population.

Regional changes in precipitation patterns will further alter the quality and supply of water delivered from forest ecosystems. Across the central U.S., the ratio of wintertime snowfall to precipitation has been declining over the past half century (Feng and Hu 2007). This trend has implications for the hydrologic cycle, meaning that a greater percentage of water is delivered through immediate surface runoff rather than through gradual release from snow packs. Cherkauer and Sinha (2010) project that this trend will continue, with increasing surface flows in spring and summer months by the late 21st century in the four states surrounding Lake Michigan. Additionally, observed trends over the 20th century indicate that a larger proportion of annual rainfall in the central U.S. is occurring in high-intensity events, and that intense rainfall events are becoming more frequent (Kunkel et al. 2008; Saunders et al. 2012 ; Andresen et al. 2014). The Midwest Region in particular stands out as experiencing substantial increases in the frequency of large precipitation events (Kunkel et al. 1999). Over the past 50 years, the frequency of rainfall events of greater than 3 inches/day has increased by 103% across the region (Saunders et al. 2012). Forest ecosystems may be less able to absorb and filter large pulses of rainfall, rain-on-snow events, or rapid snowmelt. This substantial shift in precipitation patterns will make it more difficult for forested watersheds to deliver clean water supplies, regardless of changes in the extent or condition of forest ecosystems in the Midwest Region.

Water provisioning is among the most critical ecosystem services provided by forest ecosystems for human well-being. Therefore, this vulnerability may warrant special attention and monitoring over the next several years.

6.5.3 CARBON STORAGE

7. Key Vulnerability: Climate change will result in a widespread decline in carbon storage in forest ecosystems across the region (very unlikely).

Forest ecosystems and urban forests play a valuable role as a carbon sink across the Midwest Region (Nowak and Crane 2002; Price 2008; Flickinger 2010; Minnesota Department of Natural Resources 2010; Ohio Department of Natural Resources 2010; Raeker et al. 2010; Wisconsin Department of Natural Resources 2010). Carbon sequestration and storage in forest ecosystems depends on the health and function of those ecosystems in addition to human management, episodic disturbances, and forest stressors. All of these factors will interact with climate change, but the effect on carbon storage will vary from place to place. It is possible that forest carbon stocks in localized areas will experience decreases over time under future climate change, but it is also possible that carbon stocks in some areas will increase under climate change. A large-scale decline in carbon stocks across the entire Midwest Region is very unlikely.

Each year, forests and forest products nationwide remove greenhouse gases from the atmosphere that are equivalent to more than ten percent of annual U.S. fossil fuel emissions (Birdsey et al. 2006; Smith et al. 2006; Ryan et al. 2010; McKinley et al. 2011). The accumulated terrestrial carbon pool within forest soils, belowground biomass, dead wood, aboveground live biomass, and litter represents an enormous store of carbon (Birdsey et al. 2006). Widespread land-use change in the Midwest has dramatically reduced above-ground carbon storage and re-arranged the distribution of carbon pools on the landscape (Rhemtulla et al. 2009). Terrestrial carbon stocks in the region have generally been increasing for the past few decades, and there is increased attention on the potential to manage forests to maximize and maintain this carbon pool (Flickinger 2010; Minnesota Department of Natural Resources 2010; Malmsheimer et al. 2011). The amount of carbon stored in future forests in the Midwest will be determined in large part by their extent and composition, which already varies considerably across the region. For example, in Wisconsin maple/beech/birch forests sequester an average of 224 metric tons C/acre, while spruce/fir forests sequester an average of 87 metric tons C/acre (Wisconsin Department of Natural Resources 2010). Similarly, the average carbon density in urban forests is about half that of forested ecosystems (Nowak and Crane 2002). Climate change and management are very likely to continue to influence the distribution and composition of forests throughout the region.

Episodic disturbances

Interactions of climate change with wildfires, wind storms, and insect outbreaks may result in net gains or losses of ecosystem carbon. An ecosystem model study by Lenihan et al. (2008), found that more frequent wildfires and ecosystem conversions resulted in average carbon losses of 11% across the eastern U.S. Continued fire suppression reduced the average carbon loss to 6%. Some studies have shown that repeated disturbances (clear-cut harvesting and fire) reduced annual carbon storage and forest productivity, and have projected that these trends may be amplified by climate change (Gough et al. 2008). Other studies have projected that aboveground live biomass will increase under high and low climate future scenarios, regardless of whether harvesting and wind disturbance are included in the simulations (Scheller and Mladenoff 2005). The trend of increased total biomass projected by Scheller and Mladenoff (2005) occurred despite the fact that many boreal species were extirpated from the study area in their model simulations.

Additionally, insect pests and diseases can determine whether forest ecosystems are net sinks or sources of carbon (Hicke et al. 2011). Forest ecosystems can take decades to recover from widespread pest attacks. If climate change increases the prevalence or activity of these or other disturbance agents, forests in the Midwest could suffer localized declines in growth or increased mortality.

Effects on productivity

Several studies have projected the outcome of climate change on forest growth and productivity, which could have positive and negative consequences for forest carbon sequestration. Free-Air CO_2 enrichment (FACE) experiments in forest stands across several regions have found a consistent increase in net primary production, and suggest that forests may be more responsive to elevated CO_2 than other ecosystem types (Ainsworth and Long 2005; Norby et al. 2005; Norby and Zak 2011). Ainsworth and Long (2005) estimated a 28% increase in dry matter production in four forest types in response to elevated CO_2, including aspen in northern Wisconsin. It also appears that forests in the Midwest may not face N-limitation that could otherwise dampen the response to elevated $CO_{2,}$ and that ozone-resistant genotypes and species, if present, could help forests overcome the potentially detrimental effects of elevated ozone (Norby and Zak 2011; Zak et al. 2011).

Considering species range shifts due to climate change, Chiang et al. (2008) estimated an increase in net primary production (NPP) in northern Wisconsin, with minimal changes in Ohio. Increased NPP in northern areas of the Midwest may result from greater growth from oak and cherry (*Prunus spp.*) species, which could offset reduced growth in aspen and birch.

Retrospective studies that measure the influences of temperature and precipitation on NPP are rare. Bradford (2011) examined the strength and seasonality of this relationship across the entire Laurentian Forest Province, using two decades of gathered data. The findings from this study indicate that there are multi-year and seasonal controls that govern growth in a given growing season. The weather conditions of a given year are often not directly correlated with the growth during that growing season.

6.5.4 RECREATIONAL OPPORTUNITIES

8. Key Vulnerability: Many contemporary and iconic forms of recreation within forest ecosystems will change in extent and timing due to climate change (very likely).

Forest ecosystems are one of the centerpieces of recreation in the Midwest Region. People throughout this region enjoy hunting; fishing; camping; wildlife watching; and exploring trails on foot, bicycles, skis, snowshoes, horseback, and off-highway vehicles (OHVs), among many other recreational pursuits. The vulnerabilities associated with climate change in forest ecosystems will very likely result in shifted timing or participation opportunities for forest-based recreation.

Estimates of actual participation in these activities rely on varying methods and are often limited to fee-based recreation areas, but the popularity of these types of activities reinforces the notion that forests are an important setting for enjoyment of nature. There are 10 National Forests, 3 National Parks, 4 National Lakeshores, 64 National Wildlife Refuges, and hundreds of state and county parks within the Midwest Region, all of which are hotspots of forest-based recreation and tourism. For the 10 National Forests in the Midwest Region, over 55% of visitors reported travelling more than 50 miles to visit, reflecting the potential of these locations to draw visitors from a wide area (U.S. Forest Service 2011). According to data from 2005-2009, there are approximately 10.6 million visits to the National Forests each year (data reported for different Forests in different years). Total spending associated with these visits was over $700 million per year.

The state of Wisconsin estimated that forest-based recreationists spend approximately $2.5 billion within Wisconsin communities (Marcouiller and Mace 1999). Surveys in Wisconsin also show that most types of recreation show stable or increasing demand in future projections (Wisconsin Department of Natural Resources 2010). The state of Ohio found that 62% of the state's recreational sites were located within or nearby forests (Ohio Department of Natural Resources 2010).

Forest-based recreation and tourism are strongly seasonal. Observations support the idea that seasons have shifted measurably over the previous 100 years, and projections indicate that seasonal shifts will continue toward shorter, milder winters and longer, hotter summers in the future (Andresen et al. 2014; Winkler et al. 2014). Climate change generally stands to reduce opportunities for winter recreation in the Midwest, while warm-weather forms of nature-based recreation may benefit (Jones and Scott 2006; Mcboyle et al. 2007; Dawson and Scott 2010). For example, opportunities for winter-based recreation activities such as cross-country skiing, snowmobiling, and ice fishing may be reduced due to shorter winter snowfall seasons (Notaro et al. 2011) and decreasing periods of lake-ice (Magnuson et al. 2000; Kling et al. 2003; Mishra et al. 2011). Conversely, warm-weather recreation activities such as mountain biking, OHV riding, and fishing may benefit from extended seasons in the Midwest.

Scientific literature assessing the impacts of these changes on forest-based recreation is lacking, with the majority of published studies focused on the downhill skiing industry or international tourism (Nickerson et al. 2011). Irland et al. (2001) describes the difficulties associated with projecting the impacts of climate change on the recreation industry. In many cases, it is unclear if there are particular thresholds for change that will reduce enjoyment of a given activity.

Saunders et al. (2011) provide a case study for the Midwest Region, focusing on four National Lakeshores and one National Park surrounding the Great Lakes. Total visitor attendance at these five sites is over 4 million people per year, with visitor spending over $200 million. The more immediate impacts of climate change – projected ecosystem disruption, loss of wildlife and fish, changing temperatures, disease outbreaks, and wildfire – could lead to a loss of visitor enjoyment and a drop in visitation at the region's parks.

In the National Visitor Use Monitoring program for National Forests, survey respondents were asked to choose among a few general "substitute behavior" choices, which might serve as general indicators of what the typical response might be to a situation when visiting a given recreational location at a given time was undesirable (U.S. Forest Service 2011). Fewer than half reported their preference would be to travel elsewhere for the same activity, while nearly 20% would have stayed at home or gone to work. Only 35% of visitors reported that they would be willing to travel more than 100 miles to an alternate location. If visitors are seeking a particular type of recreational experience that is shaped in large part by the well-being of the surrounding ecosystem or certain climatic factors, this extent of travel might be more necessary in the future.

The loss of visitor enjoyment, uncertainty about ideal timing of visitation, and increased travel distances could lead to reduced public interaction with a wide range of natural areas, from county parks to National Forests. Such reductions would likely be associated with a decrease in visitor spending. New opportunities could offset decreases on a regional basis, though localized areas may experience decreases in traditional recreational enjoyment and spending.

6.5.5 CULTURAL VALUES

9. Key Vulnerability: Climate change will alter many traditional and modern cultural connections to forest ecosystems (likely).

Some of humankind's fundamental and yet intangible connections with the environment are the relationships we hold with particular plant and animal species, modes of interaction with the landscape, and special places. These relationships help define culture, and they are not always straightforward to assess or interpret. However subtle these cultural relationships to forest ecosystems may be, they are likely to be transformed by climate change. Below, we present some of these potential cultural connections that may be at risk due to climate change.

Forest species

Particular species can hold unique cultural importance, often based on established uses. Changes in forest composition and extent may alter the presence or availability of culturally important species throughout the Midwest Region. For example, Dickmann and Leefers (2003) compiled a list of over 50 tree species from Michigan that were used by several Native American tribes in the region. Among these, northern white-cedar and paper birch stand out as having particular importance for defining a culture and way of life. Unfortunately, due to climate change these two species are expected to experience large declines in suitable habitat over the next century (Iverson et al. 2008b).

Non-timber forest products

Non-timber forest products (NTFPs) are important cultural features and sources of income throughout the Midwest. Some of these include mushrooms, berries, maple syrup, wild ginseng, balsam fir boughs, and Christmas trees. In some cases, NTFPs support regionally important industries based on the harvest and sale of these goods. Collection of balsam fir boughs in northern Minnesota resulted in $23 million in sales for Christmas wreaths (Minnesota Department of Natural Resources 2010). Balsam bough collection on National Forest and State-owned lands drives a $50 million per year industry in Wisconsin (Wisconsin Department of Natural Resources 2010). From 1992 to 2010, the maple syrup industry produced an average of $2.4 million in Ohio, $2.6 million in Michigan, and $2.9 million in Wisconsin (USDA Economic Research Service 2012). Data were unavailable for Minnesota, which is also a large syrup-producing state. Collection of these NTFPs may be influenced by future changes in climate if focal species experience declines or life-cycle alterations.

Special places

It may be one of the more difficult cultural connections to firmly document, but association with particular places on the landscape is an important aspect of humankind's relationship with forests. Saunders et al. (2011) provide a few useful examples of how climate change may physically alter the places that we hold dear. Erosion from rising lake levels and storm surges in the Great Lakes has already begun to wash away cultural sites within the Grand Portage National Monument and Apostle Islands National Lakeshore.

6.6 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 (Parry et al. 2007). Numerous actions can be taken to enhance the ability of ecosystems to adapt to climate change and its effects. People will have a key role in dictating these responses, which might focus on avoiding loss of forest cover, or maintaining forest productivity, or preserving ecosystem processes. Importantly, adaptation measures can also be targeted to address the environmental benefits that forests provide to people, such as water, recreation, and wood products. There is no single "silver bullet" approach to climate change adaptation, but rather a broad array of strategies and approaches that can be tailored to specific ecosystems and management goals. In many instances, targeted policy measures will be necessary to implement adaptation efforts. This section presents general adaptation measures that may be appropriate for the topic areas mentioned earlier, summarized for the entire Midwest Region.

6.6.1 FOREST ECOSYSTEMS

There is a growing library of tools and resources pertinent to climate change adaptation in forest ecosystems (Millar et al. 2007; Ogden and Innes 2008; Heller and Zavaleta 2009; Glick et al. 2011; Swanston and Janowiak 2012). Published studies evaluating adaptation methods are lacking, as is long-term monitoring on pilot projects. Nevertheless, this body of knowledge provides a framework for integrating knowledge of projected climate change impacts into natural resource planning and management. There has been an early focus on "no regrets" decision-making and adopting a triage mentality to prioritizing climate change adaptation (Millar et al. 2007). Millar and others also frame the three fundamental options for adapting to climate change as "resistance, resilience, or response."

Particular land owners or forest management entities may prefer one mode of adaptation over another, or they may be required to favor a particular course of action. For example, National Wildlife Refuges and other management units with particular mandates to preserve habitat for endangered species might automatically favor "resistance" or "resilience" options for climate change adaptation. Many other landowners, including private landowners, will be able to consider a variety of options and design specific management tactics that are suited for their individual goals.

The publication, *Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers*, describes a framework for responding to climate change and is

BOX 6.1

Options for adapting to climate change.

The concepts of resistance, resilience, and response serve as the fundamental options for managers to consider when responding to climate change (Millar, Stephenson, and Stephens 2007):

- ***Resistance*** actions improve the forest's defenses against anticipated changes or directly defend the forest against disturbance in order to maintain relatively unchanged conditions. Although this option may be effective in the short term, it is likely that resistance options will require greater resources and effort in resisting change over the long term as the climate shifts further from historical norms. Additionally, as the ecosystem persists into an unsuitable climate, the risk that the ecosystem will undergo irreversible change (such as through a severe disturbance) increases over time.
- ***Resilience*** actions accommodate some degree of change, but encourage a return to prior conditions after a disturbance, either naturally or through management. Resilience actions may also be best suited to short-term efforts, high-value resources, or areas that are well buffered from climate change impacts. Like the resistance option, this option may engender an increasing level of risk over time if an ecosystem becomes increasingly ill-suited to the altered climate.
- ***Response*** actions intentionally accommodate change and enable ecosystems to adaptively respond to changing and new conditions. A wide range of actions exists under this option, all working to influence the ways in which ecosystems adapt to future conditions, instead of being caught off-guard by rapid and catastrophic changes.

Source: Swanston and Janowiak (2012).

Table 6.2 Climate change adaptation strategies for forest management.

Strategy	Resistance	Resilience	Response
1. Sustain fundamental exological functions.	X	X	X
2. Reduce the impact of existing biological stressors.	X	X	X
3. Protext forests from severe fire and wind disturbance.	X	X	
4. Maintain or create refugia.	X		
5. Maintain and enhance species and structural diversity.	X	X	
6. Increase ecosystem redundancy across the landscape.		X	X
7. Promote landscape connectivity.		X	X
8. Enhance genetic diversity.		X	X
9. Facilitate community adjustments through species transitions.			X
10. Plan for and respond to disturbance.			X

Source: Swanston and Janowiak (2012).

broadly applicable for forest managers across the Midwest Region (Swanston and Janowiak 2012). This system creates and gathers scientific information, establishes cross-ownership partnerships, and fosters collaboration between scientists and land managers. The document provides a wide-ranging "menu" of adaptation strategies and approaches and a workbook process to help land managers consider ecosystem vulnerabilities, select adaptation approaches that meet their needs, and devise tactics for implementation. Table 6.2 highlights the overarching adaptation strategies, which are subsequently tailored to more specific local approaches and tactics.

It is important to note the role that forest management can play in the context of climate change adaptation. LANDIS simulations have shown that harvesting can create opportunities to encourage diversity and maintain vulnerable tree species over time, but harvesting can also reduce seed sources and limit regrowth (Scheller and Mladenoff 2005). Studies in Minnesota reveal similar patterns (Ravenscroft et al. 2010). Many aspects of contemporary sustainable forest management are compatible with the need for climate change adaptation, and the adaptive management paradigm can be tailored to incorporate climate change considerations for forest management (Seppälä et al. 2009; Swanston and Janowiak 2012).

6.6.2 URBAN FORESTS

A case study from Philadelphia, while outside the region, provides an example that illustrates how cities are evaluating the potential impacts of climate change on urban forests in order to develop appropriate adaptation strategies (Yang 2009). Urban forest managers found that the combination of climate-induced stress, pests, and diseases reduced the future suitability of 10 tree species commonly planted in the city. Conversely, they were also able to identify a few species that would be expected to thrive under future climate conditions. Similar assessments have also occurred to identify potential climate-adapted trees for parks and cities across Central Europe (Roloff et al. 2009). Conducting these sorts of analyses will be helpful for urban forest managers and city planners to effectively plan for change. Chicago's Climate Change Action Plan also includes a section on Adaptation, which covers strategies for maintaining and enhancing green spaces and urban forests in the city (Coffee et al. 2010). The Arbor Day Foundation's Tree City USA program, or similar national assistance programs, may offer an effective platform for engaging municipalities across the Midwest Region and sharing best practices for adaptation. As of January 2014, over 3,000 cities and towns across the 8-state region are already participating members in the Tree City USA program (Arbor Day Foundation 2014).

6.6.3 FOREST PRODUCTS

The forest products industry has undergone a great deal of change over the past century – technology is continually improving, markets are global, and the policy environment has become more complex. The forest resource base upon which the industry has depended has also been dramatically altered – first as a result of early forest industry practices and subsequent disturbance, and more recently as forests have matured and the landscape has become more fragmented.

Climate change may result in new unpredictable changes for forest ecosystems in the Midwest Region, and the forest industry will benefit most strongly as an economic sector if it continues to respond proactively to landscape changes. The entire industry – from harvest operations to manufacturing – can be actively engaged in an adaptation mindset. This will involve continually incorporating new information on climate change impacts and making calculated responses to manage risk. Species declines or migrations will affect market supplies in different regions of the country, as will climate-induced disturbance events. The timing of harvest and transport operations may also be influenced by temperature and precipitation patterns, which could have cascading impacts throughout the supply chain. New opportunities may appear if climate change has favorable influences on growth rates or results in increased habitat suitability for southern merchantable species.

A critical consideration is that the forest industry will have a vital role in sustaining healthy forest ecosystems (Seppälä et al. 2009). A planned, measured approach to climate change adaptation might ultimately depend on having a vibrant forest industry, because it will require considerable management intervention to actively influence the course of ecosystem adaptation and avoid catastrophic, unplanned outcomes. A key point is that climate change adaptation will be best pursued as a proactive, rather than reactive, course of action (Seppälä et al. 2009). Forest managers will need to be prepared to encourage resilience or facilitate ecosystem transitions through management operations, and an agile industry can take advantage of these management opportunities to produce desired goods and services.

6.6.4 WATER RESOURCES

Adaptation of forest ecosystems to global climate change will be essential for preserving the quality of water supplies throughout the Midwest. In a review of the relationship

Table 6.3 Highlighted recommendations on collaboration and action from the *Water, Climate Change, and Forests* report.

Collaborate to protect and restore watersheds
- Connect water users and watersheds
- Link to research and adaptive management
- Engage the community
  (including stakeholder groups – tribes, municipalities, etc.)
- Link water from healthy watersheds to water quality markets
- Employ new methods that facilitate collaboration
- Collaborate globally to support sustainable forests

Implement practices that protect and maintain watershed processes and services

Restore watershed processes
- Restore streams and valley bottoms
- Restore riparian areas and bottomlands
- Restore upslope water conditions

Source: Furniss et al. (2010)

between climate change impacts, forests, and water resources, Furniss et al. (2010) outline several adaptation guidelines to enhance watershed resilience. Table 6.3 summarizes some of these key ideas, and we encourage readers to refer to this publication for complete explanations.

Improving the state of knowledge and sharing information widely will help reduce the uncertainty surrounding future projections of water resources. Integrating an understanding of climate change and forest ecosystems into watershed and source water protection planning will also be essential for systematically addressing these challenges. The authors also advocate a "collaborative, participatory approach to adaptation based on connecting people, their lifestyles, and land-use decisions to their effects on critical watershed services," and outline several strategies for achieving this comprehensive goal. Land management actions across several domains – fire and fuels, wildlife habitat, timber harvest, infrastructure, and habitat restoration – can be implemented with an eye toward maintaining or enhancing watershed function.

6.6.5 CARBON STORAGE

The past few years have witnessed an increased focus on maintaining and expanding forest carbon stocks, both globally and within the U.S. While it is evident that forests in the Midwest must be managed to provide a full spectrum of ecosystem services, climate change adaptation decisions will also likely incorporate the desire to prevent forest carbon from being lost to the atmosphere. Indeed, this is one sector of activity where climate change adaptation and mitigation strategies can operate in concert.

Malmsheimer et al. (2011) offer several guiding principles for land managers and policy makers to consider when pursuing effective forest carbon management. They focus on maintaining forests as forests, which may take considerable management intervention and public support if wide-scale climate change results in localized or widespread ecosystem transitions. This is especially true for the Midwest Region, which contains a mobile prairie-forest border and competing land-use opportunities for agriculture. In addition, they advocate for market incentives to recognize the climate change mitigation benefits of carbon sequestration in long-lived wood products, product substitution for wood-based materials over carbon-intensive materials, and fuel substitution for biomass over fossil fuels.

Hennigar et al. (2008) created an optimization model to evaluate strategies for maximizing forest carbon sequestration over several hundred years. Their approach highlights the different approaches to carbon management that can result, based on whether wood products are counted as a short to medium-term carbon sink. This is a policy decision that will certainly influence carbon management and forest adaptation efforts, and cost-benefit models such as those employed in this study will be valuable tools to explore tradeoffs.

6.6.6 RECREATIONAL OPPORTUNITIES

It will be imperative for municipalities, recreation areas, and the associated recreation and tourism industries to acknowledge likely outcomes of climate change and begin preparing for the future. In the Midwest Region, winter sports that depend on snow cover or lake ice offer a clear illustration of the need to adapt our modes of recreation. It may be possible to shift the dates and locations of particular events to take advantage of more favorable conditions. In some cases, areas may become unsuitable for particular forms of recreation. This may cause economic and cultural hardship for cities and towns that have deep-rooted investments in particular forms of recreation, such as cross-country skiing, snowmobiling, or ice fishing. It is important that organizers and participants alike do not take unnecessary safety risks by continuing to operate solely according to tradition.

Conversely, climate change may also offer new opportunities for expanded recreation in forested areas. Spring and fall seasons may be extended for many forms of outdoor recreation, and planning for change sooner rather than later will ease the transition.

6.6.7 CULTURAL VALUES

Cultural connections to forest landscapes throughout the Midwest Region will likely be altered by climate change. It is important to document local uses and local knowledge of forests, as a means to record incremental changes that occur over time and to preserve these sources of knowledge. Extensive knowledge of the landscape will be essential for effectively planning localized adaptation tactics for forest ecosystems, and a cultural body of understanding can assist this process. In instances where culturally important plants or animals are at risk of local extinction, people may need to prepare for accessing these species in new places. In some cases, it may be possible to actively encourage and prepare climate refugia or design resistance options to maintain particular ecosystem components in an area.

6.7 Summary

In this chapter, we have described key vulnerabilities that climate change may present to the Forestry Sector of the Midwest Region. These statements are based on our review of available scientific literature, including both empirical studies of observed changes over the past several years as well as modeling studies that offer future projections under a range of future climates. In summarizing this information, we aim to help decision-makers evaluate potential climate-related vulnerabilities through the end of the century. The key vulnerabilities for the entire region, and our confidence determinations are listed below.

1. Climate change will amplify many **existing stressors** to forest ecosystems, such as invasive species, insect pests and pathogens, and disturbance regimes (very likely).
2. Climate change will result in **ecosystem shifts and conversions** (likely).
3. Many tree species will have **insufficient migration rates** to keep pace with climate change (likely).
4. Climate change will amplify existing stressors to **urban forests** (very likely).
5. Forests will be less able to provide a consistent supply of some **forest products** (likely).
6. Climate change impacts on forests will impair the ability of many forested watersheds to produce reliable supplies of **clean water** (possible).
7. Climate change will result in a widespread decline in **carbon storage** in forest ecosystems across the region (very unlikely).
8. Many contemporary and iconic forms of **recreation** within forest ecosystems will change in extent and timing due to climate change (very likely).
9. Climate change will alter many traditional and modern **cultural connections** to forest ecosystems (likely).

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Chapter 7

Great Lakes Nearshore and Coastal Systems

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7.1 Introduction

The Great Lakes basin contains more than 20% of the world's surface freshwater supplies and supports a population of more than 30 million people. Most of the population either lives on, or near one the Great Lakes. Coastal margin areas are where socioeconomic, environmental, and Great Lakes interests intersect, and therefore it is important to understand how potential changes in climate may impact coastal margin areas.

Climate stressors on Great Lakes and nearshore coastal systems include: 1) changing water level regimes, 2) changing storm patterns and precipitation, and 3) altered thermal regimes. These stressors have the potential to significantly alter the physical integrity of Great Lakes nearshore and coastal systems, which may affect both environmental and economic interests. The objective of this paper is to provide a brief overview of each of the climate stressors and to assess how future climate scenarios will impact Great Lakes nearshore and coastal systems. Fundamental to this assessment is the understanding that climate change impacts are primarily physical in nature (i.e., how changes in water level regime; storm frequency and magnitude; precipitation and evaporation; ice cover; and air and surface water temperatures impact nearshore and coastal systems). Climate-induced changes to physical processes will impact not only the physical characteristics of the shoreline, but create vulnerabilities for both environmental and economic interests as well. It is important to identify those vulnerabilities so that appropriate adaptive management actions can be taken.

7.2 Climate Stressors

7.2.1 GREAT LAKES WATER LEVEL REGIMES (WATER LEVELS)

Within Great Lakes coastal margin and open water systems, the equivalent of the natural flow regime is the natural water-level regime. Great Lakes water-level regimes are controlled by the interaction of two master variables, climate and hydrology. Water levels represent the integrated sum – typically expressed by a hydrologic water balance equation – of water inputs and losses from the system that are driven by climate (long-term and seasonal weather patterns), hydrology and flow regime (surface water, ground water, and connecting channel flows), and water use within the basin (water withdrawals, diversions, and connecting channel flows) (Quinn 2002).

Climatic controls, including precipitation, evapotranspiration, and the frequency, duration, and distribution of major storm events are typically driven by seasonal and longer-term climatic cycles (Baedke and Thompson 2000; Quinn 2002). Long-term and seasonal changes in precipitation and evaporation result in the interannual and seasonal variability of water levels and associated connecting channel flows within, and between, all of the Great Lakes (Derecki 1985; Lenters 2001; Quinn 2002). Seasonal Great Lakes water levels and connecting channel flows are higher in the early summer months and lower in the late winter months.

Also influencing Great Lakes water levels are short-term fluctuations in water level that are caused, in part, by local wind or storm events that perturb the water surface, such as a storm surge or seiche event (a seiche is an oscillatory change in the water level surface due to wind or storm event). These short-term fluctuations typically do not reflect a change in the net basin supply (NBS) or overall water balance of the lake or basin.

There is considerable uncertainty in how climate change, particularly changes in precipitation and evaporation may impact net basin water supplies and water levels and flows in the Great Lakes region. A more detailed evaluation of Great Lakes water resources (including water levels) based on Global Climate Model (GCM) and Regional Climate Model (RCM) scenarios is presented in a companion paper by Lofgren and Gronewold (2014).

The IJC International Upper Great Lakes Study (IUGLS) recently completed a five-year binational study examining sector impacts related to changes in water level regime resulting from Lake Superior water level regulation (IUGLS 2012). Analysis of the future sequences provided the context to determine plausible ranges of future net basin supplies (NBS). The different future water supply scenario approaches included dynamic and statistical downscaling of GCM scenarios (Angel and Kunkel 2010; Lofgren and Hunter 2010; MacKay and Seglenieks 2010), stochastic generation of contemporary and climate change NBS sequences (Fagherazzi et al. 2011) and the use of paleo NBS sequences (Ghile et al. 2012).

The IUGLS study evaluated output of 565 model runs from 23 GCMs compiled by Angel and Kunkel (2010) from the fourth Intergovernmental Panel on Climate Change (IPCC) report (Randall et al. 2007) and used the GLERL AHPS Great Lakes hydrology model (Lofgren et al. 2002; Croley 2005) to calculate anticipated changes in Great Lakes water levels. The model runs utilized three future emission scenarios: B1 (relatively

Table 7.1 Estimated lake level changes for Lakes Michigan-Huron at the 5th, 50th and 95th percentiles.

Year	**5th**	**50th**	**95th**
B1 Low Emission Scenario			
2020	-0.60 m	-0.18 m	0.28 m
2050	-0.79	-0.23	0.15
2080	-0.87	-0.25	0.31
A1B Moderate Emission Scenario			
2020	-0.55 m	-0.07 m	0.46 m
2050	-0.91	-0.24	0.40
2080	-1.43	-0.28	0.83
A2 High Emission Scenario			
2020	-0.63 m	-0.18 m	0.20 m
2050	-0.94	-0.23	0.42
2080	-1.81	-0.41	0.88

Source: IUGLS (2012), modified from Angel and Kunkel (2010).

low), A1B (moderate), and A2 (high). The high emissions scenario A2 corresponds most closely to recent experience (Angel and Kunkel 2010). Projections of estimated water level changes at the 5th, 50th, and 95th percentiles for Lakes Michigan-Huron by Angel and Kunkel (2010) are presented in Table 7.1.

Estimated water-level changes for Lakes Erie and Ontario are comparable to those for Lake Michigan-Huron, but water level change estimates for Lake Superior may be somewhat less. By 2050, water levels may be 20 to 25 cm lower than the current long term mean for Lakes Michigan-Huron, Erie, and Ontario and 25 to 40 cm lower by 2080. *Uncertainties associated with emission scenarios and the GCM/RCM models are high and the confidence level for future estimated water level changes is low.*

Results of a detailed hydroclimate analysis based on RCMs runs for the IUGLS study suggest that Great Lakes water levels will generally remain within the natural historical range of water levels with annual means slightly below long term mean water levels (MacKay and Seglenieks 2010; Lofgren et al. 2011). New methods for RCM-type modeling that include and account for important atmospheric feedbacks were evaluated and found to be important. Even though uncertainties are high, these projections are generally supported by a suite of both RCM and GCM models that indicate that evaporative losses will continue to increase due to increasing surface water temperatures and reductions in winter ice cover. However, these losses may be partially offset by increasing local and overlake precipitation in the winter and early spring months, suggesting increased seasonal variability due to loss of winter lake ice cover, loss of connecting channel ice cover, increased spring storminess, and increased wind speeds (Hayhoe et al. 2010). Current models are unable to accurately project storm track changes which may have an impact on precipitation patterns within the Great Lakes basin, thus adding to the uncertainty associated with lake level projections. Based on the most recent models, a major conclusion of the IUGLS (2012) study was that "water level changes in the near-term future may not be as extreme as previous studies have predicted. Lake levels are likely to continue to fluctuate, but still remain within a relatively narrow historical range. While lower levels are likely, the possibility of higher levels cannot be dismissed."

The confidence level for projections of the overall direction and magnitude of future Great Lakes water levels is low.

7.2.2 CHANGING STORM PATTERNS AND PRECIPITATION

Model estimates of future mean annual precipitation are equivocal and highly variable. A majority of models generally agree that there may be a slight increase in mean annual precipitation ranging from 2 to 7% over the next 30 years, which continues the documented historical trend of increased precipitation in the region (Hayhoe et al. 2010). However, there appears to be general agreement between models that the frequency and magnitude of extreme precipitation events (interpreted to mean severe storms) increases 30% for the A2 scenario, and 20% for the B1 scenario during the winter and spring months, and is less during the summer and early fall months. Increased precipitation and storm severity (and frequency) during winter and spring months, and more drought-like conditions in the summer and early fall, have implications for short-term, seasonal, and interannual water level regimes and the phenology of organisms that rely on those seasonal and interannual water level cycles.

The confidence level for projections of estimated mean annual precipitation is low. The confidence level for future changes in extreme precipitation events is moderate to low, with decreasing certainty toward the end of this century.

7.2.3 GREAT LAKES THERMAL REGIMES

The Great Lakes region could see substantial increases in annual and seasonal air temperatures and extreme heat events, particularly under the higher A2 emissions scenario (Wuebbles et al. 2010). Over the next few decades (2010–2039), it is anticipated that annual average air temperatures will increase on the order of 0.6–0.8°C. Near the end of the century (2070–2099), annual average air temperatures could increase by 1.7–2.2°C under the lower B1 emissions scenario, and by 4.5°C under the higher A2 scenario. The greatest air temperature increases will occur during the summer months (up to 6°C or 10°F). Along with warming temperatures, there will be a timing shift where the last frost date will occur 30 days earlier under the A2 scenario and 20 days earlier under the B1 scenario (Wuebbles et al. 2010).

Increasing air temperatures in the Great Lakes region will affect Great Lakes surface water temperatures by reducing the extent and duration of Great Lakes winter ice cover. An empirical temperature model developed by Trumpikas et al. (2009) was used to estimate Great Lakes surface water temperatures for several emission scenarios. For all of the Great Lakes, surface water temperatures are estimated to increase on the order of 1.5-3.9°C under the A2 scenario and 1.6-3.2°C for the B2 scenario by 2050. At the end of the century, surface water temperatures are expected to increase on the order of 3.3-6.7°C for the A2 scenario and 2.4-4.6°C for the B2 scenario.

Along with warming surface water temperatures there will also be a timing shift where surface water temperature values will increase earlier in the spring (35-47 days earlier) and later in the fall (26-51 days later) under the A2 scenario. Similarly, surface water temperatures will increase 24-31 days earlier in the spring and 18-36 days later in the fall under the B2 scenario. For Lake Superior, and to a lesser extent Lakes Michigan-Huron, summer surface water temperature warming generally exceeds the rate of atmospheric warming due to reduced winter ice cover, which results in an earlier onset of thermal stratification and a longer surface warming period (Austin and Colman 2007). Over time, it is anticipated that thermal stratification will occur earlier in the spring and later in the fall as surface water temperatures continue to increase, thereby increasing evaporation Great Lakes surface waters and lengthening the surface warming period.

The estimated surface water temperatures within the next 30 years have a moderate confidence level, and surface water temperature values estimated toward the end of the century have a low confidence level.

7.3 Vulnerability of Great Lakes Coastal Systems to Climate Change

Anticipated long-term changes in climate have the potential to significantly alter the physical integrity of the Great Lakes basin (e.g., Lee et al. 1996; Kling et al. 2003; Mackey et al. 2006; Ciborowski et al. 2008; Wuebbles et al. 2010). Potential climate-change induced alterations due to weather (i.e., precipitation, evapotranspiration, and storm frequency, severity, and patterns) will alter the physical and habitat integrity of the Great Lakes basin, including:

- *Great Lakes water levels and flow regimes* – changing net basin water supplies and water level regimes; increased water level variability (frequency and magnitude); altered coastal circulation patterns and processes; seasonal changes in flooding; loss of hydraulic connectivity; altered coastal margin and nearshore habitat structure;
- *Storm frequency, severity, and patterns* – seasonal changes in storm magnitude, frequency, and direction (storm tracks); changes in flood frequency and magnitude; changes in coastal wave power and direction; altered littoral sediment transport rates and processes; increased shore erosion; reduced nearshore water quality; reduced marina/harbor/port access (increased dredging activity);
- *Precipitation*- seasonal alterations in precipitation and flow regimes; spatial and temporal shifts in seasonal timing; altered riverine and floodplain habitat structure and connectivity;
- *Thermal regimes* – altered open-lake and nearshore surface water temperatures; reduced ice cover; deeper and stronger thermal stratification; spatial and temporal shifts in seasonal timing; and

- *Latitudinal shifts in ecoregions* – regional changes in land and vegetative cover and associated terrestrial and aquatic communities and habitats (affecting coastal margin areas).

Habitat is the critical component that links biological communities and ecosystems to natural physical processes and the underlying physical characteristics of the basin. The pattern and distribution of habitats are controlled, in part, by interactions between energy, water, and the landscape (e.g., Sly and Busch 1992; Higgins et al. 1998; Mackey and Goforth 2005; Mackey 2008). Habitats are created when there is an intersection of a range of physical, chemical, and biological characteristics that meet the life stage requirements of an organism, biological community, or ecosystem (Mackey 2008).

Seasonal changes in water level and flow regimes, thermal structure, and water mass characteristics interact with the underlying landscape to create repeatable patterns and connections within tributaries, lakes, and shorelines within the basin. The pattern of movement of water, energy, and materials through the system (which depends on connectivity) also exhibits an organizational pattern and is persistent and repeatable . For example, these patterns and connections influence the seasonal usage of Great Lakes fish spawning and nursery habitats (Chubb and Liston 1985). Moreover, high-quality coastal margin habitats (both aquatic and wetland) are created by a unique set of environmental conditions and processes that together meet the life-stage requirements of a species, biological community, or ecological function (Mackey 2008). These processes play a significant role by ultimately determining the distribution and utilization of essential coastal margin habitats within the Great Lakes system.

7.3.1 HYDROGEOMORPHOLOGY

Great Lakes coastal margins can be delineated into four major hydrogeomorphic groups: nearshore; beaches, barriers, and dunes; wetlands; and bluffs. These areas are defined by the hydrogeomorphic characteristics of the shoreline and the dominant physical processes that act on those shorelines. Climate change impacts to coastal margins are primarily physical in nature (i.e., changes in water level regime; storm frequency and magnitude; precipitation and evaporation; ice cover; and air and surface water temperatures). Climate-induced changes to physical processes will impact not only the physical characteristics of the shoreline, but create vulnerabilities for coastal habitats, biological communities, and ecosystems that rely on those shorelines.

Table 7.2 summarizes the vulnerability of Great Lakes coastal margin hydrogeomorphic groups, ecosystem components, and socioeconomic sectors to climate stressors. The confidence level associated with each hydrogeomorphic group, ecosystem component, and socioeconomic sector is stated in parentheses, and is based on the understanding we have of the interaction and resulting impacts between climate change stressors and the group, component, or sector. The confidence levels provided in this table do not incorporate the uncertainty associated with the climate change stressor, which is generally high (low confidence level).

Nearshore areas represent the area encompassed by water depths ranging from 3 to 30 meters (m) in all of the Great Lakes except Lake Erie. In Lake Erie, the nearshore is defined by the area encompassed by water depths ranging from 3 to 15 m. Dominant

Table 7.2 Summary of climate stressors and coastal margin vulnerabilities.

Stressors	**Great Lakes Water Levels**	**Water Level Vulnerability**	**Storms and Precipitation**	**Thermal Regime**
Climate Impact (Low Confidence Level)	Mean annual water levels slightly below long-term mean	Increase in magnitude and frequency of water level change; increased range of variability	Increase in magnitude and frequency of storms; change in precipitation timing and patterns	Increase in surface water temperature
Regional Effects (Low Confidence level)	Long-term mean water levels generally within normal historical range; future mean water levels slightly below long-term mean; possible seasonal shifts in annual highs and lows	Water levels generally within historical ranges, but possible short-term, seasonal, and interannual exceedances above and below historical highs and lows	Stronger more frequent storms; increase in magnitude and frequency of storm generated waves; increased precipitation during winter-early spring months, decreased precipitation (drier) during summer-fall months.	Increase in Great Lakes surface water temperatures; reduced ice cover, later fall ice formation, earlier spring breakup; stronger thermal stratification; more frequent low Dissolved Oxygen (DO) occurrences; expansion of low DO zones (e.g., Lake Erie dead zone)
Hydrogeomorphic Group				
Nearshore (Moderate Confidence level)	Levels within historical range	Low water impact: increased potential for lakebed downcutting; reduction in nearshore water quality	Increased potential for lakebed downcutting; reductions in nearshore water quality	Increase in surface water temperature
Beaches, Barriers, and Dunes (Moderate to High Confidence Level)	Relatively static shoreline position; slight increase in mean beach width due to slightly lower water levels	High water impact: reduction in effective beach widths (loss of natural shore protection) Low water impact: increase in effective beach widths	Increased variability in beach width; increased variability in littoral sediment transport rates; increased potential for beach erosion due to increased wave energy; increased potential for lakebed downcutting; reductions in nearshore water quality	Increase in surface water temperature; increased wave power due to lack of ice cover; reduced winter ice shore protection
Coastal Wetlands (Moderate Confidence Level)	Water levels within historical range	Increased wetland zonation and biodiversity; increased probability of phenological shifts due to altered timing Low water impact: potential loss of hydraulic connectivity	Increased short-term inundation; increased potential for erosion/ destruction of open-coast fringing wetlands; short-term impacts to wetland-dependent nesting birds and waterfowl	Increase in surface water temperature; increased productivity; northward expansion of invasive species (both terrestrial and aquatic)
Bluffs (Moderate to High Confidence Level)	Relatively static shoreline position; slight decrease in erosion potential due to wider beaches	High water impact: increased bluff erosion (narrower beaches) Low water impact: reduced bluff erosion (wider beaches)	Increased erosion of coastal bluffs due to elevated water levels and increased wave power; increased precipitation accelerates surface erosion	Increase in bluff erosion/ recession rates during winter months; increased wave power due to lack of ice cover; reduced winter ice shore protection

Table 7.2 (continued).

Ecosystem Component	**Great Lakes Water Levels**	**Water Level Vulnerability**	**Storms and Precipitation**	**Thermal Regime**
Productivity/ Water Quality (Moderate to High Confidence Level)	Water levels within historical range	Low water impact: potential loss of hydraulic connectivity with coastal wetlands (nutrient processing and export)	Lake Erie, Lake St. Clair: shallow embayments experience increased nutrient, contaminant, and sediment loads from increased winter-early spring precipitation/runoff; increased algal blooms *Microcystin* (productivity); lower overall lake water quality; increased turbidity; increased number of beach closings	Increase in primary production; increased algal blooms *Microcystin;* stronger thermal stratification; more frequent low DO occurrences; expansion of low DO zones (e.g., Lake Erie dead zone, but linked to Lake Erie water levels) Low water: thinner hypolimnion; increased number low DO events; longer dead zone duration
Coastal Fisheries (Low to Moderate Confidence Level)	Water levels within historical range	Increased probability of phenological shifts due to change in water level timing Low water impact: potential loss of connectivity between spawning and nursery habitats	Increased probability of phenological shifts due to change in tributary flood-pulse timing; increased storm impacts on spawning/ nursery habitats affecting recruitment Low water impact: potential short-term loss of connectivity between spawning and nursery habitats	Shift in distribution of cold and warm-water fish species; increased probability of phenological shifts; due to temperature driven changes in spawning activity; change in egg/larval maturation rates; northward expansion of aquatic invasive species.
Socioeconomic Sector				
Ports and Harbors/ Infrastructure (Moderate to High Confidence Level)	Water levels within historical range, but slightly lower than long-term mean	High water impact: increased coastal flood risk during storm events Low water: increased dredging of commercial and recreational channels; light load commercial vessels; decrease in available marina slips (water depth limited)	Increased littoral and riverine sediment transport rates; increased dredging frequency due to storm derived sediments High water impact: increased coastal flood risk; increased risk of storm damage to navigation structures	Reduced ice cover, later fall ice formation, earlier spring breakup; extended commercial shipping and recreational boating season
Coastal Property (Moderate to High Confidence Level))	Water levels within historical range, but slightly lower than long-term mean	High water impact: increased coastal flood risk during storm events; increased shoreline erosion due to narrower beaches Low water: re-establishment of SAV and emergent wetland vegetation; wider beaches	High water impact: increased coastal flood risk during periods of high water; increased shoreline erosion; increased risk of storm damage to shore protection structures	Increase in shoreline erosion/recession rates during winter months; increased wave power due to lack of ice cover; reduced winter ice shore protection

physical processes acting on the nearshore zone include wind-driven coastal circulation patterns, storm generated wave energy, nearshore lakebed sediment transport processes, and nearshore lakebed downcutting. Great Lakes nearshore areas are vulnerable to climate-induced changes in storm magnitude, frequency, and direction (i.e., changing storm tracks). Anticipated physical impacts include altered nearshore circulation patterns, erosion and removal of protective sand cover from the lakebed, increased potential for lakebed downcutting, and degradation of nearshore water quality (increase in nearshore turbidity). Nearshore spawning and nursery habitats may be impacted by a coarsening of lakebed substrates and active erosion and sediment transport on the lakebed. The resulting coarse lakebed substrates provide additional habitat for lithophylic invasive species such as dreissenids (zebra and quagga mussels) and the round goby (e.g., Janssen et al. 2004; Meadows et al. 2005).

Beaches, barriers, and dunes include high energy areas within 0 to 3 m water depths and adjacent low-relief coastal margin, embayed, and back-bay areas. Beaches and barriers are created and maintained by littoral sediment transport processes and dune complexes are created by wind-driven sand deflation processes. Dominant physical processes affecting these coastal margin areas include wind and storm generated wave energy, littoral sediment transport processes, and both long- and short-term fluctuations in Great Lakes water levels. Anticipated climate impacts include increased littoral sediment transport rates, beach erosion and reduction in beach widths, degradation of nearshore water quality (increase in nearshore turbidity) and thermal effects resulting in the reduction or loss of ice cover during the winter months (Assel 2005) and loss of winter ice shore protection (USACE 2003).

During periods of high water levels, barrier systems are more vulnerable to major storm events which may result in eventual breaching of the barrier beach. During periods of low water levels, benthic and fish communities are vulnerable to lakeward shifts of the shoreline, which may change the location and distribution of nearshore spawning and nursery habitats in low-relief shallow water areas (Mackey et al. 2006). Moreover, adjacent wetland areas may become hydraulically isolated from adjacent tributary and lake water bodies, disconnecting potential spawning and nursery habitats (e.g., Mortsch 1998; Wilcox et al. 2002; Wilcox 2004; Mortsch et al. 2006). Newly created shallow-water areas will offer potential new habitat for establishment of submergent aquatic vegetation and coastal wetland communities. But exposed lakebed areas may be vulnerable to the expansion of invasive species such as *Phragmites australis* (e.g., Tulbure et al. 2007).

In response to historically high water levels in the mid-1980s, extensive coastal engineering works and the resulting loss of littoral sand from adjacent coastal margin and nearshore areas have created habitats that are now much more coarse-grained and heterogeneous than would have naturally been present along many Great Lakes coastlines. It is anticipated that as Great Lakes water levels decline, littoral sand deposits will become stranded at higher shoreline elevations and lost to the active littoral system (M. Chrzastowski, Illinois Department of Natural Resources, personal communication 2006). The loss of these sand resources may be significant, especially along sand-poor Great Lakes cohesive shorelines.

One of the consequences of these substrate changes is the rapid colonization and spread of aquatic invasive species (such as *dreissenid* spp.) that have adversely impacted food web-dynamics and the Great Lakes ecosystem. Many of the physical changes that have occurred in the nearshore zones of the Great Lake have provided the opportunity for massive expansion of these invasive species along with significant associated ecological impacts (e.g., Janssen et al. 2004; Meadows et al. 2005).

Coastal wetlands are commonly found landward of protective beach-barrier systems, within protected embayments, along open-coast shorelines (i.e., fringing wetlands), and in unaltered (natural) rivermouths. Great Lakes coastal wetlands provide essential habitat for more than 80 species of fish (Jude and Pappas 1992). More than 50 of these species are solely dependent on wetlands, while more than 30 additional species utilize wetlands during a portion of their life history (Jude and Pappas 1992; Wilcox and Meeker 1995). Other fish species may use wetlands for short periods of time as refugia (predator avoidance) and for forage (food supply). Waterfowl, nesting birds, amphibians, mammals, and reptiles also utilize wetland and coastal margin habitats. Their distribution and abundance are intimately tied to wetland vegetative cover and the hydrogeology of the wetland (e.g., Timmermans 2001; Timmermans et al. 2008)

More recent research has documented a relationship between wetland plant zonation, biodiversity, and fish community composition (Uzarski et al. 2005, 2009; Albert et al. 2005). Intact coastal wetlands with several plant zones sustained by water level fluctuations provide cover, prey, spawning and nursery habitats (Goodyear et al. 1982; Jones et al. 1996; Lane et al. 1996a, 1996b). The high productivity and structural diversity of Great Lakes coastal wetlands are maintained by natural cycles of high and low water levels as well as natural seasonal water level fluctuations (Wilcox and Meeker 1995; Wilcox 2004; Keough et al. 1999; Mayer et al. 2004; Albert et al. 2005). On Lake Ontario, water level regulation resulted in range compression and loss of wetland biodiversity, plant community zonation, and ecological functionality (Wilcox and Meeker 1991, 1992, 1995; Busch and Lary 1996; Wilcox and Xie 2007).

As Great Lakes water level regimes are expected to remain slightly below the long-term mean, an anticipated increase in short-term, seasonal, and interannual variability of water levels driven by changes in local precipitation and increased storm frequency will benefit Great Lakes wetlands by maintaining and/or restoring plant community zonation, increasing wetland biodiversity, and enhancing environmental benefits. However, increased variability in water level regimes may alter the phenology of wetland-dependent fish communities and other aquatic organisms due to alterations in seasonal timing and duration (Casselman 2002; Kling et al. 2003; Uzarski et al. 2005, 2009; Shimoda et al. 2011).

Coastal bluffs are a dominant shoreline type in the Great Lakes and are created when upland areas are subject to mass-wasting processes initiated by instabilities created by wave erosion at the base of the bluff. These processes have been active along Great Lakes shorelines for thousands of years and have contributed most of the sediments that maintain beaches along Great Lakes shorelines. Physical processes affecting these coastal bluffs areas include the expenditure of wind and storm generated wave energy; littoral sediment transport processes; and both long- and short-term fluctuations in Great Lakes water levels. Anticipated physical climate impacts include increased bluff erosion/recession rates; degradation of nearshore water quality (increase in nearshore turbidity), and thermal effects resulting in the reduction or loss of ice cover during the winter months (Assel 2005) and loss of winter ice shore protection (USACE 2003).

Erosion of coastal bluffs is episodic and is driven primarily by a combination of wind and storm-driven waves (wave power) expended along Great Lakes shorelines and Great Lakes water levels (e.g., Brown et al. 2005). As Great Lakes water level regimes are expected to remain slightly below the long-term mean, anticipated increases in local precipitation and increased storm magnitude and frequency will increase the cumulative wave power expended along Great Lakes shorelines. The increase in cumulative wave power combined with possible changes in storm direction could significantly alter the rate and direction of littoral sediment transport, increasing the exposure of Great Lakes coastal bluffs to wave attack. During periods of high water levels, beaches become narrower, reducing the effectiveness of beaches as natural shore protection. Erosion of coastal bluffs and adjacent upland areas increases, resulting in the reduction of nearshore water quality. During periods of low water levels, more of the beach face is exposed, resulting in wider beaches that provide natural shore protection and also may reduce erosion of coastal bluffs and adjacent dune and upland areas (Brown et al. 2005; Meadows et al. 2005). Moreover, the reduction or loss of winter ice cover due to anticipated warmer air and surface water temperatures will result in an increase in wave exposure due to loss of winter ice shore protection.

7.3.2 PRODUCTIVITY AND WATER QUALITY

Warmer surface water temperatures combined with lower Great Lakes water levels affects the thermal structure of the Great Lakes, causing changes in both lake chemistry and lake ecology (Sousounis and Grover 2002). During periods of low water levels, higher surface water temperatures will create a deeper and stronger thermocline that will reduce the water volume in the hypolimnion and result in more frequent episodes of anoxia. In the central basin of Lake Erie, reduced hypolimnion water volumes combined with altered nutrient cycling by invasive zebra/quagga mussels (*Dreissenid* spp.) may result in more frequent occurrences of an expanded dead zone (Lam et al. 1987, 2002; Charlton and Milne 2004). As water temperatures increase, dissolved oxygen (DO) levels decrease as warm water holds less oxygen than cold water. Moreover, warm waters increase respiration rates for aquatic species further depleting DO levels. Even though the deep northern lakes are relatively immune from low DO levels, shallower water bodies, embayments, and some tributaries may be susceptible to low DO levels as water temperatures increase. Moreover, warmer water temperatures combined with increased nutrient loads may increase productivity and nutrient recycling, which may stimulate the growth of filamentous blue-green algae (*Cladophora* spp) which impacts nearshore water quality and habitats, is an aesthetic problem for coastal property owners and beaches, and may contain pathogens (Hellman et al. 2010). As these organisms die and settle to the bottom and decompose, oxygen is consumed reducing DO levels even further. In Lake Erie, warm surface water temperatures and increased nutrient loads have resulted in more widespread and frequent algal and cyanobacterial (*Microcystin*) blooms.

7.3.3 COASTAL FISHERIES

The abundance of several species of important recreational and commercial fish (lake trout, walleye, northern pike, and lake whitefish) varies with the amount of thermally suitable habitat (Christie and Regier 1988; Lester et al. 2004; Jones et al. 2006). A warm thermal structure may cause a northward shift of boundaries for both warm and cold-water fishes, affecting abundance, distribution, and resilience to exploitation (Minns and Moore 1992; Shuter and Meisner 1992; Magnuson et al. 1997; McCormick and Fahnenstiel 1999; Brandt et al. 2002; Casselman 2002; Kling et al. 2003; Sharma et al. 2007). Increasing surface water temperatures could also remove existing thermal constraints that have protected the Great Lakes from invasive organisms in the past, and increase the potential number of organisms that can successfully invade the lake (Mandrak 1989). In response to these shifted thermal boundaries, zebra/quagga mussels, round gobies, and other aquatic nuisance species may be able to expand their existing ranges further northward into the upper Great Lakes (GLFC 2005). Moreover, increases in water temperature are positively correlated with mercury methylation rates and increase the availability of methyl mercury for incorporation into fish tissue. Warmer surface water temperatures may facilitate the rate of mercury contaminant uptake into the food chain that will result in increased levels of mercury contamination in fish (Bodaly et al. 1993; Yediler and Jacobs 1995).

7.3.4 PORTS AND HARBORS/INFRASTRUCTURE

These coastal structures are typically designed to protect and maintain both commercial and recreational navigation channels and associated infrastructure. Maintenance of these structures is typically a Federal or State responsibility. Depending on use, the navigation channel may be dredged on an annual basis to accommodate large commercial vessels. Increased storm severity and frequency and loss of ice cover during the winter months will increase littoral sediment transport rates requiring more frequent dredging to maintain navigation channels. During high water periods, there is an increased risk of coastal flooding during major storm events and increased risk of storm damage to the navigation structure and port infrastructure. During low water periods, there will be a need for increased dredging of navigation channels to maintain design depths, light-loading of commercial vessels to maintain draft over shallow areas in navigation channels, and a decrease in the number of available commercial or recreational slips in marinas due to low water conditions. As a benefit, reduced winter ice cover due to increasing surface water temperatures may provide an opportunity to extend the commercial navigation and recreational boating seasons.

7.3.5 COASTAL PROPERTY

The effects of climate change in developed coastal areas will be exacerbated by anthropogenic activities, especially in areas where the lakebed may be exposed and development pressures in coastal areas result in encroachment of submerged lands. Climate change projections suggest that even though mean water levels will remain near, but slightly lower than long-term mean water levels, there will be increased short-term variability in water levels in response to increased storm magnitude and frequency, especially during the winter and early spring months. During periods of high water, coastal flooding risks are high; risk of shore and beach erosion due to storm derived waves is high; and there is an increased risk of damage to infrastructure (shore protection structures) and upland property loss during major storm events. During periods of low water, flooding and erosion risks are low. However, during extended periods of low water, property owners fill shoreline areas for development (encroachment), install shore protection, groom beaches to improve aesthetics, and remove submergent and emergent aquatic vegetation to promote water access and provide a viewshed. These shoreline alterations affect natural coastal processes and the ecosystem, and will have a detrimental effect on Great Lakes nearshore and coastal margin environments. Recent work by Uzarski et al. (2009) clearly demonstrated the deleterious effects of vegetation removal on local fish and aquatic plant communities and coastal biodiversity.

7.4 Discussion

Both global and regional climate models have been used to project changes in temperature, weather, precipitation, storm severity and frequency, and, indirectly, Great Lakes water levels. These projections have a high degree of uncertainty and represent a range of possible futures or scenarios. For all of these scenarios, the physical integrity of the Great Lakes will be modified or altered in response to changing climate conditions. Thus, ecological responses to climate change will be driven primarily by changes in physical integrity, and these responses may be nonlinear, especially if boundaries and thresholds are exceeded (Burkett et al. 2005). Synergistic or cross-cutting interactions between climate stressors may be additive and cause unforeseen environmental or socioeconomic impacts. Table 7.3 provides examples where multiple climate stressors interact to produce an impact (or benefit).

Table 7.3 Cross-cutting issues.

Climate Stressor	**Condition**	**Condition**	**Condition**	**Impacts**
Water level regime Thermal regime Storms and precipitation	Low water levels	Strong thermal stratification	High winter-spring precipitation, (high nutrient loads	Low dissolved oxygen; Lake Erie dead zone
Storms and precipitation Water level regime Thermal regime	Increased wave power (storms)	High water levels	Reduced ice cover; no winter ice protection	Increased shore and beach erosion (all seasons)
Thermal regime Storms and precipitation	High surface water temperatures	High winter-spring precipitation; (high nutrient loads)		Blue-green algal vlooms; *Microcystin* blooms in nearshore waters

Conditions are listed in the same order as the stressor listing. Multiple conditions are listed for each stressor. For example, in the second row of Table 7.3, more severe and frequent storms will increase wave power along the coastline. Increased wave power coupled with high water levels will increase erosion of coastal bluffs and littoral sediment transport rates. Warmer surface water temperatures will reduce or eliminate winter ice cover which will allow erosion and sediment transport to occur during the winter months. This will increase the volume of sediment that will have to be dredged from commercial and private navigation channels and result in further shoreline hardening due to the need for new shore protection. Increased littoral sediment transport rates will also affect hydraulic connectivity with coastal wetlands and riverine spawning and nursery habitats.

7.5 Recommendations

Additional work is needed to more fully understand the biophysical linkages between physical habitats, associated biological communities, and the natural processes that connect them. Future changes to the ecosystem may yield changes that have not yet been observed and for which data do not exist. It is only through an understanding of biophysical processes that we may be able to predict the ecological responses of the Great Lakes ecosystem due to changes in water-level regime. Moreover, additional tools/models need to be developed that integrate physical and ecological processes to simulate potential changes in environmental conditions and associated aquatic habitats resulting from long-term changes in water-level regime. Using these models, it will be possible to identify potential long-term management, protection, and restoration opportunities based, in part, on an understanding of biophysical processes.

The resulting management, conservation, and protection strategies must be designed to protect potential refugia and transitional or and newly created coastal margin and nearshore habitat areas from anthropogenic modification and/or degradation. As water levels recede, there will be increasing societal pressure to develop and modify newly exposed areas of the shoreline. Critical reaches of the Great Lakes shoreline (as identified by the long-term models) must be protected and preserved to ensure that essential ecological functions are maintained during periods of transition.

It will also be necessary to establish a long-term, aquatic habitat research and monitoring effort within the Great Lakes to track changes and continually update and refine the heuristic models. An important consideration will be to identify the appropriate variables to be monitored and to establish thresholds or triggers that tell us when to modify resource management and protection policies. This approach will provide the knowledge and science-based tools to build the capacity of key agencies, organizations, and institutions to identify and implement sustainable protection, restoration, and enhancement opportunities.

This discussion highlights the need to incorporate management and research strategies designed to address uncertainty and respond to potential long-term stressors, such as climate change, water diversions, and continued growth and development which have the potential to impair the physical integrity of the Great Lakes. Given the uncertainties associated with climate change, it is necessary to implement a proactive anticipatory management approach (commonly referred to as adaptive management strategies) that identifies long-term planning, protection, and restoration needs in response to climate change-induced stressors and impairments within the Great Lakes basin. Application of adaptive management strategies will help to ensure the physical and ecological integrity of the Great Lakes in the face of major environmental change.

7.6 Summary

1. Great Lakes water levels will generally remain within the natural historical range of water levels with annual means slightly below long term mean water levels. Increased precipitation, storm severity and frequency during winter and spring months, and more drought-like conditions in the summer and early fall have implications for short-term, seasonal, and interannual water level variability and the phenology of organisms that rely on those seasonal and interannual water levels. Increased short-term, seasonal, and interannual water level variability will support and maintain coastal wetland biodiversity and associated fish and wildlife habitats.
2. Major winter and spring precipitation events will increase nutrient and sediment loadings into the Great Lakes. Reduced ice cover on large lakes will increase surface water temperatures and evaporation, increase productivity, initiate longer-term thermal stratification, and increases the probability for low dissolved oxygen events in shallow embayments and other Great Lakes areas (e.g., the Lake Erie dead zone). Combined with warmer surface water temperatures, increased loadings may result in more widespread algal and cyanobacterial (*Microcystin*) blooms.
3. Increased storm magnitude and frequency coupled with warmer surface water temperatures will reduce ice cover, increase wave power, and reduce winter ice shore protection, which will increase the risk for coastal flooding and result in accelerated beach, shore, and bluff erosion.
4. During extended periods of low water levels, shallow-water areas will offer potential new habitat for submergent aquatic vegetation and new coastal wetland communities. But exposed lakebed areas may be vulnerable to expansion by *Phragmites australis* or other invasive wetland plant species.
5. Increased surface water temperatures will cause gradual ecotonal shifts in aquatic species distributions from cold-water species to warm-water species in intermediate- to shallow-water nearshore and coastal areas of the Great Lakes.

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Chapter 8

Climate Change and Energy

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8.1 Introduction

Both climate change and climate change policy are intrinsically important to the energy sector. The sector bears considerable, yet not exclusive, responsibility for climate change associated with greenhouse gas (GHG) emissions from fossil-fuel-based production facilities, namely electric power plants. Activity within the energy sector can thus be understood in the context of both problem and solution, where the sector's heavy reliance on fossil fuels makes it a target of remedial policies designed to limit and mitigate greenhouse gas emissions. These include rigorous permit processes, emissions targets, scrubbing technologies, and carbon capture methods as well as renewable portfolio standards. Consequently, the pattern of response and adaptation within the sector may be driven as much by climate change policy as by actual and anticipated climate change attributable to energy demand and production.

This review, drawing from both the academic and applied literature, focuses on climate and climate change policy with respect to both the supply-side (production) and the demand-side (consumption) of the sector. Federal and state policy developments are summarized. A number of emerging and critical policy issues are also considered.

While climate change will affect the energy sector, the effects of climate change policy are more immediate and potentially more far-reaching. Climate change considerations permeate modern energy policy, along with concerns about energy security, resource renewability, and economic development. Energy providers are subject to increasingly stringent environmental regulations that require significant investment in emissions reduction, alternative energy resources, transmission facilities, and grid modernization. Simultaneously, replacing and modernizing the aging generation, transmission, and distribution infrastructure (including "smart grid" investments) are adding to cost pressures (American Society of Civil Engineers 2011). Efficiency gains from standards, conservation programs, and load-management tools will help offset some costs. Even so, utility ratepayers can be expected to bear the cumulative burden of infrastructure investments and environmental mandates as the controversy over costs and their allocation is inevitable.

8.1.1 STRUCTURE AND REGULATION OF THE ENERGY SECTOR

Public utility companies that provide energy services comprise a significant share of the U.S. economy in terms of gross domestic product and employment (Beecher 2012c). Utility expenditures also constitute a significant share of household expenditures. Over the last decade, the average percentage change in the Consumer Price Index for electricity was approximately 4%, although this rate of change is less than the change for the entire index (Beecher 2012b).

Publicly and privately owned utilities are subject to federal environmental regulation pursuant to the Federal Clean Air Act (CAA) and Environmental Protection Agency (EPA) rules as well as other environmental mandates (including the National Environmental Policy Act, the Clean Water Act, and the Toxic Substance Control Acts). Federal and state laws and regulations are implemented through state environmental agencies.

Most electricity and natural gas utilities are privately owned and subject to economic regulation by the Federal Energy Regulatory Commission (FERC) and state public utility commissions. Federal authority is pursuant to the interstate commerce clause. Over the last two decades, energy markets have been substantially restructured, which, in turn, affects how they are regulated. The natural gas industry was restructured in the 1980s when wellhead production was deregulated; interstate pipeline transmission is subject to federal jurisdiction, and local distribution is regulated by the states.

Oversight of the electricity sector varies by state depending on market structure (U.S. Energy Information Administration 2010). In the past, generation, transmission, and distribution functions were provided by vertically integrated utilities. Vertical integration remains in about half of the states today, including Indiana, Iowa, Minnesota, Missouri, and Wisconsin, and state regulators continue to have comprehensive authority. Illinois and Ohio are considered restructured states, where vertical separation resulted in deregulated (competitive) generation companies and federally regulated transmission providers. In Michigan, transmission is separated but generation and distribution remain integrated and regulated. The federal government oversees bulk power markets through Regional Transmission Organizations (RTOs). Restructuring limits state jurisdiction for the sector to intrastate activities and retail distribution.[1]

Thus, much federal economic regulation focuses on wholesale operations while retail oversight belongs to the states. The prices and profits of vertically integrated and distribution utilities are regulated because they are organized as state-sanctioned monopolies. Various technical and economic characteristics distinguish utilities from other enterprises and contribute to their monopolistic character. Economic regulation is designed to prevent abuse of monopoly power while balancing the interests of utility investors and

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[1] For more on state regulatory jurisdiction and authority, see Institute of Public Utilities survey data available at www.ipu.msu.edu.

ratepayers. Regulators review the prudence of utility investments and expenditures in a quasi-judicial process prior to their inclusion in rates. Rate-making, or the determination and allocation of a utility's revenue requirements, is controversial, particularly in the contemporary context of rising costs.

In addition to environmental and economic regulation, energy utilities are subject to financial regulation (by the Securities and Exchange Commission), accounting rules (by the Federal Accounting Standards Board), and reliability standards (by the North American Electric Reliability Corporation). Bulk power transmission for various regions is managed by independent system operators such as MISO (Midwest) and PJM (Pennsylvania New Jersey Maryland), which impose planning and operational requirements on market participants, including congestion management and real-time pricing. As a result of extensive oversight, including market monitoring, the transmission sector is considered relatively accountable to regulators and transparent to stakeholders.

8.1.2 ENERGY PROFILE FOR THE MIDWEST

The Midwest region is home to numerous power plants and continues to rely heavily on coal for generating electricity.

The region, however, is also home to 25 nuclear power plants, about a quarter of the nation's aging fleet. Among states in the region, Illinois is highest in both production and sales of electricity.

Traditionally, large central power production has been favored due to substantial and persistent scale economies (declining unit costs) in both construction and operation.

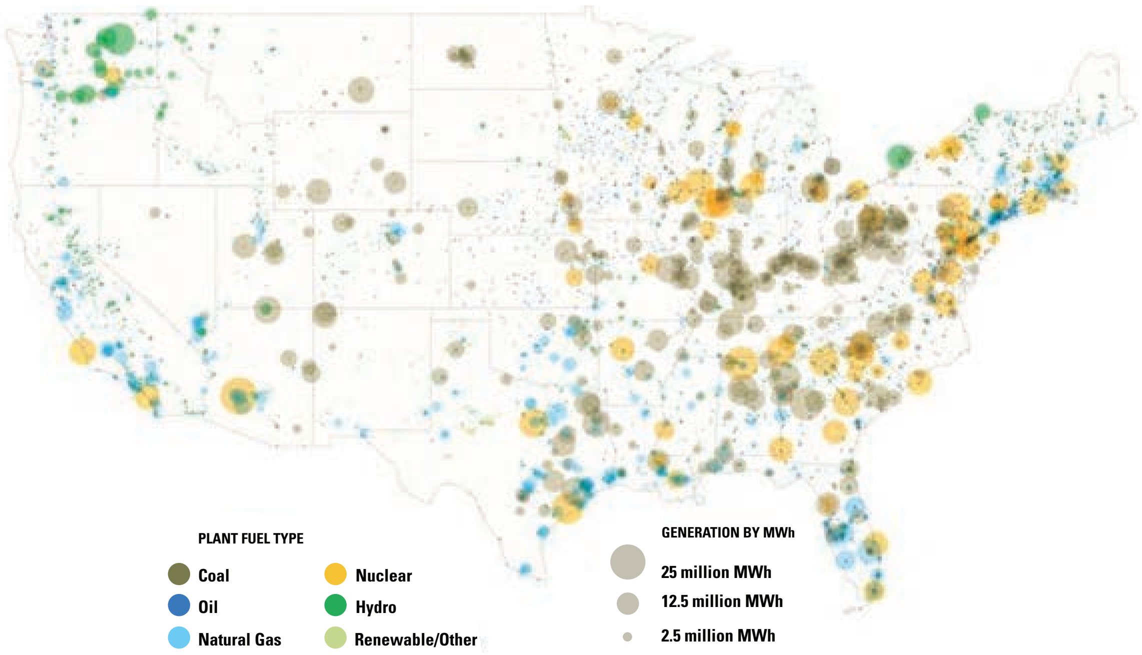


Figure 8.1. Electricity power plants in the United States and Midwest region. *Source*: Ceres (2010).

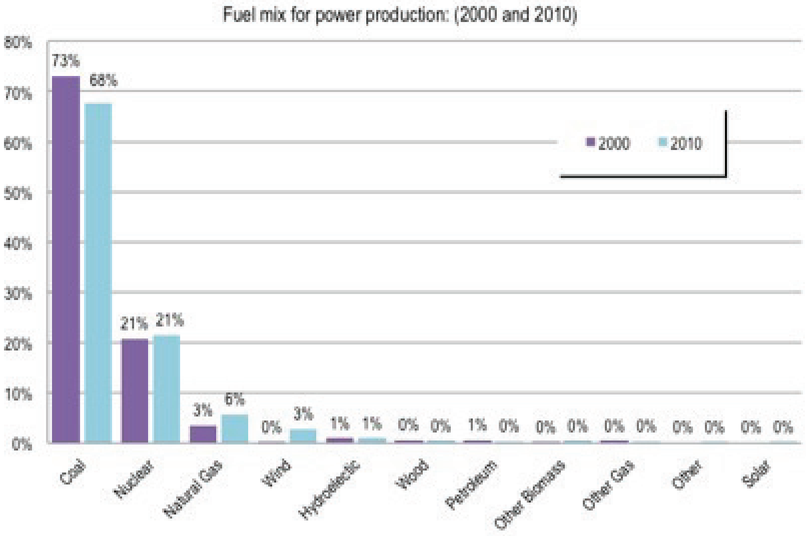


Figure 8.2. Fuel mix for power production in the Midwest region. *Source*: Authors' construct from U.S. Energy Information Administration (EIA), "Electricity" (2010).

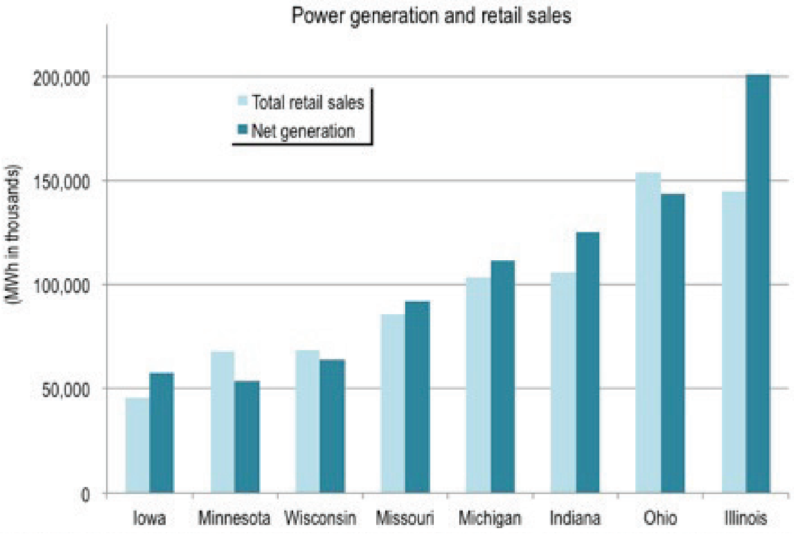
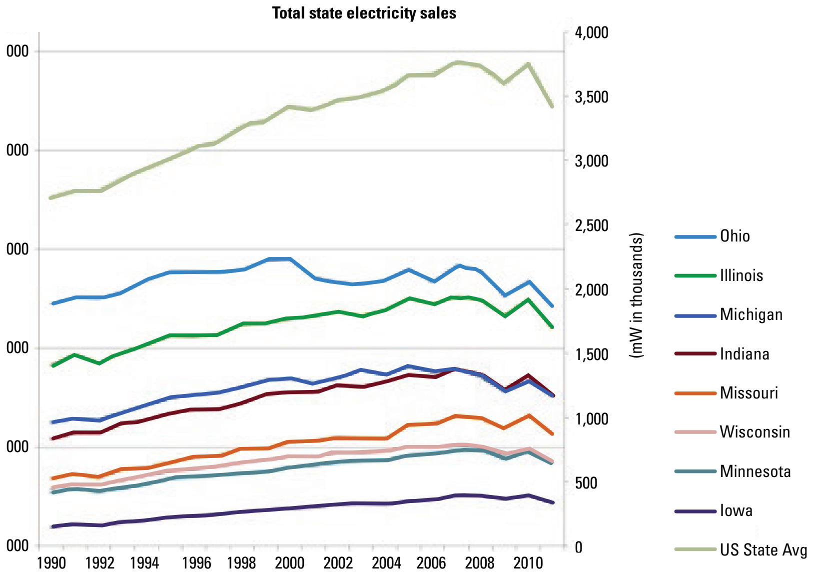


Figure 8.3. Power generation and retail sales in the Midwest region. *Source*: Authors' construct from U.S. Energy Information Administration (EIA), "Electricity" (2010).

Power plants are owned by regulated utilities or competitive providers, including independent power producers. The power production fleet is aging, and much of the recent capital investment has been in peaking facilities as compared to baseload capacity. Between 2000 and 2010, the slight shift toward natural gas and wind energy is attributable to favorable natural gas prices and policy support for renewable energy development. Low market prices for natural gas, spurred by shale development, continue to shape investment decisions in the electricity sector with regard to both fossil and renewable energy (U.S. Energy Information Administration 2012).

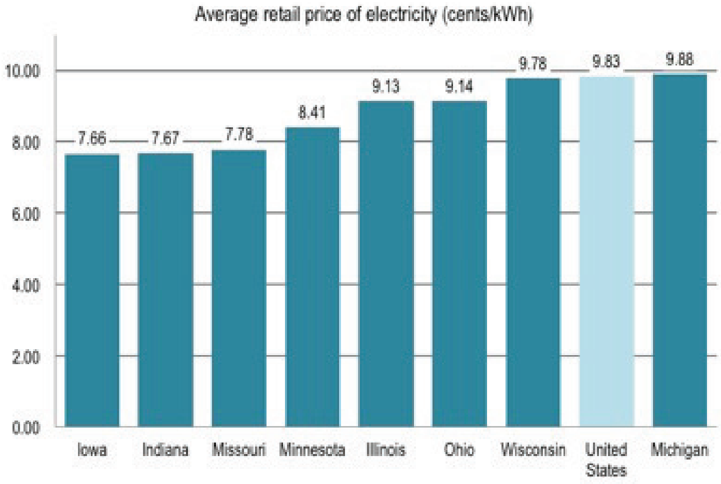
Growth in retail electricity sales in the Midwest actually began to slow prior to the recent recession. Socioeconomic trends and efficiency gains will continue to shape de-

Figure 8.4. Trends in retail electricity sales in the Midwest region. *Source*: Authors' construct from U.S. Energy Information Administration (EIA), "Electricity" (2010).



mand, which has slowly risen over the last two decades. In the short term, recessionary influences are apparent. Loss of manufacturing base and population for some of the region's legacy cities, however, will likely affect demand over a longer horizon. Higher prices, driven by higher costs, will continue to influence price sensitive (elastic) demand. Price engineering (dynamic pricing enabled by smart grid technologies) will likely be used to shape demand deliberately. Average electricity prices in the region for 2010 are comparable or below the national average, reflecting the cost of infrastructure, resources, and, increasingly, environmental mandates.

Figure 8.5. Average retail price of electricity in the Midwest region. *Source*: Authors' construct from U.S. Energy Information Administration (EIA), "Electricity" (2010).



8.2 Impacts on the Energy Sector

The impacts of climate change and climate change policy on the energy sector can be organized into demand-side and supply-side issues, as represented by the framework in Table 8.1.

The demand side considers effects on how and when energy is used by consumers. The supply side considers effects on the production of energy as well as its transmission and distribution. Demand and supply are dynamic and intersecting, so changes in one will affect the other.

Like other markets, many of the impacts described here, and the evidence that supports those changes, are not unique or confined to the Midwest region. While the effects of climate change are already being felt, they may be more gradual than some of the more immediate effects of climate policy.

Table 8.1 Climate change impacts on the energy sector.

	Climate change	**Climate change policy**
Demand-side issues	• Changes to energy usage patterns (heating and cooling) • Health effects of heat and cold (including death) due to access and affordability • Peaking demand due to extreme weather events • Changing energy needs of other sectors, including water supply	• Demand-management mandates (standards, programs) • Load-management practices (shifting load to off-peak periods) • Energy needs of electric vehicles • Higher utility prices and price elasticity effects on demand
Supply-side issues	• Renewable energy availability (wind, photovoltaic, geothermal, hydroelectric, and bioenergy, etc.) • Water availability and shift to power plant thermal cooling alternatives •Potential supply disruptions (reliability) •Stress on physical infrastructure from variable and extreme weather •Impact of variable demand on utility revenues and risks	• Changes to supply portfolio, including fuel switching from coal to natural gas and investment in alternative supplies, transmission facilities, energy storage, grid modernization, and back-up capacity • Financial incentives, including taxation, rates of return, and carbon tax or trade • Environmental impacts of renewable energy development (land, aesthetics) • Effect of variable resources on reliability Complex energy supply markets • Higher energy and water utility costs

Source: Authors' construct.

8.2.1 CLIMATE CHANGE AND ENERGY DEMAND

The influence of climate change on energy usage is relatively well understood, at least in terms of consumer response to changes in weather (Smith and Tirpak 1989; Cline 1992). Energy is used for heating and cooling to maintain safety, comfort, and lifestyle. Individuals with the means to adapt to more extreme weather are likely to utilize technologies to these ends; individuals without the means may suffer adverse health effects. Warmer weather will induce more cooling (generally from electricity) while cooler weather will induce more heating (generally from natural gas, fuel oil, or propane) (Gotham et al. 2012). Increased cooling needs would increase summer-peaking electricity loads based not only on temperature but also on humidity levels. If climate change increases the duration and frequency of heat waves, as has been suggested (Hayhoe et al. 2010), electrical demands are likely to rise during summer periods. In terms of energy demand, climate change may correlate with both overall trends in total usage and usage variability, as seen in patterns of average and peak demand. Changes in consumer demand are, in fact, well known by utilities, which routinely must adapt operations and management to weather variation and use heating-degree units and cooling-degree units for modeling and forecasting purposes. Climate change is expected to accentuate existing weather-related seasonal demand variability. The most vexing implication is that increased energy demand, particularly peak demand, would result in increased GHG emissions if fossil fuels remain the primary fuel source for supply.

Analysts have applied different methodologies to model consumer response to changes in climate (Rosenberg and Crosson 1991; Sailor and Munoz 1997; Mansur et al. 2008) and considerable regional variation is recognized (Sailor 2001). Several of these studies have focused on California or the United States in general (Baxter and Calandri 1992; Franco and Sanstad 2008; Aroonruengsawat and Auffhammer 2009), although a few speak specifically to the Midwest region. As noted, models of consumer electricity demand in the context of climate change should consider not just temperature but humidity. A combined heat index that considers temperature and humidity is the best indicator for human (residential) demand for electricity (Gotham et al. 2013).

Regional latitude is likely relevant to assessing climate change's effect on energy usage. An early study (Rosenberg and Crosson 1991) focused on Missouri, Iowa, Nebraska, and Kansas and suggested that climate change would lead to a small increase in consumer demand for energy. Another study, however, suggested that Midwestern states may actually experience a drop in energy demand (Hadley et al. (n.d.)). The West North Central zone (including Minnesota, Iowa, and Missouri) and the East North Central zone (including Wisconsin, Illinois, Michigan, Indiana, and Ohio) could experience more cooling demand in the summer but less heating demand in the winter. At the aggregate level, energy usage was predicted to decline up until 2014 but rise thereafter. Rosenthal and Gruenspecht (1995) also anticipated a drop in energy demand, estimating that a 1°C increase in temperature could also translate to substantial energy savings.

Forecasting energy demand has become particularly challenging given a host of exogenous influences, including economic and technological factors that could alter consumer behavior beyond climate change alone. Hekkenberg et al. (2009) asserted that future energy demand may be underestimated by existing models because it is influenced not just by weather but also by socioeconomic trends. Population growth, economic development, and income correlate positively with energy demand. Going forward, prices will also affect demand, both intrinsically and by design. While demand for utility services is *relatively* price inelastic, it is not perfectly so; in other words, some electricity demand is more discretionary and price sensitive. Demand response to prices can be anticipated and modeled. Higher prices are likely to induce interest in energy curtailment and efficiency, but also interest in self-supply options (such as home solar devices).

Many new technologies associated with grid modernization are aimed directly at peak-demand management (that is, load shifting) in order to mitigate these effects. Some “smart grid” technologies essentially add two-way, real-time communications capabilities. With “smart meters,” customers can receive detailed information about home energy usage and costs (Giordano and Fulli 2012). Utilities can also adopt dynamic pricing for load-management purposes, although long-term efficacy must be studied. Perhaps more importantly, smart technologies can enable automation that does not rely on significant alterations either to consumer behavior or lifestyle. Although benefits to utilities are well known, much is yet to be learned about the benefits of smart technologies to utility customers and society relative to costs. Consumer acceptance remains a considerable challenge.

In addition, the effects of climate change on other sectors may change their patterns of demand, which, in turn, will affect the energy sector. For example, the water sector is highly energy intensive, and changes in water demand could have positive or negative effects on the energy sector.

8.2.2 CLIMATE CHANGE AND ENERGY SUPPLY

Because electricity is an “on-demand” service and supply and demand must be balanced on a real-time basis, changes to demand have a direct and immediate bearing on supply. Compared to other drivers, including climate and price uncertainty, population trends are a more significant determinant of electricity demand (Aroonruengsawat and Auffhammer 2009). As noted earlier, to the extent that climate change affects weather, it will affect consumer demand for electricity, which, in turn, will shape energy supply. In effect, climate change policy is already exerting a significant influence on energy supply portfolios and the delivery infrastructure, particularly for electricity. If energy demand grows, so will production capacity needs. In the Midwest region, increased demand associated with climate change could potentially exceed 10 GW, which would require more than $6 billion in infrastructure investments (Gotham et al. 2013).

Extreme weather associated with climate change, such as stronger, more frequent hurricanes, tornadoes, floods, and droughts, would place further burdens on the supply of electricity. Major weather events are directly related to power disruptions and outages, with damage to utility and customer equipment alike, in addition to economic opportunity costs. In recent years, the number of outages affecting the bulk power grid has increased mostly due to weather-related events, arguing for modernization strategies that consider weather resilience.[2] As of 2008, 65% of all disturbances are related to

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[2] Detailed annual “Events Analysis” and “System Disturbance Reports” can be found at the North American Electricity Reliability Corporation (NERC) website (www.nerc.com).

severe weather – up from 20% in the early 1990s (Karl et al. 2009). Loss of power is a life-threatening event, and more people die of extreme heat than any other weather event (DOC, NOAA (n.d.)). Recovery can be costly, labor-intensive, and time-consuming and may raise significant liabilities. As such, the loss of power, or power reliability, has dire economic consequences. The cost of recovery is generally passed along to all utility customers, and the increased cost of planning for, mitigating the effects of, and recovering from catastrophe can exacerbate affordability concerns.

Climate-induced weather variation can stress infrastructure and add to the cost of initial investment as well as system operation and maintenance (Gotham et al. 2013). Low temperatures can increase icing on overhead power lines and nearby trees. High temperatures cause metal to expand, increasing power-line sag; lack of wind worsens the problem as it prevents natural cooling of the distribution infrastructure. Excessive sag (beyond design specifications) can bring lines into contact with vegetation or even cause an arc to form within the line. Additional investment by utilities may be needed in power line monitoring (including robotic sensors), preemptive vegetation management, and even underground relocation of power lines.

Climate change also influences the performance of generation equipment (Al-Ohaly 2003; Gotham et al. 2013). Higher temperatures result in decreased efficiency in combustion turbines that are primarily used to generate electricity in the Midwest regions. Normally, the combustion of fossil fuels produces steam, which, in turn, moves the turbines used to generate electricity. Higher ambient temperatures lower the density of the air flowing within the system. Thus, it takes both more fuel to generate energy and more generating capacity to meet demand. In the Midwest, approximately 95% of the electrical generating infrastructure is susceptible to decreased efficiency due to ambient temperature change. As long as generators rely on steam to produce electricity, these vulnerabilities will persist (Gotham et al. 2013).

The water-energy nexus is also important in terms of energy supply. The water industry depends on energy, and the energy industry depends on water. Home to the Great Lakes, the Midwest enjoys relatively plentiful water resources. The region is also home to numerous power plants at significant scale (see Figure 8.3). Most energy production processes, traditional and alternative, are water intensive. Thermoelectric power generation accounts for about half of total water withdrawals in the U.S., more than any other discrete function (U.S. Geological Survey 2009). In 2007, droughts in the Southeast jeopardized power plant operations due to their reliance on water for both steam and cooling (Manuel 2008). The unpredictable nature of water conditions presents an operational challenge to plant operators (Rice et al. 2009). With limited water for cooling, power plants operate at reduced capacity, which results in severe economic impacts in prolonged droughts. Given variability in water supply, even relatively water-rich regions are not immune from these effects; reuse and storage technologies for cooling purposes may become more important.

Although the Midwest is not highly dependent on hydropower, fluctuations in flows will directly affect supply availability from that source (Rosenberg and Crosson 1991). The use of pumped storage for energy adds to aggregate demand on water resources. For conventional resources, additional water storage or non-water cooling technologies may be needed. Climate change may also affect the availability and intermittency of

Table 8.2 Generation of hydropower in the Midwest.

State	Conventional Hydro MWh	Total MWh	Total Renewables MWh	Hydro as a % of Total	Hydro as a % of Renewable	Powered &Non-powered Dams
Illinois	136,380	193,864,357	3,666,132	0.10%	3.70%	1,504
Indiana	503,470	116,670,280	2,209,306	0.40%	22.80%	1,142
Iowa	971,165	51,860,063	8,559,766	1.90%	11.30%	3,374
Michigan	1,371,926	101,202,605	3,995,111	1.40%	34.30%	927
Minnesota	809,088	52,491,849	7,545,745	1.50%	10.70%	1,021
Missouri	1,816,693	88,354,272	2,391,498	2.10%	76%	5,099
Ohio	527,746	136,090,225	1,161,156	0.40%	45.50%	1,577
Wisconsin	1,393,988	59,959,060	3,734,283	2.30%	37.30%	1,163

Source: National Hydropower Association, http://hydro.org/why-hydro/available/hydro-in-the-states/midwest/.

some forms of renewable energy, particularly wind and photovoltaic sources. A significant consequence is the need for backup capacity to ensure reliability and resilience (Prescott and Van Kotten 2009).

In sum, climate change has the potential to affect power production, as well as distribution, with implications for reliability and cost. However, these effects are relatively well known to the sector, and both mitigative and adaptive strategies are being planned and deployed, in some cases in accordance with policy mandates (Neumann 2009).

8.2.3 CLIMATE CHANGE POLICY

Most climate policy action in the United States has been implemented at the state or local level, in the absence of comprehensive federal policy (Cohen and Miller 2012). The federal government has focused much attention on subsidizing the development of clean energy sources, along with research and education in such areas as energy efficiency and "smart grid" applications. Federal regulators have promoted investment in, and modernization of, the high-voltage transmission grid, in part to accommodate power generation from renewable resources.

Not surprisingly, a considerable amount of state and regional climate change policy targets the energy sector with the goal of reducing emissions, particularly carbon. The considerable activity in the realm of climate change policy is already shaping demand and supply in the energy sector. States in the Midwest have joined states across the nation in adopting both climate action and energy sector policies toward this end as well as in anticipation of regional or national policies (see Table 8.3).

Demand-side policies for the sector are focused on reducing energy load through end-use efficiency (load reduction) as well as shifting load to off-peak periods for more efficient utilization of power plant capacity (thus avoiding or postponing the need for extra capacity to meet peak demand and associated capital and operating costs). Price plays a critical role in cost recovery as well as an incentive-based tool of demand management.

Table 8.3 Climate and energy policy activities in the Midwest.

Climate action	**IL**	**IN**	**IA**	**MI**	**MN**	**MO**	**OH**	**WI**
Greenhouse gas reduction targets.	Yes			Yes	Yes			
Standards limiting CO2 emissions from power plants.	Yes							
Climate change action plan with steps to mitigate emissions.	Yes		Yes	Yes	Yes	Yes		Yes
Legislative advisory commission on climate change policies.	Yes		Yes	Yes	Yes			Yes
Participates in regional initiatives to address climate change.	Yes-1	Yes-2	Yes-1	Yes-1	Yes-1	Yes-3	Yes-1	Yes-1
Uniform standards for reporting GHG emissions.	Yes		Yes-4	Yes	Yes	Yes	Yes	Yes-4
Adaptation plans to preemptively prepare for climate change impacts.			Yes	Yes	Yes-5			Yes

Energy Policies	**IL**	**IN**	**IA**	**MI**	**MN**	**MO**	**OH**	**WI**
Public benefit funds for energy efficiency, renewable energy, or research.	RE			RE	R			RE
Renewable or alternative energy portfolio standards for utilities.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Net metering programs for end users that send surplus power to the grid.	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Green pricing programs providing an option to buy renewable energy.	Yes				Yes			
Decoupling policies to separate utility revenues and profits from sales.	G	G						EG
Renewable energy credit tracking systems for use in verification of state targets.	Yes		Yes		Yes			Yes
Energy efficiency resource standards to encourage reduction in energy use.	EG	E	EG	EG	EG		E	EG)
Financial Incentives for carbon capture and storage (CCS) technologies.	Yes	Yes			Yes			

(1) Midwest GHG Reduction Accord & Platform; (2) MGGRA Observer & Midwest Platform; (3) Midwest Platform; (4) Mandatory reporting also required; (5) In progress; (E) Electricity, (G) Gas, (EG) Electricity and Gas; (RE) Renewable energy and efficiency; (R) Renewable energy.

Source: Center for Climate and Energy Solutions, http://www.c2es.org/what_s_being_done/in_the_states/state_action_maps.cfm.

Real-time prices and demand-response programs take advantage of price elasticity to encourage load shifting by consumers. Demand-side programs are designed to accelerate development and deployment of efficiency practices in areas such as heating, cooling, and lighting across the residential, commercial, and industrial sectors. National standards for appliance and fixture efficiency are important to this effort.

Climate change policy looks to the supply side with the intention of shifting away from reliance on greenhouse gas-emitting fossil fuels and toward clean and renewable energy alternatives. Efficiency on the supply side can be achieved through loss reduction and heat capture strategies, including cogeneration. Leading policies include state-level renewable portfolio standards (RPSs), with various specifications and timetables, which in many respects are an alternative to carbon taxes or markets (also known as cap and trade). These changes will affect resource and labor markets as well as land-management practices. For example, wind and biomass facility siting and development have significant implications for the agricultural sector. The effects of renewable energy development are likely to vary across and within states, depending on resource availability, land and water characteristics, economic profile, and state and local policies.

Much policy attention has also focused on utility incentives and compensation for developing cleaner generation options and promoting energy efficiency. Carbon capture and storage solutions or "clean coal" have received some attention although significant technical challenges remain (Graus et al. 2011). Net metering laws allow consumers to sell excess power produced by renewable technologies back to the power company. Grid modernization and "smart" technologies (including smart meters) are regarded as enabling supply-side resource integration as well as demand management. Any large-scale use of electricity or natural gas for transportation will have a significant impact on energy markets.

8.3 Future Considerations and Issues

A perennial issue in the energy sector concerns the true cost of electricity. Direct and indirect subsidies and environmental externalities distort prices. When true costs are not accurately reflected in price, production and consumption are inefficient. In the past, fossil fuels enjoyed preferential policies whereas renewable resources are favored today. To many economists, putting a price on carbon via a tradable market or tax would promote more efficient choices among competing technologies for lowering greenhouse gas emissions (see Burtraw 2008; Parry and Williams 2010).

Instead, state RPSs have become the centerpiece of climate policy. RPSs require providers to use renewable technologies for a specified portion of the energy they produce by a target date. Many states allow the providers to purchase credits from other utilities in order to meet the mandated threshold. Considerable variability in the standards is found among the states, including differences in what constitutes renewable energy resources. Today, almost half (46%) of the electricity sold in the United States is covered by a state RPS program. More than half of the growth of renewable capacity between 1998 and 2007 occurred in states that have adopted a RPS; most of the growth is in the wind sector. While some states have achieved high rates of compliance, others have had to adjust their implementation time frames due primarily to a lack of transmission infrastructure (Wiser and Barbose 2008). Successful RPS implementation has been attributed to the identification of cost-effective renewable resources and companion policies for transmission expansion and regional collaboration (Hurlbut 2008).

Despite a favorable emissions profile, nuclear power has not found a secure place in portfolio policies. Nuclear power continues to suffer from persistent concerns about cost overruns, fuel procurement, public safety, and waste disposal. As with thermo-electric plants, nuclear power plants require significant amounts of water for cooling and prolonged droughts could impact operations. Potential disruptions of service from severe weather, including storms and flooding, raise the specter of catastrophic failure. The Browns Ferry plant in Alabama escaped major damage during a 2011 tornado, but the Fukushima disaster in Japan has cast doubt on the future of the sector globally. Nonetheless, some advocates and utility companies are again considering nuclear power options, including large-scale and smaller scaled modular or package plants. Two large-scale reactors are under construction in South Carolina.

Without preferential policies and subsidies, development of alternative energy can be cost prohibitive. Many resource alternatives raise significant technical challenges in terms of supply chains, intermittent availability, and the lack of cost-effective means of energy storage. Long-distance transmission needs and costs are especially significant, particularly for wind energy (Yang 2009). Some have argued, however, for development of lower-velocity local resources (Hoppock and Patiño-Echeverri 2010).

The potential for higher costs and lower reliability looms large, with significant economic and social implications, particularly affordability of an essential service (Berger 2009). The accurate comparison of resource alternatives requires a total life-cycle cost analysis. The regressive nature of utility prices argues further for awareness of the distributional consequences on households and attention to rate design (Beecher 2012a).

Utility infrastructure is especially capital intensive and long-lasting. Changing the resource mix and operational profile is a formidable proposition, particularly given sunk costs and underlying concerns about meeting service obligations. Utilities also have a tradition of long-term capacity planning and their planning processes are already incorporating adaptive strategies, in part due to policy mandates. Utility investors and managers are not necessarily averse to responsible climate change policy, but it is widely understood that they prefer a context of more regulatory certainty to less, particularly with regard to cost recovery. Many have argued for policy and regulatory reforms, including special financial incentives for utilities. But the central role of economic regulation is the assurance of prudent compliance with policy mandates and the fair allocation of risks and costs among utilities and their customers.

A fair amount of consensus exists in the policy community about the relevance of climate change to the energy sector. Yet despite a large amount of attention and research, the sector suffers from limited evidence and contradictory speculation with regard to potential impacts and their extent. Logically, larger changes in climate are likely to present larger challenges and consequences.

The Midwest region will experience climate change and climate change policy in ways similar to the rest of the country. Resource profiles and endowments, however, are regionally distinct, with states facing divergent packages of renewable resources from which to generate energy (Wiser and Barbose 2008). The Midwest region might be relatively disadvantaged in terms of wind and solar energy resources, which might argue for expanding development of bioenergy resources and establishing markets for renewable energy credits. The region might be advantaged by its northern latitude and relatively abundant bioenergy and water resources. The challenges remain considerable but, in theory, they should be more manageable than in regions facing more stressful ecological and economic conditions.

Regardless of climate change, climate change policy, along with related energy policy mandates, will likely have an indelible impact on the provision and cost of essential energy services. Energy utilities are already anticipating and adapting, in part to manage regulatory uncertainties. The generational challenge of climate change policy will be to strike a workable balance among the goals of clean, reliable, and affordable energy.

8.4 Summary

Both climate change and climate change policy are salient to the energy sector. Climate change policies adopted by individual states are already affecting planning and investment decisions as utilities respond to emergent policy requirements under the Clean Air Act, and state laws as well as anticipate eventual federal greenhouse gas and other climate and air regulations. The transition away from fossil fuels (particularly coal) to renewable resources, such as wind, photovoltaic, geothermal, hydroelectric, and bioenergy, has significant implications for the tradeoffs among goals of clean, reliable, and affordable energy and the respective institutions and agencies responsible for achieving those goals. Over time, the Midwest region may be comparatively advantaged with respect to climate change impacts by its northern latitude and abundant water resources.

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Chapter 9

Health

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9.1 Introduction

Many human diseases are sensitive to climate fluctuations, including those that occur in the Midwest U.S. More direct pathways through which climate change can adversely affect health include: heat-related morbidity and mortality; flooding and storms with associated trauma and mental health concerns; air pollution, especially from ground-level ozone, particulate matter (PM) and potentially from aeroallergens (e.g., pollen and molds); and infectious diseases, particularly those that are waterborne or vectorborne. Land use changes happening alongside climate change can make human health problems worse. For instance, the "urban heat island effect" could make future heat waves more severe for city-dwellers.

Downscaled global climate model projections for the Midwest region indicate that the most likely types of climate change will be: a) reductions in extreme cold, b) increases in extreme heat, c) increases in extremely heavy precipitation events, d) greater precipitation during winter and even more so during spring, and e) warming in every month/season (Vavrus and Van Dorn 2009).

We can only assess future health risks to the extent that climate/health mechanisms are understood and quantitative health models are available. Some health issues in the region may benefit from climate change, such as a reduction in cold-related deaths. But, on balance, a review of the literature suggests that adverse health ramifications outweigh potential health benefits. Of course, in addition to future climate projections, varying scenarios of future demographic and economic trends adds uncertainty for assessing human population vulnerability.

The goal of this chapter is to identify for the Midwest region health risks stemming from climate change. In addition to studies specifically conducted in the region, this review also includes relevant studies from other regions that share common pathways of risk, towards conducting a more updated literature review. Four health impacts of concern in the Midwest relate to: 1) urban heat waves, 2) air pollution, 3)water quality and waterborne diseases, and 4) vectorborne diseases.

9.2 Current Climate Sensitivities and Projected Risks for the Midwest

9.2.1 HEAT WAVES

While there is no universally accepted definition of a heat wave, a commonly accepted understanding is an unusually hot period of at least two to three days duration and with a discernible health impact. Depending on the study, various parameters have been used to quantify heat waves, such as temperatures above a selected percentile or consecutive minimum nighttime temperatures.

Heat waves are a well known cause of mortality. For example, the July 1995 Upper Midwest heat wave resulted in 700 deaths in Chicago (Semenza et al. 1996). Before the end of the century, 1995-like heat waves could occur every other year on average under lower emissions scenarios, and as frequently as three times per year under higher emissions scenarios. Annual average mortality rates are projected to equal those of 1995 under lower emissions and reach twice 1995 levels under higher emissions (Hayhoe et al. 2010).

Currently for the U.S., mortality increases nearly 4% during heat waves compared with non-heat wave days (Anderson and Bell 2010). Risk of death increases 2.5% for every 1°F increase in heat wave intensity and 0.4% for every 1-day increase in heat wave duration. Mortality increases 5.0% during the first heat wave of the summer versus 2.7% during later heat waves, compared with non-heat wave days. Heat wave mortality impacts are more pronounced in the Northeast and Midwest regions compared with the South (Anderson and Bell 2010).

According to Peng et al. (2011), in the absence of adaptation the city of Chicago could experience by 2081-2100 between 166 and 2,217 excess deaths per year attributable to heat waves, based on estimates from seven global climate models under three different emissions scenarios. The authors noted considerable variability in the projections of annual heat wave mortality; the largest source of variation was the choice of climate model (Peng et al. 2011). Regarding morbidity, analysis of heat wave admissions to hospitals in the city of Milwaukee found an increase in admissions for endocrine, genitourinary, and respiratory disorders, as well as self inflicted injuries such as from suicide attempts (Li et al. 2012).

9.2.2 AIR POLLUTION RISKS

9.2.2.1 Air Quality and Respiratory Disease

Estimates of the impact of global climate change processes on the formation of ozone air pollution have been conducted for Chicago, Illinois. Projected meteorological changes alone are expected to increase ground-level ozone by an average of 6.2 ppb (under low-growth scenarios) to 17.0 ppb (under high growth scenarios) in the summer months by the end of the current century, translating into an associated three-fold (low-growth) to eight-fold (high growth) increase in the number of exceedances of the current 84 ppb National Ambient Air Quality Standards (NAAQS) for ozone (Holloway et al. 2008).

9.2.2.2 Aeroallergens

Higher levels of carbon dioxide promote growth and reproduction by many plants, including those that produce allergens. For example, ragweed plants experimentally exposed to high levels of carbon dioxide can increase their pollen production several-fold, perhaps part of the reason for rising ragweed pollen levels in recent decades (Ziska and Caulfield 2000; Wayne et al. 2002). In a recent nationwide study, the length of the ragweed pollen season was found to have increased by as much as 13–27 days at latitudes above ~44°N since 1995 (Ziska et al. 2011).

9.2.3 WATERBORNE DISEASE

In the U.S., estimates of gastrointestinal illness (GI) attributable to drinking water are in the range of 2-19 million cases per year (Messner et al. 2006; Reynolds et al. 2008). The range comes from the fact that measuring this disease burden is difficult because symptoms are often self-limited and most infected people do not seek medical treatment. Compared to the general population, children are most commonly infected with enteric pathogens and may suffer more severe health consequences.

The Great Lakes provide drinking water to over 40 million people and have more than 500 beaches (Patz et al. 2008; Sauer et al. 2011). The Midwest region, therefore, is particularly sensitive to perturbations of the water cycle, considering the regional combination of heavy agriculture, aging water infrastructure, and recreational exposures at inland beaches. Like the Northeast, the Midwest contains many older cities that have combined sewer systems, which handle both sewage and stormwater together in large underground pipes. When municipal water systems become inundated with rainwater following heavy precipitation, they can overflow into receiving waters – called a "combined sewage overflow (or CSO) event" – presenting a health risk from contaminated surface water. The U.S. Environmental Protection Agency estimates that there are more than 3 trillion liters of untreated combined sewage released annually (U.S. EPA 2004). Certain watersheds, by virtue of their land use patterns and the presence of human and animal fecal contaminants, are at higher risk of surface water contamination after heavy rains, and this has serious implications for drinking water purity. Intense rainfall can also contaminate recreational waters and increase the risk of human illness (Schuster et al. 2005) through higher bacterial counts. Enteric viruses also are found at higher levels in both surface and ground water following heavy rainfall (Borchardt et al. 2003, 2007).

Heavy precipitation events have been implicated in outbreaks from waterborne pathogens in the U.S., which follow a distinct seasonality and spatial clustering pattern in key watersheds (Curriero et al. 2001). In Walkerton, Ontario, in May 2000, heavy precipitation combined with failing infrastructure contaminated drinking water with *E. coli 0157:H7* and *Campylobacter jejuni* resulting in 7 deaths and an estimated 2,300 illnesses (Hrudely et al. 2003). Recent sampling of stormwater across the city of Milwaukee, for example, showed high human fecal pathogen levels at all 45 outflow locations, signifying widespread sewage contamination (Sauer et al. 2011). Another instance of heavy rainfall associated with water-borne disease outbreaks is notably the 1993 *Cryptosporidium* outbreak in Milwaukee WI, exposing an estimated 405,000 people and causing 54 fatalities (Curriero et al. 2001). Also, a recent study from a pediatric hospital in Milwaukee found that admissions to the emergency department for acute gastrointestinal illness increased following rainfall (Drayna et al. 2010).

From 1895-2006, Wisconsin mean annual precipitation increased by 2.2 inches (Midwest Regional Climate Center 2009). The frequency and intensity of heavy precipitation have been increasing, and account for a rising percentage of total precipitation in the Midwest region (Ebi 2008). These events have increased in frequency by as much as 100% (Kunkel 2003). For the Great Lakes region, contamination events typically occur when daily rainfall levels exceed a threshold approximating 2 to 2.5 inches (Hayhoe and Wuebbles 2007; McLellan et al. 2007).

Given that heavy rainfalls are expressions of climate, there is heightened concern as to how this type of event may change in a warmer future climate. Precipitation intensity (total precipitation divided by the number of wet days) is projected to increase almost everywhere, particularly in middle and high latitudes where mean precipitation is also expected to increase (Tebaldi et al. 2006). Most of the Great Lakes region is projected to experience a rise in mean and intense precipitation events (IPCC 2007; Diffenbaugh et al. 2005). Downscaled Global Climate Model (GCM) projections indicate that climate change will lead to increases in heavy precipitation with greater winter and spring precipitation for the state of Wisconsin (Vavrus and Van Dorn 2009). Overall, the models project that these extremely heavy precipitation events will become 10 to 40% stronger in southern Wisconsin, resulting in higher potential for flooding and greater waterborne diseases that often accompany high discharge into Lake Michigan (Patz et al. 2008).

The combination of future thermal and hydrological changes may affect the usability of recreational beaches. Chicago beach closures are dependent on the magnitude of recent (<24-hour) precipitation, lake temperature, and lake stage (Olyphant and Whitman 2004). Projected increases in heavy rainfall, warmer lake waters, and lowered lake levels would all be expected to enhance beach contamination in the future. Although more intense rainfalls would seem to contradict a projection of lower lake levels, some lake level projections suggest a larger anticipated increase in evaporation at the lake surface (which can offset the precipitation gain), and a higher proportion of future precipitation falling as heavy events, even if the total precipitation amount does not rise.

9.2.4 CLIMATE, LAKE ECOLOGY AND HEALTH RISKS

Harmful algal blooms (HABs) also present a climate-related risk, and climate change-related regional influences on the hydrologic cycle will have ramifications for *Cyanobacteria HABs*. For example, more intense precipitation events mobilize nutrients on land and increase nutrient enrichment of receiving waters. Subsequent drought conditions would increase water residence time, promoting bloom potentials. This scenario will most likely occur if elevated winter–spring rainfall and flushing events are followed by protracted periods of drought. This sequence of events has already been responsible for massive *CyanoHABs* in the Great Lakes ecosystem threatening drinking water, fisheries and recreation (Paerl and Paul 2012). Future projections of precipitation in the region, for example the Chicago area, show more increase in the winter and spring seasons (Vavrus and Van Dorn 2009), therefore the risk of *CyanoHABs* may be altered in the future.

9.2.5 VECTORBORNE INFECTIOUS DISEASES

9.2.5.1 West Nile Virus

The summer of 2012 was the hottest on record across many locations in the Midwest. It was also a record year for cases of West Nile Virus. The 5,674 cases reported for 2012 are the highest number of West Nile Virus disease cases reported to CDC since 2003 (CDC 2013). And while analyses are pending, based on interviews with CDC officials, there is a potential causal relationship between the record heat and the record number of West Nile Virus cases (Kuehn 2012).

West Nile Virus emerged for the first time in the North America in July 1999. While international travel is suspected as the cause of this event, the unseasonable heat wave that year (as well as subsequently hot summers in the Midwest and West during peak years of 2002 and 2003) raises the question of weather's possible effect on West Nile Virus disease ecology and transmission. An outbreak of West Nile encephalomyelitis in horses in the Midwest peaked with high temperatures and significantly dropped following decreasing ambient temperatures, suggesting a temperature effect (Ward et al. 2004). Bird migratory pathways and the recent march westward of West Nile Virus across the U.S. and Canada are key factors as well, and must be considered in future assessment of temperature's role in disease dynamics.

9.2.5.2 Lyme Disease

Lyme disease is the most prevalent zoonotic disease in North America for which there is new evidence of an association with temperature (Ogden et al. 2004). Two main foci of disease occur in the Mid-Atlantic region and in western Wisconsin along the Mississippi Valley. Maximum, minimum, and mean temperatures as well as vapor pressure significantly contribute to the abundance of the tick, *Ixodes scapularis,* in the U.S. Also, an average monthly minimum temperature threshold above –7°C is required for tick survival (Brownstein et al. 2003).

9.3 Current Adaptive Capacity (Example for Heat Waves)

Air conditioning is one adaptation to heat waves, and increasing trends in air conditioning market saturation may substantially offset direct risks of more frequent heat waves (Sailor and Pavlova 2003). However, use of air conditioning will increase the demand for electrical power and subsequent production of pollution and greenhouse gases. Consequently, air conditioning is potentially an unsustainable adaptation, unless demand for electricity can by generated by renewable sources (e.g., wind and solar).

Heat response plans and heat early warning systems (EWS) can save lives. For example, in the wake of the 1995 heat wave, the city of Milwaukee initiated an "extreme heat conditions plan" that almost halved heat-related morbidity and mortality (Weisskopf et al. 2002). Currently, over two-dozen cities worldwide have a “synoptic-based” weather watch-warning system, which focuses monitoring on dangerous air masses (Sheridan and Kalkstein 2004). However, from a U.S.-based survey administered to 285 communities in 2009, only 30 local governments of the 70 that responded to the survey have established heat wave health prevention programs (O’Neill et al. 2010).

9.4 Health Co-benefits of GHG Mitigation

9.4.1 ENERGY

A recent study by Shindell et al. (2012) addressed the tropospheric ozone and black carbon contribution to both degraded air quality and global warming. The authors identified 14 best interventions targeting methane and black carbon emissions that reduce projected global mean warming ~0.5°C by 2050. The resulting “co-benefit” was the avoidance of 0.7 to 4.7 million annual premature deaths from outdoor air pollution and increases in annual crop yields by 30 to 135 million metric tons due to ozone reductions in 2030 and beyond. The valuation was dominated by health effects from reduced black carbon in the air. While this study was global in nature, the findings apply to any location with coal-fired power plants, the most substantial contributor to black carbon particulates.

9.4.2 CASE STUDY: CO-BENEFITS OF ALTERNATIVE TRANSPORTATION FUTURES FROM IMPROVING AIR QUALITY AND PHYSICAL FITNESS

The transportation sector produces one-third of U.S. greenhouse gas emissions. Automobile exhaust contributes not only to greenhouses gases but also contains precursors to fine particulate matter ($PM_{2.5}$) and ozone (O_3), posing public health risks. Adopting a greener transportation system with fewer automobiles, therefore, could have immediate health “co-benefits” via improved air quality. Grabow et al. (2012) modeled census tract-level mobile emissions for two comparative scenarios: current baseline versus a green scenario where automobile trips shorter than five miles round-trip would be removed for the 11 largest metropolitan areas in the Midwest. These relatively short car trips comprised approximately 20% of vehicle miles traveled for the region. Across the upper Midwest, an area of approximately 31.3 million people and 37,000 total square miles, mortality would decline on average by nearly 575 deaths per year from the benefit of improved air quality. Health benefits would also accrue in rural settings as well, with 25% of the air quality-related health benefits to populations outside metropolitan areas.

An active transport scenario was then added, with the assumption that 50% of the short trips (<5 miles) could be achieved by bicycle during the four months of most favorable weather conditions in the region. This theoretical maximum level of biking was selected because some locations in Europe have achieved this amount of bicycle commuting, and there already exists an observed trend of increasing bicycle share across all of the 11 Midwestern metropolitan areas (U.S. Census 2008). This active transport scenario alone yielded savings of another 700 lives/year and approximately $3.8 billion/year from avoided mortality costs (95% Confidence Interval: $2.7, $5.0 billion).

In summary, the estimated benefits of improved air quality and physical fitness from a green transportation scenario would be 1300 lives saved and $8 billion costs avoided per year for the upper Midwest region alone. Nationally, there is already evidence that U.S. cities with enhanced levels of active transport experience large health benefits. One study found that cities with the highest rates of commuting by bike or on foot have obesity and diabetes rates 20 and 23% lower, respectively, than cities with the lowest rates of active commuting (Pucher et al. 2010).

9.5 Conclusion

The Midwest region is one that remains vulnerable to health risks from climate change and associated extremes in climate variability. While some capacity to adapt is evident for the region, aging infrastructure poses concomitant risk, especially in the case of municipal water systems. Health benefits accruing from greenhouse gas mitigation can be large, as shown by a green transportation scenario. Therefore, such health benefits (e.g. 1300 lives/year saved in our region) must be included in any assessments and policy discussions related to energy production or transportation planning.

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Chapter 10

Outdoor Recreation and Tourism

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10.1 Introduction

The terms recreation and tourism are notoriously difficult to define and differentiate, and the semantics of these seemingly simple words have been discussed at length in a variety of text books and industry publications. For the purposes of this chapter, tourism will be taken to refer to travel some distance (typically more than 50 miles) away from home for some length of time (between 24 hours and one year) for the purpose of business or leisure, whereas outdoor recreation will be assumed to have no spatial or temporal boundaries or restrictions. Thus, outdoor recreation may take place anywhere, from an individual's back yard to a local park to a distant location, i.e., while engaging in tourism.

10.2 The Importance of Travel and Tourism to the U.S. Economy

The contribution of the travel and tourism industry to the U.S. economy is significant. Travel and tourism are the nation's largest services export industry, and account for 2.8% of the nation's gross domestic product. In 2012, travel and tourism activity generated $2 trillion in economic output, with the $855.4 billion spent directly by domestic and international travelers in the nation stimulating an additional $1.1 trillion in indirect and induced economic activity. In addition, the travel and tourism industry supports approximately 14.6 million jobs. The 7.7 million jobs directly related to travel and tourism generated $200.9 billion in payroll in 2012, while another 6.9 million individuals worked in positions indirectly related to travel and tourism, such as construction, finance, etc. These 14.6 million jobs represent one in every eight forms of employment across the nation. In terms of tax revenue, travel and tourism directly generated $128.8 billion for local, state and federal governments in 2012 (U.S. Travel Association 2013). Figure 10.1

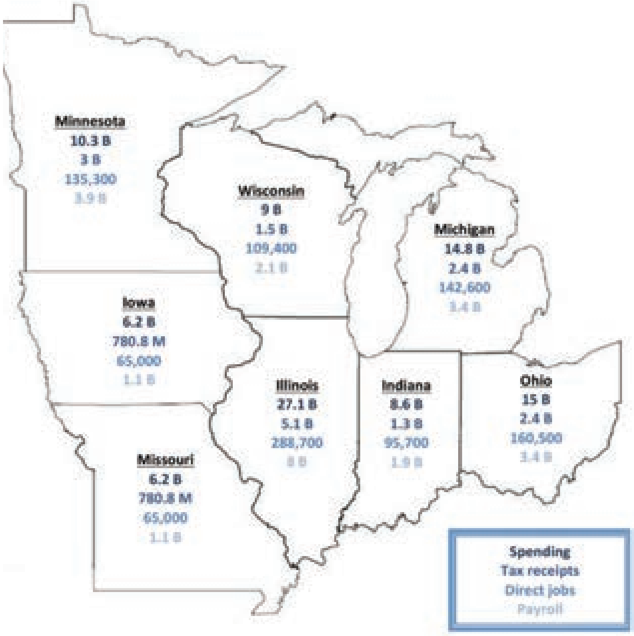

Figure 10.1. Contribution of travel and tourism to the economy of the Midwest. *Source*: U.S. Travel Association (2012).

illustrates the contribution of travel and tourism to the economies of the Midwest states in terms of visitor spending, tax receipts, direct jobs created, and payroll generated.

10.3 Outdoor Recreation and Tourism (ORT) and Climate Variability and Change (CVC)

According to Hall and Higham,"[I]n terms of the future of tourism, as well as the societies within which we live, there are probably few policy and development concerns as significant as global climate change" (2005, p. 21). These authors go on to note that, "Understanding and responding to climate change represents one of the more important, complex and challenging issues facing the contemporary tourism and recreation industries" (Higham and Hall 2005, p. 307). The complexity to which Hall and Higham alludes results from a combination of factors related not only to the difficulties associated with projecting climate change and its potential impacts on the natural environment, but also to the added complication of incorporating the human reaction to such change.

10.3.1 DIRECT AND INDIRECT IMPLICATIONS OF CVC FOR ORT

Climate variability and change have both direct and indirect implications for ORT activity. The direct implications relate to changes in key climatic variables that may directly impact the visitor experience. For example, changes in temperature, precipitation, wind speed, humidity, or snow depth may have a direct effect on (i) the feasibility of ORT activities, (ii) levels of safety associated with participation in ORT activities, and/or (iii) the quality of the experiences of those who do participate in ORT activities. Modifications to climatic conditions, resulting changes in activity feasibility and safety, and alterations in the level of enjoyment associated with activity participation may cause participants to alter the frequency, duration, timing, and/or location of future activity, or even to shift participation to an entirely different activity altogether.

Climate variability and change may also alter the distributions and compositions of natural resources such as the flora and fauna found at an ORT destination. Since much ORT activity focuses on viewing, photographing, hunting and/or fishing of such species, the implications of shifting habitat zones are profound. Such shifts in the quality and quantity of wildlife and vegetation may cause indirect, or secondary, impacts on ORT activity, as participants alter their activities to account for changes in the natural environment as a result of climate variability and change.

10.3.2 IMPLICATIONS OF CVC FOR ORT – SUPPLY AND DEMAND SIDE FACTORS

As suggested above, CVC will likely have implications for both the natural environment and the visitor experience of that environment. These implications can therefore be separated into consideration of implications for supply (how CVC might impact the natural environment and the associated supply of ORT resources) and demand (how CVC might impact participant demand for activities and destinations). As suggested previously, while projection of climate change and its potential impacts on the natural environment is complex, addition of humans – outdoor recreationalists and tourists – to the equation adds an additional layer of complexity. This additional complexity results from two important human dimensions: (i) the myriad of influences – besides weather and climate – on ORT decisions, including the availability of free time and disposable income; family commitments; economic situations in origins and destinations; prices; exchange rates; political, military and safety considerations in destination regions; media coverage; and shifting fashions; and (ii) the myriad of response options available to ORT participants, including in which activities (i.e., in what) to participate; to which destinations (i.e., where) to travel; and when, for how long, how often, etc. Given the huge number of recreation activities and tourism destinations from which modern consumers choose, the opportunity for substitution, in one or more dimensions, is tremendous, and, as a result, extraordinarily difficult to model effectively.

While the specific adaptive behavior of the ORT participant may be difficult to envisage, it is clear that in general the adaptive capacity of such participants is quite high. As noted above, outdoor recreationalists and tourists control the activities in which they choose to participate and the destinations to which they choose to travel, as well as various aspects of the timing of these choices. Innovations in outdoor clothing and recreational equipment have expanded the range of conditions under which outdoor activities are possible and enjoyable. The modern, technology-based era has also facilitated the phenomenon of last-minute booking, which further increases traveler's flexibility and responsive to unanticipated change. As discussed in the European context by Nicholls and Amelung (2008), however, the tourism industry itself, i.e., ORT providers, face lower, or at least slower, levels of adaptive capacity, much of which may be attributed to a combination of spatial fixity and sunk costs. Accommodations, food and beverage outlets, and built attractions and facilities such as theme parks and marinas are all fixed entities with considerable capital investments that are not easily liquidated or shifted.

Similarly, natural attractions such as national and state parks are static entities with defined boundaries. Faced with minimal opportunity to physically relocate in response to changes in the climate, tourism providers may be forced to consider a variety of alternative adaptation techniques in order to sustain their businesses.

10.4 Implications of CVC for ORT in the Midwest

The projections with regards to climate variability and change for the Midwest area as laid out in other chapters of this report suggest a wide variety of implications for participation in outdoor recreation and tourism activities, as well as for the sustainability of the industry that supports these activities. Table 10.1 outlines climate projections for the Midwest region and the potential implications of these changes for ORT. As illustrated, these implications reflect potential changes in both the supply of, and the demand for, ORT settings and associated activities.

Consideration of increasing temperatures raises the interesting question of the existence of thresholds for ORT activity. From a supply perspective, some thresholds are fixed, e.g., current snowmaking technologies within the US generally require conditions below 28°F wetbulb for operation. In the case of consumers, however, scientific knowledge is more limited. For example, though it has been established that the typical tourist prefers an average daily temperature of 70°F at their holiday destination (Lise and Tol 2002), these authors rightly cautioned that this average camouflages variations in preferences by country or region of origin (i.e., nationality), as well as by travelers' ages, incomes, and preferred activities. Thus, it is likely that the acceptable maximum temperature or heat index level above which ORT activity becomes unbearable will also vary with activity and location. Establishment of such thresholds, and identification and understanding of the implications of behavioral responses to them, represents a pressing need within CVC/ORT research. The existence of such thresholds has implications for providers too, for example, the need to consider indoor alternatives for visitors on extremely hot days and increasing demand for air conditioning capabilities.

In the bullet points that follow, a sampling of the indirect implications of CVC for ORT, via modifications to the natural environment which serves as the backdrop for ORT activity, is provided. It should be noted that the current volume of scientific work specifically addressing the implications of CVC for ORT in the Midwest region is extremely limited, and thus this summary represents the range and depth of knowledge currently known:

- *Reductions in Great Lakes levels* (projected towards end of century under higher emissions scenarios by some authors, e.g., Hayhoe et al. 2010) – lower lake levels could have a multitude of implications for ORT. These include: reduced access to the water, e.g., due to the increased inaccessibility of existing public and private boat ramps, docks and marina facilities; the increased need for and cost of dredging and channel maintenance; an increase in the presence of hazardous conditions such as newly exposed navigational hazards and sand bars; increased competition between ORT and other lake users, e.g., navigation, power generation, residential, industrial and agricultural use; a decline in the aesthetic

Table 10.1 Projected climate changes and potential implications for ORT in the Midwest.

Projected Change	**Potential Implications**
Warmer winters with less natural snow and ice	Some activities are directly dependent on sufficiently cold temperatures to generate natural snow or ice, e.g., cross country skiing, ice fishing, snowmobiling. Without natural snow or ice, these activities may become impossible. Other activities, i.e., downhill skiing, rely on a combination of natural and manufactured snow. The ability to make snow will depend on the continuance of sufficiently cool temperatures for this activity. The threat of CVC to the Midwest's winter sports and tourism sectors is high.
Warmer springs and falls	Warmer springs and falls would likely increase the climatic attractiveness of the Midwest as an ORT venue for activities such as camping, boating and kayaking in these seasons. Certain activities are already available on a year-round basis and the settings for those activities are prepared for visitation in any season, e.g., national and state parks, whereas commercial enterprises may require restructuring to enable them to offer year-round service to ORT participants. For example, lengthening of the spring/fall seasons will have implications for staffing (especially summer activities which currently rely on student labor that will be unavailable outside of school holiday months).
Warmer summers and an increase in the frequency of heat waves	Warmer summers may sound attractive to the typical ORT participant. However, thresholds beyond which ORT activity becomes unattractive due to excess heat remain to be identified and their implications assessed. Warmer summers may place additional constraints on providers in both urban and rural settings, e.g., urban properties may be required to considerably increase their energy usage due to increased air conditioning demands, while smaller rural properties that currently do not offer air conditioning may be forced to install such technology so as to remain competitive in the marketplace. Excessive heat would likely reduce demand for camping facilities.
More frequent and/or more severe extreme weather events	Extreme weather events such as heat waves and storms have direct and indirect implications for ORT activity. Direct implications include the safety of ORT participants due to high winds, flooding, lightning, etc., and the disruption of participation in activities (e.g., having to exit the golf course during a thunder storm) and of actual or planned travel (e.g., the delay or cancellation of flights, the closure of bridges, etc.). Severe storms and flash flooding might threaten resources such as visitor centers, archaeological sites, and trails. Severe weather events might also have implications for the quality and/or aesthetics of the natural environment, thereby indirectly impacting the ORT experience.

Sources: Hayhoe et al. (2010); Wuebbles et al. (2010); Kunkel et al. (2013).

appeal of lake-side locations; and reductions in lake-side property values and a resulting decline in the local tax base.

- *Warming waters and declining water levels in lakes and streams* – such alterations have implications for the habitat of cold-water fish species such as brook trout and walleye, and for warmer-water species such as bass, with the extent of habitat in the Midwest projected to decrease for the former and increase for the latter. These shifts have concomitant implications for the distribution of these species and the ability to fish them, whether for commercial or recreation purposes.
- *Alterations to shoreline wetlands* – such alterations have implications for the habitat of breeding and migrating waterfowl, with concomitant implications for the distribution of these species and the ability to view, photograph and/or hunt them.
- *The effect of warming air and water temperatures on the presence of algae and invasive species* – warmer conditions may exacerbate existing and generate new problems with algal blooms and with invasive species such as phragmites and zebra mussels. Such species can stress native species and reduce the aesthetic quality of ORT settings, thereby decreasing their attractiveness and negatively impacting the visitor experience.
- *The effect of warming temperatures on the distribution of plants and trees* – fall leaf viewing represents an important component of the tourism economy in many parts of the Midwest, where a good fall season can do much to ameliorate a poorer-than-expected summer season. The redistribution of suitable habitat for critical species such as maple and aspen could impact the viability of fall leaf tours by both auto-based individuals and coach-based groups.
- *The effect of warming temperatures in urban areas* – besides the discomfort associated with excess heat and the potential need for increased air-conditioning capabilities, warming in urban areas such as Chicago and Detroit could increase levels of ground-level ozone and hence exacerbate respiratory problems such as asthma among the traveling public. Such conditions have implications not only for leisure visitation but also for business travel, since major urban areas typically rely heavily on corporate activities such as meetings, exhibitions and conventions for a large proportion of their travel business and the comfort of their participants is of paramount importance to event organizers. In both cases, increased demand for indoor recreation opportunities is a real possibility, e.g., movie theatres, casinos, indoor water parks, ballgames in enclosed stadiums, etc.
- *The increased risk of fire due to warmer and/or drier conditions* – fire presents both immediate and secondary implications for ORT activity, from both a safety perspective and the impacts of fire damage on the aesthetic appeal of a location.
- *The increased presence of insects and pests due to warmer and/or wetter conditions* – insects and pests present several implications for ORT activity, including from a health and safety perspective (i.e., the potential for the increased spread of disease) and the perspective of human comfort/the visitor experience, e.g.,

camping and other outdoor activities are less desirable in the presence of large volumes of mosquitoes or black flies.

10.4.1 APPLICATION OF THE TOURISM CLIMATIC INDEX (TCI)

The Tourism Climatic Index was first developed by Mieczkowski (1985). The TCI allows quantitative evaluation of a location's climate for the purpose of general outdoor tourism activity, such as sightseeing, visiting a state or national park, etc. The TCI is based on the notion of "human comfort" and consists of five sub-indices, each represented by one or two climate variables. The five sub-indices and their constituent variables are as follows: (i) daytime comfort index (maximum daily temperature and minimum daily relative humidity), (ii) daily comfort index (mean daily temperature and mean daily relative humidity), (iii) precipitation, (iv) sunshine, and (v) wind speed. The index is weighted and computed as follows: TCI = 2*(4CID + CIA + 2R + 2S + W), where CID = daytime comfort index, CIA = daily comfort index, R = precipitation, S = sunshine, and W = wind speed. With an optimal rating for each variable of 5.0, the maximum value of the index is 100. Based on a location's index value, its suitability for general outdoor tourism activity is then rated on a scale from –30 to 100. Mieczkowski then rated the resulting range of comfort levels as shown in Table 10.2.

The TCI has been combined with projected scenarios of future climate conditions in order to assess potential changes in the climatic attractiveness of locations for general ORT activity in North America (Scott et al. 2004; Nicholls et al. 2005), Europe (Amelung and Viner 2006; Nicholls and Amelung 2008) and at the global level (Amelung et al. 2007). The TCI allows consideration of the direct implications of CVC for ORT supply conditions, though it should be noted that the TCI is not applicable to the winter sports/tourism sectors.

Figure 10.2 illustrates shifting distributions of climatic attractiveness for the Midwest region and for the wider U.S. for the coming century. The months of January and July are represented, based on the A2A scenario with the HadCM3 GCM, thus the shifts illustrated are towards the more extreme end of the projected change spectrum (a "high emissions climate future"). As might have been anticipated, winter conditions are currently and will in the next century likely remain unsuitable for general ORT activity in the Midwest. Of greater interest and potential concern are the projected changes in

Table 10.2 Tourism climatic index (TCI) rating system.

90 – 100	Ideal	40 – 49	Marginal
80 – 89	Excellent	30 – 39	Unfavorable
70 – 79	Very good	20 – 29	Very unfavorable
60 – 69	Good	10 – 19	Extremely unfavorable
50 – 59	Acceptable	Below 9	Impossible

Sources: Adopted from Mieczkowski (1985, p. 228-29).

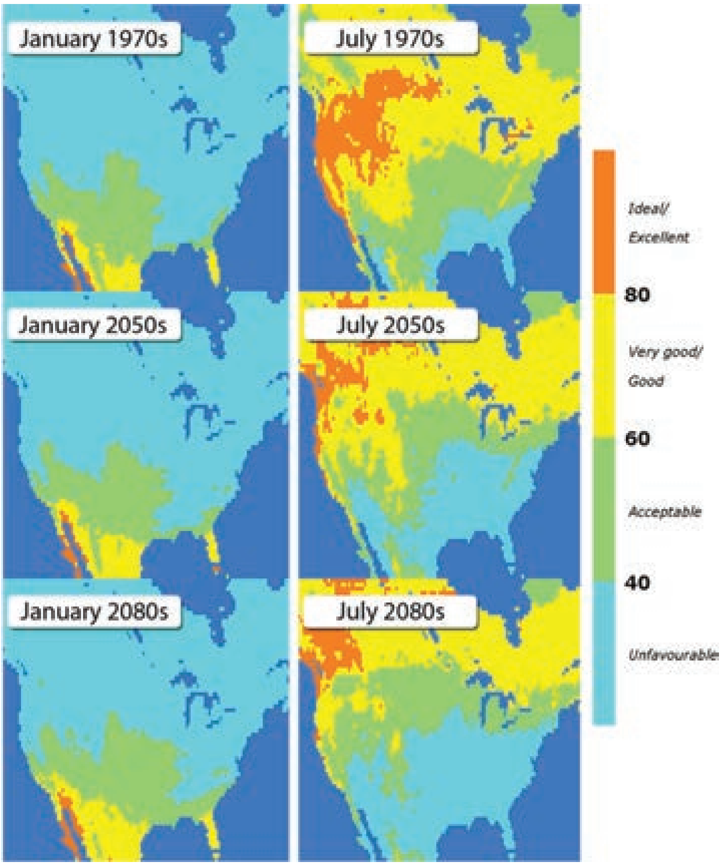

Figure 10.2. Tourism climatic index over the United States for January and July in the 1970s, 2050s, and 2080s. *Source*: Nicholls et al. (2005).

conditions in the summer period. While current conditions range from acceptable in the southern portions of the Midwest region, through good to very good for most of the region, to ideal to excellent within certain pockets, by the 2080s the distribution of these conditions is projected to shift northwards with the Midwest experiencing unfavorable conditions across most of its southern portion and acceptable conditions in the north. These projected changes in climatic attractiveness reflect the increasing heat and humidity projected for the area by the HadCM3 GCM, and the resulting decline in the desirability of being outdoors and engaging in ORT activity.

10.4.2 IMPLICATIONS FOR WINTER SPORTS

The Midwest region as defined in this report accounts for nearly one-quarter of ski areas throughout the United States (Table 10.3), and the winter sports sector is extremely vulnerable to the impacts of climate variability and change. Nevertheless, consideration of the implications of CVC for this sector and region in the literature is minimal. Most of the work on winter sports has been conducted in either a European or a Canadian context, and the majority of that work focuses on supply (i.e., the provision of adequate levels of snow) rather than demand (i.e., the behaviors of winter sports consumers) issues.

Table 10.3 Ski areas in the Midwest states.

State	Number of Ski Areas	Percent of US Ski Areas
Illinois	6	1.3%
Indiana	2	0.4%
Iowa	4	0.8%
Michigan	42	8.8%
Minnesota	18	3.8%
Missouri	2	0.4%
Ohio	6	1.3%
Wisconsin	32	6.7%
Total	112	23.4%

Source: National Ski Areas Association (2013)

That being said, one of the earliest pieces of work on the implications of CVC for winter sports was in fact conducted in Michigan (Lipski and McBoyle 1991). Using two scenarios of projected increases in temperature and precipitation (by 2030) of 6°F and 9%, and 9.7°F and 11%, respectively, they projected changes in the number of reliable winter days, i.e., days with sufficient snow cover for downhill skiing, at three ski areas throughout the state. For those three areas studied, with then current (i.e., 1990) numbers of reliable ski days in the order of 100, 79, and 59, respectively, Lipski and McBoyle projected declines to 62, 41 and 10 reliable days under their first, less extreme scenario, and the complete elimination of the industry, i.e., zero reliable days at any one of their study sites, under the second and more extreme scenario. This study did not incorporate the impacts of snowmaking capabilities on the occurrence of reliable days, whereas more recent analyses in other regions have been able to factor in this consideration, thereby providing more realistic indications of the impact on skiable days (e.g., Scott et al. 2003; Dawson et al. 2009). The potential utility of weather derivatives – with pay-offs derived from the development of an index of meteorological variables such as temperature or snowfall – has been briefly explored in an Austrian context, but not in the Midwest or wider US (Bank and Wiesner 2009).

Winter sports enthusiasts are faced with a number of options in terms of adjusting their travel and outdoor recreation behaviors in light of climate change. Though no analysis of potential reactions has been conducted in the US, a handful of studies have considered the alternatives open to European and Australian skiers, including skiing less often, continuing skiing but in another location, and giving up skiing altogether (König 1998; Bürki 2000; Unbehaun et al. 2008; Luthe 2009). All three options have implications for both the ski and the wider tourism sectors, including possible reductions in travel to, and stays at, resorts as well as reductions in the purchase of ski-related clothing and equipment.

Understanding of skiers' reactions to current as well as projected future conditions are complicated by the widely–held belief within the industry that ski activity is impacted as much as, if not more than, by weather conditions at the skier's place of origin and by the weather forecast for the coming weekend than it is by actual conditions on the slopes. Though this hypothesis has yet to be empirically supported, it does suggest the additional challenges that ski areas may face in recruiting customers under warmer conditions with less natural snow, even if snowmaking technologies are sufficient to keep the slopes themselves open for business.

10.5 Adaptation

It is critical to note that the climate changes projected suggest that there will very likely be both winners and losers from the perspective of the ORT industry. Risks and opportunities arise both directly, as a result of changing climatic conditions within a destination region, as well as indirectly via any one enterprise's ability to adapt to those changing conditions in situ. For example, while winter sports may be devastated by rising winter temperatures (which would not only reduce natural snowfall but also limit the ability to manufacture snow), spring, summer and autumn activities might see rising popularity as the shoulder and traditional high (summer) seasons extend in length. This presents considerable risk to the winter sports sector – particularly those activities for which snowmaking is irrelevant (e.g., ice fishing), has never been feasible (e.g., cross-country skiing) or in the case of downhill ski operations which have chosen not to or are simply financially unable to invest in snowmaking equipment. However, considerable opportunities might also present themselves in terms of providing for other activities in the lengthening spring-summer-fall. Ski areas, for example, are often the perfect venues for spring-summer-fall activities such as hiking, mountain biking, and alpine slides. These opportunities include the potential for new businesses which focus on the kinds of activities typical of this season, as well as the potential for existing businesses to diversify their offerings, whether in terms of the activities offered and/or the timing of those offerings. In both cases – new businesses and diversified existing businesses – considerable capital will likely be required, in addition to the knowledge and skills necessary to provide new and different activities safely and effectively. These needs are problematic given the characteristics typical of the small, family owned and operated enterprises that make up the majority of ORT providers throughout the Midwest region, including limited resources (capital, training, etc.) and a traditional lack of long-term planning, both of which limit adaptive capacity. In addition, experience has shown somewhat of a lack of concern for CVC as a pressing issue among many ORT providers, with rationales for this lack of concern including that CVC is too distant of an issue to be concerned with, especially in light of the current economic climate; that the jargon associated with CVC is too confusing for providers to fully understand; and that the uncertainty associated with CVC is too excessive to warrant genuine concern (Nicholls and Holecek 2008).

The topic of adaptation has received less attention in the literature to date than impacts and implications. Nevertheless, it is clear that adaptation is a context-specific concept, meaning that to be successful adaptation measures will need to be developed in light of the activity and geographic locale under consideration. For example, Figure 10.3

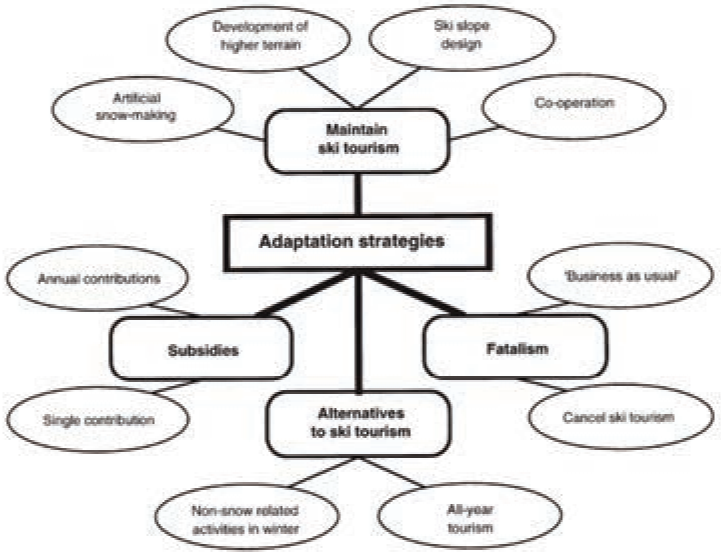

Figure 10.3. Potential adaptations to climate change in the European ski sector. *Source*: Bürki et al. (2007).

represents a suite of suggested adaptation strategies for the downhill ski sector in the European Alps (Bürki et al. 2007).

Under the 'maintain ski tourism' option, it is immediately clear that for the Midwest, the development of slopes on higher terrain is an unlikely option, since most slopes in this part of the world are already developed on the highest terrain available. The provision of subsidies to the ski industry also seems an unlikely proposition in a U.S. context. The 'alternatives to ski tourism' identified seem to offer more promise; though, as noted above, diversification into a year-round entity and the provision of alternative activities (e.g., the construction of a conference center so as to appeal to year-round business travelers, the construction of a spa to appeal both year-round and on rainy or snow-free days, or the development of a golf course or a water park for summer usage) are all capital-intensive investments. Interestingly, anecdotal as well as preliminary research suggests that in the case of winter operators, the more prominent rationale for diversification is not as a means of adapting to observed or anticipated CVC, but as a financial measure (McManus and Bicknell 2006).

Temporal diversification and the potential lengthening and strengthening of the current shoulder (spring and fall) seasons raises the issue of the extent to which the availability of free time influences ORT behavior. Studies of leisure activity in Michigan have consistently identified the availability of free time, as measured by the timing of weekends and holidays, as the single most important indicators of general leisure travel, as well as participation in specific activities such as skiing and golf (Nicholls et al. 2008; Shih et al. 2009; Shih and Nicholls 2011). The existence of more attractive conditions for ORT activity is insufficient to generate additional activity in and of themselves – potential participants must also have the time to do so. Improving conditions in the shoulder seasons may therefore generate an increase in the number of short, close-to-home day or weekend trips with a focus on outdoor activities such as hiking, biking, canoeing, etc.

Table 10.4 National Park Service sites in the Midwest.

State	National Park Service Site
Illinois	Lewis & Clark National Historical Trail* Lincoln Home National Historic Site Mormon Pioneer National Historic Trail Trail of Tears National Historic Trail
Indiana	George Rogers Clark National Historical Park Indiana Dunes National Lakeshore* Lincoln Boyhood National Memorial
Iowa	Effigy Mounds National Monument Herbert Hoover National Historic Site Lewis & Clark National Historic Trail* Mormon Pioneer National Historic Trail Silos & Smokestacks National Heritage Area
Michigan	Isle Royale National Park Keweenaw National Historical Park Motor Cities National Heritage Area North Country National Scenic Trail Pictured Rocks National Lakeshore* Sleeping Bear Dunes National Lakeshore*
Minnesota	Grand Portage National Monument Mississippi National River and Recreation Area* North Country National Scenic Trail Pipestone National Monument Saint Croix National Scenic River Voyageurs National Park*
Missouri	California National Historic Trail George Washington Carver National Monument Henry S. Truman National Historic Site Jefferson National Expansion Memorial Lewis & Clark National Historic Trail* Oregon National Historic Trail Ozark National Scenic Riverways Pony Express National Historic Trail Santa Fe National Historic Trail Trail of Tears National Historic Trail Ulysses S. Grant National Historic Site Wilson's Creek National Battlefield
Ohio	Cuyahoga Valley National Park David Berger National Memorial Dayton Aviation Heritage National Historical Park First Ladies National Historic Site Hopewell Culture National Historical Park James A. Garfield National Historical Site National Aviation Heritage Site North Country National Scenic Trail Perry's Victory and International Peace Memorial William Howard Taft National Historic Site

* Indicates official "Climate Friendly Park"

The timing of longer windows of leisure time, most typically determined by the distributions of school summer holidays, represents an additional temporal constraint. Increased climatic attractiveness and the availability of wider selections of activities in which to engage during spring and fall would only benefit those able to take time to engage in ORT in what are currently the shoulder seasons. The trend towards year-round school in some areas, with an increased number of shorter breaks distributed throughout the year (versus the current trend of one long summer break and a limited number of short breaks over holidays), could benefit ORT providers in a warming world.

The National Park Service (NPS) recognizes the threats associated with climate change via its *Climate Friendly Parks* program (http://www.nps.gov/climatefriendlyparks). Table 10.4 lists the sites managed by the NPS throughout the Midwest region; sites that have been designated as "Climate Friendly" are highlighted with an asterisk. "Climate Friendly" NPS sites engage in a range of mitigation measures designed to reduce their contribution to greenhouse gas emissions.

10.6 Summary

- Climate variability and change have both direct and indirect implications for outdoor recreation and tourism. Direct implications stem from changes in key climatic variables that may directly impact the feasibility of outdoor recreation and tourism activities, or levels of satisfaction with them. Indirect implications result from projected changes in the natural environment, as a result of climate variability and change, which will cause secondary impacts on visitor behavior and experience.
- Climate variability and change have implications for both the supply of outdoor recreation and tourism resources and settings, and the demand for outdoor recreation and tourism activities and experiences.
- Anticipating the reaction of outdoor recreation and tourism participants to climate variability and change is complicated. Weather and climate are but one of a series of factors that influence outdoor recreation and tourism decisions. Moreover, changing climatic and environmental conditions, resulting changes in the feasibility and safety of activities, and alterations in the level of enjoyment associated with activity participation, may cause participants to alter one or more of the frequency, duration, timing, and/or location of future activity, or to shift participation to an entirely different activity altogether.

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Chapter 11

Climate Change Impacts on Transportation in the Midwest

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11.1 Introduction

This paper assesses current literature on potential impacts of climate change on transportation systems in the Midwest. Four sections follow: First, a brief synopsis of recent research on general transportation impacts is offered. Second, current climate projections for different parts of the Midwest are examined in order to assess relative levels of risk for transportation impacts associated with climate change. Third, an assessment of ongoing transportation adaptation measures is presented. Finally, gaps in knowledge and research needs are discussed.

11.2 Transportation and Climate Change

Changes in temperature and precipitation associated with climate change can have different effects on different modes of transportation. Summaries of these effects may be found in Jaroszweski et al. (2010), Koetse and Rietveld (2009), Meyer and Weigel (2011), Meyer et al. (2010), PAICC (2010), Hodges (2011), and Schwartz (2011). This section briefly summarizes current thought on ways in which climate change may affect the following modes of transportation: air, water, rail, and surface transportation (i.e., roads and highways).

11.2.1 AIR

Temperature change: Warmer air temperatures can affect takeoff performance and cargo capacity by reducing the amount of lift generated by the wing of an airplane, increasing the time required to achieve a given altitude. However, there is little knowledge about the extent to which temperatures are, or may be, the limiting factor in cargo capacity or takeoff performance at airports in the Midwest. It is important to note that climate change may produce some benefits, as well as negative consequences. In the case of air travel, it may be that warmer temperatures during winter months would benefit airports that have to deal with snow and ice removal.

Precipitation change: Changes in precipitation can affect air traffic in several ways. Heavy precipitation can overwhelm airport drainage systems and inundate runways, particularly for airports built in floodplains or other low-lying areas. An increase in the frequency of heavy precipitation events could therefore lead to more airport closures. In addition, heavy precipitation can degrade aviation system operations, resulting in delayed takeoffs and landings.

Fire: Wildfire can disrupt air traffic by reducing visibility and by degrading engine performance. Places experiencing an increase in hotter and dryer conditions may be more susceptible to wildfire.

Extreme weather: Tornadoes, severe thunderstorms and heavy winds can halt airport operations, and in some cases cause physical damage to airport facilities.

11.2.2 WATER

River traffic can be disrupted by high water levels following heavy precipitation that increase flow velocities and make navigation difficult. Changes in the frequency of heavy and prolonged precipitation may therefore reduce the volume of river barge traffic. On the other hand, falling water levels in the Great Lakes have reduced the carrying capacity of cargo vessels in recent years, and climate change could exacerbate this trend.

11.2.3 RAIL

Temperature change: Rising temperatures may lead to material stress, including buckled rails.

Precipitation change: Increases in heavy precipitation events could flood low-lying tracks, forcing temporary closure of low-lying rail lines.

11.2.4 SURFACE TRANSPORTATION

Temperature change: Increases in temperature, and particularly in the frequency of extreme heat events, could increase material stress on pavement and bridge expansion joints, necessitating more frequent maintenance.

Precipitation change: Changes in precipitation patterns could affect surface transportation in three ways. First, an increase in heavy precipitation events can lead to flooded roadways. Second, increased runoff creates faster stream currents which can erode bridge piers, a condition known as bridge scour. Third, precipitation generally degrades system performance, resulting in longer travel times and more crashes.

Extreme Weather: Tornadoes, severe thunderstorms and heavy wind can disrupt highway travel, and heavy cross winds can make long bridges unsafe. The Mackinac Bridge connecting the Upper and Lower Peninsulas of Michigan has experienced accidents due to wind, and the Mackinac Bridge Authority often must close the bridge to all traffic during spells of severe weather.

11.3 Comparative Risk

Current peer-reviewed literature on climate change impacts in the Midwest does not provide a basis for quantifying the costs of impacts such as material stress, flooded roadways, bridge scour and disruptions to barge traffic. However, current projections can be used to assess relative risks associated with different types of impacts in different subregions of the Midwest. The projections described in Kunkel et al. (2013) are the basis for this section.

11.3.1 EXTREME HEAT

The number of days with a temperature greater than 95°F is a good indicator of the risk of pavement and rail buckling. North American Regional Climate Change Assessment Program (NARCCAP) projections for the years 2041-2070 show an increase of more than 20 days each year for almost all of Missouri, including the Kansas City and St. Louis metropolitan areas, as well as for southern Illinois, southern Indiana, and the Cincinnati metropolitan area. Northern portions of the Midwest, including the Minneapolis, Milwaukee, Chicago, Detroit and Indianapolis metropolitan areas, are projected to have increases of less than 20 days per year exceeding 95°F. These projections suggest that heat stress on rail and pavement may be of particular concern in Missouri and the southern portions of Illinois and Indiana.

11.3.2 CHANGING PRECIPITATION PATTERNS

11.3.2.1 Flooding Risk

Takle (2010) maintains that precipitation levels in eastern Iowa have increased over the last 30 years:

> Using these tools, we see that eastern Iowa has experienced increased precipitation of 1 to 2 inches in spring (April through June) over the last 30 years. This is consistent with increases throughout the central U.S. since about 1976 (Groisman et al. 2005). There also is increased intensity of extreme events in the warm season. Groisman et al. (2005) report a 20 percent increase in the most intense 0.3 percent of precipitation events in the central U.S. over this period. By contrast, there has been a slight decrease in the frequency of light or average precipitation events (CCSP 2008). Records from Cedar Rapids (IEM 2008) show that there were 14 days from 1901 to 1950 that had three or more inches of daily total precipitation. Between 1951 and 2000, this number rose to 23 days. Over the last 113 years, annual precipitation in Cedar Rapids has increased by about 9 inches, from 28 to 37 inches. Increases have come in both

> the warm season and cool season, with the cool season precipitation currently being about 50 percent higher than a hundred years ago. The Cedar Rapids record agrees with the regional trend of increased precipitation since 1976, but the Cedar Rapids upward trend started much earlier. So although it is hard to argue that this locale's increase in annual total precipitation is due to anthropogenic effects of the last 30 years, models suggest this existing trend will continue. The increase in number of days with intense precipitation, by contrast, has increased in the latter part of the 20th century, which is consistent with changes attributable to anthropogenic effects (p. 112).

A conference held at St. Louis University in November 2008 drew together several scientists who study climate change effects on streamflow. Several of the presenters agreed that flooding is becoming more frequent in the Mississippi River basin (Criss 2009; Pinter 2009) or that flooding is likely to become more frequent under climate change scenarios (Wuebbles et al. 2009; Pan 2009). NARCCAP projections show a continuation of several of these trends through the middle of the 21st century. The entire Midwestern region is projected to see increases in precipitation in winter, spring and fall.

Moreover, the number of days with more than 1 inch of precipitation is projected to increase throughout the Midwest. NARCCAP simulations for the period 1971-2000 indicate that most of the area south of the Missouri-Iowa border (an area extending as far as Columbus, Ohio) experienced about 6-8 days per year in which precipitation exceeded 1 inch. NARCCAP projects an increase in heavy precipitation days for the period 2041-2070. In the Mississippi River basin between the Quad Cities and LaCrosse, Wisconsin, the mean number of days per year with precipitation exceeding 1 inch is projected to rise by 1.5 to 2 days, relative to the period 1971-2000; the rest of the basin between St. Louis and Minneapolis is projected to have an increase of 1.0 to 1.5 days.

These projections suggest an increased risk of disruptions to navigation on the Ohio, Mississippi and Missouri Rivers. In addition, the projected increase in heavy precipitation throughout the Midwest suggests additional risk of temporary flooding of rails and roadways. With higher return frequencies for heavy precipitation events, the design carrying capacity of many culverts and hydraulic structures may be insufficient to prevent rail, highway, airport and other infrastructure flooding.

The observations and projections cited above are consistent with the conclusion of Pryor et al. (2009) that "the most common cause of flooding is intense and/or prolonged storm precipitation (Nott 2006). Given the increase in intensity of extreme precipitation events, an increased risk of flooding seems likely" (p. 110-111).

11.3.2.2 Snow

NARCCAP projections indicate rising winter precipitation over much of the Midwest. If increases in winter precipitation come in the form of snow or ice, this could increase the risk of traffic disruptions. On the other hand, it is possible that warmer temperatures in some areas could cause more winter precipitation to come in the form of rain. Monitoring regional changes in snow removal budgets and planning accordingly may be one simple and effective adaptation option that can be taken by state and local transportation authorities.

11.3.3 GREAT LAKES WATER LEVELS

Wang et al. (2010) report that water levels on the Great Lakes dropped in the 1990s, resulting in significant transportation impacts in the Great Lakes region:

> From the late 1990s to the early 2000s, the volume of lake ice cover was much lower than normal, which enhanced evaporation and led to a significant water level drop, as much as 1.3 meters. Lower water levels have a significant impact on the Great Lakes economy. For example, more than 200 million tons of cargo are shipped every year through the Great Lakes. Since 1998--when water levels took a severe drop--commercial ships have been forced to lighten their loads; for every inch of clearance that these oceangoing vessels sacrificed due to low water levels, each ship lost US$11,000-22,000 in profits (p. 41).

There is considerable uncertainty regarding future water levels on the Great Lakes. Angel and Kunkel (2010) report that an output of 565 model runs from 23 Global Climate Models were applied to a lake-level model. Under the A2 ("high emissions") scenario, median changes in lake levels were -.41 meters; under B1, the median drop was -.25 meters. However, the range in lake levels projected by the various models was considerable, leading to high uncertainty about future lake levels.

Hayhoe et al. (2010) note that expected increases in precipitation may offset increases in temperature, leading to uncertainty about water levels, at least by the middle of the 21st century: "Competing effects of shifting precipitation and warmer temperatures suggest little change in Great Lake levels over much of the century until the end of the century, when net decreases are expected under higher emissions" (p. 7).

The Wisconsin Initiative on Climate Change Impacts (WICCI 2011) notes that the Great Lakes have historically experienced both high water and low water decades. According to WICCI, climate change could potentially create both high and low water decades that exceed normal decadal variations. The report suggests that ports and marinas may need to take the possibility of greater fluctuations into account when designing and building new infrastructure. In addition, WICCI posits that lower water levels could force cargo vessels to carry lighter loads.

According to Cruce and Yurkovich (2011), "Great Lakes shipping is very sensitive to lower lake levels as an annual mean or during periods of seasonal variation" (p. 40). A 1,000 foot vessel loses 270 tons of capacity per inch of lost draft, which equates to about $30,000. Low water levels between 1997 and 2000 forced shippers to reduce cargo tonnage by 5% to 8%. According to Cruce and Yurkovich, research conducted by Millerd (2007) at Wilfrid Laurier University indicates that falling water levels are expected to increase operating costs by 1.9% to 7.4% by 2030, with costs projected to rise to between 13.3% and 26.7% by the end of the century. Subsequent research by Millerd (2011) places the estimated cost at between 5% and 22% by 2030. Cruce and Yurkovich also argue that falling water levels could damage port and marina infrastructure and increase dredging costs.

Cruce and Yurkovich note, however, that less ice on the St. Lawrence Seaway could present opportunities to shippers; since the 1980s, the annual amount of time in which the seaway is closed because of ice has dropped by about 10 days per year. A reduction in lake ice may partially offset some of the challenges associated with varying water levels. Warmer conditions, reducing lake ice, could result in more navigable days, which would benefit shippers.

11.4 Ongoing Adaptation Efforts

11.4.1 CHICAGO

The City of Chicago has a Climate Action Plan (CAP) (City of Chicago 2008) which largely focuses on mitigation efforts. In particular, most of the plan elements related to transportation emphasize greenhouse gas reduction, including measures to promote transit-oriented development and alternative modes of transportation. However, the CAP explicitly addresses climate change impacts on transportation, noting that an increasing frequency of heavy precipitation events is likely to result in traffic delays and damage to infrastructure.

The bulk of adaptation measures related to transportation in the Chicago CAP involve stormwater management. The CAP calls for increased use of permeable paving surfaces, rain gardens, rain barrels and landscaping to reduce storm runoff. The city's Green Urban Design (GUD) plan includes measures to modify alleys to reduce runoff, and dozens of alley modifications have been implemented thus far.

11.4.2 WISCONSIN

The Wisconsin Initiative on Climate Change Impacts (WICCI) released a report in 2011 which addresses potential impacts on both surface transportation and water transport. The report anticipates an increase in the frequency of transportation infrastructure damage and temporary flooding as a result of more frequent incidents of heavy rain.

The WICCI report highlights 2008 flooding on the Baraboo River as an example of vulnerability to high water conditions. According to the report, "the Wisconsin Department of Transportation is conducting a review of the vulnerability of the entire interstate highway system as a result of flood-triggered closures of I-39, I-90, and I-94 at the Baraboo River in Columbia County. Engineers will weigh the costs of flood-proofing stream crossings and embankments against the economic costs of temporary closures...." (p. 128).

In addition to stormwater impacts, the WICCI report also notes the need for additional research on potential material stress. In particular, WICCI suggests that projections of changes in freeze-thaw cycles could be used to predict changes in the useful life of concrete, with maintenance measures adjusted accordingly.

As in the Chicago CAP, the major adaptation elements related to transportation in the WICCI plan are those that address stormwater runoff. WICCI recommends open space preservation, Low Impact Design (LID) methods for paved surfaces, and green roofs to reduce runoff.

11.4.3 IOWA

The Iowa Climate Change Impacts Committee (ICCIC) was formed by an act of the Iowa General Assembly. In January 2011, the ICCIC issued a report on potential climate change impacts for Iowa.

The ICCIC report indicates that precipitation in Iowa has increased over the last 100 years and that the number of intense rain events has also increased. The report further asserts that certain places such as Cedar Rapids have seen greater increases than the state as a whole. In addition, the report states that streamflows have risen in recent years, and reports that streamflow projections conducted by researchers at Iowa State University indicate that increased precipitation could result in a 50% increase in streamflow in the Mississippi River basin. ICCIC concludes that these findings suggest that the risk of flooding is rising.

The report does not focus extensively on the relationship between climate change and transportation infrastructure, but it does note that higher temperatures increase the risk of road buckling and that increased precipitation and streamflow would increase the risk of washed out roads and bridges.

11.4.4 MICHIGAN DEPARTMENT OF TRANSPORTATION

MDOT has conducted an analysis of potential challenges related to climate change and has developed a menu of potential responses. MDOT staff presented their analysis at an April 2011 webinar conducted by the Transportation Research Board of the National Academies (Johnson 2011).

The main areas of concern for MDOT are the possibility of more intense storms and hotter, drier summers. Methods for adapting to more intense storms include using larger hydraulic openings for bridges, armoring of ditches to prevent erosion, installation of higher capacity pumps to ensure that drainage systems are not overwhelmed, and use of intelligent transportation systems (ITS) that help motorists adapt to changing traffic conditions. Methods for adapting to hotter and drier summers include intensifying monitoring of pavement conditions during extreme heat periods and encouraging more night work to prevent premature cracking.

11.4.5 FEDERAL HIGHWAYS ADMINISTRATION (FHWA)

FHWA is undertaking at least two initiatives to help Midwestern states prepare for challenges associated with climate change. These include updated flood frequency hydrographs and peer learning events.

Precipitation Frequency Analysis: State departments of transportation use precipitation frequency graphs to develop design standards for culverts and other hydraulic structures. These design standards are promulgated by a state DOT to ensure that adequate drainage capacity exists for roads built in the state. Basing design standards on current precipitation frequency data is an important adaptation measure because using updated information reduces the risk of road closures or infrastructure damage due to heavy precipitation. Unfortunately, in some parts of the country, precipitation maps have not been updated for decades.

FHWA is currently conducting a pooled fund program through which state DOTs can contribute funds to update precipitation estimates (Transportation Pooled Fund Program 2011). In the Midwest, contributors to the pooled fund include the transportation departments of the following states: Colorado, Iowa, Kansas, Minnesota, Missouri, Nebraska, and South Dakota. The study uses updated information from NOAA to determine annual exceedance probabilities (AEP) and average recurrence intervals (ARI) for durations ranging from 5 minutes to 60 days and for ARIs from 1 to 1,000 years. Point estimates will be spatially interpolated to a spatial resolution of approximately 4 km × 4 km.

Peer Learning: FHWA hosts peer learning events for Metropolitan Planning Organizations (MPOs) and state departments of transportation. An exchange held in May 2011 included MPOs and DOTs from the Midwest.

The final report from these sessions includes input from state and local planning officials (ICF International, 2011). Representatives from MPOs identified county hazard mitigation planning efforts as a vehicle for climate change adaptation planning. Barriers to adaptation include the lack of inter-agency collaboration and the lack of localized climate data.

The state DOT session focused on the possibility of more frequent heavy precipitation events, which could cause more bridge scour, and which could also make current culverts and drainage systems inadequate. Presenters stated that more frequent incidents of heavy precipitation could overwhelm drainage systems, leading to an increased risk of roadway flooding.

One presenter argued that an asset management approach to infrastructure maintenance and design should be considered an effective adaptation measure. Transportation asset management consists of continually monitoring the condition of assets such as roads, bridges and culverts using geographic information systems (GIS) and other tools. Assets considered critical to system performance are identified, as is the required level of service. These considerations inform investment strategies and long-term funding strategies.

By conducting peer exchanges such as these, FHWA is providing technical assistance to state and local planners who will be making adaptation decisions for transportation systems. Transportation asset management and integration with hazard mitigation plans are two useful ideas to come from the Indianapolis sessions.

11.5 Research Needs

Three main research needs emerge from the foregoing summary. First, there is a need to quantify impacts of climate change on transportation for the Midwest region, and for specific communities in the Midwest. Second, there is a need to model the effectiveness of adaptation options. Third, there is a need to integrate uncertainty into decision making about adaptation options.

11.5.1 QUANTIFYING IMPACTS

Although there is a qualitative understanding of the types of impacts that might exist under climate change scenarios, there is little peer-reviewed literature that quantifies transportation impacts in the Midwest. The area of Midwestern transportation that has had the most quantitative analysis has been Great Lakes shipping, where researchers have been able to measure likely changes in cargo capacity due to falling water levels.

Analysis at this level has not been performed for surface transportation or rail in the Midwest. For example, it is reasonable to conclude that an increase in the number of days per year over 95°F will increase material stress on pavement and rail. A useful next step would be to quantify the potential damage in terms of a pavement condition index, useful life or cost of maintenance.

To pick another example, it is reasonable to expect that flooding of roadways may increase due to changing precipitation patterns. But it would be useful to quantify the impacts in terms of vehicle miles of travel (VMT) or vehicle hours of travel (VHT). Tallying the cost of lost shipping days on the Ohio and Mississippi Rivers would also be of benefit.

11.5.2 ADAPTATION EFFECTIVENESS

There is now a rich literature on adaptation measures being undertaken. But there is a strong need for additional work that models the effectiveness of different adaptation options. In particular, there is a widespread understanding of the connection between stormwater management and transportation, with a realization that reducing runoff can also reduce flooding on roadways. Needed is a way to measure the effectiveness of different options. Modeling the effectiveness of different options, including permeable paving surfaces, open space preservation and rain gardens, would allow a more robust cost-benefit analysis, which would inform policy and planning at the local level.

11.5.3 UNCERTAINTY

The presence of uncertainty raises serious problems for decision makers. The issue of water levels on the Great Lakes is a good example. There is much uncertainty about future water levels, and there is even a possibility that water levels could rise during some years of the next century. Given the uncertainty, how can decision makers determine optimal adaptation strategies?

An approach to risk management known as Robust Decision Making (RDM) has entered the literature on transportation and climate change. The concept was introduced to the study of climate change adaptation by Lempert and Schlesinger (2000), who drew a distinction between prediction-based approaches and “robust” approaches to risk management. Predictive approaches attempt to determine the most likely scenario, and to design a management response that optimizes outcomes under a specified condition. By contrast, the RDM approach is useful for situations in which there is “deep uncertainty” about future conditions. In such a situation, according to Lempert and Schlesinger, the best solution will be one that provides acceptable outcomes across a wide range of possible scenarios. In RDM, the use of mathematical models to project outcomes under different scenarios is a key tool.

Schwartz (2011) applies this approach to the study of transportation adaptation, arguing that robust strategies “encompass structural, operational, and institutional options” (p. 8). Schwartz describes RDM as an approach that incorporates multiple views of the future, uses robustness across multiple scenarios rather than optimization as a decision criterion, and allows iterative ability to assess and adjust to vulnerabilities. Schwartz uses as an example a coastal community facing a rise in sea level and storm surge. Even if a reasonable degree of confidence exists with respect to the long term trend, the timing and amount of sea level rise remains highly uncertain. In this situation, the most robust strategy may not be to simply retrofit all existing assets. Rather, a more cost-effective approach may be to continually monitor changing conditions, rebuilding only critical assets when sea levels reach a critical height.

Another example of a possible application of RDM to transportation planning is the uncertainty over water levels in the Great Lakes. Although many models project falling water levels, the range of projections is so great that it would be risky to make major investment decisions based on optimization for a single scenario. Given the deep uncertainty, it may be rational for designers of ports, marinas, and perhaps even cargo vessels to consider performance across a range of possible water levels. Additional research on performance of adaptation measures across a range of scenarios would give policy makers the tools with which to evaluate proposed options.

11.6 Conclusions

Following is a summary of key impacts, with an assessment of the level of confidence associated with each.

Medium Confidence:

- There is a rising risk of disruption of Mississippi River navigation. Given that flooding impacts are already significant, have grown in recent decades, and are projected to continue growing, the assignment of medium confidence to these impacts seems reasonable.
- There is a rising risk of temporary flooding of roads and rails due to both riverine flooding and ponding. This assessment is based on recent increases in the frequency of intense precipitation events, projected increases in the frequency of intense precipitation events and projected increases in winter and spring precipitation in the Mississippi River basin.
- There is a rising risk of disruption to Great Lakes navigation due to variability in water levels. Recent economic impacts of falling water levels have been well documented, and projections indicate that variability is likely to increase over the next century.
- Warmer temperatures will increase rail and expansion joint stress and decrease pavement life.
- Warmer temperatures will create more difficult conditions for construction labor.

Low Confidence:

Although it is reasonable to hypothesize that the following impacts may occur, there is currently insufficient quantitative data with which to assess the likely severity of these impacts:

- Warmer air temperatures and increased frequency of extreme weather and heavy winds may disrupt air traffic.
- Faster stream currents caused by an increase in heavy precipitation events may result in increasing severity of bridge scour, which could affect both rail and highway travel.

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Chapter 12

Water Resources

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12.1 Introduction

The water resources of the Midwest, and how they are managed under a future climate, have a significant collective impact on multiple economic sectors in the U.S., North America, and the world. The North American Laurentian Great Lakes, for example, hold nearly 20% of the earth's accessible surface fresh water supply and have a coastline, and a coastal population, on the same order of magnitude as frequently-studied ocean coasts around the world (Fuller et al. 1995). In light of growing demands for clean water, access to coastal resources, and an improved understanding of climate dynamics in the Midwest region, a significant amount of research has recently been focused on understanding climate impacts on the lakes (both large and small), rivers, and streams in this region.

Various interest groups and socio-economic sectors depend on different aspects of the water cycle, often on different time scales. Rain-fed agriculture does best if soil moisture is replenished at least every 15 days or so. Streamflow, important for flood control, hydropower, navigation, fish migration, and some other ecological factors, has its high extremes controlled by abundant precipitation and snowmelt on short timescales, but its low extremes are controlled primarily by baseflow, which is water that percolates through the soil into ground water, then gradually flows through the ground into streams, wetlands, and lakes. Levels of the Great Lakes are determined by net basin supply, which is the sum of inflow from the land portion of their drainage basin and the precipitation directly over the lake, minus the evaporation from the lake. Because of the large areal extent of the Great Lakes, the effect of short-term variability in net basin supply on lake level is attenuated. Other short-term effects on lake level include wind-driven surges and seiches (waves occurring on the scale of an entire lake).

While not a specific theme of this particular assessment, we find that this region also, through explicit and implicit partnerships with the Canadian government, represents an ideal test bed for establishing effective protocols for collaborative binational water resources and ecosystem services research (Gronewold and Fortin 2012). The value of the water resource management and climate change lessons to be learned from this region, however, depends on an explicit acknowledgement of those water budget components which are uncertain or unobservable (such as overlake evaporation and evapotranspiration), and how projections of regional climate are downscaled to a suitable local scale, translated into suitable water resource management metrics, and subsequently placed within an appropriate historical context.

12.2 Historic Variability of Hydroclimate

12.2.1 SEASONAL TO MULTI-YEAR EVENTS

Pan and Pryor (2009) point out that the amount of water vapor in the atmosphere has been increasing at a greater rate in proportion to its historic values than the rate of precipitation. The total water vapor content of the atmosphere has increased in proportion to the Clausius-Clapeyron relation, i.e. it scales as an exponential function of temperature, with absolute humidity or water vapor mixing ratio increasing by about 7% per degree C. However, the mean rate of precipitation has increased by only about 2% per degree C, implying an increasing residence time of water vapor in the atmosphere. Additional theoretical consideration of this phenomenon can be found in Held and Soden (2006).

Pryor et al. (2009) have found statistically significant changes in total precipitation and number of rain days at many stations in the Midwest, mostly increases in both variables, but few stations have statistically significant change in precipitation intensity (precipitation per rain day). They also showed an increase in the amount of precipitation that came on the 10 days of the year with the greatest precipitation. However, this was not evaluated as a proportion of the total precipitation. They also found that there was generally a decrease in the mean number of consecutive days without precipitation.

Observed streamflow has shown an increasing trend since 1940 in the U.S. in general (Lettenmaier et al. 1994; Lins and Slack 1999; USGS 2005), and particularly in the Midwest. More specifically, if you rank daily streamflows from least to greatest, the low to medium range values have increased in recent years, while the largest have not (Lins and Slack 1999). Similarly, Hodgkins et al. (2007) show increasing flow at most gauging stations within the Great Lakes basin, both for the period 1935-2004 and 1955-2004. Li et al. (2010) emphasize that outflow from a region of water in streams must be balanced by net inflow of water vapor in the atmosphere, meaning that atmospheric transport is crucial to terrestrial hydrology, including streamflow.

Net basin supply (NBS) is important for the Great Lakes because it sets the level to which the lake must rise or fall so that it is balanced by outflow. Lenters (2004) showed trends of reduced seasonal cycle in NBS and lake levels on Lake Superior. This change includes a reduction between 1948 and 1999 of the NBS during the spring, and an increase of NBS during the autumn. Each of these changes is primarily attributable to changes in runoff and over-lake precipitation, as given in the dataset of Croley and Hunter (1994). During the 1948-99 period, they did not note a strong overall trend in lake level.

A possible non-climatic cause of changes in the lake level regime of the Great Lakes was proposed by Baird and Associates (2005). They proposed that a deepening of the channel of the St. Clair River, which forms part of the connection between Lake Huron and Lake Erie, was responsible for a distinct reduction in the difference in level between these two lakes. With NBS remaining constant, a less impeded flow due to a deeper channel would require that the level of Lakes Huron and Michigan be lower relative to the level of Lake Erie in order to maintain the same volume of flow out of Lake Huron. The International Joint Commission's International Upper Great Lakes Study (IUGLS) (2009) instead found that changes in climate during the period between about 1985 and 2005 were primarily responsible for this change in relative lake levels.

Trends in the entire range of hydrologic variables may depend on the range of dates that are considered in observational analysis. For example, a rapid drop in the level of Lakes Michigan and Huron occurred during the 1990s and 2000s (Baird and Associates 2005; IUGLS 2009, 2012), so whether or not an analysis extends beyond that date could affect the magnitude of an apparent long-term trend.

12.2.2 FREQUENCY OF LOCALIZED, SHORT-TERM EXTREMES

As stated above, Pryor et al. (2009) showed an increase in the amount of precipitation that came on the 10 days of the year with the greatest precipitation. That is, more precipitation came during very heavy downpours. However, this was not evaluated as a proportion of the total precipitation. They also found that there was generally a decrease in the mean number of consecutive days without precipitation. This is in basic agreement with the results of the seminal paper of Kunkel et al. (1999).

Changnon (2007) examined the frequency, intensity, and economic impact of severe winter storms in the US between 1949 and 2003. This generally showed an increase in intensity over time, and a decrease in frequency, with these effects most concentrated in the eastern U.S.

12.2.3 NON-CLIMATIC INFLUENCES

One factor aside from climate that can affect the long-term water budget of the region, as well as the shorter-term temporal characteristics of response of runoff to precipitation events, is land use. Land use in the Midwest has evolved historically from natural forest and grassland to greater agricultural use and increasing urban and suburban development. Andresen et al. (2009) showed that urban landscapes lower percolation of water into soil and increase surface runoff. Grassland landscapes have the lowest evapotranspiration (ET), while forests have the greatest amount of soil percolation. Cultivated agricultural land has fairly high ET, but also quite high surface runoff. They did not extend their analysis to include how much land was transformed from one of these classes to another. Mishra et al. (2010a) also evaluated the effects of land use on hydrology, showing that conversion of forest to cropland can lead to decreased ET and increased runoff. These effects, when combined with climate change effects, can be additive or compensating. Direct comparison of the results of Andresen et al. (2009) and Mishra et al. (2010a) is difficult because of the differing sets of results that were reported by each and because of the more static land use approach of Andresen et al. (2009) in contrast to the emphasis on land use conversion in Mishra et al. (2010a).

Properties of agricultural landscapes can make them more vulnerable to climate variability and change (Knox 2001). Natural landscapes are better at buffering moisture, making it available to plants for longer periods of time and delaying the eventual runoff of water that does not undergo ET. Thus, even aside from the possibility that precipitation will fall in more concentrated events, cultivated environments, and especially those with tiling to deliver runoff more rapidly, will promote greater extremes in streamflow than forests, grasslands, and other natural land cover types. Similarly, Mao and Cherkauer (2009) used a hydrologic model to demonstrate that land use transformations from pre-settlement times to the present result in decreased ET and increased runoff throughout much of the states of Minnesota, Wisconsin, and Michigan, where the prevailing transformation was from forest to agriculture. Even conversion from evergreen to deciduous forest resulted in decreased ET and increased runoff. A specific difference from the general results of Knox (2001), though, was that conversion from grassland to agriculture, which occurred in much of the southern and western part of the domain, resulted in increased ET and decreased runoff.

12.2.4 LAKE WATER TEMPERATURE

Austin and Colman (2007) investigated surface temperatures of Lake Superior during the period 1979-2006, and found a positive trend in these temperatures. They found the rate of increase in annual maximum lake surface temperatures to be nearly twice as large as trends in summertime near-surface air temperature over the surrounding land. This was taken as indicating positive feedback mechanisms within the lake, including greater intake of solar radiation due to the reduced duration and extent of ice cover, and the shift in timing of spring overturning of the water column.

Dobiesz and Lester (2009) looked at surface temperatures throughout the Great Lakes, as well as throughout the water column at one station in western Lake Ontario. They also found a strong trend toward greater water clarity (as measured by Secchi depth) between 1968 and 2002, which is attributable to a combination of abatement of phosphorus loads into the Great Lakes and the invasion of non-native Dreissenid mussels (zebra mussels and quagga mussels). They found positive trends in water temperatures, both at the surface and at depth, and attributed this to a combination of changes in climate and changes in water clarity. Vanderploeg et al. (2012) reinforce this result regarding water clarity and extend this result to Lake Michigan for the difference between the 1994-2003 period (before expansion of quagga mussels to deep water) and 2007-08 (after expansion).

Some of the distinctions between the conclusions of Austin and Colman (2007) and Dobiesz and Lester (2009) illuminate a particular point. It has often been either explicitly or tacitly assumed that changes in temperature occur first in the atmosphere, and then propagate to changes in temperature of the surface (or other effects at the surface). Dobiesz and Lester (2009) hew close to this line of reasoning, implying that surface water temperatures are forced by surface air temperatures, with no notable effect in the opposite direction. Austin and Colman (2007), on the other hand, first present the difference in trends of water surface temperature and air temperature as being counterintuitive, but then offer mechanisms that occur within the water to explain this distinction. This means that the lake water is itself an active player in the climate system; we prefer to view climate and climate change as phenomena of the coupled atmosphere-surface system (including both land and water surfaces).

There was a long-standing gap in measurement of fluxes of water vapor, trace gases, and sensible heat from the Great Lakes, for purposes of analysis of moisture and energy budgets of the lakes, and for validation of models. New datastreams (starting in 2008) for *in situ* measurement of these variables are documented in Blanken et al. (2011) and Spence et al. (2011). Such measurements are available from only a small number of stations on the Great Lakes (about six), and funding for this monitoring is limited and transient.

12.2.5 COUPLED ATMOSPHERIC-HYDROLOGIC PHENOMENON—WARMING HOLE

Pan et al. (2009) show observational evidence of a summer "warming hole," a region in the contiguous United States in which warming trends are reduced or even reversed for the summer season. Depending on which period is used for calculation of trends, the warming hole is located over the western portion of the Midwestern region and extending further west and south (1976-2000), or primarily to the south of the Midwestern region (1951-75). The proposed mechanism is increased influx of moist air due to the low level jet (LLJ), originating from the Gulf of Mexico. The increased moisture content of the LLJ is a straightforward result of warming of both the atmosphere and the surface, particularly the water surface of the Gulf of Mexico. The resultant increase in rainfall leads to increased evaporative cooling of the surface (the cooling effect is most pronounced for daily maximum temperatures during the summer). As noted, the location of the warming hole has shifted with time, and the mechanisms behind this shift are unclear.

12.3 Paleoclimatic Studies

Booth et al. (2006) have characterized persistent anomalies in summer precipitation as being associated with anomalies in zonal surface winds. They show that July precipitation is negatively correlated with zonal wind index (mean sea level pressure gradient between 35° and 55° N across the western hemisphere), with a $p<0.05$ level of certainty for southern Minnesota, Iowa, and northern Missouri. Note that their zonal wind index quantifies pressure gradients over a range of latitudes farther south than those indicated by the more widely-used North Atlantic Oscillation and Arctic Oscillation (NAO/AO) indices. Their examination of the possibility of explaining an extended drought in this region 600 to 800 years ago is inconclusive.

Croley and Lewis (2006) examined climatic conditions under which some of the Great Lakes might have been terminal lakes in the past (i.e. lakes with no outflow point because they lose sufficient water to evaporation to offset precipitation and runoff inputs). They arrive at figures of water level as a function of changes in air temperature and precipitation relative to late 20th century climate (their Figures 7 and 8). These figures show a range of climates yielding lake levels above the sill, meaning that there is continuous outflow from the lake. They also show a range with seasonally and interannually intermittent outflow, with the water level always very near to the sill level. Then there is a range with water below the sill level; within this range, the mechanism of balancing the water budget through changes in outflow is removed, and the water level becomes highly sensitive to climate because the water budget must be balanced by changing the evaporation from the lake surface via changing the lake area as a result of changing the lake level until a dynamic equilibrium is reached.

12.4 Future Projections

Changes in the strength of the global hydrologic cycle provide a backdrop for the regional water budget. As in the historic record, general circulation model (GCM) projections of precipitation rate generally show an increase of about 2% per degree C, while the water vapor content of the atmosphere increases by about 7%, implying longer residence time of water vapor in the atmosphere (Held and Soden 2006; Pan and Pryor 2009). Note also that, in order to maintain an equilibrium value of atmospheric water vapor content, surface ET summed over the globe must equal precipitation summed over the globe. Therefore, when summed or averaged over the globe, the ET rate also increases by about 2% per °C.

The magnitude of the most intense precipitation events has been projected to increase throughout the world due to increased greenhouse gases using both theoretical arguments (Trenberth et al. 2003) and analysis of output from GCMs (Sun et al. 2007). It is deemed likely that both floods and droughts will increase in frequency (Wetherald and Manabe 2002; Trenberth et al. 2003; Meehl et al. 2007). However, models remain a problematic tool for evaluating the magnitude and frequency of extremely heavy precipitation events, because in reality the spatial scale of the heaviest precipitation is smaller than the resolved scale of the model. This is true even for regional models with finer resolution than global models.

Trapp et al. (2007) evaluated the number of days that satisfy criteria for severe thunderstorm environmental conditions under historical greenhouse gas concentrations as compared to late 21st century concentrations. They found that there are more days with severe thunderstorm environment in the future over nearly all of the conterminous United States. Under one of the three GCMs that they evaluated, this tendency is most concentrated in the Midwest.

Some studies have projected a general increase in runoff for multiple drainage basins throughout the world (Wetherald and Manabe 2002; Manabe et al. 2004; Milly et al. 2005; Kundzewicz et al. 2007). Others have shown increases in the difference between precipitation and ET, which also imply increased outflow, and have extended these results to indicate increased soil moisture (Pan et al. 2004; Liang et al. 2006).

Cherkauer and Sinha (2010) used the Variable Infiltration Capacity (VIC) model to simulate changes in streamflow for six rivers, including four in the Upper Mississippi River basin. They found increased streamflow in these basins associated with warming by anthropogenic greenhouse gases. The anticipated influence of variability, particularly in precipitation, is to both decrease low flows and increase peak flows.

Increased winter precipitation is expected to lead to higher phosphorus loading in streams and draining into lakes (Jeppesen et al. 2009). This can lead to eutrophication, i.e. increased growth of algae and other aquatic plants, without much increase in life at higher levels of the food web. These effects are highly subject to multi-stressor effects, such as interaction with aquatic invasive species (Adrian et al. 2009).

Climate change is expected to warm the near-surface water of lakes more than water at greater depths. This will result in reduced vertical mixing of water, and in turn to reduced dissolved oxygen at depth (Fang et al. 2004). This is a threat to the habitat of fish and other species.

12.4.1 UPPER MISSISSIPPI/MISSOURI/HUDSON BAY WATERSHEDS

Using the Soil and Water Assessment Tool (SWAT), Lu et al. (2010) project that streamflow in the Upper Mississippi River basin will decrease when using climate data derived from GCM simulations in the 2046-65 period, compared to the 1961-2000 period. When averaging over the results using 10 different GCMs, these decreases occur during all seasons except winter. Wu et al. (2011) carried out similar projections for the Upper Mississippi River basin, and found increased water yield during the spring but large decreases in summer. The soil moisture likewise increases in spring and decreases in summer. Accordingly, there is increased risk of both flood and drought, depending on the season.

12.4.2 OHIO RIVER WATERSHED

Mishra et al. (2010b) used VIC driven by GCM output to investigate projected trends in drought in parts of Indiana and Illinois within the Ohio River watershed. They found that drought frequency increases during the middle part of the 21st century (2039-2068), while for later in the century, it increased only in the highest emission scenario for greenhouse gases.

12.4.3 GREAT LAKES WATERSHED

Estimation of the impact of climate change on Great Lakes water budgets and levels began with Croley (1990). The same method has been used multiple times since then, but using results from different GCMs as input (e.g. Lofgren et al. 2002; Angel and Kunkel 2010; Hayhoe et al. 2010). A recent and very comprehensive example of this approach, Angel and Kunkel (2010) assembled results from over 500 GCM simulations from different modeling centers, using various greenhouse gas emission scenarios, and different ensemble members for each model configuration. They found spread among the results of the different model runs, but a general tendency for the lakes' net basin supply and water levels to be reduced, as was generally found in the preceding model studies using the same methods.

Lofgren et al. (2011), however, found fault with this long-used methodology, in particular its formulation of ET from land. This formulation relies excessively on using air temperature as a proxy for potential ET, and does not display fidelity to the surface energy budget of the GCMs that are used to drive the offline model of land hydrology. This is also in keeping with the findings of Milly and Dunne (2011). By substituting a simple scheme to drive the hydrologic model using changes in the GCMs' surface energy budget, rather than using the air temperature proxy as previously, Lofgren et al. (2011) projected water levels to drop by a lesser amount, or to actually rise in the future.

The differential between water levels projected using the older method and the proposed new method was on the order of one meter.

Lorenz et al. (2009) evaluated the water budget for Wisconsin under climate change scenarios based on 15 atmosphere-ocean general circulation models (AOGCMs). They found that there was greater agreement among the various AOGCMs regarding the sensitivity of air temperature to increased greenhouse gases than in the changes in precipitation. They found a negative correlation during July and August between changes in air temperature and ET throughout the central United States, with maximum magnitude over the lower Mississippi River. This was taken to indicate that evaporative cooling was occurring, making both the surface and the lower atmosphere cooler when abundant ET occurred, and cloud formation associated with higher ET may also enhance this effect. They also found that the amount of precipitation that occurred in the single wettest day of the year increased by an average of 33%, although individual models had increases between 5% and 66%. These results are similar to those of Sun et al. (2007), mentioned above.

Kutzbach et al. (2005) evaluated the Great Lakes basin's future water budget based on the convergence of atmospheric water vapor flux. That is, they inferred how much water is retained at the surface and becomes outflow based on how water was being transported in the atmosphere. Their analysis of AOGCM data indicated that enhanced greenhouse gas concentration will bring greater atmospheric moisture convergence to the Great Lakes basin, i.e. increased outflow, which also directly implies higher levels of the Great Lakes. This is in contrast to the results of Angel and Kunkel (2010) and its predecessor papers.

A newer wave of models will take a more direct approach at estimating hydrologic impacts of climate change in the Great Lakes basin. These involve development of regional climate models that are fully coupled to both the land surface and simplified formulations of the Great Lakes (Lofgren 2004; MacKay et al. 2009; Zhong et al. 2012; IUGLS 2012; Bennington et al. 2014). These Great Lakes-specific modeling efforts are complemented by dynamically downscaled climate models with a domain covering all of North America, created through the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009). Initial findings from these efforts (see, for example, Holman et al. 2012) suggest that tools such as regional climate models can be used as an aid in estimating the spatial distribution of precipitation and other fields. In this light, there appears to be a need to revisit historical climate and hydrological data sets for the Great Lakes region which, to date, have served as a basis for water budget and water level planning decisions including those impacting hydropower, navigation, and shoreline recreation and infrastructure.

12.4.4 COMMONALITY AMONG MANY STUDIES

Throughout most of the projections based on general circulation models of future climate noted above, for the Midwest, there is an increase in the annual mean precipitation. And in most of them, increased precipitation happens primarily during the cold season. On the other hand, summer has little projected change or a decrease in precipitation in most models.

12.5 Uncertainty and Probability

Acknowledging and quantifying uncertainty in historical climate data and climate projections, and clearly propagating that uncertainty into policy and management decisions, represent an ongoing challenge to the water resource and climate science community and the general public. Misconceptions about uncertainty, and the confusion associated with knowledge versus ignorance (Curry and Webster 2011), have important implications for the water resource-climate science nexus, and (following Van der Sluijs 2005) have led to the term "uncertainty monster", a term intended to reflect that confusion, and represent a source of fear that drives reactions to a future we do not understand and cannot control (Curry and Webster 2011). Confirming and validating models is, of course, one approach to building confidence in projections about future climate conditions, however there is no clear consensus within the water resources or the climate science community about a metric, or set of metrics, for which the skill of complex (and in some cases, probabilistic) models can be assessed (Guillemot 2010).

Furthermore, agreement between a model and historical climatic data does not necessarily imply that projections of future climate states will be correct, or even physically reasonable, especially if the model is based more on empirical fitting rather than processes known from first principles. Curry and Webster (2011, p. 1670) say, "Continual ad hoc adjustment of the model (calibration) provides a means for the model to avoid being falsified." A particular example of the problem with empirically-based models being applied to unprecedented climate regimes is illuminated in Lofgren et al. (2011), in this case leading to demonstrably excessive sensitivity of ET to climate.

The uncertainty in the response of precipitation and ET to enhanced greenhouse gases is greater than the corresponding uncertainty of air temperature, as emphasized by Pan and Pryor (2009) and Lorenz et al. (2009). To compound this issue, the most important quantity in determining streamflow and lake levels is the difference between precipitation and ET. Thus it is the difference between two larger quantities, each having sizable uncertainty, and therefore the uncertainty proportional to this difference is even larger.

Additional insights into management of water resources in the face of uncertainty, as well as reviews of many of the findings mentioned in the current paper, can be found in Brekke et al. (2009).

12.6 Conclusions

Water resources are important to Midwestern interests, including navigation on the Great Lakes and rivers, agriculture, hydropower, and recreation, and are likely to be subject to impacts from human-caused climate change. While the basic science of climate change is well established, many of the details of impacts on particular sectors at local to regional spatial scales are subject to greater uncertainty. Even though understanding is under development, some more general patterns are emerging for water resources in the Midwestern US. In general, precipitation has been increasing and this trend is projected to continue. Precipitation increases are particularly pronounced when looking at the winter season and when looking at the few largest rain events of the year, and this is expected to continue. Methods of calculating evapotranspiration (ET) under changed climate are the subject of emerging research, showing that widely-used methods based on temperature as a proxy for potential ET exaggerate projected increases in ET, as demonstrated by severe imbalances in the surface energy budget. When incorporated into further simulations, this leads to excessive reductions in streamflow and lake levels. Simulations using a more energy-based approach to ET give more mixed results in terms of changes in streamflow and lake levels, and often show increases.

Impacts on water resources at local to regional scales remain subject to greater uncertainty than projections of basic climate variables such as air temperature and precipitation, especially when these climatic variables are aggregated to the global scale. Relevant policy responses may be to enhance resiliency in the case of occasional low levels on lakes and streams, as well as potentially larger flooding events.

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FOCUS

Midwestern Levees

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Introduction

Levees are critical infrastructure, protecting homes, farms, factories and commercial establishments. There are more than 3,700 linear miles of federal levees in the Midwest region, protecting some 7 million acres of land (U.S. Army Corps of Engineers 2012). A levee failure can be catastrophic to a community. The National Committee on Levee Safety (NCLS) (2011) offers several examples of recent levee failures in the Midwest:

- During the Great Flood of 1993, 40 federal levees were either overtopped or damaged.
- In 2008, flood waters overtopped levees in Cedar Rapids, Iowa, inundating several municipal buildings, as well as 3,900 homes. The town of Oakville, Iowa was devastated when its levee failed, with every building in town damaged. As a result, more than two thirds of its population subsequently moved away.
- Also in 2008, the Indiana communities of Munster and Hammond were flooded after a levee on the Little Calumet River breached, leading to a Presidential disaster declaration.
- In 2011, a levee five miles south of Hamburg, Iowa, breached in three locations, leading to the eventual collapse of the levee.
- In 2011, levees on the Black River in Missouri were overtopped 30 times, with levee breaches occurring four times.

Levee Condition

In recent years there have been indications that the condition of many levees is unsatisfactory. NCLS (2009) asserts that many levees were built more than 50 years ago using construction techniques that are now considered obsolete. In addition, levees originally built to protect agricultural fields now often protect densely developed urban land. As a result, according to NCLS, "many urban areas protected by levees, particularly those in deep floodplains, have an unacceptably low level of flood protection and an unacceptably high risk. Failure of such levees can result in high loss of life, property damage, and economic losses" (p. 15).

In 2009, the American Society of Civil Engineers (ASCE) gave the nation's levee system a grade of D-, asserting that $50 billion over five years would be required to bring levees up to acceptable levels; ASCE states that only $1.13 billion had been committed for this purpose.

The Water Resources Development Act of 2007 (WRDA) directed the U.S. Army Corps of Engineers to conduct an inventory and inspection of all federal levees. NCLS estimates that federal levees, which are covered by WRDA, represent only about 15% of the miles of levee systems in the country. Still, many large communities along the Mississippi, Missouri and Ohio Rivers are protected by federal levees.

As of January, 2012, the U.S. Army Corps of Engineers National Levee Database contained ratings for 1,179 linear miles of levee systems in the Midwest, with 2,520 miles unrated. Of the levee systems that had been inspected, a rating of "acceptable" was given to 74 miles of levee systems. A rating of "minimally acceptable" was given to 921 miles. A rating of "unacceptable" was given to 184 miles , about 16% of the total linear mileage (U.S. Army Corps of Engineers 2012).

In addition to the inspections conducted by USACE, the Federal Emergency Management Agency (FEMA) is conducting a review of levee systems as part of its Map Modernization Program (MMP). Communities that cannot provide documentation that levees are capable of providing protection against a 100 year flood face the possible deaccreditation of their levees, which can trigger a requirement to purchase flood insurance. FEMA has not released a list of levees that face deaccreditation, but Posey and Rogers (2010) estimate that the number of communities facing deaccreditation nationwide numbers in the hundreds. It should be noted that some communities are challenging deaccreditation decisions (County of Madison et al. 2011).

Increasing Flood Risk

As questions are raised about the adequacy of levees, the risk of flooding in the Mississippi River basin appears to be increasing.

Takle (2010) maintains that precipitation levels in eastern Iowa have increased over the last 30 years:

> Using these tools, we see that eastern Iowa has experienced increased precipitation of 1 to 2 inches in spring (April through June) over the last 30 years. This is consistent with increases throughout the central U.S. since about 1976 (Groisman et al. 2005). There also is increased intensity of extreme events in the warm season. Groisman et al. (2005) report a 20 percent increase in the most intense 0.3 percent of precipitation events in the central U.S. over this period. By contrast, there has been a slight decrease in the frequency of light

> or average precipitation events (CCSP 2008). Records from Cedar Rapids (IEM 2008) show that there were 14 days from 1901 to 1950 that had three or more inches of daily total precipitation. Between 1951 and 2000, this number rose to 23 days. Over the last 113 years, annual precipitation in Cedar Rapids has increased by about 9 inches, from 28 to 37 inches. Increases have come in both the warm season and cool season, with the cool season precipitation currently being about 50 percent higher than a hundred years ago. The Cedar Rapids record agrees with the regional trend of increased precipitation since 1976, but the Cedar Rapids upward trend started much earlier. So although it is hard to argue that this locale's increase in annual total precipitation is due to anthropogenic effects of the last 30 years, models suggest this existing trend will continue. The increase in number of days with intense precipitation, by contrast, has increased in the latter part of the 20th century, which is consistent with changes attributable to anthropogenic effects (p. 112).

A conference held at St. Louis University in November, 2008 drew together several scientists who study climate change effects on streamflow. Although the papers presented at this conference were not peer reviewed, several agreed that flooding is becoming more frequent in the Mississippi River basin (Criss 2009; Pinter 2009) or that flooding is likely to become more frequent under climate change scenarios (Pan 2009; Wuebbles et al. 2009).

Projections from the North American Regional Climate Change Assessment Project (NARCCAP) show a continuation of several of these trends through the middle of the 21st century (Kunkel 2011). The entire Midwestern region is projected to see increases in precipitation in winter, spring and fall.

Moreover, the number of days with more than 1 inch of precipitation is projected to increase throughout the Midwest. Between 1971 and 2000, most of the area south of the Missouri-Iowa border (an area extending as far as Columbus, Ohio) experienced about 6-8 days per year in which precipitation exceeded 1 inch. There were isolated sections in the Ohio River basin in southern Indiana and near the Mississippi confluence in which the total was higher, with 8-10 days per year exceeding 1 inch of precipitation. Most of the Mississippi River basin between the Iowa-Missouri border and Minneapolis saw 4-6 days per year with more than 1 inch of precipitation. NARCCAP projects an increase in heavy precipitation days for the period 2041-2070. According to Kunkel, "Most areas exhibit changes in the number of days of between 0 and 1.5 days per year, with the entire region indicating an increase in [heavy precipitation] days. The largest change is in Wisconsin and small adjacent areas, where the number of days may increase by up to 2 days per year" (p. 25). Most of eastern Iowa along the Mississippi River basin is projected to see an increase of 1.0 to 1.5 days per year; most of the northern half of Missouri is projected to experience an increase of 0.5 to 1.0 days per year.

The observations and projections cited above do not appear to contradict the opinion of Pryor et al. (2009) that "the most common cause of flooding is intense and/or prolonged storm precipitation (Nott 2006). Given the increase in intensity of extreme precipitation events, an increased risk of flooding seems likely" (p. 110-111).

Adaptation

Four adaptation options deserve consideration as the nation manages its levee system in the face of increased flooding risk. First, new development in floodplains can be discouraged. Second, buyouts can be used to encourage property owners in floodplains to move. Third, the deliberate breaching of levees is a controversial option. Finally, the rebuilding and repair of existing urban levee systems is an important task.

New development: Every new levee that is built increases pressure on existing levees. Discouraging development in floodplains that will require new levee systems is therefore a key adaptation option.

Buyouts: The acquisition of flood-prone properties has been an important tool for reducing flooding risk, and should be considered a key adaptation option. Once properties are purchased, the land is dedicated to open space, either for recreational uses or for natural wetlands. After the devastating 1993 flood, FEMA provided $54.9 million to the State of Missouri in Hazard Mitigation Grant Program funding. Missouri used the majority of these funds to acquire, relocate or elevate more than 4,800 properties (FEMA 2002).

Deliberate breaching or abandonment: The breaching of agricultural levees in sparsely populated areas for the purpose of relieving pressure on levees protecting more densely populated urban areas has been a controversial flood control tactic. It was used most recently in May, 2011, near Birds Point, Missouri. According to Olson and Morton (2012):

> Heavy snow melt and rainfall ten times greater than average across the eastern half of the ... Mississippi watershed in spring and early summer of 2011 produced one of the most powerful floods in the river's known history....The deliberate breaching of the levees in the New Madrid Floodway below Cairo in May 2011 was a planned strategy to reduce water pressure and prevent levee failures where harm to human life might occur. The induced breach and the flooding of 53,824 ha (133,000 ac) of Missouri farmland resulted in the loss of 2011 crops and damage to future soil productivity (p. 5A).

The breaching damaged about 200 buildings, including about 90 homes. Lawsuits were filed on behalf of property owners in an attempt to stop the breach, although the authority of the U.S. Army Corps of Engineers to use the floodway was upheld.

The action at Birds Point revealed a tradeoff between protection of farmland in rural communities and protection of densely populated urban areas. Many agricultural levees were built in the 1930s and protect sparsely populated areas. Allowing agricultural levees to be overtopped, or to be deliberately breached, is an option that allows low-lying land to be used for storage of water from overflowing rivers, relieving pressure on urban levees. However, this policy option is highly sensitive in rural areas. As flooding risks rise in coming years, difficult decisions may have to be faced regarding tradeoffs between protecting urban and rural lands, and just compensation for those affected by these decisions.

Abandoning selected rural levees for the purpose of relieving pressure on urban levees could result in significant damage to productive agricultural lands. On the other hand, removal of levees could have the additional benefit of allowing the restoration of wetlands, which have both high ecological significance and high flood control value.

Repairing urban levees: The possibility of increased flooding risk in the Midwest, combined with questions over the adequacy of levee systems protecting Midwestern communities, suggest that repair and enhancement of levee systems will be a key adaptation option in the region. Historically, the job of maintaining levee systems has included key roles for both local governments and the U.S. Army Corps of Engineers, and a partnership between federal and local agencies will remain crucial.

The Southwest Illinois Flood Protection District Council provides a model of regional collaboration to enhance levee protection. The following information is taken from the Council's Project Implementation Plan, approved July, 2011.

The Council was formed in 2009 through an Intergovernmental Agreement between the Flood Prevention Districts of Madison, St. Clair and Monroe counties as authorized by the Illinois Flood Prevention District Act of 2008 (70 ILCS 750). Voters in each of the three affected counties passed a 1/4 cent sales tax in 2008 to finance levee repairs. The tax has been collected since 2009, and produces about $11 million annually.

Five separate levee systems in the three counties protect a 174 square mile area known as the American Bottom. The American Bottom, part of the St. Louis metropolitan area, is home to about 155,000 residents; businesses in the area employ over 55,000 people. Many major manufacturing facilities are located in the area.

Leaders in the three counties banded together to enhance levee protection in the area, even though experience in previous floods, as well as past inspections, do not indicate that the levee systems would fail to protect against a 100 year flood. According to the Project Implementation Plan, the "American Bottom has not been flooded by the Mississippi River in the 70 years since the flood protection system was initially built, including during the flood of record in 1993, a 300-year event.... The levee systems have consistently been determined to be in acceptable or marginally acceptable condition by annual and more thorough 3-year periodic inspections by the [U.S. Army] Corps [of Engineers]" (p. 3, 5).

The Council's Project Implementation Plan outlines a five year, $150 million project to maintain the levee system's high level of flood protection. Climate change was not a factor in the decision to enhance flood protection in the American Bottom. Still, the regional collaboration that created the Council provides an illustration of how local governments can reduce risk by creating solutions across jurisdictional boundaries.

Conclusion

The projected increases in flooding risk over the next century heighten the urgency of examining the nation's levee system. Repairing urban levees that protect dense housing and heavy industry is a key adaptation option. Other potential adaptation options to be considered are protection of floodplains from further development, buying out properties currently located in floodplains, and using sparsely populated areas currently protected by agricultural levees for storage during severe floods.

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Chapter 13

Complexity and Uncertainty

Implications for Climate Change Assessments

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13.1 Introduction

The preceding chapters synthesized recent literature to highlight climate change vulnerabilities and potential impacts for the Midwest. Evident from these chapters and the literature from which they are drawn is the complexity and uncertainty of climate change. Robust decision-making by Midwestern residents and stakeholders necessitates that this complexity and uncertainty be embraced, rather than minimized, as adaptation strategies and mitigation measures are developed, evaluated, and implemented.

Our goal in this final chapter is to encourage assessment teams and decision-makers to consider complexity and uncertainty as an integral part of their activities. We focus on four components of this theme that cut across the previous chapters: the multiple sources of uncertainty underlying climate change assessments; climate extremes and their disproportionately large impacts on physical and social systems; the potential, but often difficult to evaluate, co-benefits of mitigation and adaptation strategies; and spatial interactions and linkages.

All sectors of the Midwest will be impacted by climate change to some degree, and understanding the complexity of the problem along with the underlying uncertainty will provide a foundation for more robust adaptation and mitigation strategies. Adopting a proactive attitude towards the utilization of uncertainty and complexity will benefit everyone in the long term.

13.2 Multiple Sources of Uncertainty

Most climate change assessments acknowledge uncertainty surrounding the projected future climate, although the degree to which this uncertainty is incorporated into the assessment and ensuing decision-making varies. The chapters of this volume highlight the necessity of considering climate uncertainty when developing adaptation strategies for the Midwest. Almost all of the chapters point to the critical role of precipitation in the region's natural and human processes, but, as described in Chapter 3, future precipitation projections, particularly for the warm season, are highly uncertain. Ignoring this uncertainty, and that of other climate variables, can lead to non-robust decision-making.

But climate uncertainty is not the only uncertainty source that needs to be incorporated in an assessment. Few stakeholders can directly use future projections of climate variables in their decision-making. Instead, they require information on changes in climate-influenced parameters of relevance to their activity or industry. Thus, it is common to feed climate projections into response models that translate the climate information into changes in management-related variables. The structure of these response models ranges from primarily empirical to process-based models. Model structural differences have only recently been recognized as an important additional source of uncertainty for climate assessments. For example, comparisons as part of the Agriculture Model Intercomparison and Improvement Project (AgMIP) found that the magnitude of the uncertainty in projected wheat yield that was introduced by structural differences in the alternative models for wheat yield was as large or larger than that introduced by different downscaled climate projections (Asseng et al. 2013). The complexity introduced into assessments by structural uncertainty is also illustrated by the discussion of future Great Lakes water levels found in Chapter 12. Potential evaporation is a key variable for estimating water levels, and those projections of future Great Lakes water levels where temperature was used as a proxy for potential evapotranspiration suggest substantial reductions in lake levels, whereas those that simulate evapotranspiration using an energy-based approach are inconsistent in terms of the sign (positive or negative) of future lake level changes. This uncertainty propagates into management decisions as illustrated in Chapter 7, where both "high water" and "low water" vulnerabilities are identified for Great Lakes coastal environments. These examples highlight that the inclusion of multiple response models with differing structures needs to become a standard practice in assessment studies, similar to the inclusion of multiple climate projections.

The preceding chapters also illustrate the importance of non-climatic sources of uncertainty, such as uncertainty about human demography, culture, and preferences. For example, agricultural production (Chapter 4) will need to adjust to uncertain population changes and shifts in food preferences, in addition to climate change. Human-induced land-cover change will have a large impact on the biodiversity of the Midwest (Chapters 5 and 6), as will changes in the public's support for conservation. Non-climatic factors such as potential changes in wealth can have a large impact on future recreation and tourism (Chapter 10). Very little of the large body of literature that was reviewed for this synthesis report directly considered these multiple sources of uncertainty. This remains an area of future expansion that is ripe for the development of innovative approaches and methods for estimating this uncertainty and incorporating it into decision-making.

13.3 Climate Extremes

A recurring theme in the preceding chapters is the large anticipated impacts associated with climate extremes, some of which have changed in the recent past (Chapter 2) or are projected to change in the future (Chapter 3). For example, an increased likelihood of extreme high temperatures is a concern for meat, milk, and egg production in the Midwest (Chapter 4), and future changes in flood, drought, and fire frequency will impact the region's biodiversity (Chapter 5), including its forested landscapes (Chapter 6). Changes in storm-generated wave energy will modify the beaches and dunes along the Great Lakes (Chapter 7). An increased frequency of extreme weather will place further burdens on energy supply for the region (Chapter 8), and a potential increase in heat waves poses one of the largest climate-related health risks for Midwestern residents (Chapter 9). An increased risk of wildfire due to warmer and/or drier conditions is anticipated to have a substantial impact on the region's outdoor recreation and tourism (Chapter 10). Flooding and high water levels will disrupt river traffic (Chapter 11) and stress the region's levee system (Focus Section), and more intense, but fewer, individual precipitation events will have large consequences for streamflow and runoff in the region (Chapter 12).

Projecting the future frequency of climate extremes and their impacts is complex and uncertain, however. Defining a "climate extreme" is in itself complex. For some applications, a climate extreme may be best defined as the exceedance of a threshold value that has physiological or economic significance for a particular system or activity, whereas for other applications a climate extreme may be better defined in terms of the probability of occurrence. Also, as pointed out by IPCC (2012), some climate extremes, such as droughts, are made up of individual events (i.e., warm and/or dry days) that by themselves are not extreme.

Another source of complexity is that changes in the future frequency of climate extremes can come about from shifts in the mean of the probability distribution of a climate variable, an increase or decrease in the variability of the distribution (i.e., "thinning" or "fattening" of the tails of the distribution), or changes in the symmetry of the distribution due to changes in both the mean and the variability (Wigley 1988). As seen from Chapter 3, much of the literature on the future climate for the Midwest has focused on changes in the mean value of climate parameters, although some studies have also considered changes in the frequency of selected exceedance levels, such as the frequency of freezing temperatures or precipitation events over a specified threshold. Many fewer studies have explicitly considered potential changes in the shape of the probability distribution or the combined effects of changes in the location and shape parameters of a distribution. Also, climate models imperfectly simulate natural climate variability (although their skill is improving), making it difficult to separate variability changes associated with increased greenhouse gases from natural variability. Furthermore, climate variability in the Midwest is unlikely to monotonically change into the future, but rather temporal variations in the shape of the distributions of underlying climate parameters can be expected (Guentchev et al. 2009). Non-climatic factors are another source of complexity and uncertainty, as they influence the vulnerability of human and physical systems to climate extremes, as well as the development of adaptation strategies.

Given the disproportionately large impacts of climate extremes compared to changes in the mean state, it is imperative that climate change assessments carefully consider the complexity and uncertainty surrounding the exposure, vulnerability, and impacts of these events.

13.4 Co-Benefits of Mitigation and Adaptation Strategies

Climate change assessments often neglect the potential co-benefits of mitigation and adaptation strategies, which can also lead to non-robust decision-making. “Co-benefits” is used here to refer to both intentional or direct benefits of specific actions or policies and to the secondary or ancillary benefits of these policies (U.S. EPA 2004). Challenges for climate change assessments include anticipating the wide range of possible co-benefits from mitigation and policy strategies, valuing (quantitatively and qualitatively) the full range of potential benefits, and including co-benefits in informed decision-making.

Co-benefits are discussed directly or indirectly in several of the preceding chapters. For example, in Chapter 9, improved human health is posed as a potential co-benefit of a greener transportation system, supplementing the direct benefit of decreased greenhouse gas emissions. The ancillary benefits of improved air quality and physical fitness can lead to greater human life spans. A major conclusion of Chapter 8 is that climate change policy can have as large an impact on the energy sector as climate change itself, with potential co-benefits including greater energy efficiency, a broader energy portfolio, and even changes in land-management practices.

Both of these chapters examine the co-benefits of mitigation strategies, which is reflective of the focus of the broader literature. Only recently have the co-benefits of adaptation strategies begun to receive attention (e.g., Africa Development Bank 2013). Multiple co-benefits of adaptation practices can be postulated for the sectors highlighted in this report. For example, the use of green roofs to reduce the impact of warmer temperatures on residents of urban environments can also contribute to more efficient use of water resources. Agricultural practices to decrease soil moisture loss can lead to reduced soil erosion. More sustainable land management may be a co-benefit of adaptation strategies to maintain biodiversity. Robust decision-making for the Midwest will require that the co-benefits of adaptation strategies be considered to a greater extent than currently.

13.5 Spatial Interactions and Linkages

Much of the existing climate assessment literature for the Midwest and elsewhere can be described as “place based”, taking the view that the effects of climate change are isolated to a particular sector within a spatial region. These studies emphasize the unique aspects of a location or region and generally disregard the complexity of the broader spatial linkages which exist regionally, nationally, and internationally. For example, as pointed out in Chapter 4, the Midwest is the primary producer of soybean. However, in the world context soybean prices and trade are affected by climate effects on other major soybean production regions, such as South America, and by world-wide demand. Consequently, relative changes in the productivity of one region in comparison to other production regions have implications for the viability of the agricultural activity at a particular location, in this case the Midwest. These types of spatial linkages are not only relevant for agriculture, but also for many other sectors including the energy (Chapter 8), recreation and tourism (Chapter 10) and transportation (Chapter 11) sectors.

In general, the spatial context of an assessment has to be broader than the assessment's spatial scale and include all aspects of society in the spatial context. This adds another degree of complexity to the problem; however, these aspects may be critical in the development of robust decision-making and the development of robust adaptation and mitigation strategies. Currently, few options are available for incorporating global-scale spatial interactions of relevance to a region, yet preserving the granularity in assessment outcomes that is often needed for decision-making at the regional level, and this represents an important and immediate concern for assessment studies.

13.6 Closing Remarks

Throughout the Midwest, there are many examples of the impacts of climate on every sector which directly or indirectly impact the well-being of those in the Midwest and the global community. If we are to use our information on climate change to enhance decision-making, the complexities and uncertainties associated with climate change must be considered, and novel approaches will be needed to better communicate and incorporate complexity and uncertainty in the assessment process.

In this final chapter we provided a few examples of the many complexities and uncertainties that need to be considered in climate change assessments. The preceding chapters synthesized the available literature and offer additional insights into the complexities and uncertainties associated with the climate change vulnerability and potential impacts in the Midwest. We hope that Midwestern stakeholders and decision-makers will utilize this information to further contribute to the development of enhanced and improved assessment and communication strategies that embrace complexity and uncertainty and that lead to robust decision-making in the face of climate change for the Midwest.

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