Climate Change Impacts in the United States

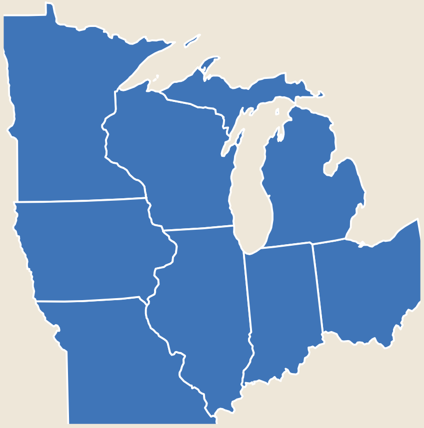
CHAPTER 18
MIDWEST

Convening Lead Authors

Sara C. Pryor, Indiana University
Donald Scavia, University of Michigan

Lead Authors

Charles Downer, U.S. Army Engineer Research and Development Center
Marc Gaden, Great Lakes Fishery Commission
Louis Iverson, U.S. Forest Service
Rolf Nordstrom, Great Plains Institute
Jonathan Patz, University of Wisconsin
G. Philip Robertson, Michigan State University



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18 MIDWEST

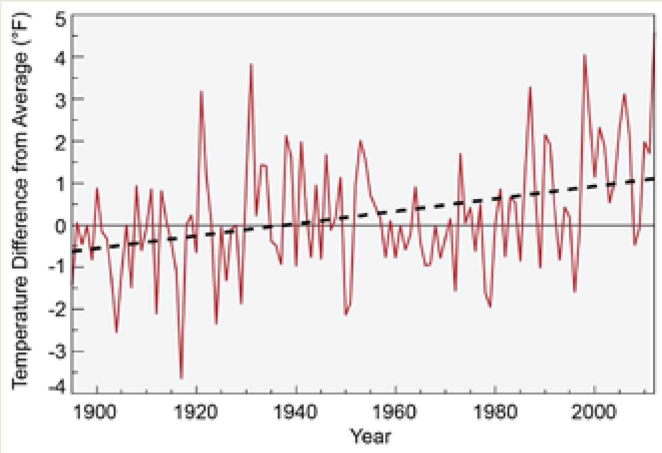
KEY MESSAGES

1. **In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.**
2. **The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.**
3. **Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.**
4. **The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.**
5. **Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.**
6. **Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.**

The Midwest has a population of more than 61 million people (about 20% of the national total) and generates a regional gross domestic product of more than $2.6 trillion (about 19% of the national total).[1] The Midwest is home to expansive agricultural lands, forests in the north, the Great Lakes, substantial industrial activity, and major urban areas, including eight of the nation's 50 most populous cities. The region has experienced shifts in population, socioeconomic changes, air and water pollution, and landscape changes, and exhibits multiple vulnerabilities to both climate variability and climate change.

In general, climate change will tend to amplify existing climate-related risks from climate to people, ecosystems, and infrastructure in the Midwest (Ch. 10: Energy, Water, and Land). Direct effects of increased heat stress, flooding, drought, and late spring freezes on natural and managed ecosystems may be multiplied by changes in pests and disease prevalence, increased competition from non-native or opportunistic native species, ecosystem disturbances, land-use change, landscape fragmentation, atmospheric pollutants, and economic shocks such as crop failures or reduced yields due to extreme weather events. These added stresses, when taken collectively, are projected to alter the ecosystem and socioeconomic patterns and processes in ways that most people in the region would consider detrimental. Much of the region's fisheries, recreation, tourism, and commerce depend on the Great Lakes and expansive northern forests, which already face pollution and invasive species pressure that will be exacerbated by climate change.

Most of the region's population lives in cities, which are particularly vulnerable to climate change related flooding and life-threatening heat waves because of aging infrastructure and other factors. Climate change may also augment or intensify other stresses on vegetation encountered in urban environments, including increased atmospheric pollution, heat island effects, a highly variable water cycle, and frequent exposure to new pests and diseases. Some cities in the region are already engaged in the process of capacity building or are actively building resilience to the threats posed by climate change. The region's highly energy-intensive economy emits a disproportionately large amount of the gases responsible for warming



Temperatures are Rising in the Midwest

Figure 18.1. Annual average temperatures (red line) across the Midwest show a trend towards increasing temperature. The trend (dashed line) calculated over the period 1895-2012 is equal to an increase of 1.5°F. (Figure source: updated from Kunkel et al. 2013[4]).

the climate (called greenhouse gases or heat-trapping gases). But as discussed below, it also has a large and increasingly realized potential to reduce these emissions.

The rate of warming in the Midwest has markedly accelerated over the past few decades. Between 1900 and 2010, the average Midwest air temperature increased by more than 1.5°F (Figure 18.1). However, between 1950 and 2010, the average temperature increased twice as quickly, and between 1980 and 2010, it increased three times as quickly as it did from 1900 to 2010.[1] Warming has been more rapid at night and during winter. These trends are consistent with expectations of increased concentrations of heat-trapping gases and observed changes in concentrations of certain particles in the atmosphere.[1,2]

The amount of future warming will depend on changes in the atmospheric concentration of heat-trapping gases. Projections for regionally averaged temperature increases by the middle of the century (2046-2065) relative to 1979-2000 are approximately 3.8°F for a scenario with substantial emissions reductions (B1) and 4.9°F with continued growth in global emissions (A2). The projections for the end of the century (2081-2100) are approximately 5.6°F for the lower emissions scenario and 8.5°F for the higher emissions scenario (see Ch. 2: Our Changing Climate, Key Message 3).[3]

In 2011, 11 of the 14 U.S. weather-related disasters with damages of more than $1 billion affected the Midwest.[5] Several types of extreme weather events have already increased in frequency and/or intensity due to climate change, and further increases are projected (Ch. 2: Our Changing Climate, Key Message 7).[6]

Key Message 1: Impacts to Agriculture

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Agriculture dominates Midwest land use, with more than two-thirds of land designated as farmland.[3] The region accounts for about 65% of U.S. corn and soybean production,[7] mostly from non-irrigated lands.[1] Corn and soybeans constitute 85% of Midwest crop receipts, with high-value crops such as fruits and vegetables making up most of the remainder.[8] Corn and soybean yields increased markedly (by a factor of more than 5) over the last century largely due to technological innovation, but are still vulnerable to year-to-year variations in weather conditions.[9]

The Midwest growing season lengthened by almost two weeks since 1950, due in large part to earlier occurrence of the last spring freeze.[10] This trend is expected to continue,[3,11] though the potential agricultural consequences are complex and vary by crop. For corn, small long-term average temperature increases will shorten the duration of reproductive development, leading to yield declines,[12] even when offset by carbon dioxide (CO_2) stimulation.[13] For soybeans, yields have a two in three chance of increasing early in this century due to CO_2 fertilization, but these increases are projected to be offset later in the century by higher temperature stress[14] (see Figure 18.2 for projections of increases in the frost-free season length and the number of summer days with temperatures over 95°F).

Future crop yields will be more strongly influenced by anomalous weather events than by changes in average temperature or annual precipitation (Ch. 6: Agriculture). Cold injury due to a freeze event after plant budding can decimate fruit crop production,[15] as happened in 2002, and again in 2012, to Michigan's $60 million tart cherry crop. Springtime cold air outbreaks (at least two consecutive days during which the daily average surface air temperature is below 95% of the simulated average wintertime surface air temperature) are projected to continue to occur throughout this century.[16] As a result, increased productivity of some crops due to higher temperatures, longer growing seasons, and elevated CO_2 concentrations could be offset by increased freeze damage.[17] Heat waves during pol-

Projected Mid-Century Temperature Changes in the Midwest

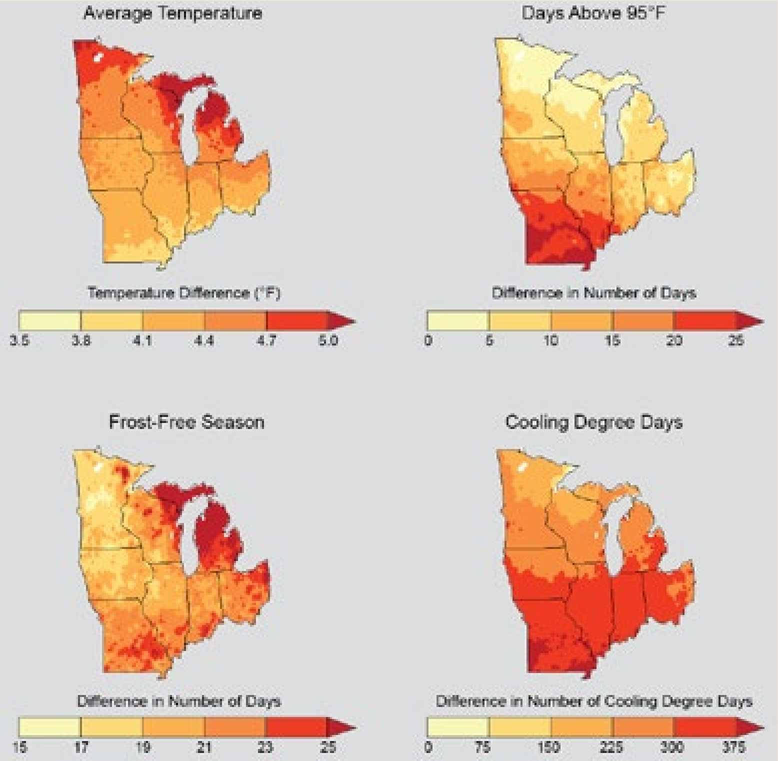


Figure 18.2. Projected increase in annual average temperatures (top left) by mid-century (2041-2070) as compared to the 1971-2000 period tell only part of the climate change story. Maps also show annual projected increases in the number of the hottest days (days over 95°F, top right), longer frost-free seasons (bottom left), and an increase in cooling degree days (bottom right), defined as the number of degrees that a day's average temperature is above 65°F, which generally leads to an increase in energy use for air conditioning. Projections are from global climate models that assume emissions of heat-trapping gases continue to rise (A2 scenario). (Figure source: NOAA NCDC / CICS-NC).

lination of field crops such as corn and soybean also reduce yields (Figure 18.3).[12] Wetter springs may reduce crop yields and profits,[18] especially if growers are forced to switch to late-planted, shorter-season varieties. A recent study suggests the volatility of U.S. corn prices is more sensitive to near-term climate change than to energy policy influences or to use of agricultural products for energy production, such as biofuel.[19]

Agriculture is responsible for about 8% of U.S. heat-trapping gas emissions,[20] and there is tremendous potential for farming practices to reduce emissions or store more carbon in soil.[21] Although large-scale agriculture in the Midwest historically led to decreased carbon in soils, higher crop residue inputs and adoption of different soil management techniques have reversed this trend. Other techniques, such as planting cover crops and no-till soil management, can further increase CO_2 uptake and reduce energy use.[22,23] Use of agricultural best management practices can also improve water quality by reducing the loss of sediments and nutrients from farm fields. Methane released from animals and their wastes can be reduced by altered diets and methane capture systems, and nitrous oxide production can be reduced by judicious fertilizer use[24] and improved waste handling.[21] In addition, if biofuel crops are grown sustainably,[25] they offer emissions reduction opportunities by substituting for fossil fuel-based energy (Ch. 10: Energy, Water, and Land).

Crop Yields Decline under Higher Temperatures

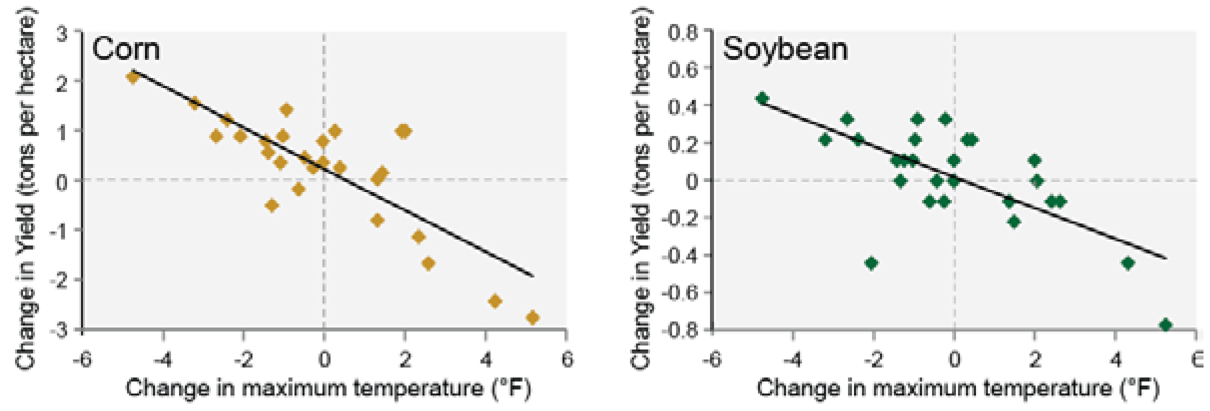


Figure 18.3. Crop yields are very sensitive to temperature and rainfall. They are especially sensitive to high temperatures during the pollination and grain filling period. For example, corn (left) and soybean (right) harvests in Illinois and Indiana, two major producers, were lower in years with average maximum summer (June, July, and August) temperatures higher than the average from 1980 to 2007. Most years with below-average yields are both warmer and drier than normal.[26,27] There is high correlation between warm and dry conditions during Midwest summers[28] due to similar meteorological conditions and drought-caused changes.[29] (Figure source: Mishra and Cherkauer 2010[26]).

Key Message 2: Forest Composition

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

The Midwest is characterized by a rich diversity of native species juxtaposed on one of the world's most productive agricultural systems.[30] The remnants of intact natural ecosystems in the region,[31] including prairies, forests, streams, and wetlands, are rich with varied species.[32] The combined effects of climate change, land-use change, and increasing numbers of invasive species are the primary threats to Midwest natural ecosystems.[33] Species most vulnerable to climate change include those that occur in isolated habitats; live near their physiological tolerance limits; have specific habitat requirements, low reproductive rates, or limited dispersal capability; are dependent on interactions with specific other species; and/or have low genetic variability.[34]

Among the varied ecosystems of the region, forest systems are particularly vulnerable to multiple stresses. The habitat ranges of many iconic tree species such as paper birch, quaking aspen, balsam fir, and black spruce are projected to decline substantially across the northern Midwest as they shift northward, while species that are common farther south, including several oaks and pines, expand their ranges northward into the region (Figure 18.4).[35,36] There is considerable variability in the likelihood of a species' habitat changing and the adaptability of the species with regard to climate change.[37] Migration to accommodate changed habitat is expected to be slow for many Midwest species, due to relatively flat topography, high latitudes, and fragmented habitats including the Great Lakes barrier. To reach areas that are 1.8°F cooler, species in mountainous terrains need to shift 550 feet higher in altitude (which can be achieved in only a few miles), whereas species in flat terrain like the Midwest must move as much as 90 miles north to reach a similarly cooler habitat.[38]

Although global forests currently capture and store more carbon each year than they emit,[39] the ability of forests to act as large, global carbon absorbers ("sinks") may be reduced by projected increased disturbances from insect outbreaks,[40] forest fire,[41] and drought,[42] leading to increases in tree mortality and carbon emissions. Some regions may even shift from being a carbon sink to being an atmospheric carbon dioxide source,[43,44] though large uncertainties exist, such as whether projected disturbances to forests will be chronic or episodic.[45] Midwest forests are more resilient to forest carbon losses than most western forests because of relatively high moisture availability, greater nitrogen deposition (which tends to act as a fertilizer), and lower wildfire risk.[43,46]

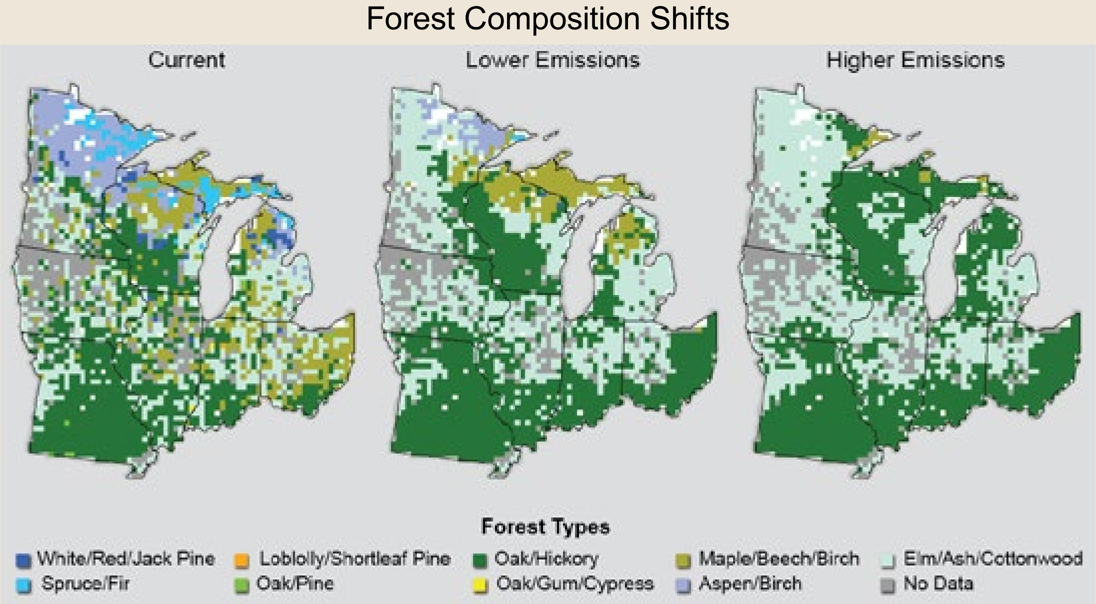


Figure 18.4. As climate changes, species can often adapt by changing their ranges. Maps show current and projected future distribution of habitats for forest types in the Midwest under two emissions scenarios, a lower scenario that assumes reductions in heat-trapping gas emissions (B1), and a very high scenario that assumes continued increases in emissions (A1FI). Habitats for white/red/jack pine, maple/beech/birch, spruce/fir, and aspen/birch forests are projected to greatly decline from the northern forests, especially under higher emissions scenarios, while various oak forest types are projected to expand.[37] While some forest types may not remain dominant, they will still be present in reduced quantities. Therefore, it is more appropriate to assess changes on an individual species basis, since all species within a forest type will not exhibit equal responses to climate change. (Figure source: Prasad et al. 2007[37]).

Key Message 3: Public Health Risks

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

The frequency of major heat waves in the Midwest has increased over the last six decades.[47] For the United States, mortality increases 4% during heat waves compared with non-heat wave days.[48] During July 2011, 132 million people across the U.S. were under a heat alert – and on July 20 of that year, the majority of the Midwest experienced temperatures in excess of 100°F. Heat stress is projected to increase as a result of both increased summer temperatures and humidity.[49,50] One study projected an increase of between 166 and 2,217 excess deaths per year from heat wave-related mortality in Chicago alone by 2081-2100.[51] The lower number assumes a climate scenario with significant reductions in emissions of greenhouse gases (B1), while the upper number assumes a scenario under which emissions continue to increase (A2). These projections are significant when compared to recent Chicago heat waves, where 114 people died from the heat wave of 1999 and about 700 died from the heat wave of 1995.[52] Heat response plans and early warning systems save lives, and from 1975 to 2004, mortality rates per heat event declined.[53] However, many municipalities lack such plans.[54]

More than 20 million people in the Midwest experience air quality that fails to meet national ambient air quality standards.[1] Degraded air quality due to human-induced emissions[55] and increased pollen season duration[56] are projected to be amplified with higher temperatures,[57] and pollution and pollen exposures, in addition to heat waves, can harm human health (Ch. 9: Human Health). Policy options exist (for example, see "Alternative Transportation Options Create Multiple Benefits") that could reduce emissions of both heat-trapping gases and other air pollutants, yielding benefits for human health and fitness. Increased temperatures and changes in precipitation patterns could also increase the vulnerability of Midwest residents to diseases carried by insects and rodents (Ch. 9: Human Health).[58]

ALTERNATIVE TRANSPORTATION OPTIONS CREATE MULTIPLE BENEFITS

The transportation sector produces one-third of U.S. greenhouse gas emissions, and automobile exhaust also contains precursors to fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3), which pose threats to public health. Adopting a low-carbon transportation system with fewer automobiles, therefore, could have immediate health "co-benefits" of both reducing climate change and improving human health via both improved air quality and physical fitness.

Reducing Emissions, Improving Health

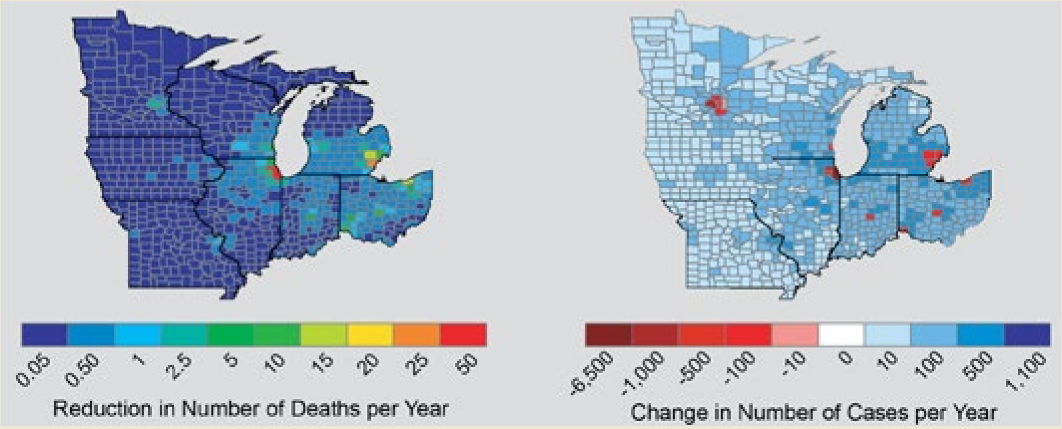


Figure 18.5. Annual reduction in the number of premature deaths (left) and annual change in the number of cases with acute respiratory symptoms (right) due to reductions in particulate matter and ozone caused by reducing automobile exhaust. The maps project health benefits if automobile trips shorter than five miles (round-trip) were eliminated for the 11 largest metropolitan areas in the Midwest. Making 50% of these trips by bicycle just during four summer months would save 1,295 lives and yield savings of more than $8 billion per year from improved air quality, avoided mortality, and reduced health care costs for the upper Midwest alone. (Figure source: Grabow et al. 2012; reproduced with permission from Environmental Health Perspectives[59]).

Key Message 4: Fossil-Fuel Dependent Electricity System

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

The Midwest is a major exporter of electricity to other U.S. regions and has a highly energy-intensive economy (Ch. 10: Energy, Water, and Land, Figure 10.4). Energy use per dollar of gross domestic product is approximately 20% above the national average, and per capita greenhouse gas emissions are 22% higher than the national average due, in part, to the reliance on fossil fuels, particularly coal for electricity generation.[1] A large range in seasonal air temperature causes energy demand for both heating and cooling, with the highest demand for winter heating. The demand for heating in major midwestern cities is typically five to seven times that for cooling,[1] although this is expected to shift as a result of longer summers, more frequent heat waves, and higher humidity, leading to an increase in the number of cooling degree days. This increased demand for cooling by the middle of this century is projected to exceed 10 gigawatts (equivalent to at least five large conventional power plants), requiring more than $6 billion in infrastructure investments.[60] Further, approximately 95% of the electrical generating infrastructure in the Midwest is susceptible to decreased efficiency due to higher temperatures.[60]

Climate change presents the Midwest's energy sector with a number of challenges, in part because of its current reliance on coal-based electricity[1] and an aging, less-reliable electric distribution grid[61] that will require significant reinvestment even without additional adaptations to climate change.[62]

Increased use of natural gas in the Midwest has the potential to reduce emissions of greenhouse gases. The Midwest also has potential to produce energy from zero- and low-carbon sources, given its wind, solar, and biomass resources, and potential for expanded nuclear power. The Midwest does not have the highest solar potential in the country (that is found in the Southwest), but its potential is nonetheless vast, with some parts of the Midwest having as good a solar resource as Florida.[63] More than one-quarter of national installed wind energy capacity, one-third of biodiesel capacity, and more than two-thirds of ethanol production are located in the Midwest (see also Ch. 4: Energy and Ch. 10: Energy, Water, and Land).[1] Progress toward increasing renewable energy is hampered by electricity prices that are distorted through a mix of direct and indirect subsidies and unaccounted-for costs for conventional energy sources.[64]

Key Message 5: Increased Rainfall and Flooding

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Precipitation in the Midwest is greatest in the east, declining towards the west. Precipitation occurs about once every seven days in the western part of the region and once every three days in the southeastern part.[65] The 10 rainiest days can contribute as much as 40% of total precipitation in a given year.[65] Generally, annual precipitation increased during the past century (by up to 20% in some locations), with much of the increase driven by intensification of the heaviest rainfalls.[65,66] This tendency towards more intense precipitation events is projected to continue in the future.[67]

Model projections for precipitation changes are less certain than those for temperature.[3,4] Under a higher emissions scenario (A2), global climate models (GCMs) project average winter and spring precipitation by late this century (2071-2099) to increase 10% to 20% relative to 1971-2000, while changes in summer and fall are not expected to be larger than natural variations. Projected changes in annual precipitation show increases larger than natural variations in the north and smaller in the south (Ch. 2: Our Changing Climate, Key Message 5).[4] Regional climate models (RCMs) using the same emissions scenario also project increased spring precipitation (9% in 2041-2062 relative to 1979-2000) and decreased summer precipitation (by an average of about 8% in 2041-2062 relative to 1979-2000) particularly in the southern portions of the Midwest.[3] Increases in the frequency and intensity of extreme precipitation are projected across the entire region in both GCM and RCM simulations (Figure 18.6), and these increases are generally larger than the projected changes in average precipitation.[3,4]

Flooding can affect the integrity and diversity of aquatic ecosystems. Flooding also causes major human and economic consequences by inundating urban and agricultural land and by disrupting navigation in the region's roads, rivers, and reservoirs (see Ch. 5: Transportation, Ch. 9: Human Health, and Ch. 11: Urban). For example, the 2008 flooding in the Midwest caused 24 deaths, $15 billion in losses via reduced agricultural yields, and closure of key transportation routes.[1] Water infrastructure for flood control, navigation, and other purposes is susceptible to climate change impacts and other forces because the de-

When it Rains, it Pours

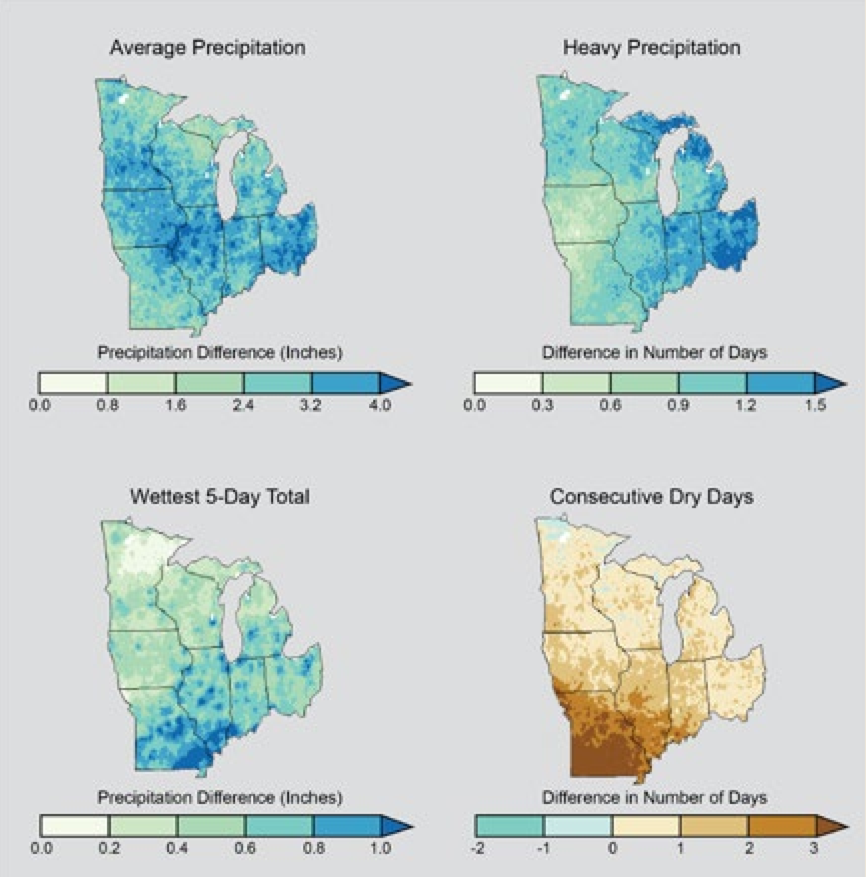


Figure 18.6. Precipitation patterns affect many aspects of life, from agriculture to urban storm drains. These maps show projected changes for the middle of the current century (2041-2070) relative to the end of the last century (1971-2000) across the Midwest under continued emissions (A2 scenario). Top left: the changes in total annual average precipitation. Across the entire Midwest, the total amount of water from rainfall and snowfall is projected to increase. Top right: increase in the number of days with very heavy precipitation (top 2% of all rainfalls each year). Bottom left: increases in the amount of rain falling in the wettest 5-day period over a year. Both (top right and bottom left) indicate that heavy precipitation events will increase in intensity in the future across the Midwest. Bottom right: change in the average maximum number of consecutive days each year with less than 0.01 inches of precipitation. An increase in this variable has been used to indicate an increase in the chance of drought in the future. (Figure source: NOAA NCDC / CICS-NC).

signs are based upon historical patterns of precipitation and streamflow, which are no longer appropriate guides.

Snowfall varies across the region, comprising less than 10% of total precipitation in the south, to more than half in the north, with as much as two inches of water available in the snowpack at the beginning of spring melt in the northern reaches of the river basins.[68] When this amount of snowmelt is combined with heavy rainfall, the resulting flooding can be widespread and catastrophic (see "Cedar Rapids: A Tale of Vulnerability and Response").[69] Historical observations indicate declines in the frequency of high magnitude snowfall years over much of the Midwest,[70] but an increase in lake effect snowfall.[71] These divergent trends and their inverse relationships with air temperatures make overall projections of regional impacts of the associated snowmelt extremely difficult. Large-scale flooding can also occur due to extreme precipitation in the absence of snowmelt (for example, Rush Creek and the Root River, Minnesota, in August 2007 and multiple rivers in southern Minnesota in September 2010).[72] These warm-season events are projected to increase in magnitude. Such events tend to be more regional and less likely to cover as large an area as those that occur in spring, in part because soil water storage capacity is typically much greater during the summer.

Changing land use and the expansion of urban areas are reducing water infiltration into the soil and increasing surface runoff. These changes exacerbate impacts caused by increased precipitation intensity. Many major Midwest cities are served by combined storm and sewage drainage systems. As surface area has been increasingly converted to impervious surfaces (such as asphalt) and extreme precipitation events have intensified, combined sewer overflow has degraded water quality, a phenomenon expected to continue to worsen with increased urbanization and climate change.[75] The U.S. Environmental Protection Agency (EPA) estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] The Great Lakes, which provide drinking water to more than 40 million people and are home to more than 500 beaches,[75] have been subject to recent sewage overflows. For example, stormwater across the city of Milwaukee recently showed high human fecal pathogen levels at all 45 outflow locations, indicating widespread sewage contamination.[77] One study estimated that increased storm events will lead to an increase of up to 120% in combined sewer overflows into Lake Michigan by 2100 under a very high emissions scenario (A1FI),[75] leading to additional human health issues and beach closures. Municipalities may be forced to invest in new infrastructure to protect human health and water quality in the Great Lakes, and local communities could face tourism losses from fouled nearshore regions.

Increased precipitation intensity also increases erosion, damaging ecosystems and increasing delivery of sediment and subsequent loss of reservoir storage capacity. Increased storm-induced agricultural runoff and rising water temperatures

CEDAR RAPIDS: A TALE OF VULNERABILITY AND RESPONSE

Cedar Rapids, Des Moines, Iowa City, and Ames, Iowa, have all suffered multi-million-dollar losses from floods since 1993. In June 2008, a record flood event exceeded the once-in-500-year flood level by more than 5 feet, causing $5 to $6 billion in damages from flooding, or more than $40,000 per resident of the city of Cedar Rapids.[73] The flood inundated much of the downtown, damaging more than 4,000 structures, including 80% of government offices, and displacing 25,000 people.[74] The record flood at Cedar Rapids was the result of low reservoir capacity and extreme rainfall on soil already saturated from unusually wet conditions. Rainfall amounts comparable to those in 1993 (8 inches over two weeks) overwhelmed a flood control system designed largely for a once-in-100-year flood event. Such events are consistent with observations and projections of wetter springs and more intense precipitation events (see Figure 18.6). With the help of more than $3 billion in funding from the federal and state government, Cedar Rapids is recovering and has taken significant steps to reduce future flood damage, with buyouts of more than 1,000 properties, and numerous buildings adapted with flood protection measures.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have increased non-point source pollution problems in recent years.[78] This has led to increased phosphorus and nitrogen loading, which in turn is contributing to more and prolonged occurrences of low-oxygen "dead zones" and to harmful, lengthy, and dense algae growth in the Great Lakes and other Midwest water bodies.[79] (Such zones and their causes are also discussed in Ch. 25: Coasts, Ch. 15: Biogeochemical Cycles, and Ch. 3: Water, Key Message 6). Watershed planning can be used to reduce water quantity and quality problems due to changing climate and land use.

While there was no apparent change in drought duration in the Midwest region as a whole over the past century,[80] the average number of days without precipitation is projected to increase in the future. This could lead to agricultural drought and suppressed crop yields.[9] This would also increase thermoelectric power plant cooling water temperatures and decrease cooling efficiency and plant capacity because of the need to avoid discharging excessively warm water (see also Ch. 4: Energy, and Ch. 10: Energy, Water, and Land).[60]

Key Message 6: Increased Risks to the Great Lakes

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

The Great Lakes, North America's largest freshwater feature, have recently recorded higher water temperatures and less ice cover as a result of changes in regional climate (see also Ch. 2: Our Changing Climate, Key Message 11). Summer surface water temperatures in Lakes Huron increased 5.2°F and in Lake Ontario, 2.7°F, between 1968 and 2002,[81] with smaller increases in Lake Erie.[81,82] Due to the reduction in ice cover, the temperature of surface waters in Lake Superior during the summer increased 4.5°F, twice the rate of increase in air temperature.[83] These lake surface temperatures are projected to rise by as much as 7°F by 2050 and 12.1°F by 2100.[84,85] Higher temperatures, increases in precipitation, and lengthened growing seasons favor production of blue-green and toxic algae that can harm fish, water quality, habitats, and aesthetics,[79,84,86] and could heighten the impact of invasive species already present.[87]

In the Great Lakes, the average annual maximum ice coverage during 2003-2013 was less than 43% compared to the 1962-2013 average of 52%,[88] lower than any other decade during the period of measurements (Figure 18.7), although there is substantial variability from year to year. During the 1970s, which included several extremely cold winters, maximum ice coverage averaged 67%. Less ice, coupled with more frequent and intense storms (as indicated by some analyses of historical wind speeds),[89] leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.[84,90] Reduced ice cover also has the potential to lengthen the shipping season.[91] The navigation season increased by an average of eight days between 1994 and 2011, and the Welland Canal in the St. Lawrence River remained open nearly two weeks longer. Increased shipping days benefit commerce but could also increase shoreline scouring and bring in more invasive species.[91,92]

Changes in lake levels can also influence the amount of cargo that can be carried on ships. On average, a 1000-foot ship sinks into the water by one inch per 270 tons of cargo;[93] thus if a ship is currently limited by water depth, any lowering of lake levels will result in a proportional reduction in the amount of cargo that it can transport to Great Lakes ports. However, current estimates of lake level changes are uncertain, even for continued increases in global greenhouse gas emissions (A2 scenario). The most recent projections suggest a slight decrease or even a small rise in levels.[94] Recent studies have also indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[94,95,96,97] The recent studies, along with the large spread in existing modeling results, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty (see Appendix 3: Climate Science Supplemental Message 8).

Ice Cover in the Great Lakes

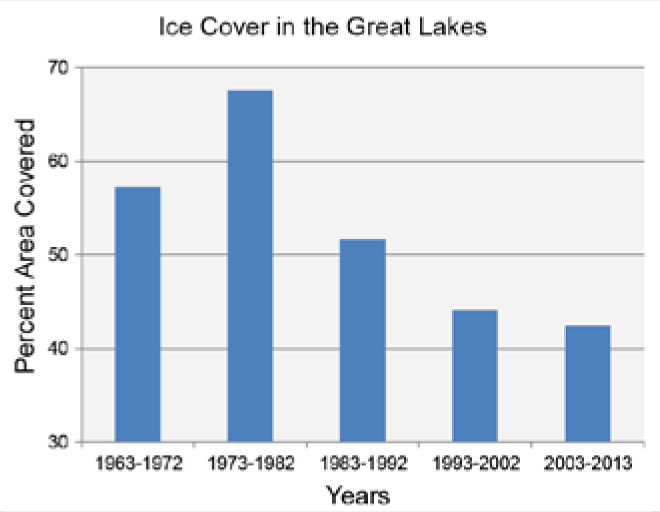

Figure 18.7. Bars show decade averages of annual maximum Great Lakes ice coverage from the winter of 1962-1963, when reliable coverage of the entire Great Lakes began, to the winter of 2012-2013. Bar labels indicate the end year of the winter; for example, 1963-1972 indicates the winter of 1962-1963 through the winter of 1971-1972. The most recent period includes the eleven years from 2003 to 2013. (Data updated from Bai and Wang, 2012[88]).

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SUPPLEMENTAL MATERIAL
TRACEABLE ACCOUNTS

Process for Developing Key Messages:

The assessment process for the Midwest Region began with a workshop was that was held July 25, 2011, in Ann Arbor, Michigan. Ten participants discussed the scope and authors for a foundational Technical Input Report (TIR) report entitled "Midwest Technical Input Report."[98] The report, which consisted of nearly 240 pages of text organized into 13 chapters, was assembled by 23 authors representing governmental agencies, non-governmental organizations (NGOs), tribes, and other entities.

The Chapter Author Team engaged in multiple technical discussions via teleconferences that permitted a careful review of the foundational TIR[98] and of approximately 45 additional technical inputs provided by the public, as well as the other published literature, and professional judgment. The Chapter Author Team convened teleconferences and exchanged extensive emails to define the scope of the chapter for their expert deliberation of input materials and to generate the chapter text and figures. Each expert drafted key messages, initial text and figure drafts and traceable accounts that pertained to their individual fields of expertise. These materials were then extensively discussed by the team and were approved by the team members.

KEY MESSAGE #1 TRACEABLE ACCOUNT

In the next few decades, longer growing seasons and rising carbon dioxide levels will increase yields of some crops, though those benefits will be progressively offset by extreme weather events. Though adaptation options can reduce some of the detrimental effects, in the long term, the combined stresses associated with climate change are expected to decrease agricultural productivity.

Description of evidence base

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical input reports on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for altered growing seasons across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] and its references provide specific details for the Midwest. Evidence for longer growing seasons in the Midwest is based on regional temperature records and is incontrovertible, as is evidence for increasing carbon dioxide concentrations.

U.S. Department of Agriculture data tables provide evidence for the importance of the eight Midwest states for U.S. agricultural production.[8] Evidence for the effect of future elevated carbon dioxide concentrations on crop yields is based on scores of greenhouse and field experiments that show a strong fertilization response for C_3 plants such as soybeans and wheat and a positive but not as strong a response for C_4 plants such as corn. Observational data, evidence from field experiments, and quantitative modeling are the evidence base of the negative effects of extreme weather events on crop yield: early spring heat waves followed by normal frost events have been shown to decimate Midwest fruit crops; heat waves during flowering, pollination, and grain filling have been shown to significantly reduce corn and wheat yields; more variable and intense spring rainfall has delayed spring planting in some years and can be expected to increase erosion and runoff; and floods have led to crop losses.[12,13,14]

New information and remaining uncertainties

Key issues (uncertainties) are: a) the rate at which grain yield improvements will continue to occur, which could help to offset the overall negative effect of extreme events at least for grain crops (though not for individual farmers); and b) the degree to which genetic improvements could make some future crops more tolerant of extreme events such as drought and heat stress. Additional uncertainties are: c) the degree to which accelerated soil carbon loss will occur as a result of warmer winters and the resulting effects on soil fertility and soil water availability; and d) the potential for increased pest and disease pressure as southern pests such as soybean rust move northward and existing pests better survive milder Midwest winters.

Assessment of confidence based on evidence

Because nearly all studies published to date in the peer-reviewed literature agree that Midwest crops benefit from CO_2 fertilization and some benefit from a longer growing season, there is **very high** confidence in this component of the key message.

Studies also agree that full benefits of climate change will be offset partly or fully by more frequent heat waves, early spring thaws followed by freezing temperatures, more variable and intense rainfall events, and floods. Again, there is **very high** confidence in this aspect.

There is less certainty (**high**) about pest effects and about the potential for adaptation actions to significantly mitigate the risk of crop loss.

Confidence Level

Very High	Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High	Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium	Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low	Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Key Message #2 Traceable Account

The composition of the region's forests is expected to change as rising temperatures drive habitats for many tree species northward. The role of the region's forests as a net absorber of carbon is at risk from disruptions to forest ecosystems, in part due to climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for increased temperatures and altered growing seasons across the U.S. is discussed in Chapter 2 (Our Changing Climate, Key Messages 3 and 4) and its Traceable Accounts. "Climate Trends and Scenarios for the U.S. National Climate Assessment,"[4] with its references, provides specific details for the Midwest. Evidence that species have been shifting northward or ascending in altitude has been mounting for numerous species, though less so for long-lived trees. Nearly all studies to date published in the peer-reviewed literature agree that many of the boreal species of the north will eventually retreat northward. The question is when. Multiple models and paleoecological evidence show these trends have occurred in the past and are projected to continue in the future.[36]

The forests of the eastern United States (including the Midwest) have been accumulating large quantities of carbon over the past century,[23] but evidence shows this trend is slowing in recent decades. There is a large amount of forest inventory data supporting the gradual decline in carbon accumulation throughout the eastern United States,[99] as well as evidence of increasing disturbances and disturbance agents that are reducing overall net productivity in many of the forests.

New information and remaining uncertainties

A key issue (uncertainty) is the rate of change of habitats and for organisms adapting or moving as habitats move. The key questions are: How much will the habitats change (what scenarios and model predictions will be most correct)? As primary habitats move north, which species will be able to keep up with changing habitats on their own or with human intervention through assisted migration, management of migration corridors, or construction or maintenance of protected habitats within species' current landscapes?

Viable avenues to improving the information base are determining which climate models exhibit the best ability to reproduce the historical and potential future change in habitats, and determining how, how fast, and how far various species can move or adapt.

An additional key source of uncertainty is whether projected disturbances to forests are chronic or episodic in nature.[45]

Assessment of confidence based on evidence

There is **very high** confidence in this key message, given the evidence base and remaining uncertainties.

Key Message #3 Traceable Account

Increased heat wave intensity and frequency, increased humidity, degraded air quality, and reduced water quality will increase public health risks.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather such as heat waves across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 7) and its Traceable Accounts. Specific details for the Midwest are in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Heat waves: The occurrence of heat waves in the recent past has been well-documented,[1,15,49] as have health outcomes (particularly with regards to mortality). Projections of thermal regimes indicate increased frequency of periods with high air temperatures (and high apparent temperatures, which are a function of both air temperature and humidity). These projections are relatively robust and consistent between studies.

Humidity: Evidence on observed and projected increased humidity can be found in a recent study.[49]

Air quality: In 2008, in the region containing North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio, over 26 million people lived in counties that failed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (particles with diameter below 2.5 microns), and over 24 million lived in counties that failed the NAAQS for ozone (O_3).[1] Because not all counties have air quality measurement stations in place, these data must be considered a lower bound on the actual number of counties that violate the NAAQS. Given that the NAAQS were designed principally with the goal of protecting human health, failure to meet these standards implies a significant fraction of the population live in counties characterized by air quality that is harmful to human health. While only relatively few studies have sought to make detailed air quality projections for the future, those that have[1] generally indicate declining air quality (see uncertainties below).

Water quality: The EPA estimates there are more than 800 billion gallons of untreated combined sewage released into the nation's waters annually.[76] Combined sewers are designed to capture both sanitary sewage and stormwater. Combined sewer overflows lead to discharge of untreated sewage as a result of precipitation events, and can threaten human health. While not all urban areas within the Midwest have combined sewers for delivery to wastewater treatment plants, many do (for example, Chicago and Milwaukee), and such systems are vulnerable to combined sewer overflows during extreme precipitation events. Given projected increases in the frequency and intensity of extreme precipitation events in the Midwest (Chapter 2: Our Changing Climate, Key Message 6),[75] it appears that sewer overflow will continue to constitute a significant current health threat and a critical source of climate change vulnerability for major urban areas within the Midwest.

New information and remaining uncertainties

Key issues (uncertainties) are: Human health outcomes are contingent on a large number of non-climate variables. For example, morbidity and mortality outcomes of extreme heat are strongly determined by a) housing stock and access to air-conditioning in residences; b) existence and efficacy of heat wave warning and response plans (for example, foreign-language-appropriate communications and transit plans to public cooling centers, especially for the elderly); and c) co-stressors (for example, air pollution). Further, heat stress is dictated by apparent temperature, which is a function of both air temperature and humidity. Urban heat islands tend to exacerbate elevated temperatures and are largely determined by urban land use and human-caused heat emissions. Urban heat island reduction plans (for example, planted green roofs) represent one ongoing intervention. Nevertheless, the occurrence of extreme heat indices will increase under all climate scenarios. Thus, in the absence of policies to reduce heat-related illness/death, these impacts will increase in the future.

Air quality is a complex function not only of physical meteorology but emissions of air pollutants and precursor species. However, since most chemical reactions are enhanced by warmer temperatures, as are many air pollutant emissions, warmer temperatures may lead to worsening of air quality, particularly with respect to tropospheric ozone (see Ch. 9: Human Health). Changes in humidity are more difficult to project but may amplify the increase in heat stress due to rising temperatures alone.[49]

Combined sewer overflow is a major threat to water quality in some midwestern cities now. The tendency towards increased magnitude of extreme rain events (documented in the historical record and projected to continue in downscaling analyses) will cause an increased risk of waterborne disease outbreaks in the absence of infrastructure overhaul. However, mitigation actions are available, and the changing structure of cities (for example, reducing impervious surfaces) may offset the impact of the changing climate.

Assessment of confidence based on evidence

In the absence of concerted efforts to reduce the threats posed by heat waves, increased humidity, degraded air quality and degraded water quality, climate change will increase the health risks associated with these phenomena. However, these projections are contingent on underlying assumptions regarding socioeconomic conditions and demographic trends in the region. Confidence is therefore **high** regarding this key message.

Key Message #4 Traceable Account

The Midwest has a highly energy-intensive economy with per capita emissions of greenhouse gases more than 20% higher than the national average. The region also has a large and increasingly utilized potential to reduce emissions that cause climate change.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

The Midwest's disproportionately large reliance on coal for electricity generation and the energy intensity of its agricultural and manufacturing sectors are all well documented in both government and industry records, as is the Midwest's contribution to greenhouse gases.[1] The region's potential for zero- and lower-carbon energy production is also well documented by government and private assessments. Official and regular reporting by state agencies and non-governmental organizations demonstrates the Midwest's progress toward a decarbonized energy mix (Ch. 4: Energy; Ch. 10: Energy, Water, and Land).[1]

There is evidence that the Midwest is steadily decarbonizing its electricity generation through a combination of new state-level policies (for example, energy efficiency and renewable energy standards) and will continue to do so in response to low natural gas prices, falling prices for renewable electricity (for example, wind and solar), greater market demand for lower-carbon energy from consumers, and new EPA regulations governing new power plants. Several midwestern states have established Renewable Portfolio Standards (see https://www.misoenergy.org/WhatWeDo/StrategicInitiatives/Pages/RenewablePortfolioStandards.aspx).

New information and remaining uncertainties

There are four key uncertainties. The first uncertainty is the net effect of emerging EPA regulations on the future energy mix of the Midwest. Assessments to date suggest a significant number of coal plants will be closed or repowered with lower-carbon natural gas; and even coal plants that are currently thought of as "must run" (to maintain the electric grid's reliability) may be able to be replaced in some circumstances with the right combination of energy efficiency, new transmission lines, demand response, and distributed generation. A second key uncertainty is whether or not natural gas prices will remain at their historically low levels. Given that there are really only five options for meeting electricity demand – energy efficiency, renewables, coal, nuclear, and natural gas – the replacement of coal with natural gas for electricity production would have a significant impact on greenhouse gas emissions in the region. Third is the uncertain future for federal policies that have spurred renewable energy development to date, such as the Production Tax Credit for wind. While prices for both wind and solar continue to fall, the potential loss of tax credits may dampen additional market penetration of these technologies. A fourth uncertainty is the net effect of climate change on energy demand, and the cost of meeting that new demand profile. Research to date suggests the potential for a significant swing from the historically larger demand for heating in the winter to more demand in the summer instead, due to a warmer, more humid climate.[3]

Assessment of confidence based on evidence

There is no dispute about the energy intensity of the midwestern economy, nor its disproportionately large contribution of greenhouse gas emissions. Similarly, there is broad agreement about the Midwest's potential for—and progress toward—lower-carbon electricity production. There is therefore **very high** confidence in this statement.

Key Message #5 Traceable Account

Extreme rainfall events and flooding have increased during the last century, and these trends are expected to continue, causing erosion, declining water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for extreme weather and increased precipitation across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Messages 5, 6, and 7) and its Traceable Accounts. Specific details for the Midwest are detailed in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

There is compelling evidence that annual total precipitation has been increasing in the region, with wetter winters and springs, drier summers, an increase in extreme precipitation events, and changes in snowfall patterns. These observations are consistent with climate model projections. Both the observed trends and climate models suggest these trends will increase in the future.

Recent records also indicate evidence of a number of high-impact flood events in the region. Heavy precipitation events cause increased kinetic energy of surface water and thus increase erosion. Heavy precipitation events in the historical records have been shown to be associated with discharge of partially or completely untreated sewage due to the volumes of water overwhelming combined sewer systems that are designed to capture both domestic sewage and stormwater.

Climate downscaling projections tend to indicate an increase in the frequency and duration of extreme events (both heavy precipitation and meteorological drought) in the future.

An extensive literature survey and synthetic analysis is presented in chapters in a recent book[100] for impacts on water quality, transportation, agriculture, health, and infrastructure.

New information and remaining uncertainties

Precipitation is much less readily measured or modeled than air temperature.[3] Thus both historical tendencies and projections for precipitation are inherently less certain than for temperature. Most regional climate models still have a positive bias in precipitation frequency but a negative bias in terms of precipitation amount in extreme events.

Flood records are very heterogeneous and there is some ambiguity about the degree to which flooding is a result of atmospheric conditions.[69] Flooding is not solely the result of incident precipitation but is also a complex function of the preceding conditions such as soil moisture content and extent of landscape infiltration. A key issue (uncertainty) is the future distribution of snowfall. Records indicate that snowfall is decreasing in the southern parts of the region, along with increasing lake effect snow. Climate models predict these trends will increase. There is insufficient knowledge about how this change in snowfall patterns will affect flooding and associated problems, but it is projected to affect the very large spring floods that typically cause the worst flooding in the region. In addition, recent data and climate predictions indicate drier summer conditions, which could tend to offset the effects of higher intensity summer storms by providing increased water storage in the soils. The relative effects of these offsetting trends need to be assessed. To determine future flooding risks, hydrologic modeling is needed that includes the effects of the increase in extreme events, changing snow patterns, and shifts in rainfall patterns. Adaptation measures to reduce soil erosion and combined sewer overflow (CSO) events are available and could be widely adopted.

The impacts of increased magnitude of heavy precipitation events on water quality, agriculture, human health, transportation, and infrastructure will be strongly determined by the degree to which the resilience of such systems is enhanced (for example, some cities are already implementing enhanced water removal systems).

Assessment of confidence based on evidence

There have been improvements in agreement between observed precipitation patterns and model simulations. Also an increase in extreme precipitation events is consistent with first-order reasoning and increased atmospheric water burdens due to increased air temperature. Recent data suggest an increase in flooding in the region but there is uncertainty about how changing snow patterns will affect flood events in the future. Thus there is **high** confidence in increases in high-magnitude rainfall events and extreme precipitation events, and that these trends are expected to continue. There is **medium** confidence that, in the absence of substantial adaptation actions, the enhancement in extreme precipitation and other tendencies in land use and land cover result in a projected increase in flooding. There is **medium** confidence that, in the absence of major adaptation actions, the enhancement in extreme precipitation will tend to increase the risk of erosion, declines in water quality, and negative impacts on transportation, agriculture, human health, and infrastructure.[3]

KEY MESSAGE #6 TRACEABLE ACCOUNT

Climate change will exacerbate a range of risks to the Great Lakes, including changes in the range and distribution of certain fish species, increased invasive species and harmful blooms of algae, and declining beach health. Ice cover declines will lengthen the commercial navigation season.

Description of evidence

The key message and supporting text summarize extensive evidence documented in the Technical Input Report.[98] Technical inputs on a wide range of topics were also received and reviewed as part of the Federal Register Notice solicitation for public input.

Evidence for changes in ice cover due to increased temperatures across the U.S. are discussed in Chapter 2 (Our Changing Climate, Key Message 11) and its Traceable Accounts. Specific details for the Midwest are detailed in "Climate Trends and Scenarios for the U.S. National Climate Assessment"[4] with its references. A recent book[100] also contains chapters detailing the most current evidence for the region.

Altered fish communities: Warmer lakes and streams will certainly provide more habitat for warmwater species as conditions in northern reaches of the basin become more suitable for warmwater fish and as lakes and streams are vacated by cool- and coldwater species.[84] Habitat for coldwater fish, though not expected to disappear, will shrink substantially, though it could also expand in some areas, such as Lake Superior. Whether climate change expands the range of any type of fish is dependent on the availability of forage fish, as higher temperatures also necessitate greater food intake.

Increased abundances of invasive species: As climate change alters water temperatures, habitat, and fish communities, conditions that once were barriers to alien species become conduits for establishment and spread.[84] This migration will alter drastically the fish communities of the Great Lakes basin. Climate change is also projected to heighten the impact of invasive species already present in the Great Lakes basin. Warmer winter conditions, for instance, have the potential to benefit alewife, round gobies, ruffe, sea lamprey, rainbow smelt, and other non-native species. These species have spread rapidly throughout the basin and have already inflicted significant ecological and economic harm.

Declining beach health and harmful algal blooms: Extreme events increase runoff, adding sediments, pollutants, and nutrients to the Great Lakes. The Midwest has experienced rising trends in precipitation and runoff. Agricultural runoff, in combination with increased water temperatures, has caused considerable non-point source pollution problems in recent years, with increased phosphorus and nitrogen loadings from farms contributing to more frequent and prolonged occurrences of anoxic "dead zones" and harmful, dense algae growth for long periods. Stormwater runoff that overloads urban sewer systems during extreme events adds to increased levels of toxic substances, sewage, and bacteria in the Great Lakes, affecting water quality, beach health, and human well-being. Increased storm events caused by climate change will lead to an increase in combined sewer overflows.[84]

Decreased ice cover: Increasingly mild winters have shortened the time between when a lake freezes and when it thaws.[101] Scientists have documented a relatively constant decrease in Great Lakes ice cover since the 1970s, particularly for Lakes Superior, Michigan, Huron, and Ontario. The loss of ice cover on the Great Lakes has both ecological and economic implications. Ice serves to protect shorelines and habitat from storms and wave power. Less ice—coupled with more frequent and intense storms—leaves shores vulnerable to erosion and flooding and could harm property and fish habitat.

Water levels: The 2009 NCA[102] included predictions of a significant drop in Great Lakes levels by the end of the century, based on methods of linking climate models to hydrologic models. These methods have been significantly improved by fully coupling the hydrologic cycle among land, lake, and atmosphere.[97] Without accounting for that cycle of interactions, a study[96] concluded that increases in precipitation would be negated by increases in winter evaporation from less ice cover and by increases in summer evaporation and evapotranspiration from warmer air temperatures, under a scenario of continued increases in global emissions (SRES A2 scenario). Declines of 8 inches to 2 feet have been projected by the end of this century, depending on the specific lake in question.[96] A recent comprehensive assessment,[94] however, has concluded that with a continuation of current rising emissions trends (A2), the lakes will experience a slight decrease or even a rise in water levels; the difference from earlier studies is because earlier studies tended to overstress the amount of evapotranspiration expected to occur. The range of potential future lake levels remains large and includes the earlier projected decline. Overall, however, scientists project an increase in precipitation in the Great Lakes region (with extreme events projected to contribute to this increase), which will contribute to maintenance of or an increase in Great Lakes water levels. However, water level changes are not predicted to be uniform throughout the basin.

Shipping: Ice cover is expected to decrease dramatically by the end of the century, possibly lengthening the shipping season and, thus, facilitating more shipping activity. Current science suggests water levels in the Great Lakes are projected to fall slightly or might even rise over the short run. However, by causing even a small drop in water levels, climate change could make the costs of shipping increase substantially. For instance, for every inch of draft a 1000-foot ship gives up, its capacity is reduced by 270 tons.[93] Lightened loads today already add about $200,000 in costs to each voyage.

New information and remaining uncertainties

Key issues (uncertainties) are: Water levels are influenced by the amount of evaporation from decreased ice cover and warmer air temperatures, by evapotranspiration from warmer air temperatures, and by potential increases in inflow from more precipitation. Uncertainties about Great Lakes water levels are high, though most models suggest that the decrease in ice cover will lead to slightly lower water levels, beyond natural fluctuations.

The spread of invasive species into the system is near-certain (given the rate of introductions over the previous 50 years) without major policy and regulatory changes. However, the changes in Great Lakes fish communities are based on extrapolation from known fishery responses to projected responses to expected changing conditions in the basin. Moreover, many variables beyond water temperature and condition affect fisheries, not the least of which is the availability of forage fish. Higher water temperatures necessitate greater food intake, yet the forage base is changing rapidly in many parts of the Great Lakes basin, thus making the projected impact of climate change on fisheries difficult to discern with very high certainty.

Assessment of confidence based on evidence

Peer-reviewed literature about the effects of climate change are in broad agreement that air and surface water temperatures are rising and will continue to do so, that ice cover is declining steadily, and that precipitation and extreme events are on the rise. For large lake ecosystems, these changes have well-documented effects, such as effects on algal production, stratification (change in water temperature with depth), beach health, and fisheries. Key uncertainties exist about Great Lakes water levels and the impact of climate change on fisheries.

A qualitative summary of climate stressors and coastal margin vulnerabilities for the Great Lakes is given in a technical input report.[84] We have high confidence that the sum of these stressors will exceed the risk posed by any individual stressor. However, quantifying the cumulative impacts of those stressors is very challenging.

Given the evidence and remaining uncertainties, there is **very high** confidence in this key message, except **high** confidence for lake levels changing, and **high** confidence that declines in ice cover will continue to lengthen the commercial navigation season. There is limited information regarding exactly how invasive species may respond to changes in the regional climate, resulting in **medium** confidence for that part of the key message.