CHAPTER
Two

Scenarios of Change: Past, Current, and Future Climate

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

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

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

Climate Trends and Variability in the Great Lakes Region

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

The International Consensus on Climate Change

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

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

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

changes and their causes is described in the box above.

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

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

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

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

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

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

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

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

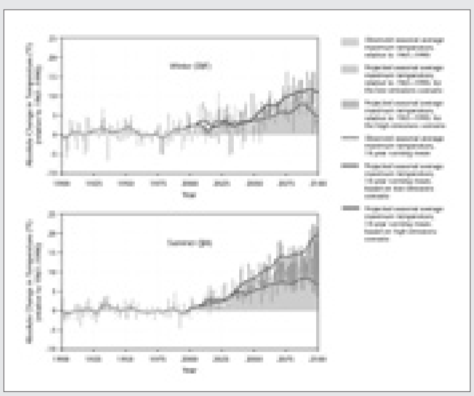

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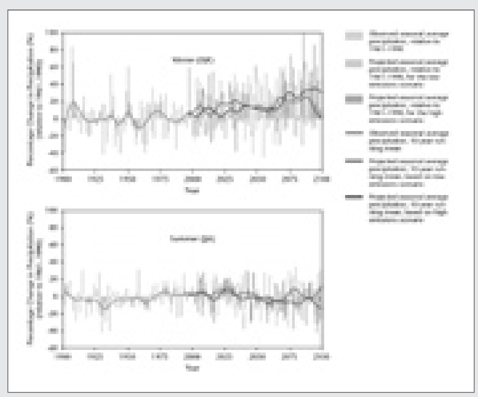
FIGURE 6B
Observed and Projected Change in Average Daily Precipitation
(Averaged Over Entire Region)



See page 37
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1900s. Growing seasons have also begun to lengthen in the past two decades.

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

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

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

Water Temperatures

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

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

Duration and Extent of Lake Ice

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

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

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

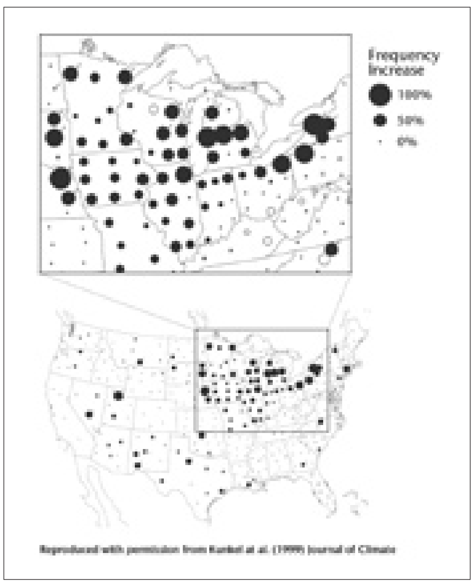

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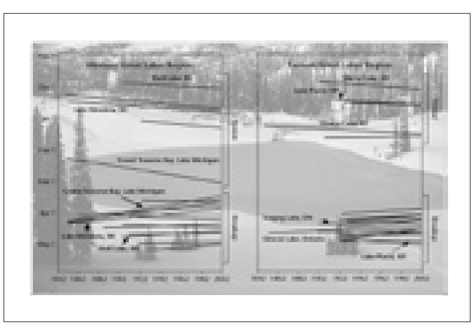
FIGURE 8
Change in Timing of Lake Freezes and Thaws



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On Thin Ice in Madison

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

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

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

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

FIGURE 9A

Ice Cover Duration on Lake Mendota, Wisconsin

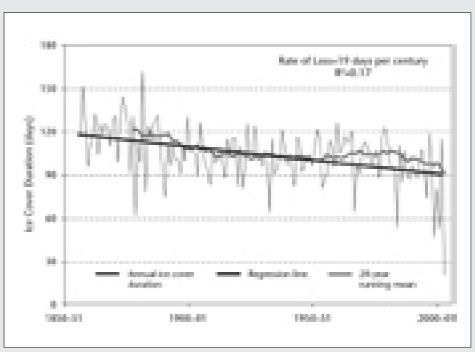

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FIGURE 9B

Kites on Ice Winter Festival 2002 on Lake Monona, Wisconsin

See page 39
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greenhouse gases. Recent analyses suggest that El Niños are becoming stronger,[32] and the influence of El Niños on earlier ice breakup has increased in recent years.[33]

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

Lake Water Levels and Stream Flows

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

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

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

Projections of Future Climate in the Great Lakes Region

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

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

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

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

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

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

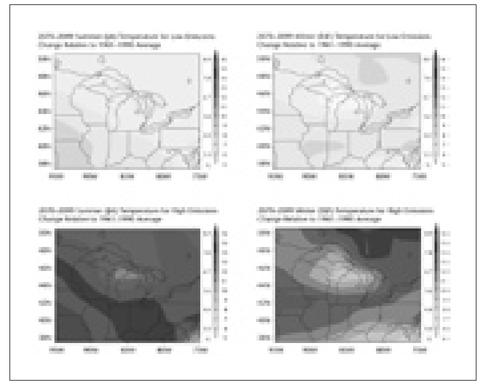

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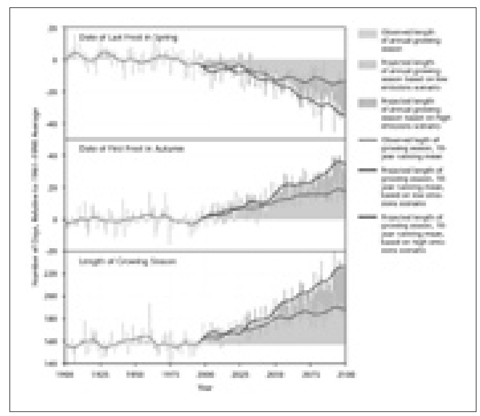
FIGURE 11
Growing Season in the Great Lakes Region (1900–2100)



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Temperature

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

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

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

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

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

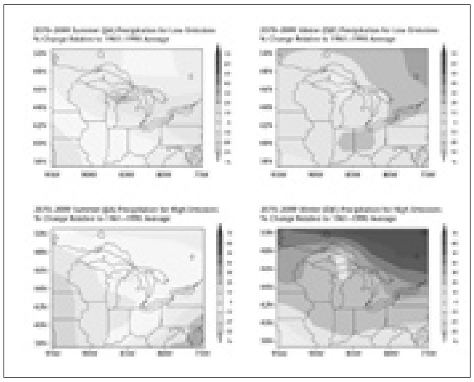

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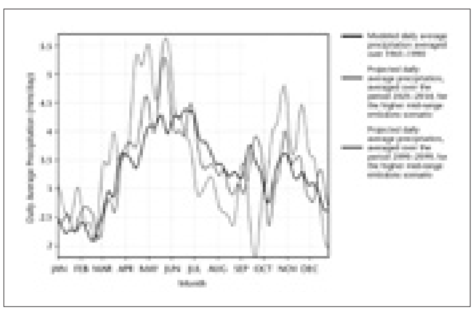
FIGURE 13
Seasonal Precipitation Cycle (Historical Baseline and Projected Changes, 10-Day Running Mean)



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

Precipitation, Extreme Events, and Runoff

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

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

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

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

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

Migrating Climates

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

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

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

The Potential for Surprise

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

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

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

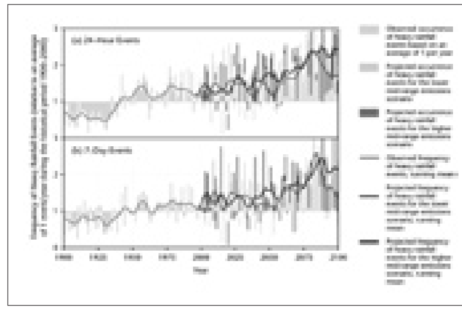

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FIGURE 15
Precipitation Shifts Signal Trouble for Farmers

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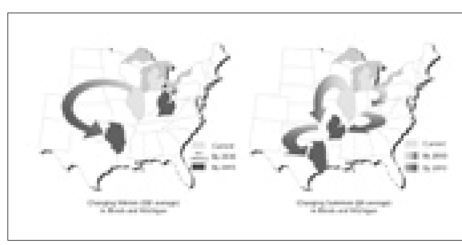
FIGURE 16
Migrating Climate: Changing Winters and Summers in Illinois and Michigan



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