Environmental Law & Policy Center

An Assessment of the Impacts of Climate Change on the Great Lakes

by Scientists and Experts from Universities and Institutions in the Great Lakes Region

The Environmental Law & Policy Center, in concert with the Chicago Council on Global Affairs, commissioned the following scientists and experts to produce this report pro bono to educate policymakers and the public about the significant changes affecting the Great Lakes, and the vital importance of taking actions now to protect our natural resources.

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Executive Summary

Introduction

Climate change is causing significant and far-reaching impacts on the Great Lakes and the Great Lakes region. In recent years, our planet has experienced some of the warmest temperatures ever recorded, record-breaking weather extremes, powerful storms, increasing tragic flooding from rising sea levels and associated storm surge, huge wildfires, and continued melting of glaciers and polar sea ice. The accelerating pattern of changes in the Earth's climate is affecting the Great Lakes. Here, we draw on the array of existing research to assess how the shifting global climate impacts the unique Great Lakes region.

The Great Lakes have an enormous impact, seen and unseen, on the 34+ million people who live within its Basin. These millions of people rely on the freshwater lakes for drinking water, fisheries, recreation, and commerce and industry. The Great Lakes contain 5,500 cubic miles of freshwater, one of the very largest freshwater resources in the world. The Great Lakes support one of the world's largest regional economies similar to those of whole developed nations. Agriculture, industrial manufacturing, fishing, and recreation together form an economic engine. Regional fisheries alone represent a $7 billion per year industry. Tourism generates $16 billion more.

Heavy human use over the past two centuries has taken its toll in the forms of habitat loss and fragmentation, influxes of invasive species, and polluted air, water, and sediments. Soil and nutrient runoff from agricultural fields and concentrated animal feedlot operations (CAFOs) imperil water quality and wildlife populations in many parts of the basin, threatening public and wildlife health and the economic vitality of the region. Climatic changes now underway further stress these ecosystems, alternatively raising and lowering lake levels and threatening the region in new ways.

The Great Lakes sustain remarkable populations of fish and habitats for wildlife. More than 170 species of fish live in the lakes, streams, rivers, and connecting waterways. Trout, sturgeon, walleye, lake whitefish and other varieties of fish are once again becoming plentiful among the five Great Lakes. The basin's ecosystems support wolves and moose while providing resting and breeding grounds for large flocks of migratory birds and waterfowl. More than 3,500 species of plants and animals use its large network of streams, lakes, inland wetlands, coastal marshes and forests. Many of these species are rare or are found nowhere else.

The Great Lakes are large enough to themselves influence weather in the region. The Lakes moderate temperatures throughout the year, helping to cool nearby lands in the summer and warm them in winter. Their humidity feeds cloud cover and precipitation both over the lakes and downwind. That causes both "lake effect" snowstorms, and summer rainfall that provides ideal growing conditions for orchards in Michigan's "fruit belt."

Climate change presents challenges to the Great Lakes, with complicated effects and inter-relationships.

Air Temperature Increases

The Great Lakes region has tracked global increases in temperature and outpaced trends in some parts of the contiguous United States. Between 1901-1960 and 1985-2016, the Great Lakes basin has warmed 1.6°F in annual mean temperature, exceeding average changes of 1.2°F for the rest of the contiguous United States. By the end of the 21st century, global average temperatures are expected to rise an additional 2.7°F to 7.2°F, depending on future greenhouse gas emissions, with corresponding changes in the Great Lakes region.

Heavy Precipitation and Flooding

A warmer atmosphere holds more moisture, increasing the frequency and intensity of heavy rain and snow events. Overall U.S. annual precipitation increased 4% between 1901 and 2015, but the Great Lakes region saw an almost 10% increase over this interval with more of this precipitation coming as unusually large events. In the future, precipitation will likely redistribute across the seasons. We expect wetter winters and springs, while summer precipitation should decrease by 5-15% for most of Great Lake states by 2100.

These increases in precipitation will likely increase flooding across the Great Lakes region. In cities with abundant roofs, concrete, and other impermeable surfaces, this will likely damage homes, roadways, and other infrastructure. In rural areas, intense rains and melting snows will increase runoff and erode soils. In rural areas, increased flooding will also cause soil erosion. In combination with more unpredictable precipitation and warmer temperatures, these effects could seriously curtail Midwestern agricultural production.

Extreme Weather

Climate change is causing more extreme weather across the United States. Heat waves have become more common since the 1960s while extreme cold temperatures have generally decreased. Intense summer storms occur more often as temperatures rise.

Extreme weather events have already taken their toll on the Midwest. The 2012 Midwestern heat wave and drought caused more than $30 billion in economic damage, 123 deaths, and harmful long-term health impacts across most of the central and western United States.

Extremely warm days (above 90°F) will increase for states bordering the Great Lakes, especially in the southern parts of the region. By century's end, the region will experience 30 to 60 additional days each year of these extremely warm temperatures. Areas within the Great Lakes Basin will see an increase of 17 to 40 extremely warm days as annual average temperatures continue to rise.

Meanwhile, in states surrounding the Great Lakes, the number of extremely cold days (with temperature less than 32°F) will decrease significantly. Lake effect snowfalls could be even more dramatic, particularly across the Lake Ontario snowbelt in upper western areas of New York state where three- and four-feet snowstorms are already routine.

Agriculture, Irrigation, and Decreased Crop Yields

Changes in seasonal precipitation are already affecting farmers in Midwestern states, with planting delays caused by spring flooding and excessively wet soil conditions. Delayed planting puts crops at greater risk during hotter and drier conditions later in the growing season, and that increases the demand for irrigation to mitigate crop losses. Hot temperatures interfere with pollination in corn and other crops, thereby reducing yields.

Yet, even with increased water management in agricultural watersheds, climate change will likely reduce crop yields for both soybean and maize by 10% - 30% by mid-century in the southern parts of the Great Lakes watershed. Soybean and maize production will likely move northward.

Urban Issues

In the summer, high temperatures and heat waves cause poorer air quality, which harms public health, especially for the most vulnerable people – the elderly and children with asthma. For the many millions of people living in urban areas across the Great Lakes states, heat waves and summer air pollution events increase the risk for heat-related illness, respiratory diseases, and death.

Projected increases in extreme precipitation will likely exacerbate flooding, especially in winter, spring, and during summer thunderstorms. Extreme winter rain events in 2017 and 2018 led to serious flooding. Rain events exceeding 6 inches now occur regularly, exceeding the capacity of culverts and storm sewers to handle runoff. Under-resourced communities in low-lying, flood-prone areas have become vulnerable to infrastructure damage, transportation barriers, and displacement from homes due to these intensified floods.

Water Quality and Consumption

Climate change will likely threaten drinking water quality and place great stress on water infrastructure. For example, in southern Wisconsin, extreme precipitation could rise by 10% to 40%, overloading water treatment infrastructure, increasing sewer overflows, and increasing the quantity of water-born pathogens flowing into streams, rivers, and Lake Michigan.

The Great Lakes have higher levels of E. coli bacteria than other U.S. coastal regions. This untreated effluent is a public health hazard and economically costly to mitigate. Cities like Chicago have spent enormous sums to protect against water pollution. Nutrients (primarily nitrogen and phosphorous) run off from farms into surface waters during intense rain events. These excess nutrients threaten human health both directly (e.g., "blue baby" syndrome) and indirectly by contributing to toxic harmful algal blooms in shallow water bays of the Great Lakes and the "dead zone" in the Gulf of Mexico that has decimated shellfisheries.

In 2011, Lake Erie experienced the largest harmful algal bloom in its recorded history, with peak intensity more than three times greater than any previously observed blooms. In 2014, 500,000 people in the Toledo area were without safe local drinking water supplies for 72 hours because of toxic algae blooms in western Lake Erie. Algal blooms will likely become more frequent in the future as higher temperatures and heavy precipitation mix heavy nutrient loads with warmer waters. These pollutants have dramatically raised the cost of water treatment.

Lake Ecology

Climate change has already increased bacteria levels in the Great Lakes, as the water warms earlier in the spring and warming contributes to vertical mixing that changes lake ecosystems. Sewer overflows, the dumping of ship ballast water, and nutrient runoff from agriculture and industry all contribute to growth of bacteria and several invasive species in the lakes. Heavier rainstorms and warmer weather exacerbate these challenges.

Hundreds of new species of pathogenic bacteria, viruses, protozoa, and non-native species could be introduced and flourish in the warming conditions, displacing local native species. While climate change may not directly drive lake species extinct, the persistence of many native species will be threatened as they confront more invasive species, species replacements, and proliferating pest and disease organisms.

Fish

Fish respond sensitively to water temperature, assembling in distinct cold, cool, and warm water groupings. This means that warmer temperatures, seasonal weather shifts, and storms that bring a quick influx of water will all affect fish species. The geographic ranges of fish, demographics within species, system productivity, species-specific productivity, the spatial arrangement of species, and their physiological state and performance will all change in response.

For example, game fish like bluegill, smallmouth bass, largemouth bass, and brown bullhead have migrated poleward as water warms in those areas. This may increase diversity of species in some Ontario lakes by as much as 81% by the end of the century. Growth rates of yellow perch, lake whitefish, and many others, however, are likely to decrease.

Wildlife

The Great Lakes region supports many species of mammals, birds, amphibians, reptiles, and macroinvertebrates. As air temperatures increase and precipitation patterns shift, habitat conditions, soil moisture, and other conditions will shift, thereby driving some wildlife species northward and others westward. Individual species however, will respond in different ways to local conditions such as ice cover on lakes and specific patterns of regional precipitation.

Among mammals, moose may be especially vulnerable to climate change. In Minnesota, moose populations have already declined precipitously. Moose density is expected to also decline at southern parts of the Ontario region and increase at northern extents. Milder winters increase overwinter survival in white-tailed deer allowing them to expand northward into habitats historically dominated by moose.

With water levels falling and temperature rising, diseases like botulism will increase, spreading more disease and killing more birds that consume fish. Birds could also suffer from phenological mismatch, as the insect species they relied on for food hatch earlier with warmer springs or decline as vegetation shifts northward.

Shipping, Power Generation and Shorelines

Fluctuating lake levels resulting from climate change greatly affect the ability of ships to safely navigate shallow portions of the Great Lakes' channels and harbors. Both lower lake levels and higher water temperatures pose technical challenges for power generation. Changing lake levels affect marinas, docks, and shoreline homes and other buildings.

Recreation and Beach Closures

The Great Lakes Commission estimated that boating contributed approximately $9 billion to the Great Lakes economy in 2003. Boating activities such as skiing could be affected by warming temperatures, shifts in the length of seasons, and changes in lake levels.

It's become common in recent years for beaches in Chicago and Michigan to close or be under swim advisories because of bacterial contamination. Beach closures are expected to increase as heavy precipitation exacerbates issues associated with runoff and pushes up bacterial counts as well as algal blooms and E. coli alerts.

Conclusion

We should not and cannot take the vast natural resources of the Great Lakes for granted. Allowing the Great Lakes to be degraded through human activities, including climate change, is not an option. For economic, aesthetic, recreational, and ecological reasons, the Great Lakes should be restored to be healthy, unpolluted, and productive. We must reduce the effects of climate change on the Great Lakes.

Public support for protecting the Great Lakes is strong across the region. Scientific analyses clearly show that climate change has already greatly affected the region and that these impacts will continue and expand as the pace of climate change accelerates. It is critical that we recognize the importance of one of the world's most abundant freshwater resources and ensure its protection for generations to come.

1. Introduction

The North American Great Lakes are amongst the largest freshwater resources on our planet. The five Great Lakes (Superior, Michigan, Erie, Huron, and Ontario) cover a total area of more than 94,000 square miles (243,000 square kilometers) with over 9,000 miles (14,500 kilometers) of shoreline. They hold 5,500 cubic miles (22,700 cubic kilometers) of freshwater, which is enough water to cover the area of the continental United States with almost 10 feet (3 meters) of water. They also include 5,000 tributaries and have a drainage area of 288,000 square miles. The watersheds comprising the Great Lakes Basin span major areas of the United States and Canada (see Figure 1).

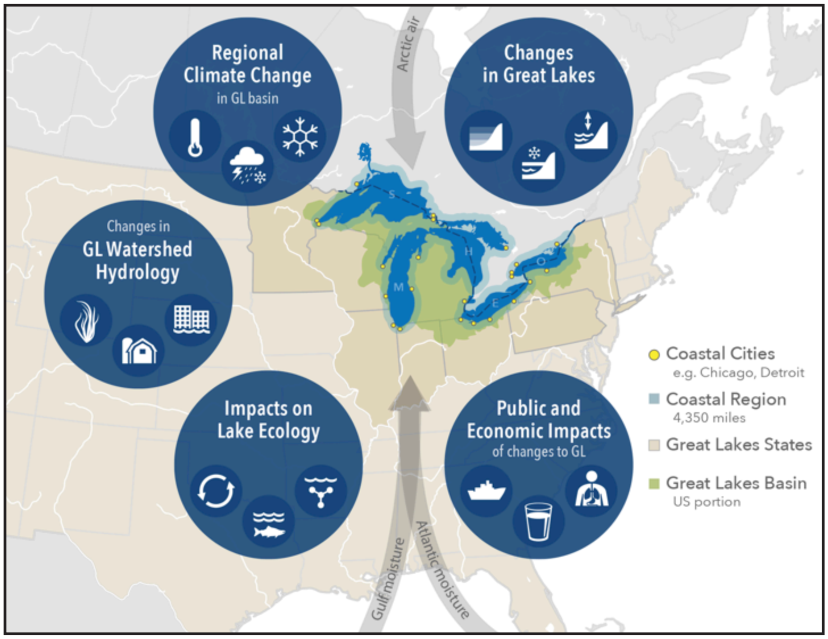


Figure 1. A schematic diagram highlighting the focus areas and themes of the assessment and the major impact pathways.

The Great Lakes are extremely important both to humans and to wildlife – they are an abundant freshwater resource for water supplies, industry, shipping, fishing, and recreation, as well as a rich and diverse ecosystem. However, over the last two centuries, the Great Lakes and the broader basin have been significantly affected by human activities, leading to habitat loss and fragmentation, invasive species, and an influx of biological and chemical pollutants that present substantial environmental challenges (e.g., Riley, 2014). These impacts have impaired water quality, threatened wildlife populations, and jeopardized the health and economic vitality of the region. Now, climate change is adding new challenges and significant additional stress to conditions in and surrounding the Great Lakes (Melillo et al., 2014; Sharma et al., 2018).

This report assesses the current and projected impacts of climate change on the Great Lakes. This assessment aims to evaluate the effects of climate change on the Great Lakes, its shorelines, regional land use, biodiversity, and urban cities on the lakes. The assessment does not aim to address all of the basins feeding the lakes or the states around the lakes. This study provides an update on prior analyses of such impacts – including GLISA (2016), McDermid et al. (2015), Walsh et al. (2014), Pryor et al. (2014), Wuebbles et al. (2010), Wuebbles and Kling (2006), Wuebbles and Hayhoe (2004), Kling et al. (2003), and Lofgren et al. (2002). The Midwest chapter from Volume II of the 4th National Climate Assessment (USGCRP, 2018) also includes some discussion of the impacts of climate change on the Great Lakes; this assessment is intended to be a more thorough look at those current and potential impacts.

1.1 Importance of the Great Lakes

By total area, the Great Lakes is the largest group of freshwater lakes on Earth, and second largest by total volume, containing 21% of the world's surface fresh water by volume. They contain 95% of the surface water in the United States and 84% of the surface fresh water available in North America (https://www.epa.gov/greatlakes/great-lakes-facts-and-figures).

About 34 million people rely on the Great Lakes for drinking water, jobs, and their way of life (their choices for recreation, etc.) — about 24 million people in the U.S. and about 9.8 million in Canada. That's roughly 8 percent of the U.S. population and 32 percent of Canada's (University of Wisconsin Sea Grant Institute 2018). The United States draws more than 40 million gallons (151 million liters) of water from the Great Lakes every day – more than half used for electrical power production, with the rest used for drinking water, industrial production, and agriculture.

The Great Lakes support one of the world's largest regional economies, including a $7 billion fishing and $16 billion tourism industry. Accounting for agricultural production within the region, commercial and sport fishing, industrial manufacturing, and tourism and recreation, the Great Lakes' economic activity surpasses that of most developed nations. A third of the basin's land is used for agriculture. Tourists spend hundreds of millions of dollars each year in the basin with more than 60 million people annually visiting the many parks that dot the shores. The lakes and their waterways serve as shipping conduits to transport bulk cargo from the basin to the markets of the world. Canals, rivers, straits, locks and channels connect the lakes together to form one of the busiest shipping areas in the world. Over 150 million tons of cargo are transported over the Great Lakes each year, supporting 44,000 jobs (https://www.mlive.com/news/muskegon/index.ssf/2009/03/sat_transporting_goods_by_ship.html). Since 1959, more than 2 billion metric tons of iron, coal, steel, oil, grains, and other products have been shipped over the Great Lakes.

A large variety of fish and wildlife species is supported by the waters and lands of the Great Lakes Basin. More than 170 species of fish inhabit the Great Lakes, their tributaries, and connecting waterways. These include lake trout, lake sturgeon, lake whitefish, walleye, landlocked Atlantic salmon, and associated forage fish species. The Great Lakes basin also provides critical breeding, feeding, and resting areas, as well as migration corridors, for waterfowl, colonial nesting birds, neotropical migrants, and many other species of migratory birds. In general, the region of the Great Lakes contains an immense network of streams, lakes, inland wetlands, coastal marshes, and forests. These habitats support more than 3,500 species of plants and animals, including more than 200 globally rare species and 46 species found nowhere else in the world. The Great Lakes Basin provides the diverse habitats needed by more than 180 fish species to complete their life cycles. A critical stopover region for more than 350 migratory bird species, the basin provides resources to sustain hundreds of millions of birds along their migratory routes each year. In addition to supporting fish and wildlife populations, the diverse habitats of the basin provide numerous critical ecological services, including water filtration and storage, flood control, nutrient cycling, and carbon storage. These diverse habitats are also important to the culture of the native people in the Great Lakes region.

The Great Lakes also play an important role in influencing local weather patterns across the region. The Great Lakes influence daily weather by 1) moderating temperatures in all seasons, producing cooler summers and warmer winters; 2) increasing cloud cover and precipitation over and just downwind of the lakes during winter; and 3) decreasing summertime convective clouds and rainfall over the lakes (Scott and Huff, 1996; Notaro et al., 2013).

These effects range from moderate (e.g., mild cooling breezes that help lakeshore orchards and vineyards flourish) to extreme (e.g., harsh lake effect snow and ice storms that close airports, shut down interstate freeways, and knock out power grids). The Great Lakes therefore provide diverse benefits and challenges to the weather of the surrounding urban and rural landscapes.

1.2 Climate change: From global to the Great Lakes region

The global climate continues to change rapidly compared to the pace of natural variations that have occurred throughout Earth's history. Trends in globally averaged temperature, sea level rise, upper-ocean heat content, land-based ice melt, Arctic sea ice, depth of seasonal permafrost thaw, and other climate variables provide consistent evidence of a warming planet. These observed trends are robust and have been confirmed by multiple independent research groups around the world (USGCRP, 2017; IPCC, 2013).

The global annual-average temperature has increased by 1.8°F (1.0°C) from 1901 through 2016 (as calculated from instrumental records over both land and oceans) (USGCRP, 2017). Sixteen of the 17 warmest years in the measurement record (which spans over 130 years) occurred in the period from 2001 to 2017. (The one exception in the highest 17 warm years was 1998, a major El Niño year.). The global average temperature for 2016 was the warmest on record, surpassing 2017 and 2015 by a small amount. The years 2017 and 2015 far surpassed the 4th warmest year on record, 2014, by 0.29°F (0.16°C), four times greater than the difference between 2014 and the next warmest year, 2010 (NCEI, 2016).

The frequency and intensity of extreme heat and heavy precipitation events are increasing throughout most of the world, including the Great Lakes region. These trends are consistent with the expected response to a warming climate and are likely to continue. Observed and projected trends for some other types of extreme events, such as floods, droughts, and severe storms, have more variable regional characteristics. The shift to warmer winters, greater winter precipitation, and more intense rainfall is likely to increase flooding in Great Lakes cities.

The 4th U.S. National Climate Assessment (USGCRP, 2017), building upon prior assessments of the science (e.g., IPCC, 2013; Melillo et al., 2014) and extensive new evidence, concludes that it is extremely likely that human activities, especially emissions of greenhouse gases and land use change, are the dominant cause of global warming since at least the mid-20th century. For the last century, there are no convincing alternative explanations for the observed warming supported by observational evidence. Natural variability cannot account for the amount of global warming observed over the industrial era. Changes in solar output and internal variability can only contribute marginally to the changes in climate observed over the last century, and there is no convincing evidence for natural cycles that could explain the changes in climate over the last century. The warming over recent decades cannot be attributed to the Sun; in fact, extremely accurate satellite observations show that solar output has declined slightly over the last four decades (USGCRP, 2017).

Global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse (heat-trapping) gases emitted globally and on the remaining uncertainty in the sensitivity of Earth's climate to those emissions. With significant reductions in the emissions of greenhouse gases, the global annually averaged temperature rise could be limited to 3.6°F (2°C) or less. Without major reductions in these emissions, the increase in annual average global temperatures relative to preindustrial times could reach 9°F (5°C) or more by the end of this century (USGCRP, 2017).

Similarly, annual average temperature over the contiguous United States increased by 1.8°F (1.0°C) for the period 1901–2016 and is projected to continue to rise. As with the global changes, there have been marked increases in temperature extremes across the United States. The number of high temperature records set in the past two decades far exceeds the number of low temperature records. Heavy precipitation events in most parts of the United States have also increased in both intensity and frequency since 1901. There are important regional differences in these trends, with the largest increases occurring in the U.S. Northeast and Midwest.

1.3 Potential risks and vulnerabilities for the Great Lakes

Prior studies have shown that global climate change is already affecting both the climate of the Great Lakes region and the physical behavior of the Great Lakes themselves (e.g., Melillo et al., 2014, and other reference above). Regional weather extremes in temperature and precipitation are intensifying (Winkler et al., 2012). In recent decades, a number of changes in the climate of the Great Lakes region have been documented, including a significant warming trend (Schoof, 2013; Zobel et al., 2017a,b), an increase in extreme summertime precipitation (Kunkel et al. 2003, 2012; Zobel et al., 2018), changing lake levels (Gronewold et al., 2013a), and changing trends in lake-effect snows (Norton et al., 1993; Kunkel et al., 1999; Bard and Kristovich, 2012; Notaro et al., 2013; Clark et al., 2016; Suriano and Leathers, 2017). The region has also recently witnessed unprecedented extreme changes in the timing of precipitation and runoff, with important implications for flooding, soil erosion, nutrient export, and agricultural practices (Carpenter et al., 2017; Kelly et al., 2017). Warm, wet winters are producing extensive early-season flooding, which threatens people and infrastructure. Associated runoff and soil erosion are also a concern for future agricultural productivity.

Further changes in climate projected over the coming decades are likely to add significantly to the vulnerabilities and risks to the Great Lakes and the Great Lakes Region. There are many vulnerabilities and risks discussed in this assessment, including potential changes in lake water levels and their effects on coastal erosion and wave damage, effects on lake temperature and stratification, effects on water quality, effects on the ecology and wildlife in both the lakes and the region, and effects on the public and the economy of the Great Lakes region. Figure 1 highlights the basic topics and themes that are covered throughout the rest of this report.

1.4 Public perception of the Great Lakes: Value and vulnerability

A binational poll conducted by the International Joint Commission's Water Quality Board in 2015 indicates that the vast majority (85%) of the residents in the Great Lakes basin feel it is important to protect the Great Lakes, largely for the provision of drinking water and the fact that they are a valuable resource with economic, recreational, and environmental importance (IJC, 2016). Residents were less certain whether the health of the Great Lakes is increasing, getting worse, or staying the same. The poll indicated that 56% believe the lakes are getting worse or staying the same. When asked about problems facing the Great Lakes and the surrounding tributaries, residents were most likely to identify pollution (roughly 50%), while a significant minority (31%) did not know what the biggest threat might be. Although the majority of respondents (78%) felt they personally played a role in protecting the Great Lakes through their own education and decision making, many (30%) were unsure what specifically they could do. These high levels of concern and personal responsibility exist despite the fact that only 42% of residents in the basin use the lakes for leisure or recreational purposes.

Residents responding to the poll did not directly identify climate change as a threat to the Great Lakes. However, many of the top issues mentioned by residents are exacerbated by climate change, in particular the trends in the region for increasing temperature and precipitation moving into the future. For example, residents were concerned about pollution (including runoff) and invasive and endangered species, threats that become greater under the impacts of a changing climate. Agricultural runoff, a major threat to lakes, and in particular Lake Erie, occurs during spring storms and will worsen as the intensity of spring rainfall events increases (Michalak et al., 2013). Similarly, the movement and loss of species is often exacerbated by shifting habitat needs as the climate warms (Ryan et al., 2018).

This binational poll was replicated in 2018 (IJC, 2018), affirming that public support for protecting the Great Lakes remains high (up by 3% points to a total of 88%). This report also indicated that 55% of residents are willing to pay more for consumer products as a result of regulations designed to restore and protect the Lakes. In a new question about the top ten issues facing the Great Lakes, 73% of residents ranked climate change as having an extremely negative impact, just behind other issues exacerbated by climate change (e.g., invasive species, algae blooms, and runoff). Residents in the Great Lakes were not keen to engage socially or politically in these issues (only ~30%), but the majority were willing to be more careful about what they dispose down the drain (83%) and with their water use (74%).

An annual poll on climate change perception in the United States finds that 70% of Americans believe global warming is happening, and these beliefs are becoming increasingly certain over time (Leiserowitz et al., 2018; Howe et al., 2015). For the Great Lakes states and provinces, these numbers ranged from a low of 64% (in Indiana) to a high of 77% (in New York) (Marlon et al., 2018). In addition, approximately 60% of Americans were worried about global warming and believe that it is affecting weather in the United States (increasing extreme heat, droughts, flooding, and water shortages) (Leiserowitz et al., 2017). For the Great Lakes states, this sense of worry about climate change ranged from a low of 49% (in Indiana) to a high of 67% (in New York). At the county level, concern and belief increased more in urban areas than in rural areas (Marlon et al., 2018). In general, beliefs about climate change were largely driven by political orientation and ideology (Hornsey et al., 2016), explaining why we see this variation in the Great Lakes states where political ideology is more evenly divided among liberals, moderates, and conservatives relative to portions of the rest of the country (IJC, 2016).

2. Regional climate change in the Great Lakes

The climate is changing over the Great Lakes and is projected to change much more over the coming century. This section summarizes the observed and projected changes in climate variables such as near-surface air temperature and precipitation over the Great Lakes and bordering U.S. states. The methodology used in these analyses is similar to that used in the 4th National Climate Assessment (USGCRP, 2017), and is based on the analyses of observational datasets for past changes and from modeling and downscaled datasets for projections produced for NCA4. Projections use a weighting system for global climate models, that are then statistically downscaled for temperature and precipitation at about 6 km resolution across the continental United States. The methodology is described in more detail in the Supplementary Material.

The projected global average temperatures are expected to rise an additional 2.7°F to 7.2°F if greenhouse gas emissions from fossil fuels in energy and transportation systems continue to rise over the 21st century (see Figure 2). Future pathways range from assuming continued large dependence on fossil fuels as a high scenario, called Representative Concentration Pathway 8.5 W/m2 (RCP8.5), to a low scenario, RCP4.5, assuming rapid reductions in the use of fossil fuels after mid-century, to a very low RCP2.6 scenario, assuming major emissions-reduction actions. As discussed below, the Great Lakes regional climate shows strong signals of weather extremes that get even stronger in the future (refer to the Supplementary Material for details on the selection of historical observational datasets and the ensemble of statistically downscaled future projections).

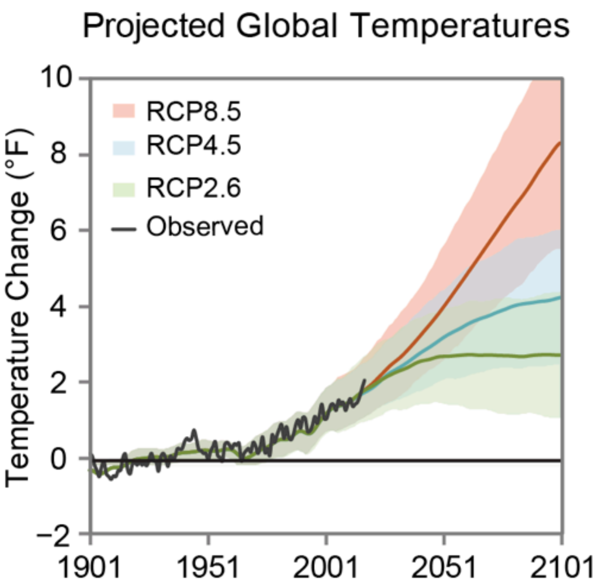


Figure 2. Multi-model simulated time series from 1900 to 2100 for the projected change in global annual mean surface temperature relative to 1901–1960 for a range of the Representative Concentration Pathways (RCPs). These scenarios account for the uncertainty in future emissions from human activities (as analyzed with the 20+ models from around the world used in the most recent international assessment [IPCC, 2013]). Source: USGCRP (2017)

2.1 Air temperature changes and trends

Of the many indicators of climate, temperature is one of the most important, because it affects our lifestyles and our decision-making. For example, temperature data are used by builders and insurers for planning and risk management and by energy companies and regulators to predict demand and to set utility rates. As the most widely and consistently observed climate variable, air temperature is very convenient for users. Long-term temperature trends are also an important indicator of the changes occurring in climate.

In the Great Lakes region, the U.S. states bordering the Great Lakes have seen an overall increase in annually averaged temperature of 1.4°F for the period 1985-2016 relative to 1901-1960, with the largest changes at the higher latitudes (see Figure 3 and Table 1). For the extent of the Great Lakes Basin (see Figure 1), the temperature change is 1.6°F over this time period. These trends are higher than the overall change of 1.2°F over the contiguous United States (and found globally) for the trends over these time periods (USGCRP, 2018).

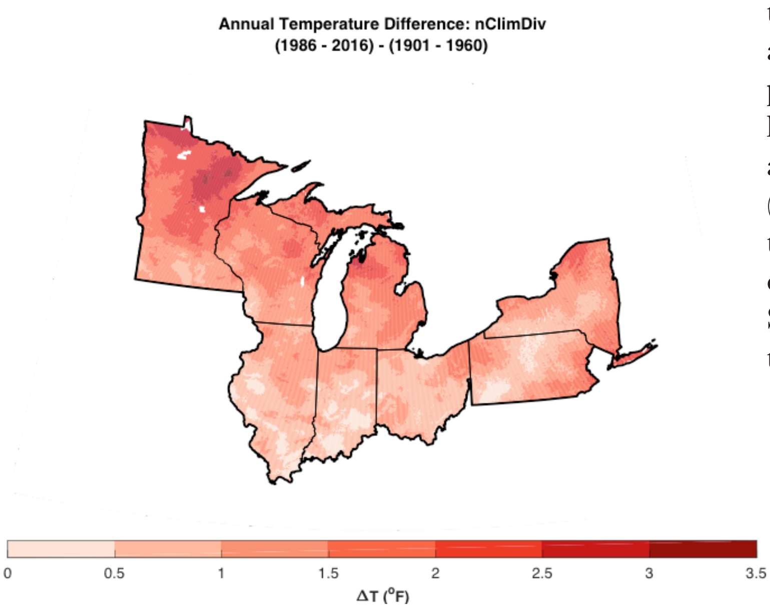


Figure 3. Observed changes in annually-averaged temperature (°F) for the U.S. states bordering the Great Lakes for present-day (1986–2016) relative to 1901–1960. Derived from the NOAA nClimDiv dataset (Vose et al. 2014). Source: NOAA/NCEI.

	U.S. States Bordering the Great Lakes	Great Lakes Basin
Observed trend	1.4	1.6
2016-2045 Lower Scenario	3.0	3.0
2016-2045 Higher Scenario	3.3	3.3
2036-2065 Lower Scenario	4.4	4.4
2036-2065 Higher Scenario	5.5	5.6
2070-2099 Lower Scenario	5.7	5.8
2070-2099 Higher Scenario	9.8	10.1

Table 1. Change in annually-averaged temperature (°F) for U.S. states bordering the Great Lakes and for the smaller area of the Great Lakes basin. The observed trend is the difference for annually-averaged temperature for 1986-2016 period relative to 1901-1960. The future projections for annually-averaged temperature due to emissions from the higher (RCP8.5) and lower (RCP4.5) scenarios are shown for the periods 2030 (2016-2045), 2050 (2036-2065), and 2085 (2070-2099) time periods.

	U.S. States Bordering the Great Lakes	Great Lakes Basin
Observed trend	9.6	10.0
2016-2045 Lower Scenario	4.0	4.5
2016-2045 Higher Scenario	4.0	4.2
2036-2065 Lower Scenario	5.5	6.4
2036-2065 Higher Scenario	6.2	7.0
2070-2099 Lower Scenario	6.2	7.2
2070-2099 Higher Scenario	9.8	11.4

Table 2. Change in annual precipitation (as equivalent rainfall) (%) for U.S. states bordering the Great Lakes and for the smaller area of the Great Lakes basin. The observed trend is the difference for annual precipitation for 1986-2016 period relative to 1901-1960. The future projections for annual precipitation due to emissions from the higher (RCP8.5) and lower (RCP4.5) scenarios are shown for the periods 2030 (2016-2045), 2050 (2036-2065), and 2085 (2070-2099) time periods.

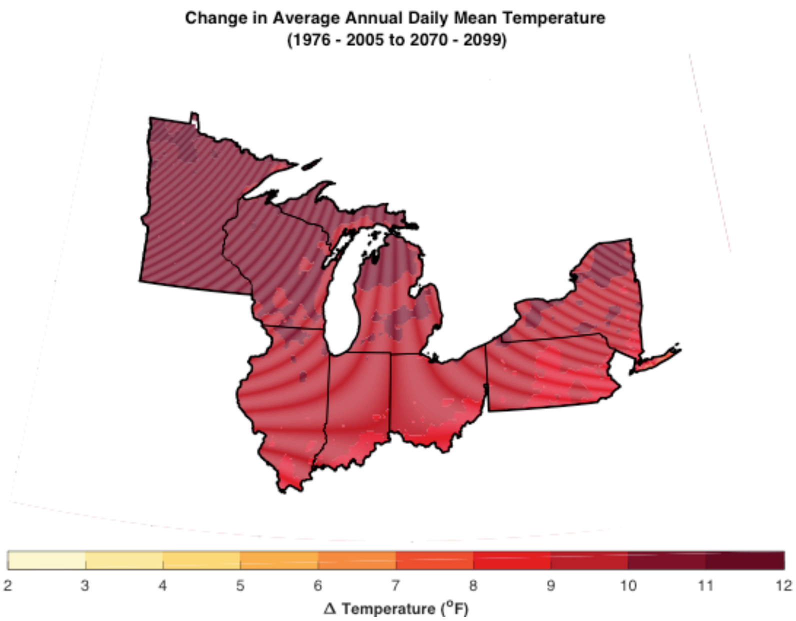
	U.S. States Bordering the Great Lakes	Great Lakes Basin
Observed (1984-2013 vs 1954-1983)	-1.93	-2.25
2020s RCP4.5	-16.49	-15.65
2020s RCP8.5	-17.87	-17.04
2050 RCP4.5	-27.94	-26.18
2050 RCP8.5	-33.17	-31.56
2080 RCP4.5	-30.48	-28.15
2080 RCP8.5	-49.08	-47.46

Table 3. Change in annual snowfall (%) for U.S. states bordering the Great Lakes and for the smaller area of the Great Lakes basin. The observed trend is the difference for annual snowfall for 1986-2013 period relative to 1954-1983. The future projections for annual snowfall are calculated based on the ensemble mean of 10 statistically-downscaled GCMs by Hybrid Delta for the higher (RCP8.5) and lower (RCP4.5) scenarios (Byun and Hamlet, 2018) associated with three 30-yr periods centered on 2020s, 2050s, and 2080s. Also, the values for the future periods represent the projected changes relative to observed mean for 1976-2005.

Land Use/Land Cover Class	% Basin	% Change 2000-2011
Developed	10.52	0.38
Agriculture	38.02	-0.27
Forest	29.55	-0.50
Grass/Shrub	3.62	0.35
Wetland	15.80	0.01
Barren	0.35	0.02
Water	2.15	0.01

Table 4. Land use and land cover for the Great Lakes basin, based on data for year 2011. Change from 2001 to 2011 is also shown. Data derived from U.S. National Land Cover Database (NLCD) for the U.S. side, and the Ontario Land Cover Compilation V2.0 for the Canadian side of the basin. (Data from SOLEC, in review).

The projected changes in annual average temperature for the U.S. states bordering the Great Lakes are shown in Figure 4 for the higher (RCP8.5) and lower (RCP4.5) emissions scenarios for the 2085 (2070-2099) time period relative to 1976-2005. The patterns of warming over these states for the 2030 (2016-2045) and 2050 (2036-2065) time periods are similar but with smaller temperature changes. Averaged over the entire Great Lakes region, slightly greater increases are projected in summer than winter, and average maximums are expected to rise slightly faster than average minimums. These seasonal variations are reversed in the northern Great Lakes region, with winter temperature rising more than summer and average minimums warming more than average maximums (WICCI, 2011; IPCC, 2013; USGCRP, 2017). Table 1 shows that projected changes in temperature for these scenarios are 3.3, 5.5, and 9.8°F (1.8, 3.1, and 5.4°C) for the 2030, 2050, and 2085 time periods for the higher scenario, and 3.0, 4.4, and 5.7°F (1.7, 2.4, and 3.2°C) for the 2030, 2050, and 2085 time periods for the lower scenario. The projected changes in temperature for the Great Lakes Basin are similar but slightly higher for the same time periods and scenarios (see Table 1). Not surprisingly, there is little difference in the projected effects on temperature over the next few decades between the different scenarios, but large differences between the scenarios by the end of the century. Similar projections along with monthly changes were found by Zhang et al. (2018). The potential societal and ecological impacts on our planet, including those associated with the Great Lakes, are likely to increase in proportion to annual average temperature (Stern et al., 2006; Melillo et al., 2014).



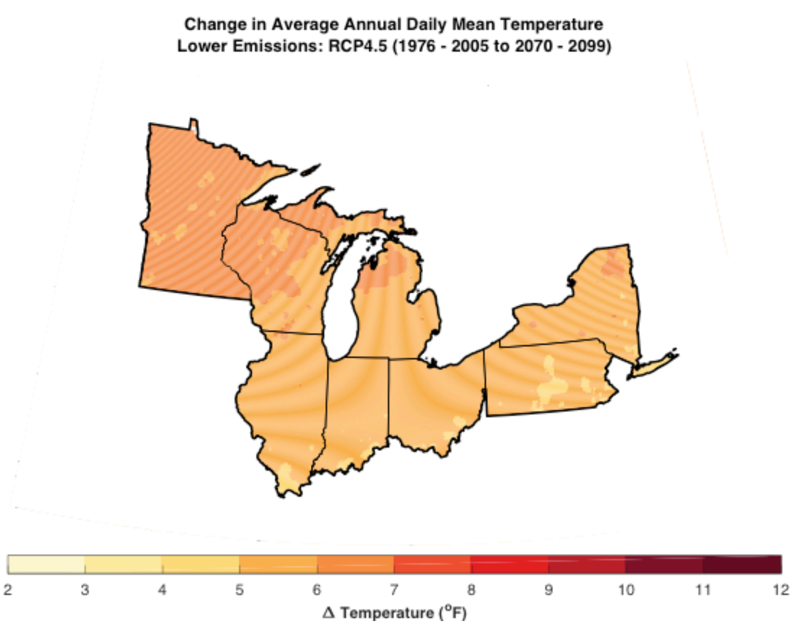


Figure 4. Projected change in annually-averaged temperature (°F) for U.S. states bordering the Great Lakes from the (a) higher (RCP8.5) and (b) lower (RCP4.5) scenarios for the 2085 (2070-2099) time period relative to 1976-2005. Source: NOAA/NCEI

2.2 Precipitation trends

Annual precipitation averaged across the United States has increased by approximately 4% from 1901 to 2015 (USGCRP, 2017). Figure A1 shows that there is a generally positive trend for U.S. states bordering the Great Lakes in annual precipitation for present-day (1986–2016) relative to 1901–1960, but with strong local variations in the trend across the states. There is a 9.6% increase in annual precipitation averaged over these states (Table 2), while the Great Lakes Basin shows a comparable 10.0% increase. The largest increasing trends are for fall-season (~15.8% for the bordering states), with summer (9.9%) precipitation also being larger relative to winter precipitation (7.7%) and spring precipitation (7.0%).

The patterns of projected future annual precipitation changes over the U.S. states bordering the Great Lakes states and for the Great Lakes Basin for the earlier periods are similar but with smaller changes (Figure A2; Table 2). The greatest differences arise in how precipitation change is distributed across seasons, with future increases concentrated in winter and spring months for both emission scenarios, while summer precipitation decreases by 5% to 15% for most of the Great Lake states by the end of the century (Byun and Hamlet, 2018). The likely reason for this trend is that increasing warming with time will allow the atmosphere to hold more moisture and thus generate higher precipitation. As in temperatures, there is little difference in the effects between scenarios over the next few decades, but larger differences between the scenarios by the end of the century. The likely reason for this trend is that increasing warming with time will allow the atmosphere to hold more moisture and thus generate higher precipitation.

2.3 Extreme events

Along with the overall changes in climate, there is strong evidence of an increasing trend in the intensity in some types of extreme weather events over recent decades. Changes in the characteristics of extreme weather events are particularly important for human safety, infrastructure, agriculture, water quality and quantity, and natural ecosystems. For example, heatwaves have become more frequent in the United States since the 1960s, while extreme cold temperatures and cold waves have become less frequent (USGCRP, 2017). These extreme temperature conditions provide a direct risk to the public of the Great Lakes region (Patz et al., 2014). For example, the 2012 Midwestern heat wave and drought caused more than $30B in economic damage, and 123 direct deaths. It contributed to considerable long-term health impacts across most of the central and western United States (Rippey, 2015). The chances for record-breaking high temperature extremes have increased and will continue to increase as the global climate warms. Recent record-setting hot years are projected to become common in the near future for the United States, as annual average temperatures continue to rise.

Heavy rainfall is increasing in intensity and frequency across the United States and globally and is expected to continue to increase (Karl and Knight, 1998; O'Gorman and Schneider, 2009). The largest observed changes in extreme precipitation in the United States have occurred in the Midwest and Northeast. Changes in climate are increasing the likelihood for these types of severe events. Past and projected trends remain uncertain for some types of severe storm events, including the intensity and frequency of tornadoes, hail, and damaging thunderstorm winds. Tornado activity in the United States has become more variable, particularly during the 2000s, with a decrease in the number of days per year with tornadoes and an increase in the number of tornadoes on days when they do occur (USGCRP, 2017).

The number of future extremely warm days (with temperature greater than 90°F) is projected to increase for the states bordering the Great Lakes, especially in the southern parts of the region, but less so near the Lakes (Figure

A3). By the end of the century there is a projected increase of 60 extremely warm days in the Great Lakes states for the higher scenario and 30 days for the lower scenario. Areas within the Great Lakes Basin show similar trends, with an increase of 40 extremely warm days projected for the higher scenario and 17 for the lower scenario, based on an average over the basin. For midcentury, 2050s, the number of days greater than 90°F for the U.S. states bordering the Great Lakes is projected to increase by 30 days for the higher scenario and 21 for the lower (17 for the Great Lakes basin with the higher scenario and 11 for the lower). For 2085, hot days with >100°F are projected to increase by 17 days for the higher scenario and 5 for the lower scenario (8 for the Great Lakes basin with the higher scenario and 2 for the lower, relative to none in the recent 30-year period).

The number of extremely cold days (with minimum temperature less than 32°F) is projected to decrease dramatically over the century because of wintertime warming in the states bordering the Great Lakes (Figure A4). The largest decrease in freezing days is projected for the most northern states and for the Great Lakes Basin, consistent with regional variations in winter temperature trends. There is a projected decrease of 33 days for the higher scenario and 21 for the lower scenario (42 for the Great Lakes Basin with the higher scenario and 27 for the lower scenario). For midcentury, 2050, the number of days less than 32°F for the U.S. states bordering the Great Lakes is projected to decrease by 20 days for the higher scenario and 17 for the lower (25 for the Great Lakes Basin with the higher scenario and 21 for the lower). By the 2030s, the Great Lakes Basin is projected to see 15-16 fewer freezing days per year. Similarly, the frost-free season (and the corresponding growing season) should also lengthen throughout the century for these scenarios.

The number of days projected to have high temperatures under 32°F (these are days that do not get above freezing, so different than the previous paragraph) are also projected to decrease, by as many as 56 days in the Great Lakes Basin by the end of the century for the higher scenario and 31 days for the lower scenario.

The amount of precipitation coming in extreme events has already increased over the last five decades in the Great Lakes region (USGCRP, 2017), and is projected to increase further over the coming decades. The amount of precipitation occurring in storms with a 5-year return period is projected to increase by 18.7% by 2085 for the higher scenario and 10.8% for the lower scenario (20.8% and 11.3%, respectively, for the Great Lakes Basin) (Figure A5). The amount of precipitation in such extreme storms is projected to increase by 7-8% by the 2030s and by 9-12% by the 2050s. The precipitation from what are currently considered to be 1 in 50 and 1 in 100-year storms are projected to increase similarly, meaning that very large amounts of precipitation are expected from these once-unusual events.

2.4 Cold-season processes (snow and ice)

With a changing climate, both rain and snow precipitation patterns are expected to change over the Great Lakes, complicating projections of snow processes. While the increase in precipitation may lead to more snow fall in individual events, the winter warming trend across the United States will lead to a reduction in the number of snow events compared to rain events. Further, warming can lead to shifts in seasonal distributions of snow cover in the Great Lakes. As a result, rising temperatures in the Great Lakes states have had little effect on historical total annual snowfall across the region (Figure A6 and Table 3), but their effect on reducing seasonal duration of snow cover is more pronounced (Brown and Mote, 2009; Notaro et al., 2014). Some areas affected by lake effect snows have actually experienced significant increases in seasonal snowfall in recent decades (e.g., Burnett et al., 2003).
Despite small overall trends in snow fall during the historical record, by the end of the century, annual total snowfall

over Great Lakes states is projected to decrease by 50% for the higher scenario and 30% for the lower scenario (Figure A7 and Table A1). This results in substantial reductions in snow cover, with days of snow depth greater than 5.9 inches (15 cm) reduced from the historical average of 61 days for the entire region to 19 days for the higher scenario or 35 days for the lower scenario by the end of the century (Chin et al, 2018; results are consistent with findings of Notaro et al., 2014). The projected snowfall reductions are not uniform in the Great Lakes states. The snowfall amounts are projected to decrease slightly less within the Great Lakes Basin in comparison to the total Great Lakes states, possibly due to lake-effect snow in the basin. Lake-effect snow is largely limited to Michigan (the upper peninsula and western parts of the lower peninsula), upper Indiana, northern Ohio, parts of Ontario to the east of Lakes Superior and Huron, and parts of New York and Pennsylvania to the east of Lakes Erie and Ontario. More southerly states in the basin will have more reduction in snow than more northerly states because of the (climatological) greater frequency of days when mean daily temperature goes above 32°F. Similarly, far northern latitudes may experience less reduction in snow cover due to the (climatological) greater frequency of days when the mean temperature stays below 32F.

Projections suggest that more precipitation will fall as rain and less as snow during the cold season, particularly in southern Great Lakes states under the high emission scenario. Changing climate is expected to shift the hydrological cycle in several ways simultaneously: increasing temperatures, decreasing snowfall, and increasing spring rainfall. This would lead to early spring snowmelt and increasing flood risks in many watersheds (Byun et al., 2018; Cherkauer and Sinha, 2010). During periods of colder temperatures, lower snow accumulations could also cause greater freezing of soils, at least in the near term, further exacerbating winter and spring flood risk, especially following rain on snow events (Sinha and Cherkauer, 2010).

LAKE EFFECT SNOWS

Some of the heaviest snowfalls on record in the United States were generated by the Great Lakes. For example, three- to four-foot snowstorms are routine in the Lake Ontario snow belt, including the upper western areas of New York in the fall and winter. On January 8, 2011, a snowband spanning virtually the entire north-south length of Lake Michigan curled into South Bend, Indiana, hammering the city with some of the highest snowfall rates ever seen outside of the Lake Ontario snow belt (https://weather.com/storms/winter/news/great-lakes-snowbelts-lake-effect-snow-records). Lake Erie has also had large effects from northeast Ohio to western New York. Prior to the U.S. Thanksgiving in 2014, a multi-day event covering the Buffalo area with up to 88 inches of lake-effect snow, bringing city activity to a grinding halt.

The ingredients for lake effect snow are straightforward and come together a number of times each fall and winter. Cold air from Canada pours over the still unfrozen, relatively warm Great Lakes. The lake moisture and instability from this temperature contrast build one or more bands of snow, which are then deposited over locations downwind from the lakes. Climate change, including warmer lake temperatures, could enhance these effects when the conditions are appropriate for snowfall. The observed trend of precipitation tending to occur in larger events throughout the Great Lakes basin could also mean larger lake effect snowfalls when the conditions are ripe.

3. Changes in the Great Lakes

Climate is a coupled surface-atmosphere process. This means that climate change alters the exchange of heat between the atmosphere and the Great Lakes. This changes the overall temperature and ice cover of the lakes, and also changes the timing of overturnings (seasonal mixing of lake water) associated with seasonal thermal changes. Although projections of climate change show increases in both precipitation and evapotranspiration in the Great Lakes Basin, observations to date have not shown significant long-term trends. The state of science on the projection of the net effect on lake level has undergone a major change of course in the last several years, changing from projections of large drops in lake level under older methodologies to smaller drops on average and the possibility of a small rise in lake levels through the end of this century.

3.1 Changes in lake temperature and stratification

Climate change in the Great Lakes involves both direct input of heat to the Lakes by increased downward longwave emissions by greenhouse gases, and inhibited loss of heat to the air by turbulent heat fluxes associated with the effects of the lakes. This should be expected to increase water temperatures within the lakes, but will also have particular influences on the temperature profile within the lakes and the phenology (timing) of the lakes' temperature structure (i.e., timing of particular events that occur during the seasonal cycle). Figure 5b shows the change in summer temperatures in the Great Lakes from 1994 to 2013 (USGCRP, 2018) – all of the Great Lakes show a significant increase over the 20 year period, especially Lake Superior.

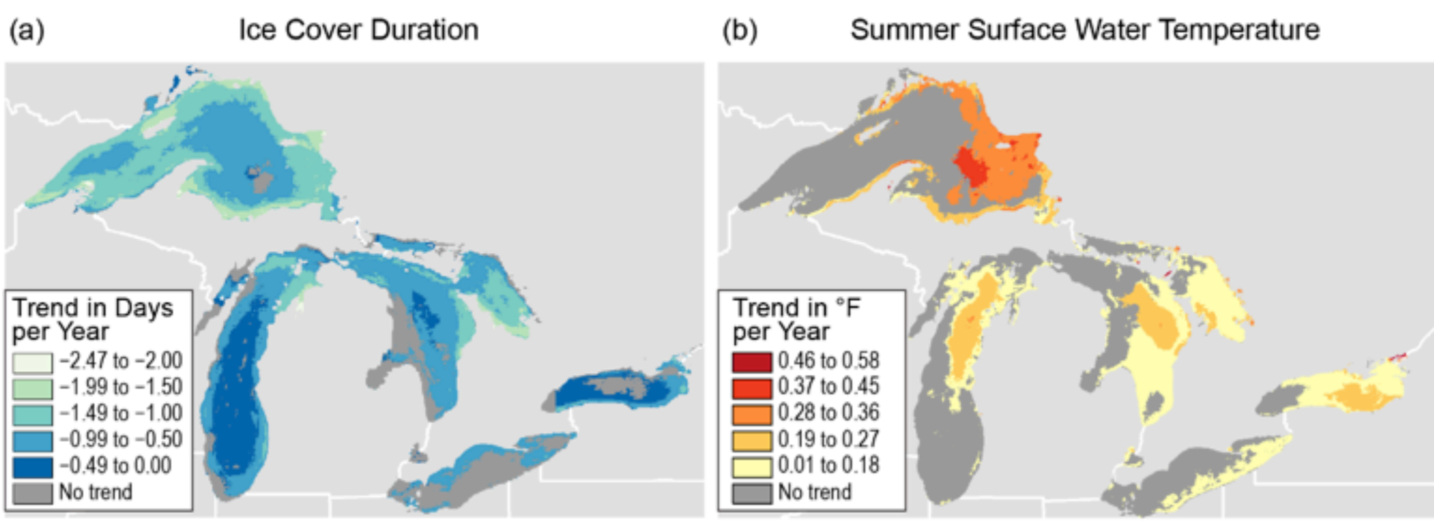


Figure 5. The duration of seasonal ice cover decreased in most areas of the Great Lakes between 1973 and 2013, while summer surface water temperature (SWT) increased in most areas between 1994 and 2013. (a) The map shows the rate of change in ice cover duration. The greatest rate of decrease in seasonal ice cover duration is seen near shorelines, with smaller rates occurring in the deeper central parts of Lakes Michigan and Ontario, which rarely have ice cover. (b) The map shows the rate of change in summer SWT. The greatest rates of increase in summer SWT occurred in deeper water, with smaller increases occurring near shorelines. Source: USGCRP 2018); adapted from Mason et al. (2016) by Kaye Lafond of NOAA GLERL.

Fresh water has its maximum density at a temperature of 4°C (39°F). This means that water at temperatures above or below this value can form a stable layer above deeper water that is closer to this temperature. Historically, the surface water of the Great Lakes has passed through this temperature threshold twice during each year. As the surface water cools from its maximum temperature of the year (usually during September), it begins to mix with warmer and less dense water at greater depths. Continued cooling makes this mixing reach even deeper into the water column until it reaches the 4°C threshold, after which further cooling produces less dense water that can form a stable layer at the surface. Ice may form, but eventually the water will warm, again causing it to mix downward until complete mixing occurs when it approaches 4 °C.

Temperature changes in the lake-atmosphere system are expected to shift the timing of these overturning episodes, as well as the timing of ice formation and melting. Lake surface temperatures simulated by Xiao et al. (2018) show that points in Lakes Superior, Michigan, and Erie reach the 4°C mixing threshold earlier in the spring and later in the fall (other lakes were not analyzed). This also leads to suppressed mixing once the temperature threshold is passed in the spring, yielding stronger vertical gradients of water temperature, and an earlier, more stable thermocline.

Lake Superior summer surface temperatures have increased more quickly than the air temperatures over land in the region (Austin and Colman 2007, Desai et al. 2009). This is believed to be due to earlier onset of summer stratification (initiated by warming beyond the 4 °C threshold, after which the warmest water is at the surface), which reinforces itself by inhibiting mixing of colder water from deeper in the lake. This mechanism is likely to continue, causing reduced stability of the lower atmosphere in the Great Lakes' vicinity during the summer.

3.2 Great Lakes ice cover trends

Ice cover on the Great Lakes has seen a slight decreasing trend between the time when systematic observations began in 1973 and 2018 based on data from NOAA GLERL. Figure 5a shows a significant decrease in duration of ice cover over many parts of the Great Lakes from 1973 to 2013. Figure 6a shows the overall time series of maximum ice coverage over the entire Great Lakes from 1973 to 2018 while Figure 6b shows the long-term trends based on this data. Lake Erie typically has the highest percentage of ice cover during a given season due to the shallow nature of the lake. Superior, Huron, and Erie are losing ice cover more quickly than the other Great Lakes over this time period.

The winters of 2013-14 and 2014-15 had plentiful ice cover and decreased the time trend found in earlier studies (e.g., Wang et al., 2012). There have been efforts to connect the extreme cold spells during those two winters with anthropogenic climate change, specifically its tendency to reduce the equator-to-pole temperature gradient by warming the poles more than the tropics (Francis and Vavrus, 2012, 2015). The understanding of these connections still has major uncertainties, however (e.g., Wallace et al., 2014). The ice cover data can be found in the online Great Lakes Ice Atlas at https://www.glerl.noaa.gov/data/ice/atlas/.

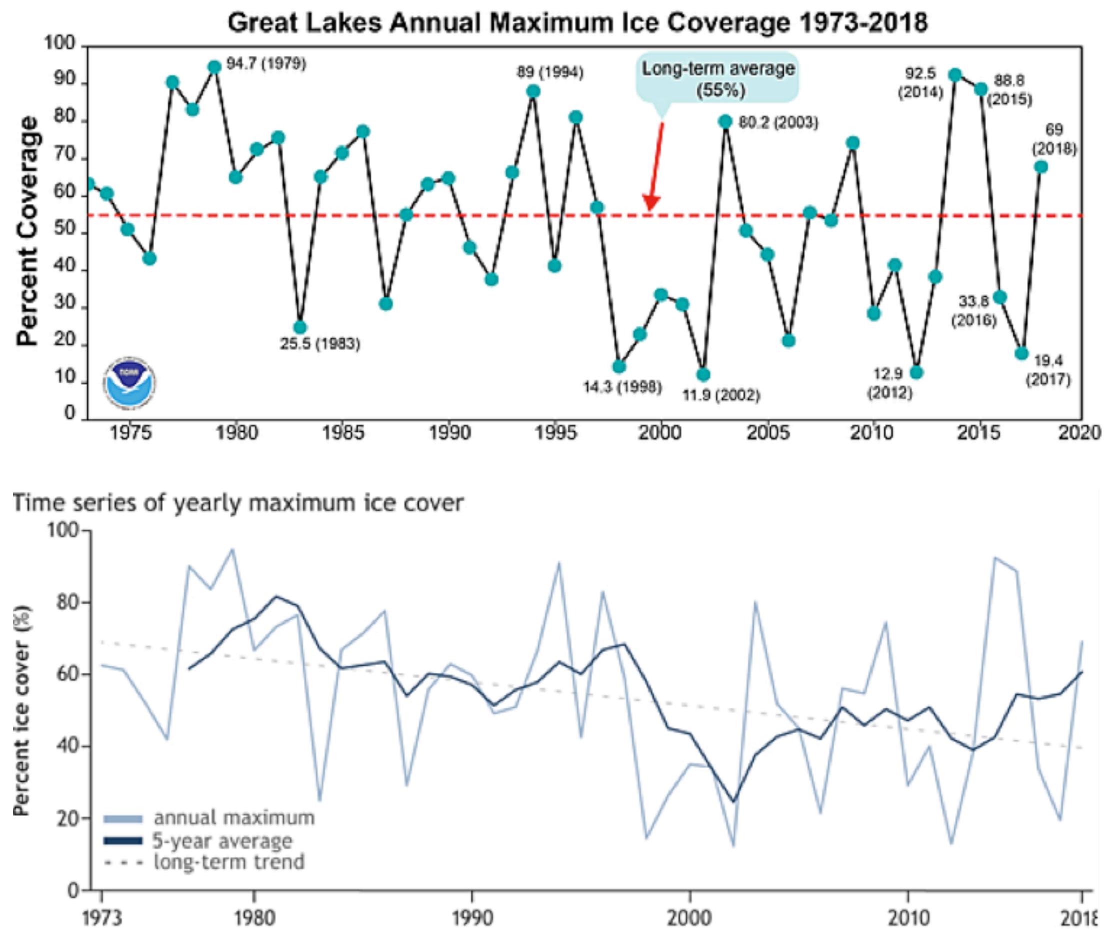


Figure 6. (a) Time series of the maximum ice coverage over the entire Great Lakes from 1973 to 2018. (b) Time series for the same data with solid line added for the 5-year running mean and a dashed line for the long term linear trend. Source: NOAA GLERL.

Ice cover is projected to decrease over the remainder of the 21st century. Croley (1990) showed reduced ice cover in spatially lumped models of each lake (i.e. without any spatial divisions within the lake). Notaro et al. (2015) showed reduced ice cover and a retreat of ice to the shallowest parts of the lakes even when complete removal is not indicated, but the model used by Notaro et al. did not consider transport of ice.

3.3 Hydrologic trends (over-lake evaporation, precipitation, runoff, groundwater, and inter-lake flows)

The recent release of the North American Great Lakes hydrometeorological database (Hunter et al., 2015; Smith et al., 2016) makes it possible to assess historical changes in the hydrometeorology over the Great Lakes. Inflows to the lakes include direct over-lake precipitation and discharge from the surrounding watersheds into each lake. Between the periods 1954-1983 and 1984-2013, over-lake precipitation decreased by 7.9% over Lake Superior, 6.8% over Lake Erie, and by 2.0% over Lakes Michigan and Huron (treated as a single lake in the database because they are hydrologically one water body). An increase of 3.5% was found over Lake Ontario. The decreases over Lakes Huron, Michigan, and Erie are strictly based on over-lake precipitation, while precipitation over both the Lakes themselves and the surrounding Great Lakes Basin increased for the same periods. The decrease in

Lake Superior precipitation corresponds to the decrease in annual precipitation over the upper peninsula of Michigan. Runoff from the lake watersheds into each lake has decreased by 8.6% for Lake Superior, and increased by 7.3% for Lake Erie and by 9.8% for Lake Ontario.

Evaporation of lake water is driven by the gradient of water vapor mixing ratio between the surface (the saturation vapor pressure corresponding to the surface water temperature) and a reference level in the atmospheric boundary layer, along with mixing by wind and turbulence. Evaporation requires energy, known as the latent heat of evaporation, and therefore is constrained by the amount of energy that the lake receives by input of shortwave radiation from the Sun, longwave radiation exchanged with the atmosphere, and sensible heat flux. This latter is heat that is transferred directly between surface and atmosphere by direct contact between molecules of different temperatures and, similar to evaporation, it is driven by a gradient of temperature between surface and atmosphere, along with strength of mixing. Because lakes have significant heat capacity, they can store energy to be released later through evaporation and other means. Thus, maximum evaporation from deep lakes occurs when the lake water is still relatively warm, while the air is much cooler, i.e., in fall and early winter. Van Cleave et al. (2014) proposed that evaporation is aided by pre-conditioning, so there is unusually high evaporation during cold periods that were preceded by unusually warm seasons or years. Annual over-lake evaporation has increased for all of the Lakes, with a minimum increase of 2.3% for Lake Ontario and a maximum increase of 7.8% for Lake Erie. Air temperature has increased most rapidly over Lake Superior and, combined with a decrease in ice cover, has resulted in a 6.5% increase in evaporation.

The Net Basin Supply (NBS) is quantified as precipitation + runoff − evaporation for each lake. Lake Superior, with decreasing precipitation and runoff and increasing evaporation has experienced a 17.5% decrease in NBS. Increases in runoff into Lake Erie have not entirely offset decreased precipitation and increased evaporation, resulting in a 7.3% decrease in NBS. Lakes Michigan and Huron have experienced a 3.0% increase in NBS, while Lake Ontario has increased by 9.5%. Change in NBS can also affect the movement of water between the lakes, with flows from Lake Superior into Lakes Michigan and Huron decreasing by 9.7%. There is little to no change between the other lakes. Discharge from Lake Ontario to the St. Lawrence River has increased by 2.8%. Connecting channel flows must, in the long run, balance the net basin supply. On shorter time scales (a few years), the net basin supply can lead to changes in lake level, which then affect connecting channel flow until an equilibrium is reached.

Three inter-basin diversions were identified by Hunter et al. (2015) as being large enough to have a potentially significant impact on basin-scale runoff. Two of these, the Ogoki Diversion and the Long Lac Diversion, shift water into the Lake Superior watershed from the Hudson Bay watershed. Historically this inflow varies from 120 to 200 m3/s, and there has been a 5.9% decrease in discharge into Lake Superior through these diversions for the period of record. The other significant diversion transfers 80 to 110 m3/s of water from Lake Michigan to the Illinois and Mississippi River basins via the Chicago Sanitary and Ship Canal. Water removed from Lake Michigan through this system has decreased by 2.5% in the period of observation.

In the future, annual precipitation is expected to increase with a general shift to wetter winter and spring conditions (Section 2.2) and more variable summers that are likely to become hotter and drier by the end of the century. Less ice cover and warmer air temperatures will continue to increase evaporation. Runoff will increase in the winter and spring, and it will decrease in the summer (Section 4). The effect of these changes on NBS is critical to determining future lake levels (Gronewold et al., 2013).

3.4 Changes in lake level

Water levels have fluctuated considerably over multi-decadal time scales. Figure 7 shows annual changes in the water levels for the Great Lakes from 1860 to 2015. The combined Lake Michigan and Lake Huron are the most variable among the Great Lakes. Lake Superior has smaller variability, especially because of its large size relative to its drainage basin. Superior's outflow is one of the drivers of Lake Michigan-Huron water level. Lake Erie's water levels generally fluctuate along with Lake Michigan-Huron's but with somewhat smaller amplitude, and causing a backwater effect by influencing the slope of the connecting channels.

Water levels across all of the Great Lakes have risen over the past several years following a period of record low levels. Lake Ontario, the farthest downstream, is driven mostly by inflow from the Niagara River but also by its own watershed. Its outflow is also regulated, dampening the water level variability somewhat, but extremely high levels in Lake Ontario during 2017 led to conflicting interests of lakeshore property owners, who wanted maximum release of water to lower water levels, and shipping interests downstream in the St. Lawrence River, who wanted at least some periods of lower flow for safer shipping. Record-breaking heavy precipitation in the basin appears to have largely driven the increases in lake levels and may have exceeded the capacity of the regulatory system to respond. The major variability in lake levels in recent years demonstrates the need for better understanding of the drivers of water level variability towards improving regional water resources management and policy (Gronewold and Rood, 2018).

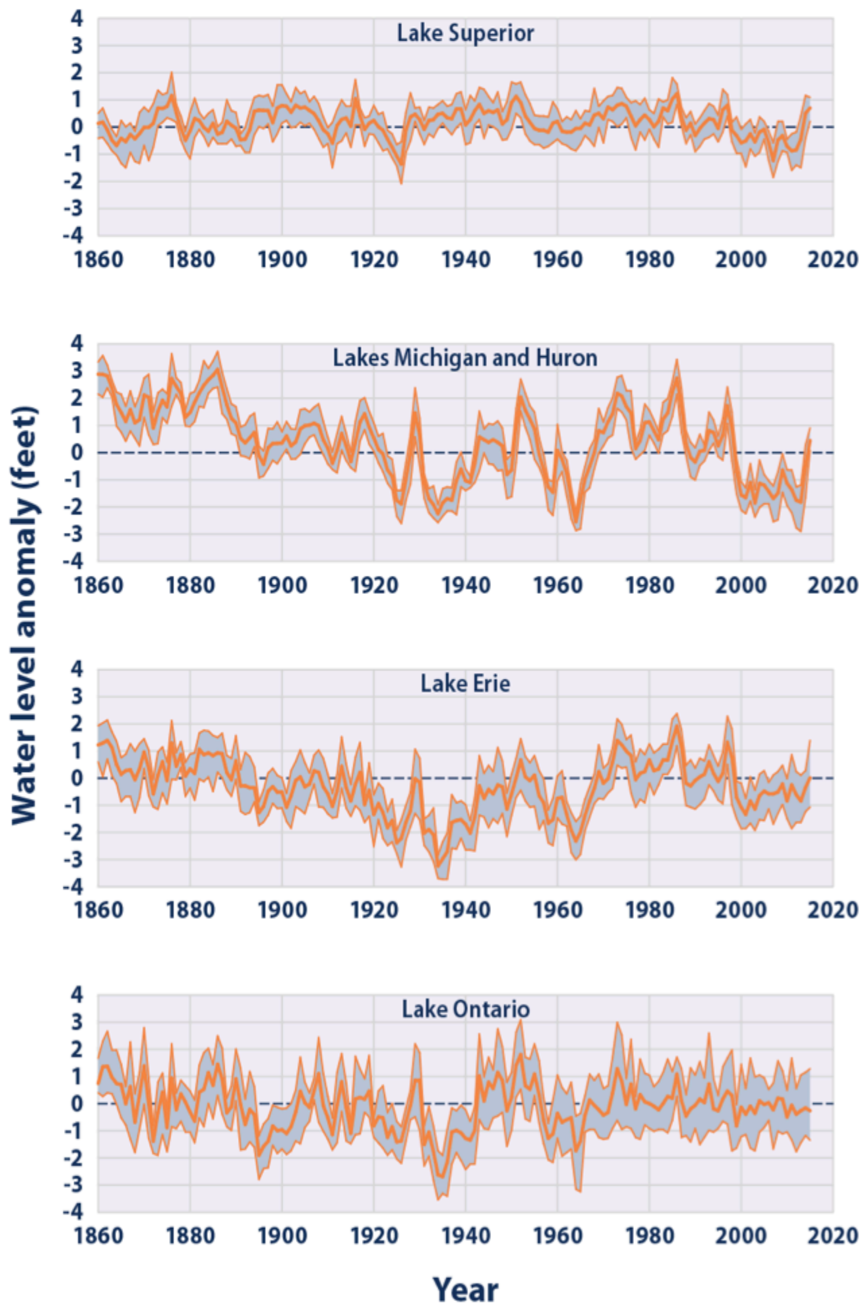


Figure 7. Water levels of the Great Lakes from 1860 to 2015 as an anomaly relative to the 1981-2010 average. The shaded band shows the range of monthly average water levels, and the line in the middle shows the annual average. Choosing a different baseline period would not change the shape of the data over time. Lakes Michigan and Huron are shown together, because they are connected at the same water level. Source: Data from NOAA as reported by https://www.epa.gov/climate-indicators/great-lakes.

Methods of projecting lake levels in the mid to late 21st century have undergone a revolution in recent years. Lofgren et al. (2011) and Lofgren and Rouhana (2016) have shown that evapotranspiration from land (part of the calculation of runoff) was depicted in older models (as used in Angel and Kunkel, 2010; Lofgren et al., 2002; and many others) as extremely sensitive to climate change. We now know that those earlier analyses tended to overestimate the evapotranspiration effects. Results using other methodologies (Milly et al., 2005; MacKay and Seglenieks, 2012; Notaro et al., 2015; Lofgren et al., 2016) have generally projected very modest drops in lake levels and appreciable probability of small rises, in contrast to the large drops in lake level projected by the prior methods.

LAKE LEVELS

Comparison between historical trends in variables related to Great Lakes Basin hydrology and model-predicted results at the time scale of a century have differing levels of agreement, and historical time series often have issues of signal-to-noise ratio (i.e. they show trends, but variability over the decades of record is also highly significant in comparison). Trends in lake surface temperature are quite notable, with interactions between the lake surface temperature and the stability of the lake temperature profile helping to amplify the surface temperature trends. Trends in ice cover are also robust, with large decreases since the beginning of record in 1973, despite some reversals in this trend from some recent cold winters. Precipitation, evaporation, and runoff show more mixed results, with precipitation and evaporation generally increasing, with specific locations as exceptions, and runoff differing significantly among the individual lakes. The trend in Net Basin Supply also differs from lake to lake. Records of lake level over several decades show that trends are small and variability is high. Newer model-based projections of lake level (since 2011) foresee a central tendency toward small drops in lake levels to the end of the 21st century, with appreciable probability of small rises in lake levels, in contrast to the large drops projected using the older, now-defunct methodology.

4. Changes in Great Lakes watershed hydrology

Regional watershed hydrology will be driven by change in climate and land use, as well as by changes in demand. Warmer and wetter conditions will prevail on average, but increasing evaporative demand coupled with potential decreases in summer precipitation will likely lead to increased irrigation demand during the growing season. Continued expansion of urban land use will increase the need for stormwater management. Both agriculture and urban land use will continue to affect water quality in the future.

This section reviews some of the main ways in which climate will affect Great Lakes watershed hydrology and how that may be exacerbated by land use / land cover change occurring throughout the basin. Additionally, more specific impacts that may result from agricultural and urban land use are also reviewed to provide key insights for these dominant human landscape stressors.

4.1 Climate change effects on lake hydrology

Historically, precipitation increases have been relatively well distributed across the year. Future climate projections, however, suggest that precipitation will continue to increase in the winter and spring months. Summer and fall precipitation will be more variable in the near term but tending towards decreases by the end of the century.

Drier summer conditions are most likely under high emission scenarios. Increased winter and spring precipitation will directly increase river discharge in winter and spring months (Cherkauer and Sinha, 2010; Byun et al., 2018).

With less precipitation falling as snow, there is a decrease in flooding associated with spring snow melt, but mean streamflow will still be higher during those months because of greater overall precipitation (i.e., more rain). For larger watersheds this is expected to shift annual peak flows earlier in the season (Byun et al., 2018), while for smaller watersheds the increased frequency and magnitude of storms in the late spring will compete with snow melt as the primary driver of annual peak flow events, potentially shifting some peak flows later in the year (Cherkauer et al., 2018). Flood risk is also projected to increase in the future (Cherkauer and Sinha, 2010; Byun et al., 2018). Water storage in the landscape, as soil moisture, aquifer recharge, and the refilling of wetlands and small lakes will also increase during the winter and spring (Cherkauer et al., 2018; Byun et al., 2018), though water storage as snow will decrease.

Higher summer and fall air temperatures will increase evaporation during the growing season. Coupled with summer precipitation that is increasingly variable and likely lower, summer river flows will be lower than historical observations by the end of the century (Byun et al., 2018). The increased intensity of summer storm events is likely to contribute to an increase in the flashiness, or day-to-day variability, of river discharge (Cherkauer and Sinha, 2010). Increased evaporation during the growing season will also reduce water stored in the landscape, increasing soil moisture deficits in the fall (Byun et al., 2018; Cherkauer et al., 2018). This will increase the difference in water storage between wet and dry seasons. For example, Byun et al. (2018) project that soil moisture storage will decrease by about 8% in September and October by the end of the century under the high emissions scenario. For the same scenario, they project soil moisture storage to increase by around 10% in February and March by the end of the century.

4.2 Land use / land cover change

Land use and land cover influences climate by changing regional temperatures, precipitation, vegetation, and the patterns of thunderstorms (Pielke, 2005). Land use is projected to remain an important contributor to local changes in climate (Sala et al., 2000; Pielke et al., 2002; Pielke, 2005; Mahmood et al., 2010) and often occurs concurrently with hydrologic change (see Lee et al., 2011; Jarsjö et al., 2012, Destouni et al., 2013). Urban areas, in particular, have a disproportionate influence on climate, hydrology, and water quality (Price, 2011).

Table 4 summarizes the current land use and land cover for the Great Lakes Basin. Over 34 million people reside in the Great Lakes Basin, with two-thirds in urban settings (IJC, 2009). These urban areas cover around 10% of the basin, but represent the fastest growing land use type (Wolter et al., 2006, SOLEC, in review). Changes in land cover and land use are difficult to track for the entirety of the Great Lakes Basin due to differences in timing of land cover mapping, map resolution, and classification across the United States and Canada (SOLEC, 2017). For the period 2000 – 2011, the SOLEC (2017) Land Use Change indicator reported a net conversion of only 0.05% for the entire basin, but the majority of that change reflected an increase in developed areas (+0.38%) and a decrease in forest area (-0.5%). Data from a remote sensing study of the U.S. side of the basin (Wolter et al., 2006) reported a 2.5% change in land use from 1992 – 2001, with the greatest increases occurring in low intensity development (+33.5%), road area (+7.5%), and decreases of about -2.3% each in agricultural and forest lands. Increases in urbanization were concentrated in coastal areas of the Great Lakes.

There is strong evidence that forest ecosystems are already responding to climate change in the Great Lakes region (e.g., Iverson et al., 2008; Woodall et al., 2009; Zhu et al., 2012; Fei et al., 2017). In general, evidence suggests that individual tree species are moving northward and westward at 10-15 km per decade, with relatively strong shifts northward in northern hardwood forests around the Great Lakes (Woodall et al., 2009; Fei et al., 2017). However, some studies have also shown some eastern tree species are susceptible to range contraction due to climate change (Zhu et al., 2012; Iverson et al. 2017). Similarly, recent studies examining potential range shifts over a decade in the eastern United States found little evidence of range shifts, despite underlying changes in climatic conditions, raising concerns about range contraction.

One important factor that will influence land use and land cover change, and resulting effects on hydrology, is carbon fertilization. The Free Air Enrichment Studies (FACE) illustrated that elevated CO2 would increase net primary productivity in forests (e.g., Norby et al., 2005; Norby and Zak, 2011). Keenan et al. (2013) find strong increases in water use efficiency, suggesting that as CO2 levels increase, forested ecosystems will use water differently, potentially shifting watershed hydrology. There are important feedbacks between land use, land cover, and hydrologic response in the Great Lakes that are only poorly understood at present.

Policy responses to climate change could also have strong influences on land use change. Stavins (1999), Plantinga et al. (1999), Adams et al. (1999), Sohngen and Mendelsohn (2003), Murray et al. (2005), and recently Fargione et al. (2018) have suggested that implementation of natural climate solutions, including expansion of forests to sequester carbon, are economically feasible at costs comparable to energy sector mitigation options. According to these studies, there are significant opportunities to establish forests throughout the Great Lakes watershed, and policy efforts aimed at mitigating climate change could strongly influence future land use and land cover throughout the region. In general, these changes would involve expansion of forests at the expense of agriculture and grazing land.

4.3 Agricultural watersheds and agricultural impacts

The Fourth National Climate Assessment (USGCRP, 2018; Angel et al., 2018) illustrates key changes in Midwestern climate conditions that will affect crop productivity, including lengthening growing seasons; changes in precipitation patterns; shifts in minimum, maximum, and average temperatures; shifts in humidity levels, etc. These changes are already affecting crop production and are expected to continue shifting in the future. For instance, changes in seasonal precipitation are already affecting farmers in Midwestern states, with planting delays related to spring flooding and excessively wet soil conditions (Bowling et al., 2018). Outflow from subsurface drainage, historically at its peak in winter and spring months, is expected to increase in the future (Cherkauer et al., 2018). This is in part due to increased precipitation during those months, but also due to warming via the decreasing influence of snow and soil frost on infiltration.

Delayed planting puts crops at greater risk under hotter and drier conditions later in the growing season. This increases the demand for irrigation to mitigate crop losses (Bowling et al., 2018). Increased irrigation is already appearing in many Great Lake states. Groundwater is increasingly being used for irrigation throughout the Midwest, and in some cases pumping is lowering groundwater levels (e.g., Cherkauer et al., 2018). There is growing awareness that water storage must increase in the region to capture more of the plentiful winter and spring precipitation, and store it until needed to reduce summer losses. Increased storage on farms distributed across the landscape will have an effect not yet quantified, related to flood risk and water availability, discussed in Section 4.1.

A number of empirical studies have examined the influence of weather and climate on crop yields, focusing on the U.S. Midwest given its global importance. These studies have suggested that climate change could have significant impacts on corn and soybean yields in the Great Lakes region (e.g., Schlenker and Roberts, 2009; Urban et al., 2012; Lobell et al., 2014; Gustafson et al., 2015; Bowling et al., 2018; and Jin et al., 2017). Depending on climate mitigation efforts and adaptation, climate change could reduce crop yields by 10-30% by the middle to latter parts of this century. The largest negative effects will occur in the southern Great Lake states (Urban et al., 2012; Bowling et al., 2018), as maize in particular is increasingly at risk to drought stress (Lobell et al., 2014). Despite potential falling productivity in currently important crops in the region, agriculture is expected to remain in important land use in the Great Lakes region due to adaptation (Haim et al., 2011).

Efforts to adapt with irrigation, adaptation of new varieties, and alternative management approaches can help mitigate some of the yield losses experienced by growers. Climate change will also encourage farmers to adapt their management by switching to new crops, among other approaches (Mendelsohn et al., 1994; Easterling et al., 2000; Deschenes and Greenstone, 2007; Massetti et al., 2016; Mendelsohn and Massetti, 2017). For some areas, this may include double cropping where more than one crop is grown in a field per year, increased use of cover crops, and changes to new mixtures of crops better suited for the future climate (recognizing the large differences in soil productivity across the Great Lakes region). There is evidence that important crops, in particular corn and soybean, will shift northward (e.g., Easterling et al., 2000; Laingen, 2017).

4.4 Urban watersheds and urban impacts on the Great Lakes

Land use impacts on climate are well documented (Mahmood et al., 2010), as are effects of land use / land cover on hydrology (e.g., Mao and Cherkauer, 2009). Interacting effects of climate, land use, and human population are difficult to quantify independently, and the simultaneous effects have rarely been studied. Direct impacts of urban land use on hydrology stem from water diversions. These include massive infrastructure projects such as the Chicago Water Diversion, which in 1900 reversed the flow of the Illinois River to drain to the Mississippi River instead of to Lake Michigan (Annin, 2018), and more modest diversions resulting from shallow groundwater withdrawals, rerouted stormwater runoff, or smaller wastewater systems exported outside catchments (Price, 2010). The Great Lakes Compact, signed in 2008, is designed to protect the basin from further withdrawals, through a set of protocols that define the geographic boundaries and the conditions under which water is withdrawn and then returned (Annin, 2018). Unfortunately, this agreement does not address the potential impacts of climate change on groundwater and surface water quantity and quality.

There is emerging understanding that the hydrologic behavior of urban areas is more complex than was previously known. The dogma that vegetation removal and replacement with impervious surfaces decreases baseflow due to changes in recharge has been challenged by more recent studies that demonstrate both increased and decreased recharge associated with urban areas (Price, 2010). Some effects of urban development are well known: decreased groundwater recharge from impervious surface and soil compaction, rapid transmission of stormwater to waterways, shallow groundwater leakage to stormwater sewers, shallow stormwater withdrawal, and rerouted wastewater. But increased groundwater recharge can result from changes in surface distribution of imported water from irrigation and outdoor water use, infrastructure leakage, stormwater detention in artificial structures, and movement of stormwater to shallow groundwater via storm sewers (Lerner, 2002; Price, 2010). Green infrastructure such as parks, green street corridors, rain gardens, and natural areas, are increasingly being examined as cost-effective strategies for cities to increase water storage in soil and groundwater, thereby decreasing stormwater runoff (Hopton et al., 2015; Carlson and White, 2017).

Increasing variability in precipitation patterns, especially during early spring when grounds are frozen or when rainfall occurs onto snow, are likely to exacerbate stormwater runoff and flooding events. However, these processes will have variable results on baseflow and groundwater recharge depending on the regional geology, type and status of infrastructure repair, and stormwater and wastewater management practices. Direct effects of climate on baseflow are likely to be highly variable depending on regional conditions. For example, higher summer time temperatures are likely to result in increased convective precipitation and more intense storms. Modeling studies suggest that seasonality of flow regimes, combined with warmer temperatures are likely to reduce base flow (e.g., Choi, et al., 2009). An empirical study in Wisconsin showed that climate change was the dominant driver of baseflow timing, but land use change interacted with climate to alter the magnitude of changes (Juckem et al., 2008). The amount of impervious surface and compacted soil are likely to be strong determinants of those responses (Smakhtin, 2001; Easterling et al., 2000). Vegetation type and distribution have a strong impact on both local and regional hydrology, and land use conversion can either increase or decrease runoff as a result (Mao and Cherkauer, 2009).

4.5 Water quality impacts on the Great Lakes

Urban influences on water quality are strongly linked to hydrology and climate, especially to changing precipitation patterns (IJC, 2009). Globally, increases in climate-mediated precipitation are predicted to result in increased total nitrogen loads to rivers, although much of this is due to agricultural activities rather than urban inputs. Future cross-model mean projections of nitrogen loading for the Great Lakes region show the large regional increases (+21%) for the 2071-2100 period under the high emission scenario (RCP8.5) (Sinha et al., 2017). An additional concern for the Great Lakes lies in loading of dissolved phosphorus from watersheds, with a special concern for its effect on harmful algal blooms and dissolved oxygen concentrations (Scavia et al., 2014; Burlakova et al., 2018). Since the 1990's algae blooms, benthic algae, and extensive hypoxia zones have re-emerged as problems in Lake Erie (Scavia et al. 2014), and have been linked to phosphorus loading from agricultural sectors. SPARROW model output for the U.S. tributaries of the Great Lakes have identified sources of phosphorus to the Great Lakes from a wide variety of sources including point sources (industrial, commercial, and sewage), confined and unconfined manure, farm fertilizer, nonpoint sources from urban and developed land, as well as forest and wetland areas (Robertson and Saad, 2011; ELPC, 2018). Across the Great Lakes, inputs from urban and agricultural sources were similar for all lakes except Lake Superior, which supports little agricultural activity. Around 50% of phosphorus inputs were derived from point sources and urban sources for all Great Lakes except Lake Superior. Manure was an important source of phosphorus in Lakes Michigan and Ontario (Robertson and Saad, 2015). Sources of nitrogen were mainly attributed to agricultural practices and atmospheric deposition. From the standpoint of climate change impacts, nutrient delivery via tributaries is the dominant input to the Great Lakes, thus climate-driven patterns influencing flow regimes are likely to have a large impact on future nutrient delivery to the Great Lakes (Robertson and Saad, 2015). Large storms are likely to increase the incidence of sewage bypass in urban areas (i.e., combined sewer overflows) and flooding of manure management systems, thereby increasing the input of phosphorus into the Great Lakes.

URBAN ISSUES IN THE GREAT LAKES REGION

In the Midwest and Great Lakes regions, high weather variability, high-intensity urban development, and undersized infrastructure yield severe and accelerating vulnerability to urban areas as a result of such extreme events (Borden et al., 2007; Wilson et al., 2010; Pryor et al. 2014, Kristovich et al. [in review]). Interaction of the Great Lakes with coastal urban environments modify the lake breeze and shifts the urban heat island inwards (Sharma et al., 2017). Heat waves and poor air quality often co-occur because they are both associated with air stagnation (Schnell and Prather 2017; Sharma et al., 2016). The combination of high heat and poor air quality produces severe adverse impacts on public health, including considerable numbers of deaths during heat waves (Changnon et al., 1996; Palecki et al., 2001; Anderson and Bell, 2011). Increasing urban temperature and development of hot-spots adversely affect vulnerable low-income urban communities (Sharma et al., 2018). Projected increases in extremely warm and hot days, described previously, indicates that these risks are increasing in Great Lakes cites (Luber and McGeehin, 2008). Green infrastructure is likely to reduce urban stress in the Great Lakes region. However, an aggressive implementation of an adaptive strategy may reduce lake breeze and vertical mixing during daytime and could lead to stagnation of air near the surface causing poor air quality (Sharma et al., 2016). Thus, green infrastructure such as green and cool rooftops can provide relief for hot Great Lakes cities, but should be sited carefully (https://theconversation.com/green-and-cool-roofs-provide-relief-for-hot-cities-but-should-be-sited-carefully-60766).

Increased precipitation in extreme storms is also expected to present particular hazards to cities. Many Great Lakes cities experience frequent flooding from intense, localized storms (CNT, 2013; Winters et al., 2015). Under-resourced communities suffer a disproportionate burden of storm impacts, owing to the confluence of low property values and lack of infrastructure in low-lying flood-prone areas (Wilson et al. 2010, CNT 2013). The projected increase in extreme precipitation events in this region, as documented previously, is likely to exacerbate these problems, leading to increased flooding in the winter and early spring, as well as increased flooding from summer thunderstorms. These effects are already being seen, for example in extreme winter rain events and associated flooding in 2017 and 2018 (e.g., https://www.nbcchicago.com/news/local/flood-photos-chicago-south-suburbs-474717273.html, https://www.npr.org/sections/thetwo-way/2018/02/22/587881723/widespread-flooding-brings-misery-to-midwest).

5. Impacts on ecology of the Great Lakes and the region

The ecology of the Great Lakes region is already being affected by climate change, and these impacts are likely to strengthen in the future as the climate in the region continues to change. This section explores the understanding of these current and potential impacts.

5.1 Mixing and oxygenation

As mentioned in section 3.1, since fresh water has its maximum density at 4°C, the water column becomes unstable when surface water that was previously at a temperature farther away from that temperature moves closer toward it (e.g. after the surface water has reached its maximum temperature for the year and starts cooling, it becomes denser than the water below it and will start mixing). The water column typically passes through the 4°C threshold and mixes completely twice each year, on the way up in the spring and on the way down in the fall (they are "dimictic"). The spring overturning has become earlier with warming and the fall overturning later. Since the spring overturning represents the initiation of a stable configuration of the water column with the warmest water on top, inhibiting deep mixing as time goes on and enhancing the warming at the surface, this is noted as a mechanism for summer surface water temperatures to be increasing at a greater rate than air temperatures over adjacent land areas (Austin and Colman 2007). Animations available at https://coastwatch.glerl.noaa.gov show that there are parts of southern Lake Michigan and of Lake Ontario whose surface temperature stayed above 4°C during the winters of 2011-12 and 2016-17, so their water columns presumably did not mix fully during those years.

That vertical mixing brings nutrients up from the sediment at the bottom of the lake, and oxygen down from the surface, so it is crucial for ecosystems. In addition to altering the seasonal character of vertical mixing, the observed (and expected continuing) trend toward rainfall being concentrated in very heavy events is likely to increase the amount of nutrients reaching the lakes. Scavia et al. (2014) and Bosch et al. (2014) show this as one of the influences leading to increased nutrient load into the lakes, along with practices surrounding agricultural fertilizer application and drainage. This is particularly serious in the central basin of Lake Erie, because the water depth is such that not much mixing occurs to the bottom, yet the mass of water below the thermocline is small enough that decomposition of organic matter in the sediment can consume the oxygen within that layer. Michalak et al. (2013) document a major algal bloom in western Lake Erie that made Toledo, Ohio's municipal water unsafe to drink for weeks. This occurred following sudden increased water flow in tributary rivers in that area that transported a heavy load of nutrients, in particular from the Maumee River. Such events could become more likely given the intermittent, but very heavy rainfall events expected under a warming climate.

5.2 Biodiversity and invasive species

Over geologic time-scales, the Earth's climate has been the single most important factor controlling the distribution of the world's species and the biodiversity of species in any given location (Parmesan and Yohe 2003). Climate sets the physiological limits of species range distributions, controls the co-evolutionary processes that cause species to become mutually dependent, and influences the spread and interactions among species that control community membership. Therefore, climate change is predicted to have significant impacts on the biodiversity of all ecosystems, with these impacts occurring on short time-scales matching the timing of changes projected to occur through the current century.

The ultimate impact of climate change on biodiversity in the Great Lake ecosystem will depend on how the various components of climate change (warming, increased CO2 concentrations, changes in water acidity and oxygen levels, altered frequency and intensity of storms, etc.) collectively impact four factors that regulate biodiversity: (1) invasion rates by new, non-native species, (2) replacement of widespread or abundant species by those that are presently uncommon or rare, (3) emergence or proliferation of new pests and disease that might impact established species populations, and (4) extinction rates of the existing established species assemblage (Figure 8).

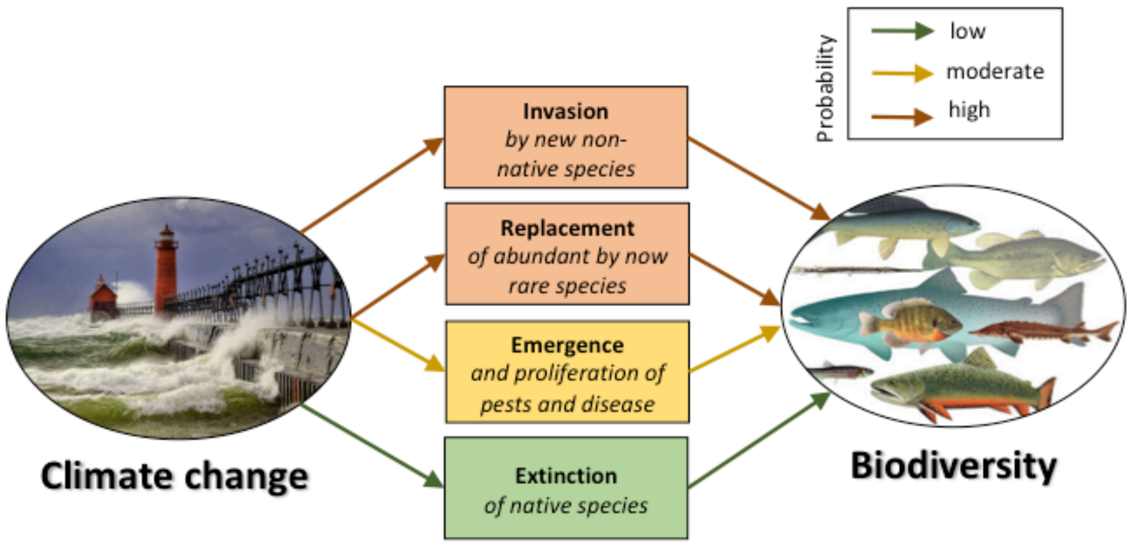


Figure 8. The impact of climate change on biodiversity in the Great Lakes will depend on how climate change impacts four factors that contribute to diversity: (1) invasion by new, non-native species, (2) replacement of currently dominant species by those that are now rare (i.e. species turnover), (3) the emergence and proliferation of pest and disease species that impact of native populations, and (4) extinction of currently native species. These are ranked from their highest to lowest probability or risk.

The greatest effects of climate change are expected to occur from the redistribution of flora and fauna that lead to the introduction of non-native species (Pecl et al., 2017). There are already well-documented examples of climate change altering the range distributions of species, leading to introduction of novel species into ecosystems. Indeed, 87% of all species monitored have displayed range shifts as they have migrated towards the poles at rates exceeding 3.7 miles (6 km) per decade (Parmesan and Yohe, 2003).

Within the Great Lakes watershed, one of the best examples of range shifts altering biological communities comes from surveys of sport and baitfish populations. The range boundaries of numerous sportfish have shifted northward at a rate of 8 to 11 miles (12.9 to 17.5 km) per decade over the past 30 years, which has led to widespread introductions of formerly “southern” warm-water fish species into northern latitude lakes (Alofs et al., 2013).

There is also good evidence that climate change has initiated species ‘turnover’ as formerly rare or uncommon species have benefited from climate change and begun to proliferate (Collingsworth et al., 2017). For example, smallmouth bass (Micropterus dolomieu) have historically been limited in their northern distribution by the length of the ice-free growing season and overwinter survival of their young-of-the-year (yoy). As the ice-free season has increased, and as warming has improved young of year survival, populations of smallmouth bass have proliferated in lakes that they currently occupy, and expanded to waterbodies throughout the Great Lakes watershed they did not formerly occupy (Alofs et al., 2013; Alofs and Jackson, 2014). Because smallmouth bass are voracious predators, their expansion has reduced more than 25,000 populations of northern redbelly dace (Phoxinus eos), finescale dace (Phoxinus neogaeus), fathead minnow (Pimephales promelas), and pearl dace (Margariscus margarita) throughout lakes in Ontario (Jackson and Mandrak, 2002).

In Lake Superior, white perch (Morone americana) and alewife (Alosa pseudoharengus) have historically been rare, but are expected to expand their distributions with continued climate warming (Bronte et al., 2005), likely owing to reduced overwinter mortality (Hook et al., 2007). The invasive round goby (Neogobius melanostomus) is also expected to gain more beneficial habitat with continued warming across the Great Lakes (Kornis et al., 2012), as may the flathead catfish (Pylodictis oliverus) (Fuller and Whelan, 2018).

Climate change is also likely to exacerbate the emergence and proliferation of pest and disease species. For example, bioenergetics modeling has demonstrated how sea lamprey (Petromyzon marinus) have benefitted from the warming of Lake Superior since 1979 by growing larger and more fecund (Cline et al., 2013). These trends are problematic because invasive sea lamprey have already had large negative effects on fisheries by parasitizing and killing recreationally important piscivores and commercially important lake whitefish (Coregonus clupeaformis) as adults (Bence et al., 2003). Larger more fecund individuals are likely to inflict even higher mortality rates on their hosts.

Patz et al. (2008) suggested the prevalence of water-born pathogens will increase with climate change. They showed that climate change models predict an increase of extreme precipitation events by 10% to 40% in southern Wisconsin, which will result in a 50% to 120% increase in the frequency of combined sewer overflows into Lake Michigan. Those overflows are projected to introduce hundreds of new species of pathogenic bacteria, viruses, and protozoa.

Although climate change will undoubtedly affect Great Lakes biodiversity by promoting invasion by non-native species, replacement of common by formerly rare species, and the proliferation of pests and disease, the risk of extinctions caused directly by climate change is uncertain. Even while climate change is often touted as a great risk to biodiversity (Thomas et al., 2004), few empirical examples of extinctions have ever been directly linked to climate change (the first was reported by Gynther et al., 2016). Nor have any extinctions of native species that we know of have been directly attributed to climate change in the Great Lakes.

While extinctions caused directly by climate change are likely to be rare, the potential of extinctions caused indirectly through climate change's impact on invasive species, species replacement, or the proliferation of new pests and disease are possible. However, the importance of these indirect effects is currently controversial, and has a high degree of uncertainty. For example, while it has historically been assumed that invasive species are a leading cause of native species extinction (Wilcove et al., 1998), recent evidence suggests that invasive species rarely cause extinctions (Gurevitch and Padilla, 2004) and, in fact, non-native introductions often cause biodiversity to increase as invasion rates outpace extinction rates (Sax and Gaines, 2003; Dornelas et al., 2014). Therefore, the cumulative impact of climate change on extinctions (direct and indirect effects) is presently unknown.

5.3 Nutrient loading and algal blooms

Harmful algal blooms (HABs) are increasing in frequency and severity worldwide. Many of the variables that control the frequency and severity of HABs – such as nutrient loading, water temperature, and stratification -- are directly influenced by climate change (Wells et al. 2015). As such, climate change is expected to alter the frequency and severity of HABs. Increased nutrient loading caused by agricultural fertilizers, urban wastewater, and soil erosion is the primary cause of HABs in water bodies throughout the world (Heisler et al. 2008), including in the Great Lakes (Watson et al., 2016). Nutrient loading to Great Lakes coastal zones is generally expected to increase as a result of climate change, mostly due to a greater frequency of large precipitation events that increase runoff from agricultural landscapes in the surrounding watersheds. For example, Cousino et al. (2015) incorporated predictions from recent climate change models into a Soil & Water Assessment Tool (SWAT model) of the Maumee River to predict the effects of climate change on water, sediment, and nutrient yields. The Maumee River, which is a dominant source of nutrients to the western basin of Lake Erie that experiences frequent HABs, is expected to experience more extreme precipitation and runoff events in the future. Unless nutrient and sediment loads are offset by improved land management practices (Scavia et al., 2017), models predict that climate change will increase eutrophication of western Lake Erie with greater nutrient loading by the Maumee River.

There is some evidence that extreme climatic events have already contributed to HAB formation in the western basin of Lake Erie (Figure 9). Michalak et al. (2013) studied the record-setting 2011 algal bloom in Lake Erie, which was caused by the toxin-forming cyanobacteria Microcystis (July and August) and Anabaena (September and October). Although agricultural runoff is the normal cause of the routine blooms that form in the basin, several climactic anomalies contributed to the 2011 event being unusually large. In particular, a May 2011 storm caused the Maumee River to reach the 99.8th percentile for its daily discharge, leading to an abnormally high amount of nutrient runoff. Then, after the bloom started, weather conditions were unusually conducive for growth – with "warm and quiescent conditions" for 62% of the time after bloom onset, relative to 35%-36% in other years. This study suggests that the increasing frequency of large precipitation events in the Great Lakes region and general warming patterns could increase the probability of particularly large or severe blooms.

Figure 9. In 2011, Lake Erie experienced the largest harmful algal bloom in its recorded history, with a peak intensity over three times greater than any previously observed bloom. Climate change is expected to increase the frequency of these large algal blooms
Source: MERIS/ ESA Satellite photo, processed by NOAA/NOS/NCCOS; https://www.canr.msu.edu/news/lake_erie_harmful_algae_bloom_threatens_drinking_water_supplies.

In addition to nutrient loadings, higher water temperatures are known to preferentially favor growth by certain types of bloom-forming algae and cyanobacteria (O'Neil et al., 2012). At water temperatures above 20ºC, the growth rates of freshwater eukaryotic phytoplankton stabilize or decrease, while growth rates of many bloom-forming cyanobacteria increase (e.g., Microcystis, Anabaena, and Cylindrospermopsis). Warming water temperatures may have been responsible for an unprecedented algal bloom in Lake Superior that spread across 50 miles of Lake Superior shoreline in 2018, from Superior, WI to the Apostle Islands (https://www.nytimes.com/2018/08/29/science/lake-superior-algae-toxic.html)

Increased water temperature can also increase the frequency of toxin production by bloom-forming species. For example, Davis et al. (2009) found that enhanced temperatures yielded significantly increased growth rates of toxic Microcystis in 83% of the experiments conducted, but did so for non-toxic Microcystis in only 33% of experiments. This suggests that elevated water temperatures may yield more toxic blooms.

Climate change is also increasing the duration and intensity of lake stratification (Kraemer et al., 2015), which is expected to promote HABs. Lehman (2002), for example, used nested physical and biological models to simulate future stratification and mixing conditions for the Great Lakes that are projected under climate change through 2090. Those models predicted elevated mixed layer and bottom temperatures in all five Great Lakes by as much as 5 ºC this century, with longer duration of thermal stratification, stronger stability of stratification, and deeper daily mixing depths during peak thermal stratification. Many HAB species uniquely adapted to exploit stratified conditions. For example, most bloom-forming cyanobacteria contain gas vesicles that provide buoyancy, enabling them to form dense surface blooms in stratified waters where they can take advantage of high levels of irradiance to optimize photosynthesis (Paerl and Paul, 2012). Many surface-dwelling cyanobacteria also contain photoprotective accessory pigments (e.g. carotenoids) and UV-absorbing compounds (mycosporine-like amino acids [MAAs], scytonemin) that ensure long-term survival under high irradiance conditions, while suppressing non-buoyant species through competition for light (Paerl and Paul, 2012).

5.4 Fish

Fish species in the Great Lakes region will be directly affected by climate change phenomena including temperature increases, increases in storm intensity and frequency, and shifting seasonal patterns. Many Great Lakes fishes are influenced by water temperature, for example, which contributes to distinct cold, cool, and warm-water assemblages throughout the region (e.g., Magnuson et al., 1997; Wehrly et al., 2003). Additionally, shifting seasonal patterns of precipitation and ice formation can similarly affect species whose behavior is cued to those events. Besides these direct changes, effects of climate change phenomena on fish habitats will further impact species. Changing precipitation patterns and storm impact hydrology will impact drainage patterns, connectivity, water levels, and the extent and quality of littoral habitat. Increases in water temperature, along with earlier warming in spring, will increase the depth and duration of stratification. This, in turn, will promote depletion of upper oxygenated layers of water, resulting in more widespread and profound periods of bottom anoxia (Trumpickas et al., 2009; Collingsworth et al., 2017). Together, these changing environmental drivers will have multiple effects on Great Lakes fishes by changing 1) geographic ranges, 2) overall system productivity, 3) species-specific productivity, 4) spatial arrangement within a system due to changing habitat suitability (Shuter et al., 2012; Poesch et al., 2016; Lynch et al., 2016) and 5) changes in physiological state and performance (Whitney et al. 2016).

Many modeling studies have been conducted predicting impacts of climate change on fish (e.g., Jackson & Mandrak, 2002; Sharma et al., 2007; Sharma and Jackson, 2008; Herb et al., 2016; Van Zuiden et al., 2016), with many of these focused on coldwater fish species or assemblages. Fewer studies have reported empirical observations of climate change impacts. Such studies (reviewed by Comte et al., 2013; Lynch et al., 2016) have documented shifts in geographic range, changes in demographics (abundance, growth, recruitment), increased occurrence of diseases, phenological shifts (earlier migration, spawning), extirpation (especially of coldwater species), and hybridization resulting from novel species interactions (Lynch et al., 2016; Collingsworth et al., 2017). Comte et al. (2013) compared predicted versus observed responses and found that in general, the observed effects of climate change are much greater (mean of 8x) than those derived from model predictions. Overall positive impacts from empirical observations were found on Cyprinidae, Percidae, Ictaluridae, and Salmonidae; although Salmonidae showed more mixed effects than the other families. In general, predicted studies reported a high proportion of negative effects for coldwater species. In Lake Superior, the coldwater fish assemblage was predicted to experience little change, with the exception of the lake siscowet (a variety of lake trout [Salvelinus namaycush]), which have extreme cold thermal tolerances (Magnuson et al. 1997).

Range expansions have been among the most commonly observed changes that indicate climate change impacts on fish. At mid-latitudes (40°N to 50°N), warm- and coolwater species have exhibited increased presence, abundance, and distribution (Johnson and Evans, 1990; Alofs et al., 2014). Within the Great Lakes Basin in Ontario, range expansions have been documented for game fish (mainly bluegill [Lepomis macrochirus]), largemouth bass [Micropterus salmoides], smallmouth bass [Micropterus dolomieu], and brown bullhead [Ameiurus nebulosus]), which have migrated poleward at the rate of 13 km per decade over a recent 30 year period. In contrast, there were no statistically significant changes observed in the range of preyfish species, although the trend was towards range contraction (Alofs et al., 2014). Studies assessing factors that control establishment of novel species suggest that abiotic factors (habitat, water temperature) are the primary drivers at regional scales, but that biotic factors are more important on a lake by lake basis (Alofs and Jackson, 2015).

Many studies have predicted northward expansion of warmwater species (e.g., Jackson and Mandrak, 2002; Chu et al., 2011; Sharma et al., 2007, Van Zuiden et al., 2016). As geographic ranges expand, community composition is expected to be altered, with greater diversity expected as cool and warm water species invade cold water habitats. In addition to altering predator-prey interactions as a result of these novel species interactions, Biwas et al. (2017) predict an increase in species richness in Ontario lakes of 60-81% by the end of the century, along with changes in the functional traits of the fish community. These include changes in the average thermal guild of species present, smaller body length and weight, lower fecundity, and shorter trophic breadth by 2070 under both a business as usual and best-case emission scenario. Under the best-case emission scenario, 10-40% of Ontario lakes are expected to be impacted by major shifts in community composition. Species that will be affected include lake trout, northern pike (Esox lucius), walleye (Sander vitreus), whitefish (Coregonus clupeaformis) and yellow perch (Perca flavescens). Jackson and Mandrak (2002) predict that range expansion of smallmouth bass will be extremely detrimental to the populations of forage fish; a pattern confirmed by Vander Zanden et al. (2004) and Alofs et al. (2014). This pattern was also confirmed by Robillard and Fox (2006), who reported declines in walleye relative abundance and increases in relative abundance of smallmouth bass in conjunction with decreases in phosphorus concentrations, increased water clarity, and increased water temperature. The later study highlights the difficulty of isolating the impact of climate change versus other environmental stressors such as land use change, which can lead to nutrient loading and the presence of invasive species.

In addition to range expansion and community realignment, climate change has been shown to influence recruitment and spawning behavior, with both "winner" and "loser" species throughout the basin and with some results varying by region. For example, increased temperatures and altered aquatic conditions have facilitated increased recruitment and abundance for some warmwater species (e.g., black basses [Robillard and Fox, 2006]), with increased temperature contributing to declines in cisco (Coregonus artedi) abundance in Minnesota glacial lakes (Jacobson et al., 2012). In Lake Michigan near Milwaukee, yellow perch have been observed to be spawning earlier, by 6.2 days per decade (for the period 1988-2012), while in Green Bay, earlier spawning occurs by 1.8 d/decade (1983-2016; Lyons et al., 2015). In Lake Erie, the timing of yellow perch spawning has not changed despite shorter, warmer winters; however, females are producing smaller eggs that both hatch at lower rates and produce smaller larvae than females exposed to long winters (Farmer et al., 2015). This effect may be explained by shifts in the peak of zooplankton production, a key food for yellow perch larvae. However, there is some evidence that increased river discharge and associated turbidity plumes in Lake Erie may benefit larval yellow perch (reviewed by Collingsworth et al., 2017). Trends for lake trout spawning in Lakes Superior and Michigan are unclear. Lyons et al. (2015) speculate that spring spawning species are likely to be more strongly affected than fall spawning species due to the high variability in water temperature changes during spring, compared to fall. In some Minnesota lakes, walleye are also spawning earlier, in conjunction with earlier ice out patterns (Schneider et al., 2010). In Lake Erie, greater variability in spring warming has been shown to be associated with more variability in spring spawning species such as walleye, and the same pattern was observed for summer spawning smallmouth bass in Lake Opeongo in Ontario. Furthermore, increased summer water temperatures were associated with greater growth rates in walleye (Shuter et al., 2002). These authors predict that fish species that are most sensitive to winter conditions (e.g., alewife [Alosa pseudoharengus]) could be expected to be most sensitive to warming climate in the region, due to the prevalence of winter warming that has characterized the shifting climate patterns

In addition to observed and predicted changes in phenology, simulations of fish growth using bioenergetics models for yellow perch and lake whitefish under different climate scenarios predict that growth rates will decrease more for yellow perch than lake whitefish (Kao et al., 2015). This study also concluded that prey availability may offset the effects of climate change in terms of regulating fish growth rates. This finding provides a caution that temperature tolerance is not the only consideration when predicting effects of climate change on fish.

In conjunction with climate change impacts, the Great Lakes fisheries are heavily impacted by the presence of nonnative invasive species such as the quagga mussels (Dreissena bugensis) and zebra mussels (Dreissena polymorpha), which have dramatically influenced nutrient dynamics and the food web in general (Karatayevet al., 2015; special issue edited by Burlakova et al., 2018). In Lake Erie, in particular, dissolved phosphorus concentrations have increased, and harmful algal blooms and water column anoxia are prevalent, especially in the western and central basins (Scavia et al., 2014). In Lakes Michigan, Huron, and Ontario, nearshore benthic algal production is of special concern, especially for residents of the coastal areas; but offshore, declining phosphorus concentrations and productivity threaten the collapse of the food web (Bunnell et al., 2014; Dove and Chapra, 2015; Barbiero et al., 2018). The importance of water temperature as a key driver of fish distributions was recently highlighted in a study that assessed the major environmental factors explaining distributions of individual fish species in coastal areas of the Great Lakes. In the northern ecoprovince of the Great Lake, an analysis of the main drivers explaining fish presence / absence in coastal areas identified cumulative degree days as the most consistent predictor in models of 12 out of 13 fish species (Kovalenko et al., 2018). In the southern ecoprovince of the Great Lakes, primary drivers were related to water quality and physical habitat factors associated with habitat structure. The confounding effects of climate change and further land use change (especially in the coastal zone) have not yet been addressed in the context of these issues. Future studies are encouraged to incorporate an ecosystem approach, account for the interaction of multiple, interacting stressors, and to consider the effects of predator-prey interactions as well as availability of prey (Collingsworth et al., 2017).

5.5 Wildlife

Wildlife in the Great Lakes region includes many species of mammals, birds, amphibians, reptiles, and macroinvertebrates. Due in large part to warming air temperatures, but also due to changes in types and patterns in precipitation, soil moisture, and the specific physiology of different organisms (Inkley et al., 2004), geographic ranges of many Great Lakes wildlife species are generally expected to shift northward (Gitay et al., 2002). This broad trend, however, will vary due to local conditions including changes in ice cover and regional precipitation. Additionally, the ability of wildlife to adapt to changing climate will be exacerbated by habitat loss, habitat fragmentation, competition from invasive species, threats from new and emerging diseases, and altered ecological processes (Hoving et al., 2013; Merila and Hendry, 2014). To aid efforts to proactively manage or mitigate for those changes, many attempts have been made to anticipate the vulnerability of key wildlife species to changes in climate, or describe how species distributions may change throughout the Great Lakes region and nationally in the U.S. and Canada (e.g., Frelich and Reich, 2009; Hellman et al., 2010; Hoving et al., 2013; Lawler et al., 2013; Culp et al., 2017). Due to uncertainties in climate change impacts on wildlife habitats and in how those changes could lead to changes in wildlife communities, it is challenging to fully anticipate how individual species may respond to changes in climate. Here, we provide a broad overview of current understanding of how climate has or will affect select wildlife species in the Great Lakes region, with the goals of emphasizing how different groups of taxa may be vulnerable, and to highlight some of the complex mechanism by which species and communities may be affected.

Mammals

Currently, nearly half of the 80 species of native Great Lakes mammals occur at either their southern or northern distributional limits (Kurta, 2017; Myers et al., 2009). This is due in part to the transition that exists between boreal forests in portions of the northern Great Lakes region with systems more common in southern regions like eastern oak hickory woodland, oak savannas, and prairies. In a recent study focused on distributions of 9 common woodland rodent species in Michigan, several species with ranges centered south of the state (white-footed mouse [Peromyscus leucopus], eastern chipmunk [Tamias striatus], southern flying squirrel [Glaucomys volans], common opossum [Didelphis virginiana] were found to have expanded northward into Michigan, while species with northern ranges (woodland deer mice [Peromyscus maniculatus gracilis], southern red-backed vole [Myodes gapperi], woodland jumping mouse [Napaeozapus insignis], least chipmunk [Tamias minimus], northern flying squirrel [Glaucomys sabrinus]) showed range declines in the state (Myers et al., 2009). The authors of this study acknowledge that regeneration of forests and changes in human population may be partially responsible for observed distributional changes, but they assert that warming temperatures are likely the leading factor due to the co-occurring increase in multiple species with historically southern-centered ranges and a decrease in their northern counterparts. In some cases, consequences of range changes are known to have greater impacts than just species replacement. A focused investigation of the white-footed mouse attempted to predict its range expansion in Quebec through the year 2050 (Roy-Dufresene et al., 2013). The white-footed mouse is a carrier of Borrelia burgdorferi, the known pathogen for Lyme disease. The study concluded that warmer, shorter winters will allow the mice to colonize new areas, including southern Quebec, and this is likely to have public health impacts in northern regions that have not currently been exposed to Lyme disease.

Large mammals are also being affected in the Great Lakes region. In Ontario, changes in forest type resulting from changes in climate are expected to affect wildlife species with larger body sizes more substantially than species with smaller body sizes (Thompson et al., 1998). Moose (Alces alces) may be especially vulnerable to climate change. In Minnesota and other part of their range, moose populations have declined precipitously, resulting in an elimination of the moose hunting season in some parts of Minnesota. Changes in climate will affect moose directly; their ability to thermo-regulate in both winter and summer may change with changes in air temperature and precipitation (Rempel et al., 2011). Hoy et al. (2018) have shown a decrease in moose size on Isle Royale, Michigan that they attribute to warming winter temperatures. Compounding these effects, changes in climate will have indirect effects on moose. Preferred habitat and available browse may change with changes in forest cover (e.g., Thompson et al., 1998). Additionally, white-tailed deer (Odocoileus virginianus) are expected to expand northward into habitats historically dominated by moose. White-tailed deer carry the parasite Paralaphostrongylus tenuis which is fatal to moose (Thompson et al., 1998; Murray et al., 2006). Parasites, particularly ticks, are surviving in greater number and have been found to provide yet another stress factor for moose. Finally, increased mortality from wolves may be an additional factor leading to declines in moose populations, and evidence for how changing climate is altering behavior of wolves and increasing mortality of moose has been described on Isle Royale (Post et al., 1999).

Dynamics among Isle Royale grey wolves (Canis lupis) and moose have been studied extensively since 1959 when wolves colonized the island. Pack size of wolves increases with snow depth to increase hunting efficiency, leading to more moose killed by wolf packs per day on the island. These increased kills include more calves and old moose, with kills of old moose being further facilitated by deeper snows (Post et al., 1999). Deeper snows are a consequence of more lake effect snowfall that occurs with an absence of ice cover throughout the Great Lakes, a trend that has been observed around Lake Superior and that is expected to continue in the region (GLISA, 2018). In Ontario, a recent modeling effort attempted to predict moose population dynamics in Ontario through mid-century (Rempel et al., 2011) by accounting for some of the direct and indirect effects of climate change influences on moose, including greater heat stress and parasite loads, reductions in habitat carrying capacity, and more predation by wolves under the A2 climate scenario. All models predicted a decline of moose density at the southern limits of the Ontario range and an increase in density at northern extents.

Birds

Coastal marshes of the lower Great Lakes are among the most biologically significant wetland types in the Great Lakes region, in part due to their role as habitat for staging, nesting, and wintering waterfowl (Hagy et al., 2014) and as stopover sites for migratory birds (Ewart et al., 2012). In coastal marshes of Lake Erie and Ontario, researchers characterized the degree to which fluctuating water levels and associated changes in vegetation affected marsh bird communities (Chin et al., 2014). They found that an index characterizing integrity of bird communities decreased with decreasing water levels. In Lake Erie, the reduced index resulted from a loss of specialist bird species, which include obligate marsh-nesting birds. These findings followed those of an earlier study which showed that habitat suitability for American bittern (Botaurus lentiginosus), American coot (Fulica americana), black tern (Chlidonias niger), least bittern (Ixobrychus exilis), marsh wren (Cistothorus palustris), pied-billed grebe (Podilymbus podiceps), sora (Porzana carolina), swamp sparrow (Melospiza georgiana), and Virginia rail (Rallus limicola) decreased with decreasing water levels in Lakes Erie and Huron-Michigan (Timmermans et al., 2008), in part because marsh bird species tend to avoid dry patches of marsh (e.g., Manci and Rusch, 1988). While expected changes in lake levels described previously in this report include only modest drops overall (e.g., Lofgren et al., 2016), impacts of potential decreases will vary around the basin due to lake bathymetry, unique characteristics of the shoreline, and other regional influences. This may yield some coastal marsh habitats and their bird communities vulnerable to water level changes that may occur with changing climate.

Lower water levels and higher summer water temperatures are also affecting some Great Lakes birds by encouraging spread of disease. Recent deaths of fish eating birds within the Great Lakes region including red-breasted mergansers (Mergus serrator), ring-billed gulls (Larus delawarensis), and common loons (Gavia immer) have been attributed to the birds ingesting fish infected with a type of avian botulism, Clostridium botulinum (Culligan et al., 2002; Michigan SeaGrant, 2018). While botulism has long been present in the Great Lakes region, outbreaks are occurring more frequently, with researchers attributing those increases to changes in environmental conditions that will be exacerbated by climate change. Lafrancois et al. (2011) described the increased frequency of botulism outbreaks in Lake Michigan from 1963 to 2008 and showed that the outbreaks were related to higher summer water temperatures and lower water levels. They suggested that the frequency and magnitude of outbreaks should increase through the coming century and they called for more comprehensive monitoring of bird communities in response.

5.6 Coastal ecosystems

Like other coastal regions around the world, human activities are concentrated near the ~16,000 km of coastline in the Laurentian Great Lakes. These low-lying areas are particularly vulnerable to the effects of climate change, especially with respect to effects of intense storms and precipitation regimes that influence water level regimes (see Coastal Processes Section below). Water level interacts with geology to determine the extent and type of structural features at the shoreline (e.g., beaches, dunes, barriers, wetlands, and bluffs). Each of these structural features has a particular set of vulnerabilities associated with effects of changing climate as a result of changes in water level regimes, storm patterns and precipitation, ice cover and temperature regimes. These climate stressors and vulnerabilities of coastal ecosystems were reviewed by Mackey (2012).

Due to the long history of concentrated human activity in coastal areas of the Great Lakes, many of the larger ports and estuaries are highly disturbed 43 such sites have received designations as “Areas of Concern” (https://www.epa.gov/great-lakes-aocs) due to degradation of beneficial uses associated with physical, chemical or biological features. As of 2018, restorations have been completed for five sites and are ongoing for a similar number. It is unclear the extent to which climate change is a consideration in these restorations.

Among the coastal ecosystem types, wetlands have received the greatest attention, due largely to their importance as productivity and biodiversity “hotspots” (Cardinali et al., 1998; Vandeboncoeur et al., 2011; fish: Jude and Pappas, 1992; Trebitz and Hoffman, 2015; wetland vegetation: Wilcox, 1995, Lougheed et al., 2001; algae: McNair and Chow-Fraser, 2003; Reavie et al., 2007; birds, waterfowl, amphibians: Timmermans et al., 2008; amphibians: Houlahan and Findlay, 2003; functional richness and traits: Kovalenko et al., in revision). Coastal wetlands are among the most vulnerable ecosystem types in the Great Lakes as a result of changing water level regimes, increased storm frequency and intensity, and increased surface water temperatures. Increased water levels and storm surges are detrimental to aquatic vegetation communities, and open shoreline wetlands are likely to be the most directly impacted. However, such storms are also associated with increased nutrient, sediment, and contaminant loading from tributaries and increased coastal erosion, which can directly impact habitat and biota in coastal areas. While phosphorus loading is anticipated to increase as a result of higher spring flow and increased storm events (LaBeau et al., 2015), phosphorus reduction targets for Lake Erie, in particular, are expected to ameliorate this loading (Scavia et al., 2014), but current efforts may not be sufficient to prevent future cyanobacteria blooms and accompanying challenges to municipal water systems. Additional stressors impacting coastal areas include wetland drainage and diking, shoreline hardening, and human activities associated with shipping and recreation (Allan et al., 2013).

Warming water temperatures are expected to cause increases in primary production (Magnuson et al., 1997), but it is now clear that these changes are associated with changes in assemblage composition (Reavie et al., 2014). In shallow, coastal areas, increased primary production and warmer water temperatures will lead to more rapid decomposition, leading to the potential for summer hypoxia to develop (Nelson et al., 2009); increased hypoxia would exert a negative influence on the invertebrate community (Collingsworth et al., 2017).

Although water level fluctuation is a component of the natural hydrology of the Great Lakes, low water levels are a special concern in coastal systems especially when it leads to reduced hydraulic connectivity between tributaries and the lakes. This has multiple impacts on ecosystem structure and function affecting, for example, fish migration, flow of organic matter and other materials, and dispersal of invasive species (Januchowski-Hartley et al., 2013). Connectivity losses due to low water levels are exacerbated by physical structures in the watershed, such as dams and culverts, which impede movement between critical habitats during migration periods and when conditions are less than optimal, i.e., during periods with elevated water temperatures, and low dissolved oxygen (Nagrodski et al., 2012; Januchowski-Hartley et al., 2013).

Ice cover has declined across the Great Lakes region, with declines of 5 days per decade reported over the period 1974-2004 (Jensen et al., 2007). In coastal areas, ice cover serves to reduce wave action in shallow areas, thereby stabilizing the spawning habitat for fall and winter spawning species (e.g., lake whitefish). Lack of ice cover is also associated with further warming during summer months (Austin and Colman, 2007; Gronewold et al., 2015). Exposed shorelines and reduced ice protection increase the vulnerability of beaches, shorelines and bluffs to erosion (Mackey et al., 2012). Further, because human activity is so heavily concentrated along coastal regions, these areas are increasingly exposed to hazards that pose a threat to both infrastructure and human well-being.

5.7 Coastal processes

Hard rock shorelines in the Great Lakes such as those along the Canadian Shield on Lake Superior and eastern Georgian Bay, and the limestone and dolomites of the Niagara Escarpment in northern Lakes Huron and Michigan will for the most part not be significantly affected by climate change over the next 100 years. However, there is the potential for significant impacts on two types of shoreline that are especially important in southern Lake Huron, and much of Lakes Michigan, Erie and Ontario. These shoreline types are: 1) soft rock shorelines – bluff coasts developed in lacustrine silts and clay, glacial till, outwash sediments, and relatively weak shale bedrock; and 2) sandy beach and dune coasts, especially those formed on spits and baymouth barriers with their associated wetland systems. On both shoreline types, changes to wave characteristics over time (i.e., the wave climate) in each of the lakes is likely to have the greatest impact, and changes in mean lake level could be significant depending on the magnitude of the change.

The average annual wave climate at any point on the lake reflects primarily: 1) the shape of the lake and the fetch length for all onshore directions; 2) the average annual frequency and magnitude of winds by direction; and 3) the presence of ice during the winter which may act to reduce the open water fetch and/or to protect the beach and parts of the nearshore from wave action (Barnes et al., 1994; Forbes and Taylor, 1994). The first factor is considered fixed and, because wave generation during large storm events is usually fetch-limited on all of the lakes, it acts to limit the potential impact of modest changes to the wind climate. As a result, the most important potential impact of climate change on the wave climate is the reduction in the duration and extent of winter ice cover due to global warming, and in particular warmer winter temperatures. This manifests itself as the increasing occurrence of open water conditions into January or February and the disappearance of ice cover in April and as early as March. There will also be more frequent years in which there is virtually no ice cover. This means that the coast will be exposed to a greater number of storm events each year and the effect is heightened by the fact that this additional open water occurs during a period of the year when storm intensity is generally greatest.

As discussed in Section 3.2, there was a significant reduction in the mean winter ice cover on Lakes Superior, Huron, and Michigan for the period 1973-2010 and similar trends have been noted for maximum ice coverage (Wang et al., 2012). In terms of the effectiveness of wave action on beaches and nearshore, a better measure is one that is linked to the ability of waves to reach the toe on cohesive bluff shorelines or the base of the stoss slope of sand dunes on sandy coasts. Here, 10% ice cover is used as a measure of the transition from unrestricted wave action to restricted wave action and 20% ice cover as the transition to complete protection of the shoreline and nearshore from wave action and severe restrictions on wave generation within the lake. The number of days with ice cover on Lake Erie greater than 10% and 20% for the winter-seasons 1973-74 to 2017-18 have decreased by 23 and 24 days, respectively over the 44 year time period (based on data from NOAA/GLERL, https://www.glerl.noaa.gov/data/). Winter ice cover >10% now averages about two months a year, and since 1997 there have been 6 years with fewer than 30 days with ice cover exceeding 20%.

An increase in the average number of storms in the winter months will have a direct impact on erosion of cohesive bluff shorelines and lead to an increase in the rates of bluff recession on all of the lakes. Because lake levels are generally low in the winter months, there may be limited increases in short-term bluff toe erosion, but erosion of the nearshore profile will be enhanced. In turn this will lead to an increase in the long term recession rate (e.g., Davidson-Arnott and Askin, 1980; Davidson-Arnott and Ollerhead, 1995; Trenhaile, 2009; Geomorphic Solutions, 2010a, b; Sunamura, 2015). It is likely that the increase in long-term recession rates will be on the order of 20-30% by the middle of the century. This is similar to the impact of reduced ice cover documented for areas such as the Gulf of St. Lawrence (Manson et al., 2016a) and the Arctic (Overeem et al., 2011; Irrgang et al., 2018). The increased rate of downcutting also puts additional stress on shore protection structures along these shores, leading to a reduction in lifetime expectancy (Keillor, 2003; Coldwater Consultants, 2010). Indirectly, warmer temperatures also lead to a decrease in the extent and duration of frost and snow cover on the bluff face and an increase in precipitation in the form of rain at a time when vegetation cover is at its lowest. This will enhance erosion of the sub-aerial bluff face due to overland flow and rill and gulley development and may also enhance the rate of shallow slumping (Mickleson et al., 2004).

Reduced ice cover in early and late winter may have an impact on sandy beach systems as a result of increased frequency of intense storm events generating large waves and extreme storm surge. There is therefore a greater probability of major dune erosion on mainland beaches, particularly during periods of high lake level. There is also increased potential for overwash and breaching of barriers, particularly at vulnerable locations such as the proximal end of spits, e.g., Presque Isle and Long Point on Lake Erie (Davidson-Arnott and Fisher, 1992; Matheus, 2016) and along baymouth barriers, e.g., those enclosing Sodus Bay and Hamilton Harbour on Lake Ontario.

The effects of an increase in the number of winter storms generating waves can also change the magnitude and direction of littoral drift within littoral drift cells along the lakes. Locally this may lead to a change from accretion to erosion and vice versa at some locations along the shoreline. However, because of the restrictions imposed by the size, shape and alignment of lakes, the potential impacts on the littoral sediment budget are generally relatively small. Pinpointing these locations will require generating an ice-free wind climate and using this to model the wave climate and in turn to use this as input to sediment transport models (e.g., Manson et al., 2015, 2016b).

There is now a good understanding of the effects of seasonal and long-term lake level fluctuations on the dynamics of cohesive bluff shorelines (e.g., Quigley et al., 1977; Geomorphic Solutions, 2010b) and of sandy beach shorelines (Olsen, 1956; van Dyck). Based on this, a decrease in mean lake level will result in reduced bluff recession rates for a period of several decades and dune progradation of sandy shores. Conversely, an increase in the mean lake level will result in an increase in the rate of bluff recession for several decades and landward migration of the shoreline and foredune on sandy beaches. In addition, we can use shoreline response in areas of ongoing isostatic uplift or drowning in parts of the Great Lakes basin as a proxy for shoreline response to an increase or decrease in the mean lake level resulting from climate change. The issue here is that it will likely take several decades to separate a change in mean level from the long-term fluctuations.

WATER SUPPLY DISRUPTIONS (LAKE ERIE/TOLEDO)

Lake Erie is the source of drinking water for many communities in northern Ohio, including Cleveland and Toledo. In 2014, the drinking water in Cleveland and 28 other water systems in Northeast Ohio were found to contain chromium, a cancer-causing toxin, in very small quantities that still met federal standards. In 2015, almost all of the water systems in Ohio produced tap water with detectable levels of the same seven or eight contaminants, sufficient to exceed health guidelines, but within federals standards.

A much bigger problem occurred in Toledo and parts of southeast Michigan in 2014 as a result of a harmful algae bloom in the water supply itself (Jane Herbert, https://www.canr.msu.edu/news/the_toledo_water_supply_shut_down._why_boil_water_advisories_were_not_enoug). Warming water temperatures and nutrient loading in Lake Erie were responsible. And boiling the water would have been insufficient – it would kill the organism but not eliminate the toxin. As a result, Toledo and other communities had to scramble to find alternative water sources.

Public and economic impacts of changes to the Great Lakes

The Great Lakes have an enormous number of impacts—seen and unseen—on the well-being of the more than 34 million people who live within the basin. We drink, play in, and rely on the Lakes for commerce and industry. Investments in ensuring long-term resilience to climate change are investments in the future stability and productivity of the region. While it is tempting to limit ourselves to studying more easily measurable strictly natural phenomena, there is ultimately no way to fully remove human social activities from our understanding of how climate change is affecting and will affect the Lake system. This section considers a selection of important public and economic activities influenced by the impacts described above.

6.1 Shipping

If lake level changes result from climate change, it can affect the ability of ships to safely navigate shallow portions of the Great Lakes' channels and harbors. The most important research in this area is primarily concerned with the "salties" that traverse the oceans in addition to the Great Lakes. Because of the distance these ships travel, the light loading needed to travel through shallow spots in the Great Lakes system during times of low water becomes particularly expensive in terms of tons of cargo hauled relative to time and fuel required.

Because the water level of Lake Michigan-Huron is especially sensitive to changes in the water budget, it largely determines the need for light loading. Millerd (2011) found that as much as a 1 meter decrease in the levels of Lake Michigan-Huron results in 3.6% to 12.2% increases in shipping costs (1.9% to 7.4% increase for a 0.7 m drop). The ranges result from differences in the types of goods shipped, as well as whether the cargo was inbound or outbound to the United States or Canada. Based on Lofgren and Rouhana (2016), the drops in lake levels used by Millerd (2011) should be regarded as very high-end estimates of water level drops within the 21st century. Shlozberg et al. (2014) found that any significant decrease in lake levels, like those found in the earlier studies, would have significant economic impacts, not only on shipping, but also through effects on hydroelectric generation, water use, and waterfront property values.

6.2 Water supply

Consumptive use is the amount of water withdrawn from groundwater or surface water that is not returned to the environment. Consumptive use data are more readily available for states than drainage basins such as the Great Lakes basin. The U.S. Geological Survey (USGS 2008) aggregated the withdrawal and consumptive use data for the eight Great Lakes states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin by categories of use. The largest consumptive use is public supply — 1,200 million gallons per day (Mgal/day), or 4,540 million liters per day (Ml/d). This is out of a withdrawal of 10,200 Mgal/d (38,600 Ml/d), with the rest returned to the environment after treatment by a sewer system. This is the largest consumptive use category. It is followed by thermoelectric power at 1,100 Mgal/d (4,160 Ml/d), irrigation at 860 Mgal/d (3,260 Ml/d), industrial at 640 Mgal/d (2,420 Ml/d), livestock at 200 Mgal/d (757 Ml/d), self-supplied domestic at 130 Mgal/d (492 Ml/d), and mining at 94 Mgal/d (356 Ml/d). Compare this to a typical value of 16,000 Mgal/d (60,500 Ml/d) of outflow from Lake Ontario into the St. Lawrence River. The consumptive use seems to represent a highly significant fraction of the ultimate outflow from the Great Lakes.

Water consumption and climate change are related. The consumptive-use coefficient is the ratio of the amount of water consumed to the amount withdrawn, and its value by use category ranges from a median of 2% for thermoelectric use to a median of 90% for irrigation. The irrigation category is most likely to be strongly affected by climate change because of its high consumptive-use coefficient and increased evaporative demand in projected future climates. Fischer et al. (2007) examine evaporative demand from irrigated land on a global basis, and results differed considerably between the two global climate models that they used. In the UK Hadley center model, North America's irrigation needs were less than other parts of the world; while the Australia's CSIRO model show irrigation needs were comparable or larger. Fischer et al. (2007) also show that North America is generally more responsive to mitigation of human-generated greenhouse gas emissions and concentrations than most parts of the world. Globally, they estimate that US$10 billion in irrigation costs can be saved between 1990 and 2080 by shifting from a high emission scenario to a lower emission scenario.

The Great Lakes region and the eastern United States have particularly large percentage increases in irrigation water demand when comparing projections for the 2080s with a baseline in the 2000s (Wada et al., 2013). This is likely partially due to low irrigation water demand in the baseline period. With the amount depending on which scenario is followed, much of the Great lakes region has projected increases in irrigation –in the high scenario, nearly all of the eastern United States has increases greater than 25%.

Caution is warranted, however. Some of the offline hydrologic models used by Wada et al. formulate evapotranspiration very strongly based on temperature, rather than also including sunlight and other forms of radiation, and so overstate the influence of climate change on evapotranspiration (Milly and Dunne, 2016). In the Great Lakes Basin, these models overestimate the sensitivity of evapotranspiration to climate change at a much greater magnitude (Lofgren and Rouhana, 2016). Non-climatic drivers, such as development, changes in electrical power generation, and changes in agricultural and industrial practices, can also be expected to affect consumptive use in the future.

6.3 Infrastructure

Changing weather and climatic conditions in the Great Lakes put predictable stresses on existing physical infrastructure, such as roads and sewers. However, the fact that the condition and resilience of this infrastructure is heavily dependent on human investment and maintenance makes the long-term consequences of climate change on infrastructure less clear.

Climate change is very likely to have significant negative effects on source water quality that will put great stress on drinking water infrastructure. Nutrient runoff, primarily nitrogen and phosphorus washed off of farms and into surface waters, accumulates rapidly in a small number of intense rain events (Carpenter et al., 2018; Kleinman, 2006). These excess nutrients are directly hazardous for humans and feed massive algae blooms that dramatically raise the cost of water treatment (Michalak et al., 2013). The extra organic matter can react with water disinfectants, especially chlorine, to produce toxic disinfection byproducts (USEPA, 2015). Higher mean temperatures and more heavy precipitation events are favorable for this algal growth (Shigaki et al., 2007; Drake and Davenport, 2011).

Urban wastewater and stormwater systems also deliver significant nutrient loads to surface and groundwater (Preston, et al., 2011). Some of the largest cities in the Great Lakes region have combined sewer systems, which aggregate stormwater runoff and sewage. While this allows them to capture and treat this water collectively, it also creates a risk of combined sewer overflows (CSOs) when the sewer system is overwhelmed. This is most common during intense rain events in which large amounts of rain fall on areas with a high percentage of impervious surface. In these cases, the collected wastewater may be released untreated directly into surface water systems. The Great Lakes region has high numbers of federal action level exceedances for E. coli bacteria compared to other U.S. coastal regions (Hobbs and Mogerman, 2014; Patz, et al., 2008). This untreated effluent is a public health hazard and economically costly to mitigate.

Consider Chicago, the largest point source emitter of phosphorus in the Mississippi River Basin (Robertson et al., 2009). The city has made enormous investments in containment infrastructure designed to decouple intense rain events from CSOs (Hawthorne, 2018). However, the high percentage of impervious surface (59%) and increasing number of intense rain events associated with climate change make containing pollution difficult and expensive (Neuman et al., 2015). One can see that this is partially climate-driven by trends in river system "reversals" into

Lake Michigan (see Figure 10). The direction of the Chicago River was reversed in 1900 to shunt waste away from Lake Michigan. During periods of very heavy rain, water levels in the river system become high enough that they flow back into the lake. The volume of these reversals has continued over the last 25 years despite large gains in catchment capacity (USEPA, 2016; MWRD, 2017).

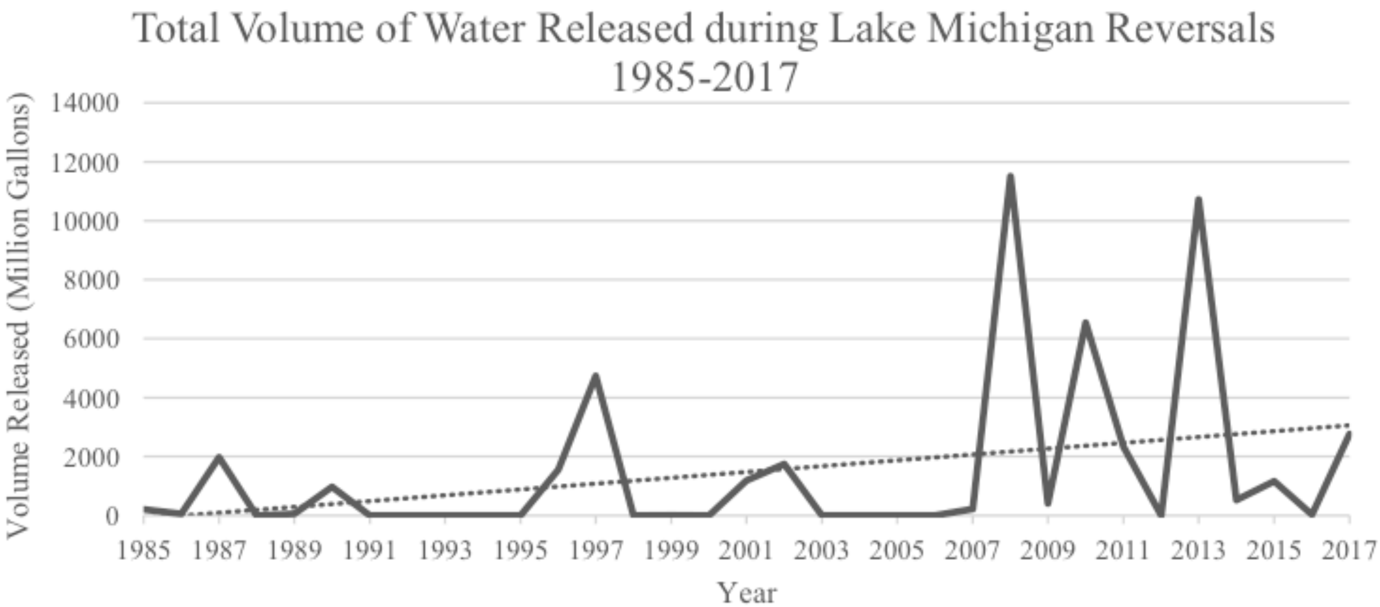


Figure 10. Combined volume of water released into Lake Michigan (Millions of Gallons) for the period 1985-2017 from O'Brien Lock, Chicago River Controlling Works (CRCW), and the Wilmette Gate. (Data source: Metropolitan Water Reclamation District)

Preparing water infrastructure for climate change in the Great Lakes region is expensive. Higher rates of HAB activity associated with climate change are likely to increase future treatment costs (Michalak et al., 2013). Investment for updating and maintaining water infrastructure has nevertheless decreased over the last few decades, at the same time as costs related to managing the effects of climate change are beginning to rise (Neumann, et al., 2015). Water treatment (both drinking water purification and waste treatment) accounts for 30%-40% of a municipality's energy costs (Copeland, 2014). Higher treatment demands resulting from climate-exacerbated runoff and sedimentation therefore translate rather directly into a higher carbon footprint (Cisneros, 2014). However, biological water treatment has been shown to be more efficient at higher water temperatures (Tchobanoglous, et al., 2003). Higher temperatures and longer dry periods also have the potential to reduce soil moisture to levels that can be harmful to buried pipe infrastructure through subsidence.

Other forms of infrastructure located on Great Lakes coastal areas are also affected by climate change. The Great Lakes coastlines include some of the densest road networks in the United States. Coastal roads are vulnerable to erosion from higher amounts of precipitation and wave heights, as well as damage from extreme heat (Swenson, et al., 2006). The high cost associated with updating these road systems for climate change result largely from the need to change the composition of asphalt binders in roads in order to handle higher temperatures and different freeze-thaw patterns (Chinowsky et al., 2013). Yet warmer winter temperatures and less ice on roadways potentially have some positive effects including extending the life of road surfaces and reducing the need to use salt or ice-melting chemicals which wash into the water system.

Changes in precipitation and lake levels can have serious consequences for the health of fixed infrastructure. While projections of future lake levels are disputed, whether rise or fall, there are negative consequences for infrastructure (see Angel and Kunkel, 2010; cf. Lofgren and Rouhana, 2016). On a business-as-usual response to climate change and generally wetter future, 28.9% of road bridges within the U.S. Great Lakes Basin are vulnerable to damage from increased peak flows following rain events (Neumann et al., 2015). Not all of these bridges lie along coastal areas, but those face the additional threat of increased runoff and coastal erosion (Lofgren and Rouhana, 2016). Flood events make bridge scour—erosion around a bridge's supports caused by swiftly moving water—more likely. Scour is among the leading causes of bridge failure (Transportation Research Board, 2008).

Dropping lake levels and increasing temperatures pose a risk to electrical power production critical to the functioning of many other infrastructure systems, such as wastewater management. Most energy production in the Midwest U.S. is built along waterways, and the largest portion of water withdrawals from the Great Lakes (64.8%) is for once-through cooling for thermoelectric power plants (GLC, 2016). Lower lake levels and higher water temperatures both pose technical challenges for power generation. There is a concern about potential interruptions in thermoelectric power generation associated with decreased water levels, which may drop below water intake levels and increase energy required to pump water up to facilities. Increased temperatures reduce heat-transfer efficiency for cooling, which can limit power production to the level necessary to avoid overheating. Power plants along tributary waterways and the Great Lakes themselves are vulnerable to these effects. A critical issue is that energy infrastructure is built for long-term operation, and current energy infrastructure was built based on historical water levels and temperature regimes. Changes in climate that decrease water availability or effectiveness for cooling are therefore likely to decrease regional energy production.

6.4 Recreation

The outdoor recreational sector has grown to over 2% of value-added activity in the United States, and since 2014, growth in the outdoor recreational sector has outpaced growth in the economy as a whole (U.S. Bureau of Economic Analysis, 2018). The largest single activity is boating and fishing, accounting for around $38 billion in economic activity nationwide. Estimates have not been down-scaled to the Great Lakes, although some estimates of the economic contribution of various sectors have been made in the past. The Great Lakes Commission (2007) estimated that the economic contribution of boating in the Great Lakes was around $9 billion in 2003. A similar number of boats are registered in the region now, over 4 million according to the U.S. Coast Guard (2017), so the level of economic activity in boating is likely of similar scale (adjusted for inflation) at present. The effect of climate change on boating activities such as skiing or recreational boat driving will be driven by temperature changes, shifts in the length of seasons, and lake levels. The effects of these various changes could drive aggregate impacts upward or downward, however, no studies to our knowledge have attempted to assess the range of effects of climate change on recreational boating alone.

In contrast, there is significantly more information available on sports angling. The U.S. Fish and Wildlife Service (2017) estimates that 1.8 million anglers fish in the Great Lakes and its tributaries each year and they take 7.4 trips per year on average in the region for a total of 13 million trips. Nationally, anglers spend $10 per day on fishing related items, suggesting annual expenditures of about $133 million per year. The largest share of Great

Lake trips occurs in Lake Michigan, followed by Lake Erie. According to data collected by the U.S. Fish and Wildlife Service (2017), the number of anglers has increased over the last decade in the Great Lakes, but overall fishing days have declined. It is not clear what has caused these trends to emerge. Burkett and Winkler (2018) show a declining trend in license sales due to demographic shifts (e.g., aging cohort of male anglers). However, environmental factors cannot be ruled out as a causal factor related to declining participation. For instance, Wolf et al. (2017) have recently shown how HAB activity in Lake Erie reduces license sales.

While climate change could affect participation and expenditures in fishing, it may have more important effects on the value of ecosystem services related to recreational fishing in the Great Lakes. There is a large and robust literature valuing Great Lakes recreational activities, ranging from boating and fishing to beach recreation, as well as estimating how environmental changes affect recreational value (e.g., Provencher and Bishop, 1997; Murray et al., 2001; Provencher and Bishop, 2004; Yeh et al., 2006; Lupi et al., 2003; Melstrom and Lupi, 2013; Wolf et al., 2017; Zhang and Sohngen, 2017; Ready et al., 2018). Recent estimates of recreational fishing values in the Great Lakes region range from \$20 per day to over \$75 per day (Loomis and Richardson, 2008; Melstrom and Lupi, 2013; Ready et al., 2012). These estimates suggest that, at present, recreational fishing in the region provides ecosystem services values ranging from \$0.3 to over \$1.0 billion per year. These ecosystem service values exceed the effects of fishing on local economies, and imply that if climate change reduces the quality of ecosystem services, value could be lost even if the number of trips does not.

In preparing this review, no studies were found that directly addressed the role of climate change on fishing. Nonetheless, many of the stressors existing studies have addressed – invasive species, harmful algal blooms, e. coli contamination – are also likely strengthened by climate change. Ready et al. (2018), for instance, find that establishment of Asian carp in the Great Lakes could reduce anadromous fish populations in some of the most valuable parts of the fishery, namely Lake Michigan, reducing economic value by \$139 million per year. The ranges of many fish species likely will change due to climate change (see section 5.4), shifting both trip intensity and economic value. For instance, coldwater fishing is more valuable than warmwater fishing, and anadromous fishing is the most valuable form of fishing the Great Lakes (Melstrom and Lupi, 2013; Ready et al., 2018). If climate change shifts the relative abundance of species composition towards warm-water types and away from cold-water types, then the overall value of fishing may decline over time. For instance, according to Melstrom and Lupi (2013), increasing the catch rate of coldwater species by 1 fish per trip enhances day trips by \$40-\$80 per trip, while increasing the catch rate of warm water species by one fish per trip enhances day trips by \$1-\$24 per trip.

Climate change could also have effects on recreation by altering aesthetic components unrelated to catch rates. Zhang and Sohngen (2017), for instance, show that fishing trip value in Lake Erie could be reduced by \$40 per trip due to the presence of HABs. These reductions in value are driven by the lost amenity value associated with recreating in waters with diminished environmental quality rather than the effect of lost catch. Climate change is expected to exacerbate HAB activity in many parts of the Great Lakes (Section 5.3), potentially reducing the value of recreational activity.

Climate change could also influence beach recreation, either directly through temperature or indirectly through the effects on HABs and other pathogens that influence recreational activity. Murray et al. (2001) estimates that Lake Erie beach trips were worth \$15-\$25 per trip. Chen (2013) estimates that beach recreation in the lower peninsula of Michigan was worth \$32-\$39 per trip for day trips, and around \$50 per day for multiple day trips, for a total value of $400 million per year in recreational use value. It is not clear how climate change would affect beach recreation, given that warmer temperatures and longer seasons could spur increased visitation. However, if climate change reduces water quality and makes beach closures more likely, damages could grow. Murray et al. (2001) found that a single beach closure due to a pathogen like E. coli reduces recreational value by around $2 per trip, or around 10%. Palm-Forster et al. (2015) estimated the impact of HABs on beach recreation in Lake Erie, finding impacts of up to $2 million per year in lost recreational value if all beaches are affected.

Other recreational opportunities in the Great Lakes region, such as birding, are likely to be affected by climate change, although the effects are not known. What is known is that a large share of the population engages in bird and wildlife viewing, with 30-35% of the population engaged in this activity within a mile of their home in the Great Lakes States, and 8-12% engaged in this activity further than a mile from their home in the Great Lakes States (U.S. Fish and Wildlife Service, 2017). Loomis and Richardson (2008) suggest an average per day value of $25. Based on these two studies, there are around 139 million wildlife viewing trips away from home in the Great Lakes States each year, with an annual value of over $3 billion per year. The large majority of these trips involve birding, although it is difficult to know how many of these trips occur explicitly along the shores of the Great Lakes or within them. Climate change could affect the local habitat or the migratory patterns of many bird species frequenting the region, but integrated assessments need to be undertaken to determine how these would affect the avid population of people who engage in birding or other wildlife viewing activities.

Winter activities could experience the largest impacts of climate change. For instance decreases in the depth and duration of winter snow cover will result in fewer opportunities for winter recreation, including skiing, snowmobiling, and snowshoeing. Of the 122 resort-style businesses in the Great Lakes states currently identified as supporting winter recreation, only 80 are currently in areas that receive enough snow now to regularly support such activities (Chin et al., 2018). By the end of the century, under the highest emission scenario, all existing ski resorts in the region will become non-viable due to lack of snow and the conditions required to make snow. Duration and thickness of ice on small lakes is also decreasing (Mishra et al., 2011), potentially limiting the availability of sites suitable for ice fishing within the Great Lakes watershed.

6.5 Public health

As mentioned in section 4 and amplified upon in this section, the key vulnerabilities to public health as a result of climate change in the Great Lakes Region include those associated with rising temperatures and hydrologic extremes (Pryor et al., 2014; Patz et al., 2005). For those living across the Great Lakes Basin, heat waves and summertime air pollution events will increase the risk for heat-related illness and death, as well as respiratory diseases that often threaten the most vulnerable (elderly, those with existing conditions, children with asthma, etc.) (Luber and McGeehin, 2008; Kovats and Hajat, 2008; Bell et al., 2007; Mickley et al., 2004). Vector-borne disease is also expected to increase as conditions become more favorable for insects that carry disease (i.e., shifts in the range of mosquitos, ticks, etc.) (Gubler et al., 2001). Increasing variability in rain events will lead to seasonal flooding and drought events, creating issues with the availability of high quality water for drinking and other human uses (see Section 6.3 and 6.6). Issues with flooding and standing water can also increase the incidence of water-borne disease (Patz et al., 2008; Curriero and Patz, et al., 2001). Finally, the indirect effect of climate change on the Great Lakes region may be through the psychological or mental health impacts of social, demographic and economic disruption (Clayton et al., 2017; McMichael et al. 2006).

Of particular concern within the Great Lakes themselves are the microcystin, pathogens, and bacteria that increase in downstream water bodies during intense rain events. Extensive harmful algal blooms are expected to increase in frequency and severity under climate change, and they present multiple threats to public health. Cyanobacteria-dominated HABs can produce several toxins, such as anatoxins, saxitoxins, cylindrospermopsin, nodularins, and microcystins (Cheung et al., 2015). Exposure to cyanotoxins can occur through ingestion, inhalation, and dermal contact pathways. Ingestion during recreation and consumption of contaminated drinking water are the most common exposure cases (USEPA, 2017). However, increased concern has been raised over the ingestion of contaminated seafood and vegetables, which can accumulate cyanotoxins (Lee et al., 2017; Wituszynski et al., 2017). Furthermore, interaction with soils irrigated with HAB contaminated waters, can lead to dermal exposure and possibly irritation and rash development. Finally, cyanotoxins can accumulate in fish tissue, therefore consumption of fish from frequently blooming waters may lead to additional cyanotoxin exposures (Wituszynski et al., 2017). Inhalation is another route of exposure to cyanotoxins. It happens by breathing in bioaerosol and mist from a HAB-affected water body. Those who regularly work on or near water get exposed via inhalation (boaters, anglers and lifeguards, for example). Further research is recommended to better understand the chronic effect of toxin inhalation (Backer et al., 2010).

6.6 Impacts on Indigenous people in the Great Lakes Basin

There are many communities of Indigenous people and tribes within the Great Lakes region, especially within the Great Lakes Basin. Though they may also be affected by climate change in ways that are similar to others in the United States, Indigenous peoples can also be affected uniquely and disproportionately (USGCRP, 2018). Climate impacts to lands, waters, foods, and other plant and animal species threaten cultural heritage sites and practices that sustain intra- and intergenerational relationships built on sharing traditional knowledges, food, and ceremonial or cultural objects. The 4th National Climate Assessment (USGCRP 2018, and references therein) found that "Climate change threatens Indigenous peoples' livelihoods and economies, including agriculture, hunting and gathering, fishing, forestry, energy, recreation, and tourism enterprises. Indigenous peoples' economies rely on, but face institutional barriers to, their self-determined management of water, land, other natural resources, and infrastructure that will be impacted increasingly by changes in climate." They also found that Indigenous health is based on interconnected social and ecological systems that are being disrupted by a changing climate.

6.7 Industrial needs for water

The freshwater resources of the Great Lakes underwrite a significant portion of the region's economic productivity (Campbell et al., 2015). Considering both the United States and Canada, consumptive industrial uses represent 4,465 million gallons per day (mgd) or 10.8% of total withdrawals for consumptive use, outpaced only slightly by public drinking water consumption at 5,537 mgd or 13.1% (GLC, 2016). The amount of water consumed by industry over the last thirty years, however, has remained relatively stable (see Figure 11). Given that water resources have become progressively more regulated and competitive over time, there is little indication that water will, in general, become cheaper for industry. Some have speculated that businesses currently located in less water-secure places will begin to migrate toward the region (e.g., Austin and Steinman, 2015). But because the price of water is heavily mediated by policy and regional economics, local scarcity or abundance does not tell us much about the attractiveness of water development all by themselves (Shaw, 2007). Midwestern Great Lakes states, because of their historical contributions to transportation equipment, heavy manufacturing, energy production, and agriculture produce more than a quarter of national greenhouse gas emissions (Livingston et al., 2009).

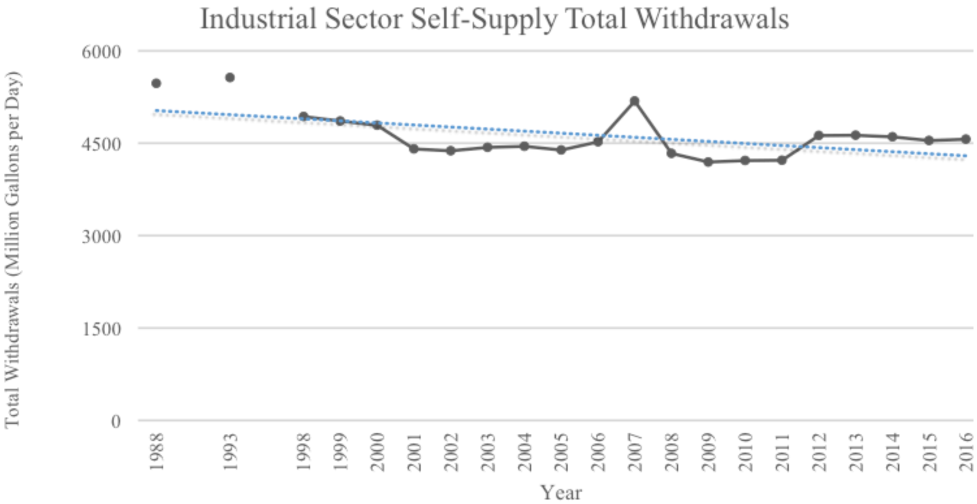


Figure 11. Total volume of water withdrawn from the Great Lakes for the period of 1988-2016 by the industrial sector. Data source: Great Lakes Regional Water Use Database

There has long been speculation that the water itself would become a major commodity—bottled and shipped as bulk water or pumped out of the region via inter-basin transfers. This is unlikely as large interbasin transfer schemes to move water long distances from the lakes are economically impractical (Annin, 2018). Bottled water has not represented a significant stress compared to other regional consumptive uses, especially given the amount of water diverted into the lake system (IJC and CMI, 2000). A large portion of bottled water is packaged tap water, however, and is thus folded into public drinking water consumption (Hu et al., 2011).

Existing industrial demands in a variety of sectors are very sensitive to changes in water availability and quality related to climate change. Agriculture, refineries, and commercial fishing offer examples of impact. Agricultural consumption generally increases with higher temperatures and longer dry periods (Schoengold and Zilberman, 2007). If regulatory action is taken to control nutrient pollution flows from farm and livestock operations created by more intense rainfall, it will increase the cost of farm operations (Rathinasamy et al., 2015). Fuel refineries along Great Lakes coastlines continue to represent a large portion of industrial withdrawals (USGS, 2008; Wu et al., 2009). While the number of refineries operating in the region has declined over the last 30 years, as these refineries increase in size, water consumption will increase in proportion to their overall crude processing capacity (US EIA, 2018; Wu, et al., 2009). The commercial fishing industry is directly impacted by climate related changes in water quality in particular. Invasive species and oxygen level changes have produced an average of 3.5% decline in yield per year across all the Great Lakes (Brenden et al., 2012; see 6.4 above).

It is unclear whether regional diversion regulations will constrain future industrial uses. The 2008 Great Lakes—St. Lawrence River Basin Water Resources Compact ("Great Lakes Compact"), severely restricts the amount of water that can be diverted out of the Great Lakes Basin and puts environmental review conditions on large new consumptive uses within the basin. However, it was designed mainly to control the expansion of municipal uses beyond the basin line by regulating new consumption by utilities, rather than new large industrial uses.

The most recent high-profile test of this by water intensive industry relocating to the Great Lakes Basin is the planned development of a Foxconn liquid crystal display factory in the Village of Mount Pleasant, Wisconsin. The Wisconsin Department of Natural Resources has granted the southwest portion of the City of Racine a diversion allowance of up to 7 mgd, much of which is expected to go to the Foxconn plant (Thomas, 2018). The State of

Wisconsin, in order to encourage the construction of the plant, waived or weakened diversion restrictions, air pollution control permits, stormwater permits, and pretreatment requirements (MEA, 2018). Foxconn ultimately pulled out of the deal. So far, this is an isolated case, but if it were to become a general trend in the region, it would create intense new demands on water resources given that individual factories can consume about the same amount of water every day as a small city.

BEACH CLOSURES AND RISKS OF GETTING SICK DURING RECREATION.

Fifteen Michigan beaches were either closed or are under advisories because of bacterial contamination during the 2018 Labor Day weekend. In June 2018, 24 Michigan beaches were closed because of elevated bacteria levels, just when a heat wave made it especially desirable for people to head to the beach. This is not an uncommon occurrence, especially during the summer months, on the coastlines of the Great Lakes.

Summer is also the time of algal blooms and E.coli alerts -- and that can put a damper on plans to cool off. While various studies (e.g., Never et al., 2018) have shown that fecal matter from gulls and pets are a major contributor, climate change is also a factor. The increase in the frequency and intensity of extreme precipitation events are likely to exacerbate the issues associated with runoff and the associated effects on bacterial counts.

Conclusions

Allowing the vast, natural resource of the Great Lakes to be taken for granted and degraded through human activities, including the effects of climate change, is not an option. For economic, aesthetic, and ecological reasons, we need the Great Lakes to remain healthy, unpolluted, and productive. Climate change is already having an impact on the region, and there is evidence that such impacts may increase under expected future climate change. Responding to these stressors requires both adaptations to the impacts that cannot be avoided (e.g., improving agricultural land management to decrease nutrient loading), as well as mitigation to reduce the possibility of experiencing the most extreme impacts (e.g., decreasing carbon emissions from the household to the industrial sector). Public support for protecting the Great Lakes is strong across the region, and despite differing concern about climate change as a threat, overall public support for action to address climate change is high. It is critical that we recognize the importance of this freshwater resource and ensure its protection for generations to come.

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Supplementary Material
An Assessment of the Impacts of Climate Change on the Great Lakes

Development of the Graphics

While some of the graphics in the Assessment are based on existing peer-reviewed publications or on websites associated with observational datasets, some of the graphics is produced for this assessment based on other datasets. The analyses of the past and projected climate changes are derived based on the analyses of observational datasets for past changes and from modeling and downscaled datasets for projections produced for NCA4 (USGCRP, 2017, 2018). The reference periods used in these analyses are the same as those used in NCA4. Projections use a weighting system for global climate models, that are then statistically downscaled for temperature and precipitation at about 6 km resolution across the continental United States based on the LOcalized Constructed Analogs approach (LOCA; Pierce et al. 2014) that spatially matches model-simulated days, past and future, to analogs from observations.

Until NCA4, assessments used a simple averaging of the multimodel ensemble. NCA4 uses model weighting to refine future climate change projections. In NCA4, model independence and selected global and North American model quality metrics are considered in order to determine the weighting parameters (Sanderson et al., 2017, building upon the earlier study by Knutti et al., 2017). The weighting approach takes into account the interdependence of individual climate models as well as their relative abilities in simulating North American climate. Understanding of the calculated time history, together with the fingerprints of particular model biases, has been used to identify model pairs that are not independent. Thus, this approach considers the skill in the climatological performance of the models for the area over North America as well as the inter-dependency of models.

Projections are based on global models and downscaled products from CMIP5 (Coupled Model Intercomparison Project Phase 5) using a suite of Representative Concentration Pathways (RCPs). Figure 1 shows the projected changes in globally averaged temperature for a range of future pathways that vary from assuming strong continued dependence on fossil fuels in energy and transportation systems over the 21st century (the high scenario is Representative Concentration Pathway 8.5, or RCP8.5) to assuming major emissions-reduction actions (the very low scenario, RCP2.6).

Most of the graphics in this report will use either the high RCP8.5 scenario or the low RCP4.5 scenario. At the higher end of the range, the RCP8.5 scenario corresponds to a future where carbon and methane emissions continue to rise as a result of fossil fuel use, albeit with significant declines in emission growth rates over the second half of the century, significant reduction in aerosols, and modest improvements in energy intensity and technology (Riahi et al., 2011, USGCRP, 2017). RCP8.5 reflects the upper range of the open literature on emissions, but is not intended to serve as an upper limit on possible emissions. RCP4.5 assumes a rapid movement away from the fossil fuels over the coming decades. Under the RCP8.5 scenario, CO¬2 concentrations are projected to reach 936 ppm by 2100. Under the lower RCP4.5 and RCP2.6 scenarios (van Vuuren et al., 2011; Thomson et al., 2011), atmospheric CO2 levels remain below 550 and 450 ppm by 2100, respectively.

For future projections, 30-year periods are used. Projections are centered around 2030, 2050, and 2085 with an interval of plus and minus 15 years (for example, results for 2030 cover the period 2015–2045). The reference period for these projections is the recent past, from 1976–2005. The choice of a 30-year period is chosen to account for natural variations and to have a reasonable sampling in order to estimate likelihoods of trends in extremes; this period is consistent with the World Meteorological Organi¬zation's recommendation for climate statistics.

Additional figures on Climate Changes in the Great Lakes region

Figure A1 shows observed percentage changes in precipitation for the U.S. states bordering the Great Lakes for present day (1986-2016) relative to 1901-1960. All of these states show an increasing trend except for a few isolated locations in Michigan (especially the Upper Peninsula), Ohio, and Pennsylvania that show a minor decrease in precipitation. However, future precipitation for 2085 period (2070-2099) relative to 1976-2005 for both RCP 8.5 and 4.5 show increases in precipitation all across the Great Lakes states (Figure A2). With the high emission scenario (RCP8.5), the precipitation is projected to generally increase 8-10% evenly across all of the Great Lakes states, but with a strong seasonal dependence (especially more in winter and spring, less in summer). The RCP4.5 scenario projects an overall increase of 6-10% for the Great Lakes basin and the eastern Great Lakes states by the end of the century. The rest of the region shows a more moderate 2-4% increase in annual precipitation.

For extreme events related to temperature, the projections show high variability across the Great Lakes states. For example, an increasing trend for future extreme warm days with temperature greater than 90°F is projected for both RCP 8.5 and RCP4.5 (Figure A3). However, due to the presence of the Great Lakes, the basin region shows relatively less number of extreme warm days in comparison to the rest of the region. In general, it is projected that the southern Great Lakes region will have more than 100 days with a temperature greater than 90°F for RCP8.5. For the lesser emissions of the RCP4.5 scenario, parts of southern Illinois and Indiana project 60-70 extreme warm days and the rest of region projects a smaller increase in extreme warm days. In general as rule of thumb, the upper limit in the uncertainty range for RCP4.5 wprojects to be about the same as the lower limit for the higher emissions RCP8.5 scenario for future extreme warm days in the Great Lakes states.

Likewise, future climate warming will reduce the extreme cold days with temperature less than 32°F (Figure A4). The decrease in extreme cold days is projected to be much larger for RCP8.5 in comparison to RCP4.5 – the Great Lakes basin is greatly affected for both future scenarios. Similarly, the future extreme events with a 5-year return period show an increase (Figure A5). This increase is as high as 25% in many parts of the Great Lakes region for RCP8.5. For the lower RCP4.5 scenario, most of region projects about a 10% increase by the end of the century, with about a 15% increase in eastern Pennsylvania and New York.

For snow analysis, snowfall was determined using a criterion of daily mean temperature below −0.5°C for any precipitation days for both the observed and the statistically-downscaled climate model-based data (Byun and Hamlet, 2018). A decrease in annual snowfall in the Great Lakes states for the period from 1984 to 2013 has been observed (Figure A6). Future snow projections are calculated based on the ensemble mean of statistically-downscaled analyses of ten global climate models for the RCP8.5 and for RCP4.5 scenarios. With a significant warming in future during the winter months, both the RCP 8.5 and 4.5 scenarios project a substantial decrease in snowfall over the ground by the end of the century (Figure A7). Minnesota is likely to get less reduction in snow in comparison to all other Great Lakes states.

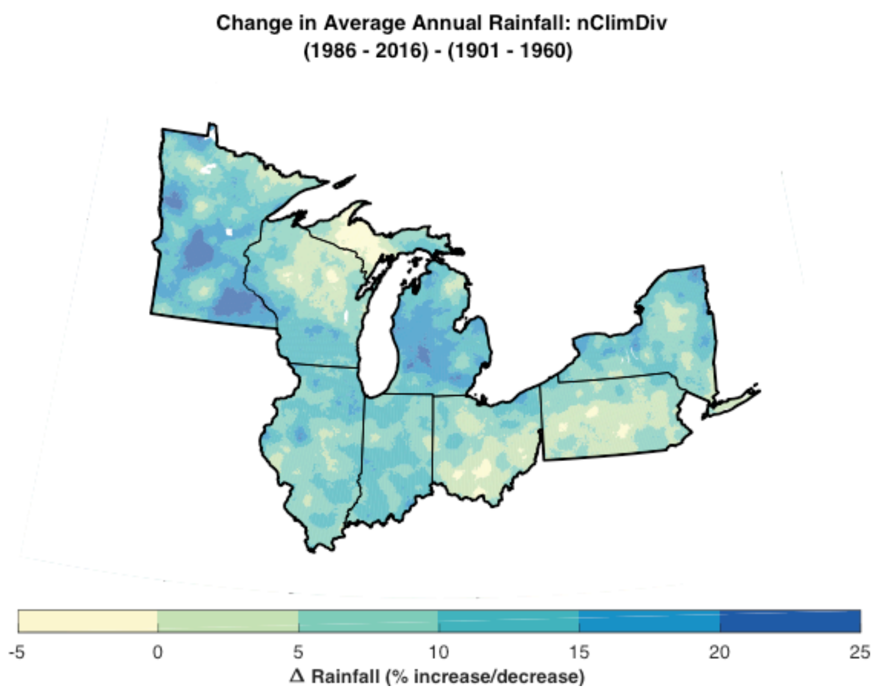


Figure A1. Observed changes in annual precipitation (as equivalent rainfall) (%) for the U.S. states bordering the Great Lakes for present-day (1986–2016) relative to 1901–1960. Derived from the NOAA nClimDiv dataset (Vose et al., 2014). (Figure source: NOAA/NCEI)

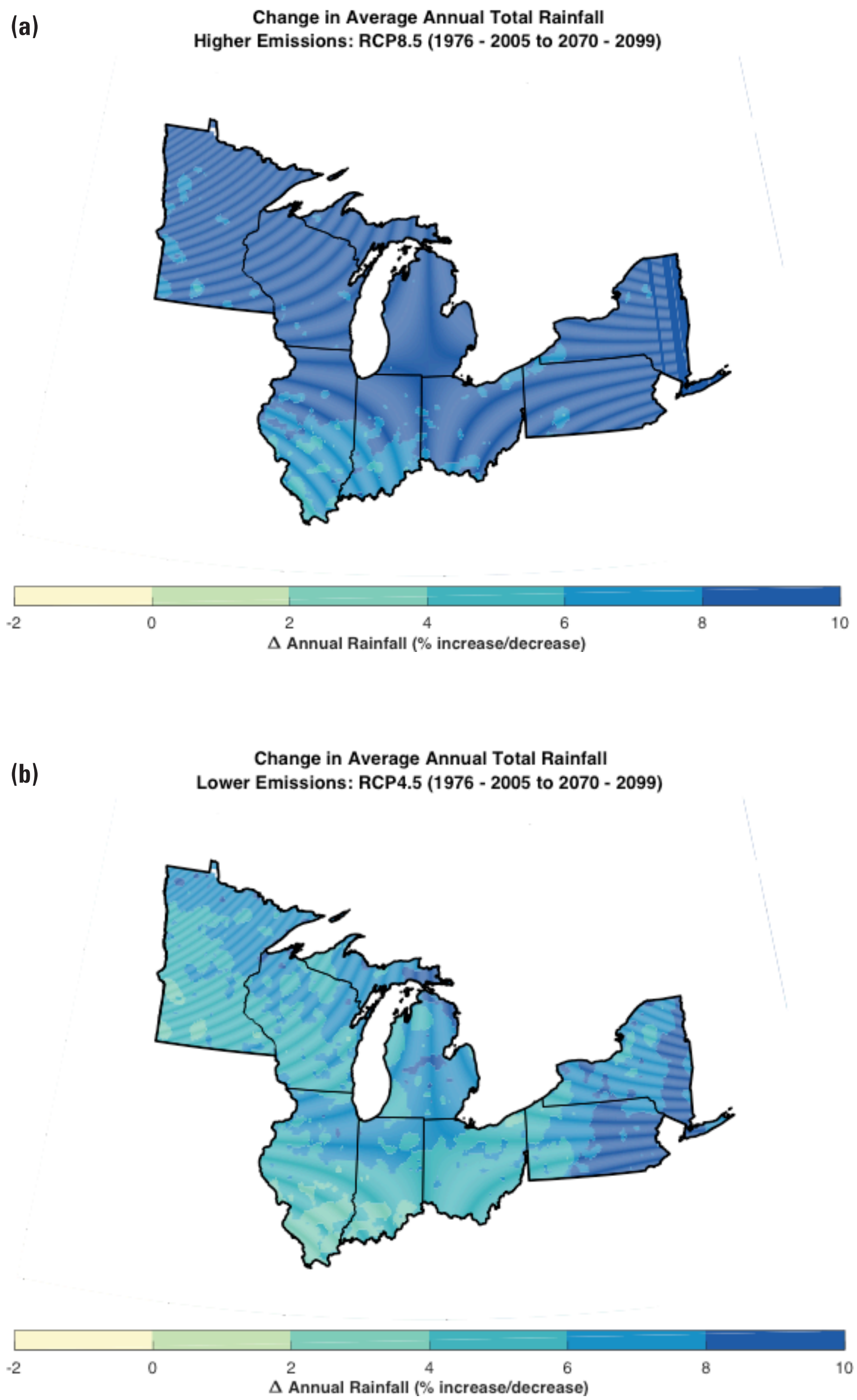
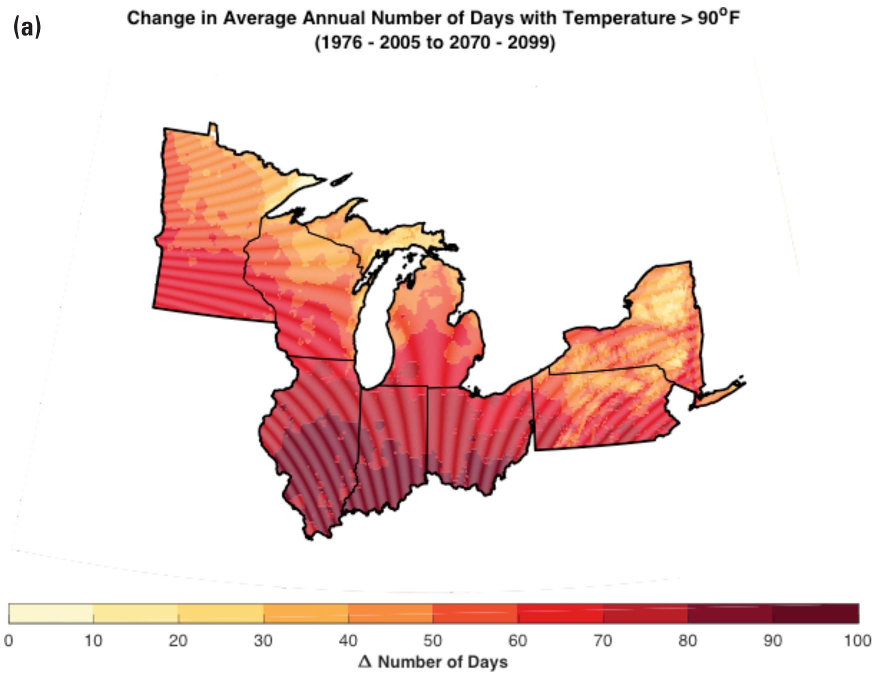


Figure A2. Change in annual precipitation (as equivalent rainfall) (%) for U.S. states bordering the Great Lakes from the (a) higher (RCP8.5) and (b) lower (RCP4.5) scenarios for the 2085 (2070-2099) time period relative to 1976-2005. (Figure source: NOAA/NCEI)

(a)



(b)

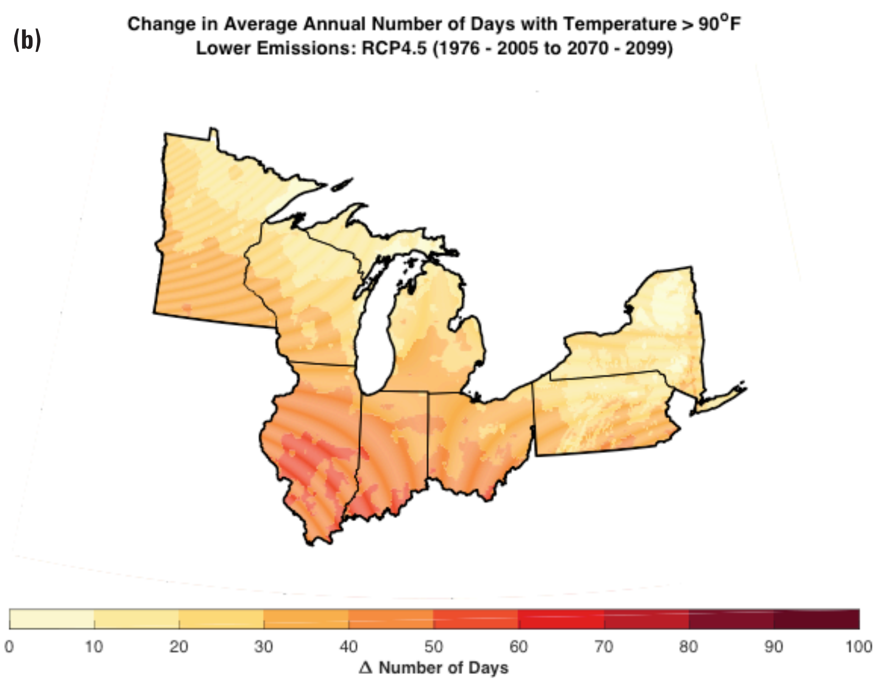


Figure A3. Change in the number of days with temperature greater than 90°F for U.S. states bordering the Great Lakes from the (a) higher (RCP8.5) and (b) lower (RCP4.5) scenarios for the 2085 (2070-2099) time period relative to 1976-2005. (Figure source: NOAA/NCEI)

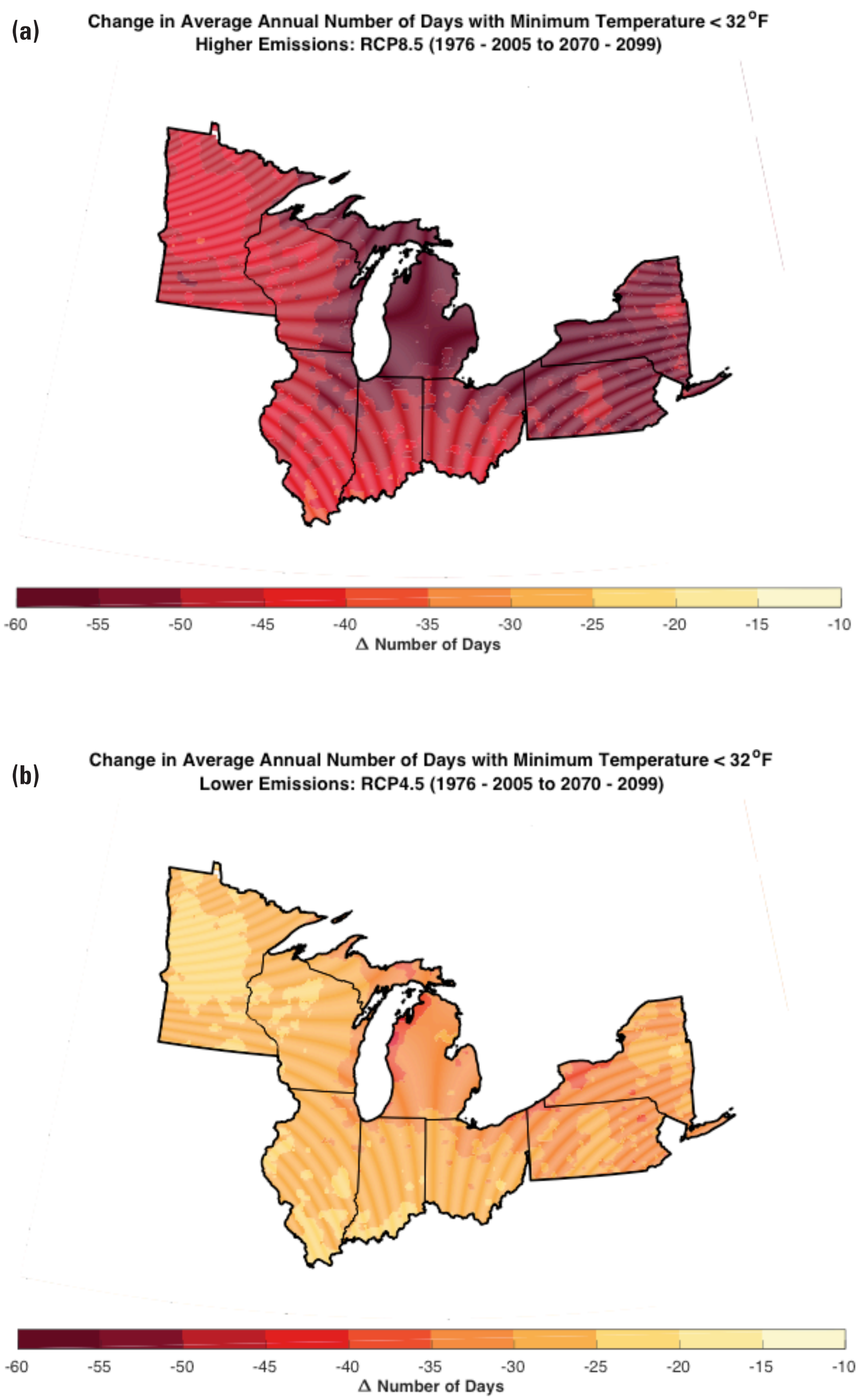


Figure A4. Change in the number of days with temperature less than 32°F for U.S. states bordering the Great Lakes from the (a) higher (RCP8.5) and (b) lower (RCP4.5) scenarios for the 2085 (2070-2099) time period relative to 1976-2005. (Figure source: NOAA/NCEI)

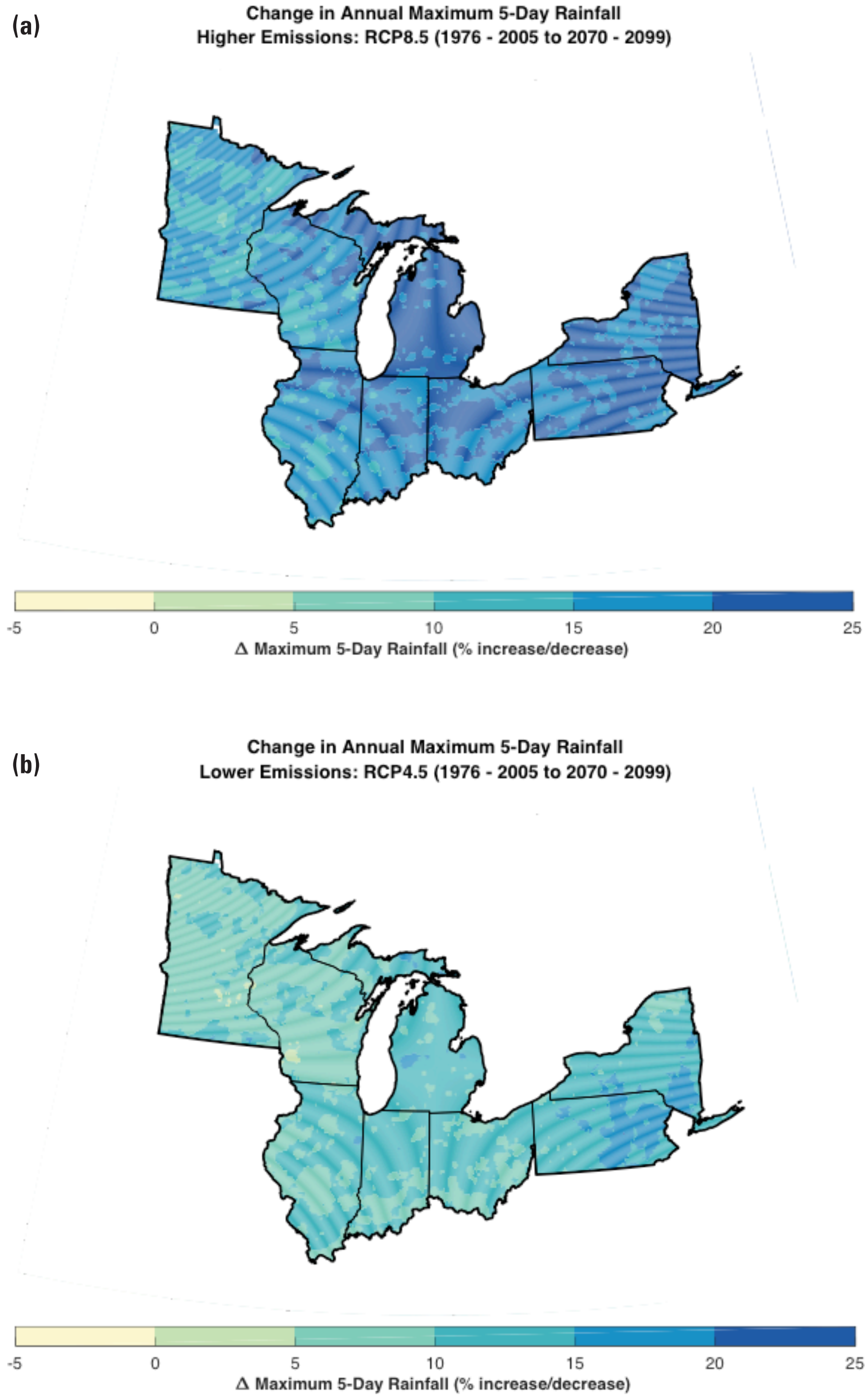


Figure A5. Percentage change in annual maximum five-day rainfall amounts for U.S. states bordering the Great Lakes from the (a) higher (RCP8.5) and (b) lower (RCP4.5) scenarios for the 2085 (2070-2099) time period relative to 1976-2005. (Figure source: NOAA/NCEI)

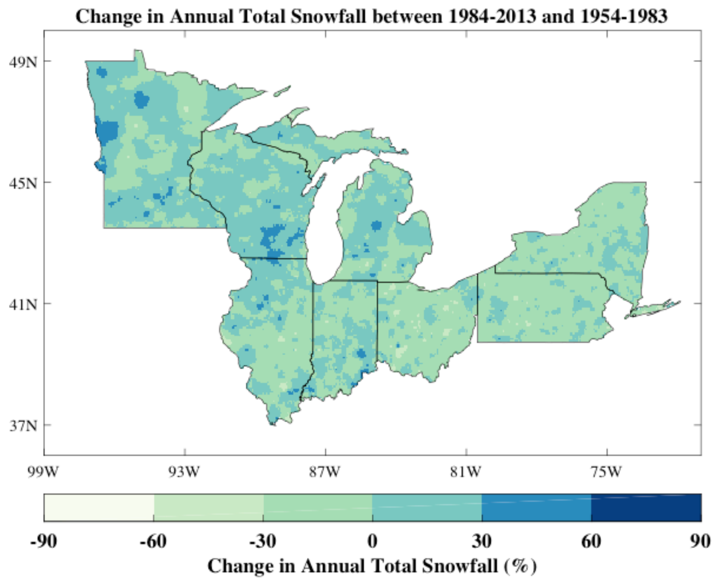
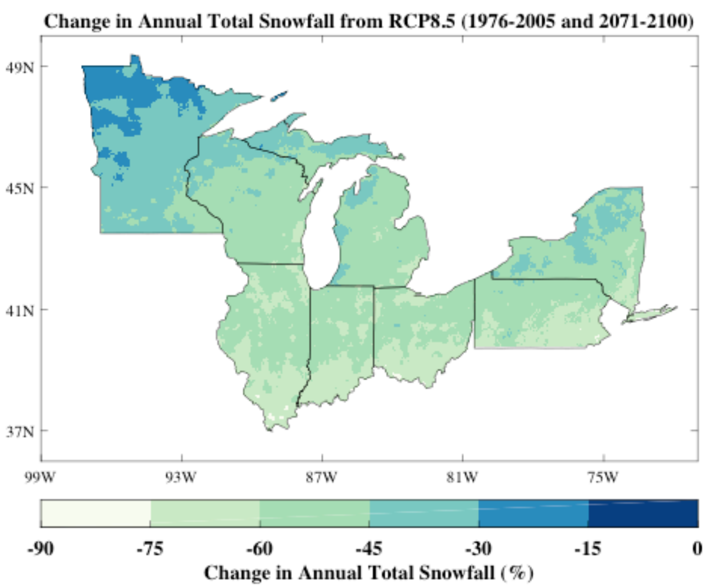


Figure A6. Observed changes in annual snowfall (%) for the U.S. states bordering the Great Lakes for present-day (1984-2013) relative to 1954-1983. Derived from bias corrected and gridded observational station dataset (Byun and Hamlet, 2018).

(a)



(b)

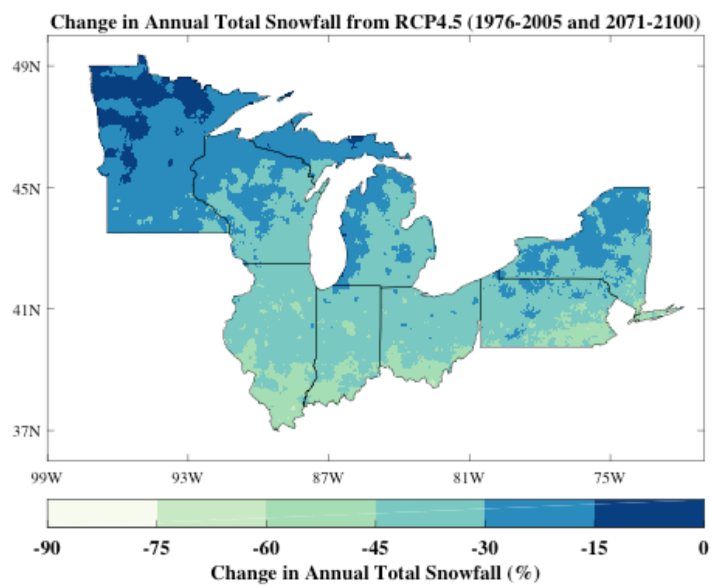


Figure A7. Change in annual snowfall (%) for U.S. states bordering the Great Lakes from the (a) higher (RCP8.5) and (b) lower (RCP4.5) scenarios for the 2085 (2070-2099) time period relative to 1976-2005. Derived from the ensemble mean of 10 statistically-downcaled CMIP5 GCMs by Hybrid Delta method (Byun and Hamlet, 2018).

Environmental Law & Policy Center

The Environmental Law & Policy Center is the Midwest's leading public interest environmental legal advocacy and eco-business innovation organization. We develop and lead successful strategic advocacy campaigns to improve environmental quality and protect our natural resources. We are public interest environmental entrepreneurs who engage in creative business dealmaking with diverse interests to put into practice our belief that environmental progress and economic development can be achieved together. ELPC's multidisciplinary staff of talented and experienced public interest attorneys, environmental business specialists, public policy advocates and communications specialists brings a strong and effective combination of skills to solve environmental problems.

ELPC's vision embraces both smart, persuasive advocacy and sustainable development principles to win the most important environmental cases and create positive solutions to protect the environment. ELPC's teamwork approach uses legal, economic and public policy analysis, and communications advocacy tools to produce successes. ELPC's strategic advocacy and business dealmaking involves proposing solutions when we oppose threats to the Midwest environment. We say "yes" to better solutions; we don't just say "no."

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Des Moines, IA
Grand Rapids, MI
Indianapolis, IN
Madison, WI
Minneapolis/St. Paul, MN
Washington, D.C.