Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

GREAT LAKES REGION 04

FINAL

April 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

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14. ABSTRACT

To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Great Lakes Region, is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

15. SUBJECT TERMS

Great Lakes Region	Observed Hydrology	Business Line
Water Resources Region 04	Projected Climate	Climate Vulnerability
Observed Climate	Projected Hydrology	Regional Climate Synthesis

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CLIMATE CHANGE AND HYDROLOGY LITERATURE SYNTHESIS FOR THE US ARMY CORPS OF ENGINEERS MISSIONS IN THE UNITED STATES

GREAT LAKES REGION 04

April 28, 2015

CDM Smith
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Water Resources Region 04: Great Lakes

1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long–term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly–accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of 21 regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of 2–digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUCs) across the continental United States, Alaska, Hawaii, and Puerto Rico. The 21 Water Resources Regions included in this series of reports are shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer–reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and watershed vulnerability assessment tools.

This report focuses on Water Resources Region 04, the Great Lakes, the boundaries for which are shown in **Figure 1.2**. The Detroit, Buffalo, New York, and New England USACE districts each include territory within Water Resources Region 04.

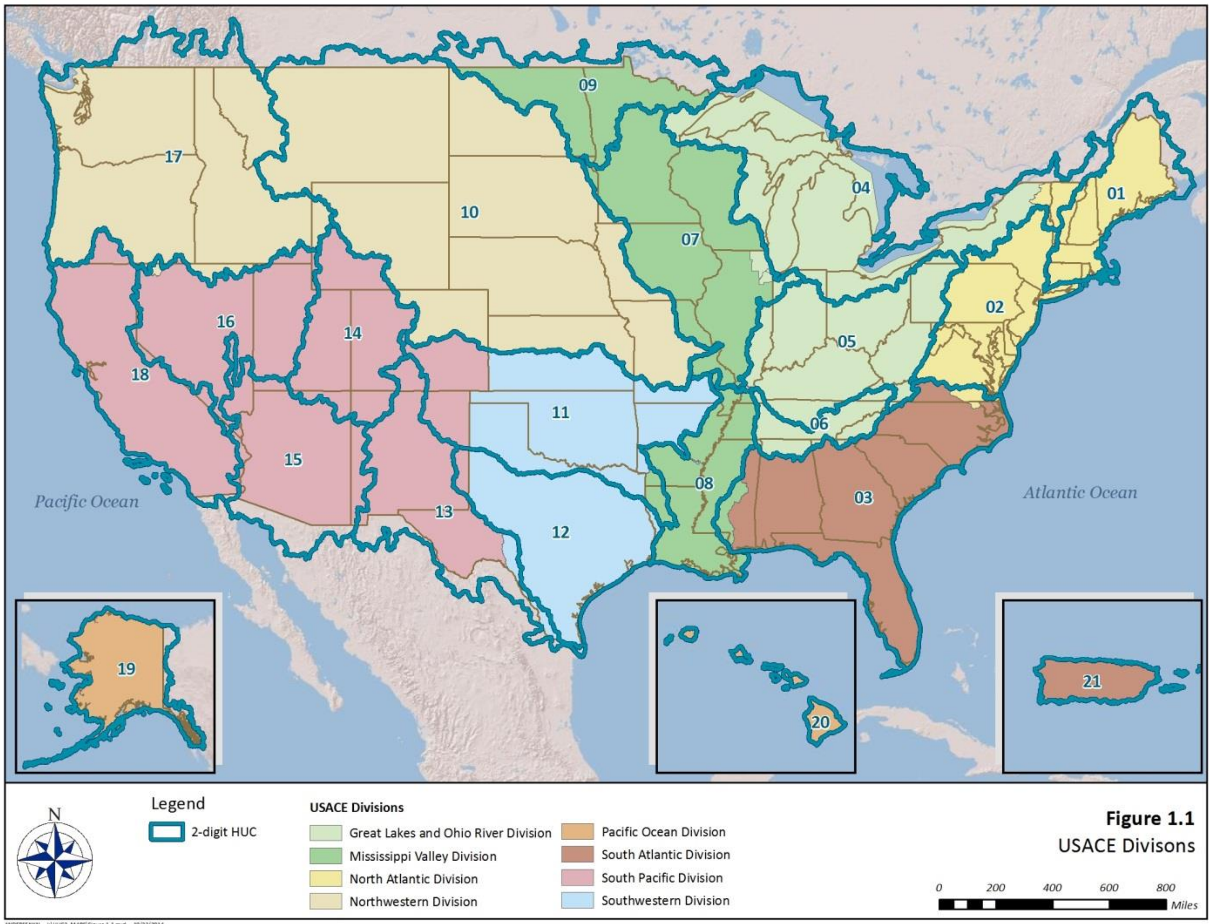

Figure 1.1. 2–digit Hydrologic Unit Code Boundaries for the continental United States, Alaska, Hawaii, and Puerto Rico

Figure 1.2. Water Resources Region 4: Great Lakes Region Boundary.

1.1. A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science–based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local–to–regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post–processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub–continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2–digit HUCs (Water Resources Regions), and that confidence in the driving climate model outputs declines below the level of a reasonable trade–off between precision and accuracy for areas smaller than the watershed scale of the 4–digit HUCs (Water Resources Subregions). Hence, these summaries group information at the Water Resources Region scale both to introduce relevant climate change literature and to support the vulnerability assessment USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 04, both the 2–digit and 4–digit HUC boundaries are shown in Figure 1.2.

2. Observed Climate Trends

Observed climate trends within the Great Lakes Region are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human–induced increases in atmosphere levels of heat–trapping gases (Walsh et al., 2014), this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA), which includes not only regional assessments, but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer–reviewed literature on the subject of observed climate. To the extent possible, studies specific to the Great Lakes Region or its sub–watersheds were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer–reviewed literature addressing climate change within the geographic region or inclusive of Water Resources Region 04 (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The results presented below indicate mild upward trending in temperature, precipitation, and streamflow in the Great Lakes Region. However, there is a greater level of agreement on temperature trends than on precipitation or streamflow trends. Historical precipitation trends also appear to vary spatially within the region.

2.1. Temperature

A number of studies focusing on observed trends in historical temperatures were reviewed for this report. These include both national scale studies inclusive of results relevant to the Great Lakes Region and regional studies focused more specifically on the region. Results from both types of studies, relevant to the Great Lakes Region, are discussed below.

At a national scale, an study by Wang et al. (2009) examined historical climate trends across the continental United States. Gridded (0.5 degrees x 0.5 degrees) mean monthly climate data for the period 1950 to 2000 were used. The focus of this work was on the link between observed seasonality and regionality of trends and sea surface temperature variability. The authors identified positive statistically significant trends in recent observed seasonal mean surface air temperature for most of the U.S. (**Figure 2.1**). For the Great Lakes Region, seasonal differences are evident. A positive warming trend is identified for most of the region in the winter (December to February), spring (March to May), and summer (June to August). In fall (September to November), a cooling trend is identified. Both warming and cooling trends are less than 1 ºC during the period 1950–2000. The authors do not provide information on statistical significance of the presented observed trends.

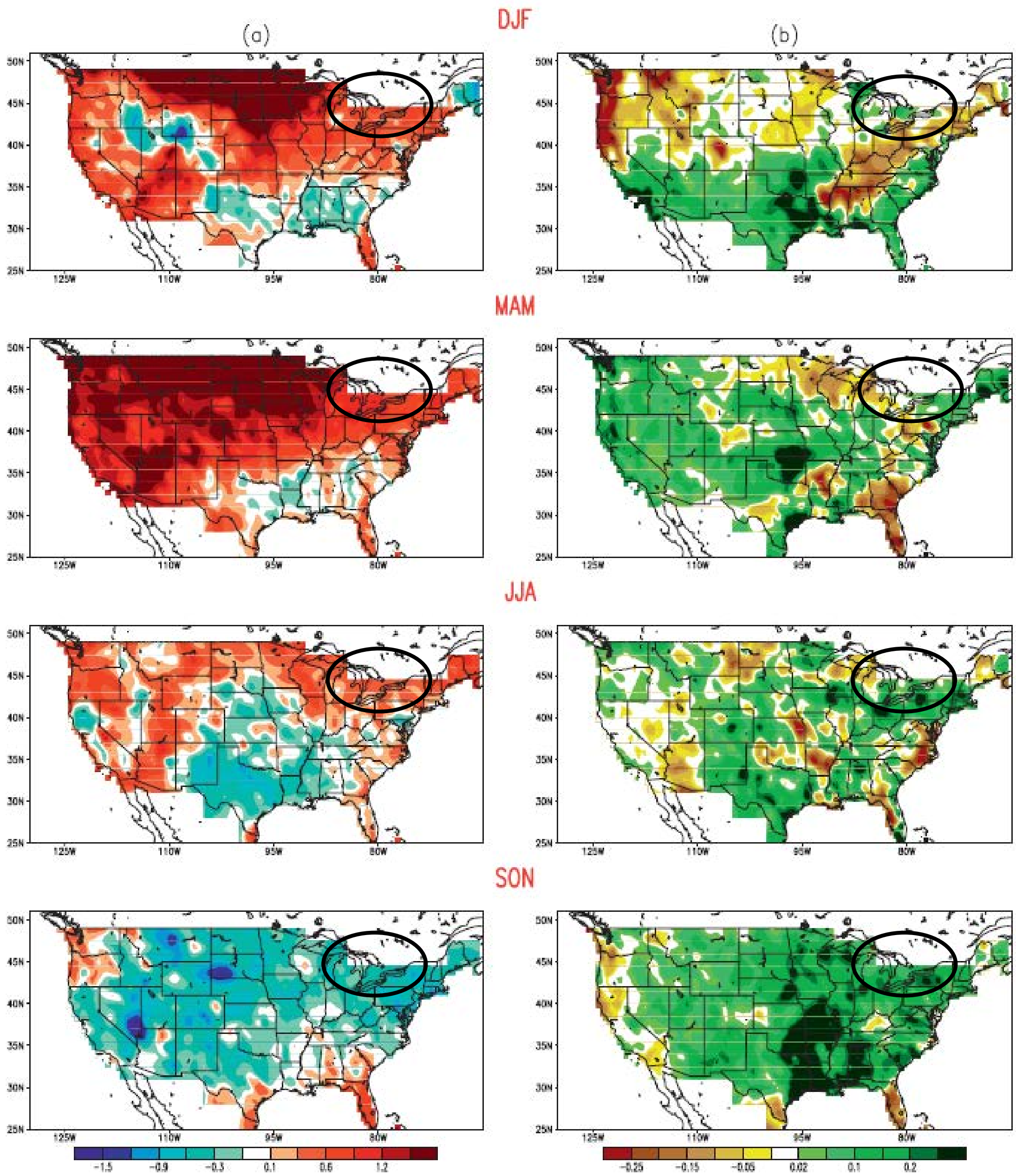

Figure 2.1. Linear trends in (a) surface air temperature (ºC) and (b) precipitation (mm/day) over the United States, 1950 – 2000. The Great Lakes Region is within the black oval (Wang et al., 2009).

A later study by Westby et al. (2013), using data from the period 1949 to 2011, showed a warming trend (up to 0.03 ºC per year) through most of the region, with a cooling trend (down to 0.02 ºC per year) in the southern area of the region. These trends, however, were not statistically significant at a 95% confidence interval (C.I.).

The third NCA report presents historical annual average temperatures for the country and by region. Most of the Great Lakes Region is within the Midwest region, except the area in western New York state and Vermont, which is in the Northeast region. The nationwide NCA summary (Walsh et al., 2014) shows a warming trend of up to 1.5 ºF (0.83 ºC) in the Great Lakes Region when comparing the past 22 years with the 1901 to 1960 average (**Figure 2.2**). The Midwest regional summary (Pryor et al., 2014) notes an average change of 1.5 ºF (0.83 ºC) across the entire Midwest region from 1985 through 2012. This is consistent with **Figure 2.2**, showing greater increase in temperature in the Great Lakes Region than in the Midwest region overall. Details on statistical significance are not provided.

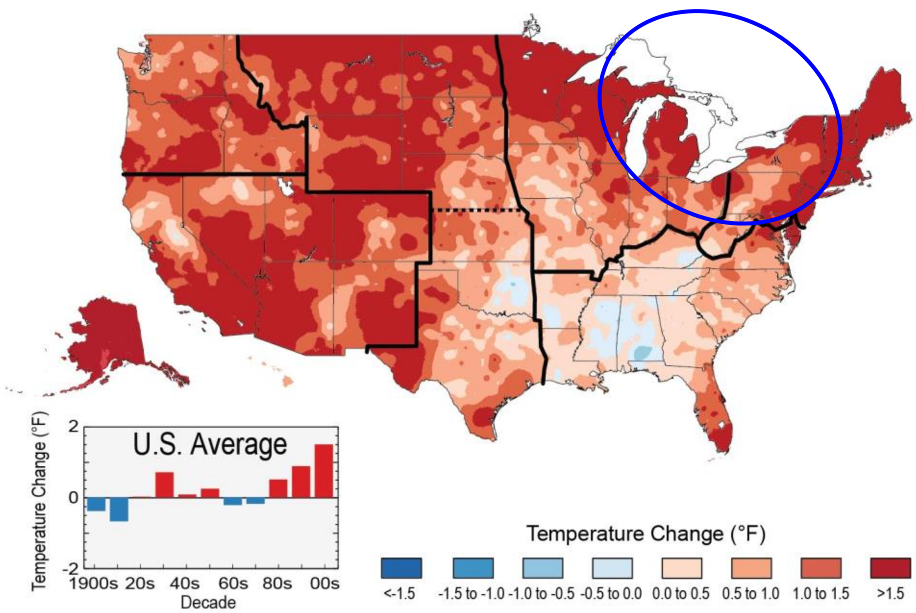

Figure 2.2. Temperature changes over the past 22 years (1991 – 2012) compared to the 1901 – 1960 average, and compared to the 1951 – 1980 average for Alaska and Hawaii (Walsh et al., 2014). The blue oval indicates the Great Lakes Region.

Meehl et al. (2012) analyzed climate data from 1950 to 1999. On an annual basis, they identified little to no warming trend (less than 0.25 ºC per 50 years) within the Great Lakes Region, except in western New York state, where slight warming (up to 0.5ºC per 50 years) was noted. This study did show some seasonal variation, with a winter (December through February) cooling trend (down to –1.75 ºC) and a summer warming trend (up to 1 ºC) during the study period.

Schwartz et al. (2013) investigated changes in spring onset for the continental U.S. Their particular focus was on changes in the seasonality of plant growth as dictated by changing temperature regimes. The authors used historical data from over 22,000 stations across the United States, obtained from the National Climatic Data Center (NCDC) with periods of record extending through 2010. Most of the stations in the Great Lakes Region had earlier first leaf dates by greater than 4 days when comparing 2001 – 2010 to 1951 – 1960, indicating earlier arrival of spring throughout the region (**Figure 2.3**).

Figure 2.3. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Great Lakes Region is within the black oval (Schwartz et al., 2013).

Qian et al. (2007) studied temperature trends in the Mississippi River watershed using observed data from 1948 to 2004. Although the Great Lakes Region is not in the Mississippi River watershed, they present nationwide temperature data (**Figure 2.4**). They show a warming trend of 0.4 to 1.6 °C per century, with a greater warming trend in the northwest.

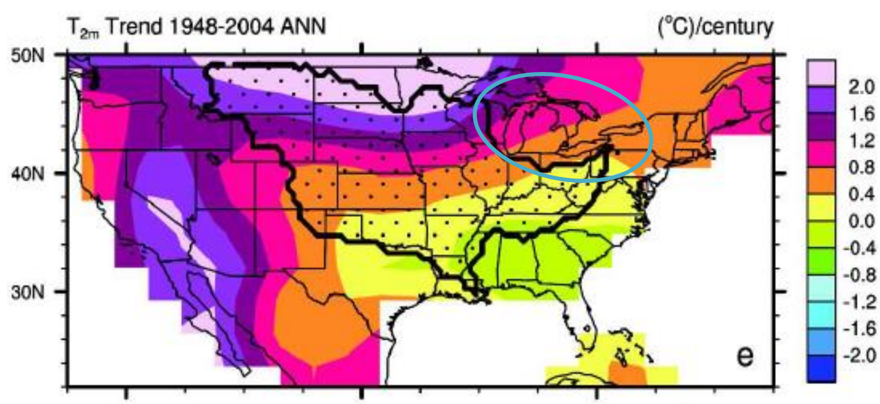

Figure 2.4. Linear trend from October 1948 to September 2004 in annual observed temperature (Qian et al., 2007). The Great Lakes Region is within the blue oval.

Grundstein and Dowd (2011) investigated trends in one–day extreme maximum and minimum apparent temperatures across the continental U.S. The study was based on daily temperature data compiled by the NCDC for 187 stations across the country for the period 1949 to 2010. The researchers used a parameter called "apparent temperature", a metric which incorporates humidity and temperature in an attempt to better represent human sensation of heat, and defined extreme temperatures as exceeding the 85th percentile for historical data at each station. For the

Great Lakes Region, they found a statistically significant (95% C.I.) increasing trend in the number of one–day extreme minimum temperature occurrences at three of the ten to twelve stations in the region. There was no significant trend in one–day extreme maximum temperatures.

Key point: Nearly all studies note an upward trend in average temperatures, but generally the observed change is small. Some studies note seasonal differences, with possible cooling trends in fall or winter.

2.2. Precipitation

The third NCA report presents historical annual total precipitation changes for the country (Walsh et al., 2014). The NCA compared changes in precipitation totals for 1991 to 2012 relative to the 1901 to 1960 average (**Figure 2.5**). Increases in precipitation of up to 15% were shown throughout the region, with larger increases in central Michigan and little to no change in Wisconsin and Michigan's Upper Peninsula.

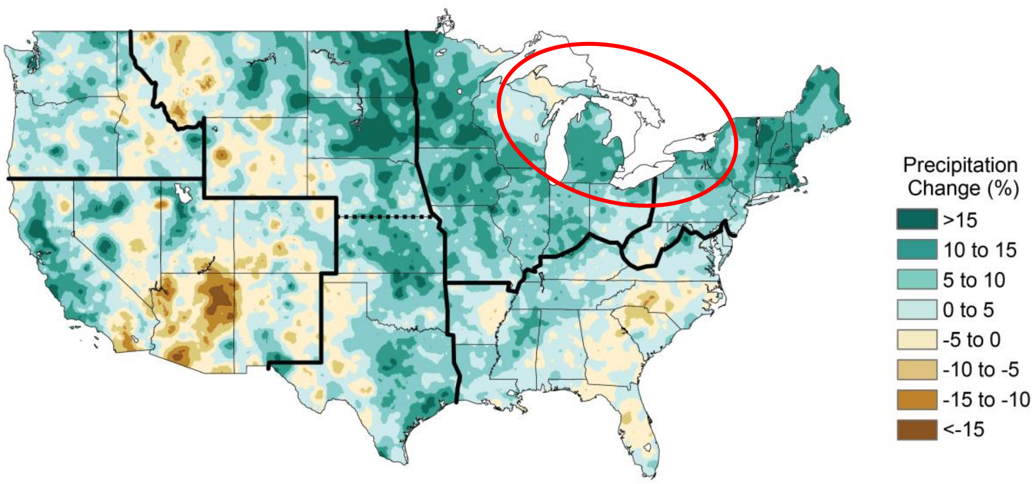

Figure 2.5. Observed changes in precipitation over the past 22 years (1991–2012) compared to the 1901–1960 average (Walsh et al., 2014). The red oval indicates the Great Lakes Region.

The NCA also reported on the observed change in very heavy precipitation for the U.S., defined as the amount of precipitation falling during the heaviest 1% of all daily events (**Figure 2.6**) The Great Lakes Region spans the two regions with the highest percent change in very heavy precipitation from 1958 to 2012 – the Midwest (37%) and the Northeast (71%). The NCA results indicate that more precipitation is falling in the Great Lakes Region now as compared with the first half of the 20th century, and that the precipitation is concentrated in larger events.

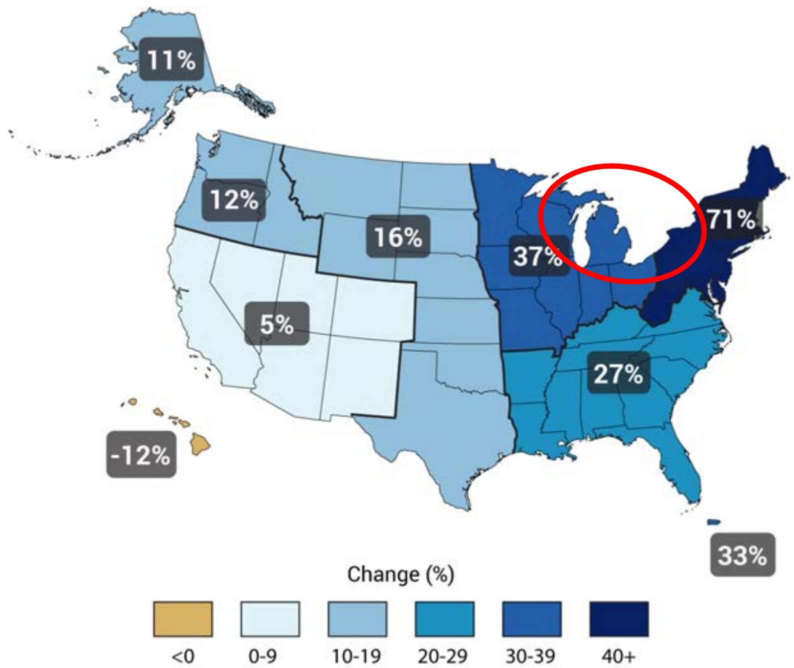

Figure 2.6. Percent changes in the amount of precipitation falling in the heaviest 1% of events from 1958 to 2012 for each region (Walsh et al., 2014). The red oval indicates the Great Lakes Region.

Multiple authors have studied the trends in observed annual total precipitation for the entire U.S. and regions that include the Great Lakes Region. A study by McRoberts and Nielsen–Gammon (2011) used a new continuous and homogenous data set to perform precipitation trend analyses for sub–basins across the United States. The extended data period used for the analysis was 1895 to 2009. Linear positive trends in annual precipitation were identified for most of the U.S. (**Figure 2.7**). The authors observed annual precipitation increases throughout the region of up to 20% per century. Variability within the region was similar to the NCA report, with larger increases in central and western Michigan and western New York.

Qian et al. (2007) also studied the trend in annual precipitation amounts. These authors focused on the Mississippi River basin, using data from 1948 to 2004 to develop linear trends (**Figure 2.8**). Although the Great Lakes Region is not within the Mississippi River basin, they present historical precipitation trends nationwide. These results show an increase in annual average precipitation of 0 – 60 mm per year through much of the region, with precipitation decreases shown in the northwest. Although neither Walsh et al. (2014) nor McRoberts and Nielsen–Gammon (2011) showed precipitation decreases, the overall geographic trend showing greater increases in central Michigan and western New York is still seen here.

Walter et al. (2004) also found an increase in precipitation in a review of records from 1950 – 2000. For the U.S. portion of the St Lawrence River watershed, which includes the Great Lakes Region as well as areas of northern New York and Vermont, the authors report an increase of 1.23 mm/year.

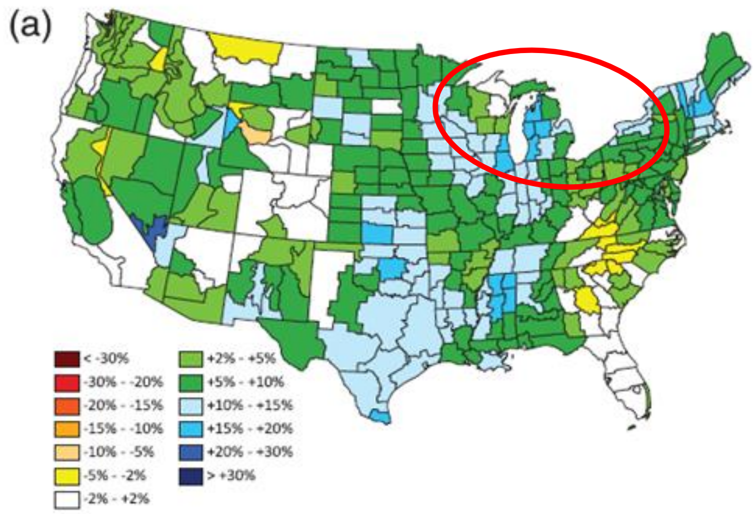

Figure 2.7. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Great Lakes Region is within the red oval (McRoberts and Nielsen–Gammon, 2011).

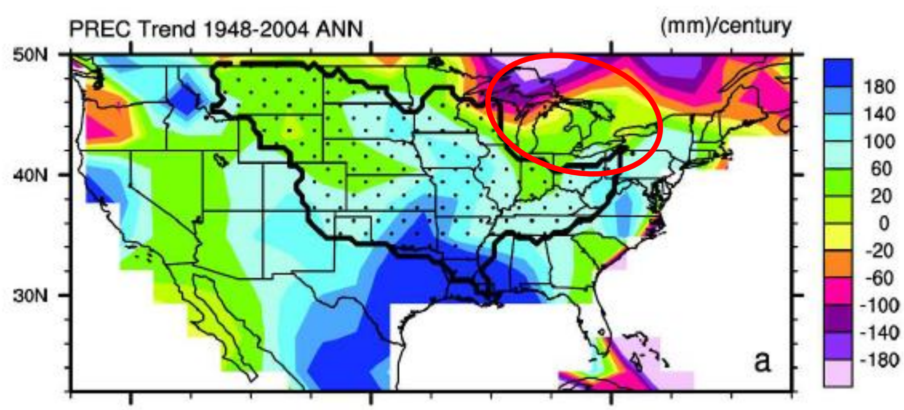

Figure 2.8. Linear trend from October 1948 to September 2004 in annual observed precipitation (Qian et al., 2007). The Great Lakes Region is within the red oval.

Pryor et al. (2009) performed statistical analysis on 20th century rainfall data to investigate for trends across a range of precipitation metrics. They used data from 643 stations scattered across the continental U.S. This study reports an increasing trend of precipitation at stations throughout the Great Lakes Region. It also shows an increase in the number of precipitation days per year and, correspondingly, a decrease in the average precipitation on a precipitation day, i.e. total annual precipitation has gone up due to a larger number of smaller events.

a) Annual precipitation

b) 90th percentile daily precipitation

c) Precipitation intensity (annual total / number of precipitation days)

d) Number of precipitation days per year

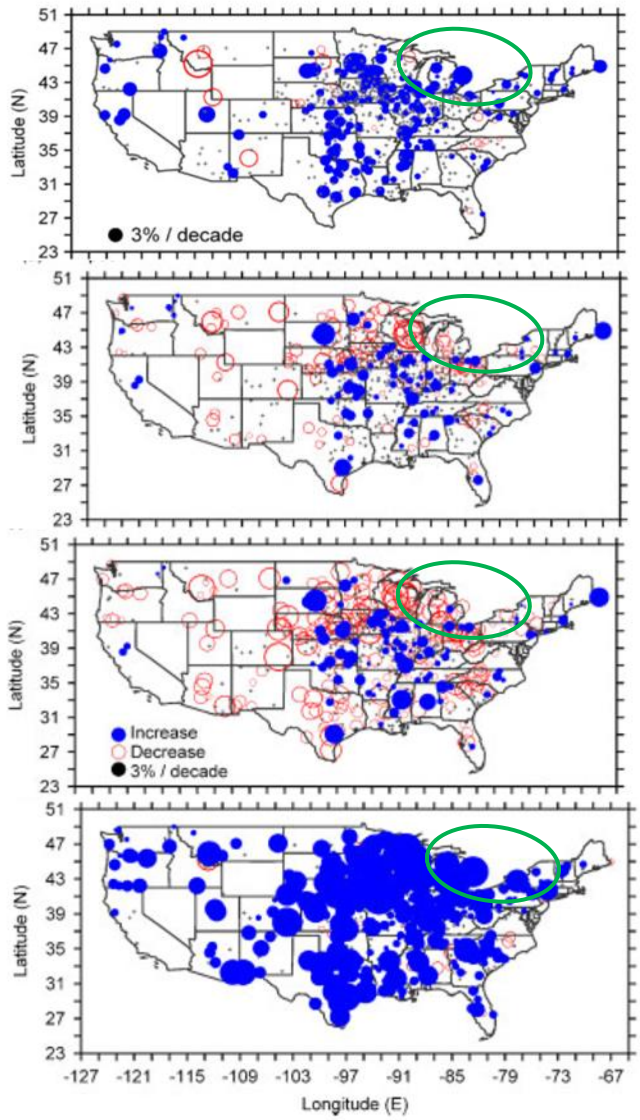

Figure 2.9. Historical precipitation trends (20th century). a.) annual totals, b.) 90th percentile daily, c.) precipitation intensity (annual total/number of precipitation days), and d.) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative trend, and symbol sizes are scaled to 3% change per decade. The Great Lakes Region is within the green ovals (Pryor et al., 2009).

Grundstein (2009) identified statistically significant (95% C.I.) increasing trends in the Thornthwaite soil moisture index for a number of stations in the region (**Figure 2.10**) based on annual data from 1895 to 2006. The Thornthwaite soil moisture index is a function of both supply (precipitation) and demand (evapo–transpiration [ET]), and therefore is an effective proxy for both precipitation and ET. A statistically significant trend in annual precipitation for the same time period, of up to 20 cm per century, was also observed at several stations.

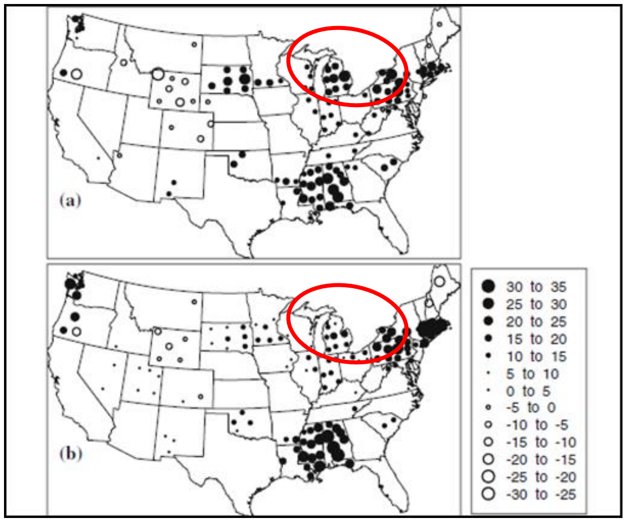

Figure 2.10. Statistically significant linear trends in (a) Thornthwaite soil moisture index (unitless) and (b) annual precipitation (cm per 100 years) for the continental U.S., 1895 – 2006. The Great Lakes Region is within the red oval (Grundstein, 2009).

The work of Small et al. (2006) included analysis of the Great Lakes Region specifically for annual and fall (September through November) precipitation trends. These authors investigated trends in various precipitation and flow metrics based on USGS Hydroclimatologic Data Network (HCDN) climate data from 1948 to 1997. Statistically significant (95% C.I.) increasing trends were identified for the region in annual precipitation for several locations throughout the region (**Figure 2.11**). Increasing trends in fall precipitation were identified as well.

Wang et al. (2009) also studied seasonal precipitation patterns, but for all four seasons and the entire country. As described in Section 2.1, the study focused on historical climate trends across the continental U.S. using gridded climate data and a period of record similar to Small et al. (2006) and Qian et al. (2007) (1950 – 2000). The authors identified positive trends in annual precipitation for most of the U.S. For the Great Lakes Region, precipitation trends are mixed throughout the region in winter, spring, and summer, increasing in some areas and decreasing in others. Fall (September through November) showed an increase of up to 0.2 mm/day (**Figure 2.1**). The authors do not provide information on statistical significance of the presented observed trends.

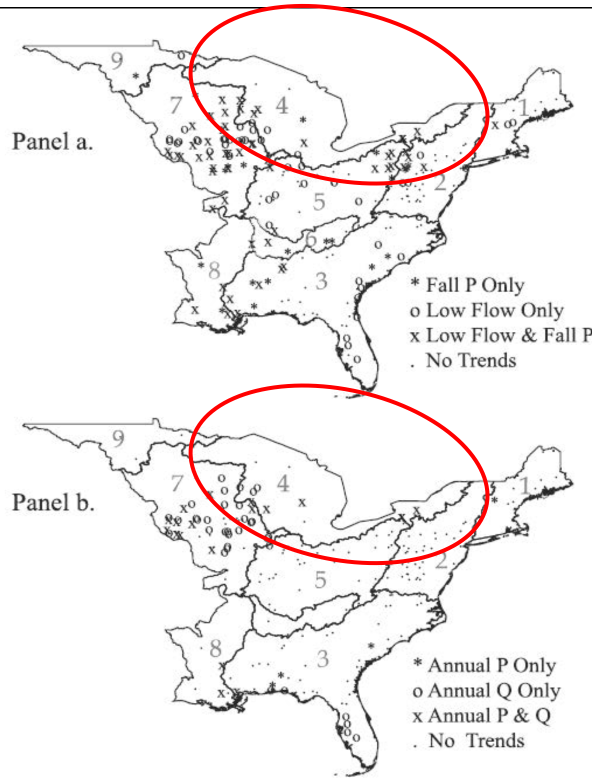

Figure 2.11. Historical trends in precipitation (P) and streamflow (Q), 1948 – 1997. The Great Lakes Region is within the red oval (Small et al., 2006).

A number of authors have studied historical trends for storm events. Palecki et al. (2005) examined historical precipitation data from across the continental U.S. They identified trends in precipitation for the period 1972 to 2002 using NCDC 15–minute rainfall data. The authors created zones based on similar storm characteristics. Most of the Great Lakes Region falls into Zone 6, which also includes West Virginia, Pennsylvania, and northern New England. Zone 6 had different trends in the various seasons. In spring (March to May), total storm precipitation and storm duration increased while storm intensity decreased, consistent with the Pryor et al. (2009) results noted above (**Figure 2.9**). In contrast, winter, summer, and fall showed decreases in storm precipitation and duration with increases in intensity.

Wang and Zhang (2008) used historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. The authors examined trends in both historical data and future projections. They identified the 20–year maximum daily precipitation amount for the period from 1949 – 1976 and compared the return frequency of the same event magnitude over the period 1977 – 1999. Within the Great Lakes Region, the authors found that an event with the 20–year daily precipitation volume from 1949 – 1976 was equally or slightly less likely during the period 1977 – 1999.

Villarini et al. (2013) identified statistically significant ($p \leq 0.05$) increasing trends in the frequency of occurrence of heavy rainfall in a region overlapping the western portion of the Great Lakes Region for multiple climate stations with at least 50 years of historical record. While significant trends were identified for a number of stations in the region, an even greater number of stations in the Great Lakes Region exhibited no significant trends.

Key point: Studies generally show an increasing trend in average precipitation in the study region, but varying seasonally and geographically. The northwestern portion of the region may be experiencing a lower rate of increase or a decrease in annual precipitation. Most studies of extreme precipitation show that extreme events are becoming slightly larger and more frequent.

2.3. Hydrology

Studies of trends in streamflow data collected over the past century have been performed throughout the continental U.S. at global, national, and regional levels. Kalra et al. (2008) aggregated data (1951 – 2002) by Water Resources Region, and found significant (95% C.I.) trends upward at a number of stations throughout the Great Lakes Region, both seasonally and on a water-year basis. Similarly, the Small et al. (2006) study, referenced above, noted significant (95% C.I.) increasing trends in both annual and low streamflow at most, but not all, stream gages within the Great Lakes Region, using HCDN data for the period 1948 – 1997 (**Figure 2.11**).

Other authors have found trends in streamflow over the past 50 to 100 years in the Great Lakes Region. A recent study (Sagarika et al., 2014) of unimpaired streamflow stations with data from 1951 to 2010 found, using annual records, three to four (depending on the statistical test used) of ten stations with increasing trends (**Figure 2.12**). The increasing trend was seen in fall at two to three stations, winter at seven stations, spring at two stations, and summer at four to five stations. Decreasing trends were noted for two stations on an annual basis, three or four in the spring, and two in the fall. All trends were significant within a 95% confidence interval.

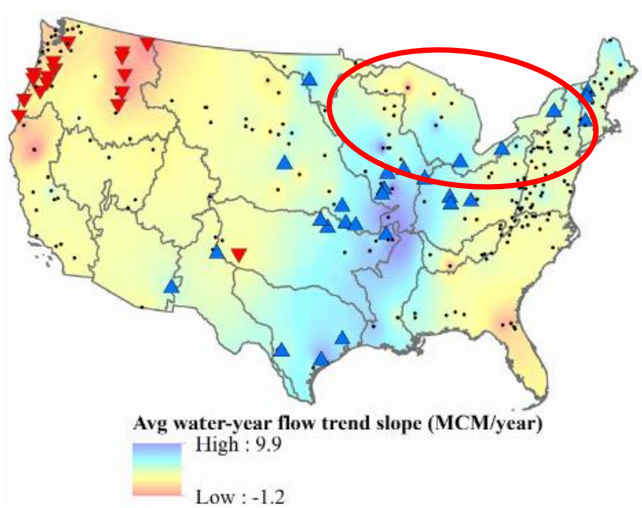

Figure 2.12. Map showing water–year trends. Upward–pointing triangles indicate statistically significant increasing trends at p = 0.10. The Great Lakes Region is within the red oval (Sagarika et al., 2014).

Qian et al. (2007) studied trends in precipitation, temperature, and modeled runoff throughout the Mississippi River basin using data from 1948 to 2004. As noted above, although this study focuses on the Mississippi river basin, some climate observations are shown for the Great Lakes Region. The results showed variability within the region, with much of the central portion of the region showing an increase of around 60 mm per century, but a decreasing trend was shown in the northwest (**Figure 2.13**).

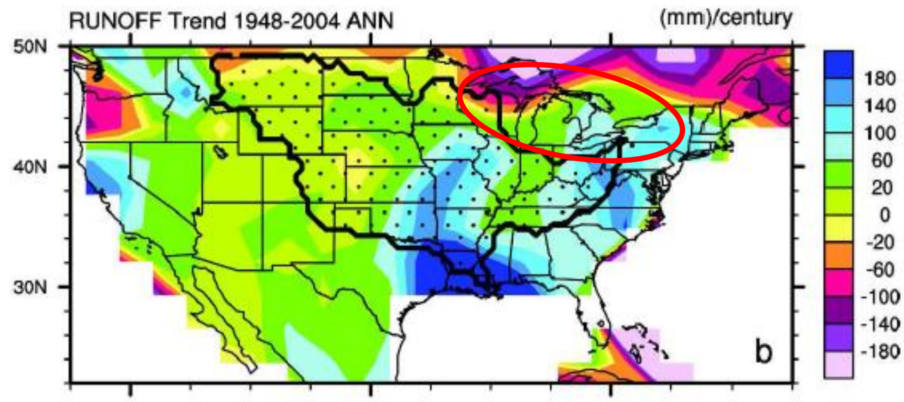

Figure 2.13. Linear trend from October 1948 to September 2004 in annual modeled runoff (Qian et al., 2007). The Great Lakes Region is within the red oval.

As noted above, Walter et al. (2004) identified trends in precipitation and streamflow within the St. Lawrence River watershed, which includes the Great Lakes Region. They noted an increase of 0.8 mm per year, higher than the Qian et al. (2007) study.

On a more local level, Novotny and Stefan (2007) studied stream flow trends in Minnesota, including two streamflow stations in the Great Lakes Region, both located along tributaries to Lake Superior. They looked for "geographically significant" trends in annual streamflow and in the number of high flow days per year over four periods: 1953 – 2002 (50 years), 1973 – 2002 (30 years), 1988 – 2002 (15 years), and 1993 – 2002 (10 years). One station had an increase of 0 – 3% per year in the number of high flow days over the 15–year period, but no other statistically significant trends were found for either station for any of the four study periods.

Villarini et al. (2009) studied trends in annual instantaneous peak streamflow across the U.S., including a streamflow station on the Grand River near Lansing, Michigan, located in the Great Lakes Region. This gage was selected due to a long period of record; the authors do not supply the exact period of record but note that 107 years of data are included. They first did a change point analysis, noting an abrupt change in the mean peak annual streamflow in 1920. An abrupt change may indicate non–climatic factors, such as changing a gage location or changes in tributary land use. Therefore, they analyzed the dataset for long-term trends separately before and after 1920. Neither partial time series showed a statistically significant change in annual peak streamflow.

Key point: Small increases in streamflow were found in some areas by some studies, but others showed no significant changes.

2.4. Summary of Observed Climate Findings

In general, temperatures, precipitation, and streamflow have all been noted to increase throughout the Great Lakes Region, although consensus is lower among studies of precipitation and streamflow

Temperatures are noted to increase throughout the region, although some studies of seasonality show a decrease in fall or winter. Although precipitation increases overall, several studies showed variability within the region, with lower increases or decreases towards the northwest and greater increases in Michigan and western New York.

Finally, several studies noted increases in streamflow in some areas of the region, while other areas showed no significant trends.

3. Projected Climate Trends

While historical data is essential to understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long–term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2005). Consequently, the scientific and engineering communities are actively using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. Although significant uncertainties are inherent in these model projections, the models, termed GCMs, are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Great Lakes Region identified in a review of recent peer–reviewed literature. The information presented should be considered an overview and, similar to **Section 2** on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed or basin–scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

The results presented below indicate a strong consensus that temperatures are expected to increase over the next century in the Great Lakes Region. Precipitation volumes, frequency, and durations are also expected to increase, although the degree of increase is uncertain. There is considerable variability and uncertainty in hydrologic predictions, and future changes to streamflow may vary seasonally and geographically.

3.1. Temperature

Maximum air temperature projections were investigated by Liu et al. (2013) using a single downscaled GCM and assuming an A2 greenhouse gas emissions scenario (worst case) in a national analysis. The results of their study in the Great Lakes Region show a projected increase in winter and spring maximum air temperature between 2 and 2.5 ºC for a 2055 planning horizon compared to a baseline period of 1971 – 2000 (**Figure 3.1**). The results of the study project increases in maximum air temperature from 3 to 4.5 ºC for summer temperatures and 2.5 to 3.5 ºC for fall temperatures.

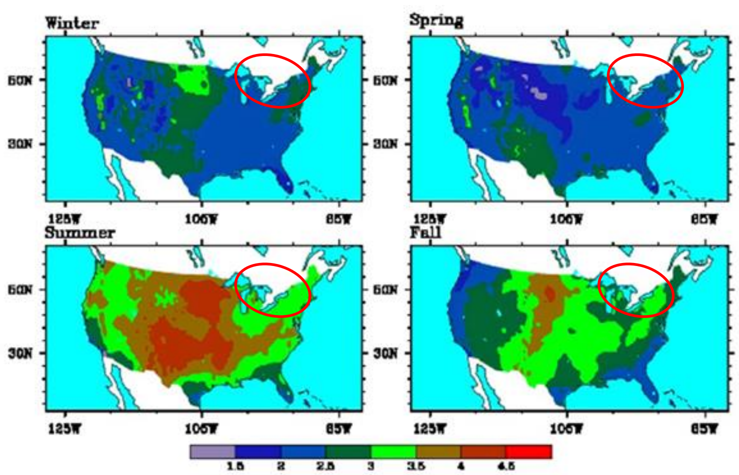

Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2041 – 2070 vs. 1971 – 2000. The Great Lakes Region is within the red oval (Liu et al., 2013).

Similar results are presented by Scherer and Diffenbaugh (2014). These authors apply a multi–member ensemble regionally–scaled GCM, assuming an A1B (middle of the road) emissions scenario, to the continental U.S. They present results by region. The majority of the Great Lakes Region is within the Midwest region, with the area in western New York State located in the Northeast region.

Results for both regions indicate steadily increasing air temperatures throughout the 21st century for both summer and winter seasons (**Figure 3.2**). Projections for 2090 show an expected increase in average daily maximum summer temperatures of 5.2 to 5.7 ºC and an expected increase in average daily minimum winter temperatures of 1.7 to 3.6 ºC. The larger projected increase in summer temperatures supports the findings of Liu et al. (2013), though the expected increases are greater in the Scherer and Diffenbaugh (2014) study.

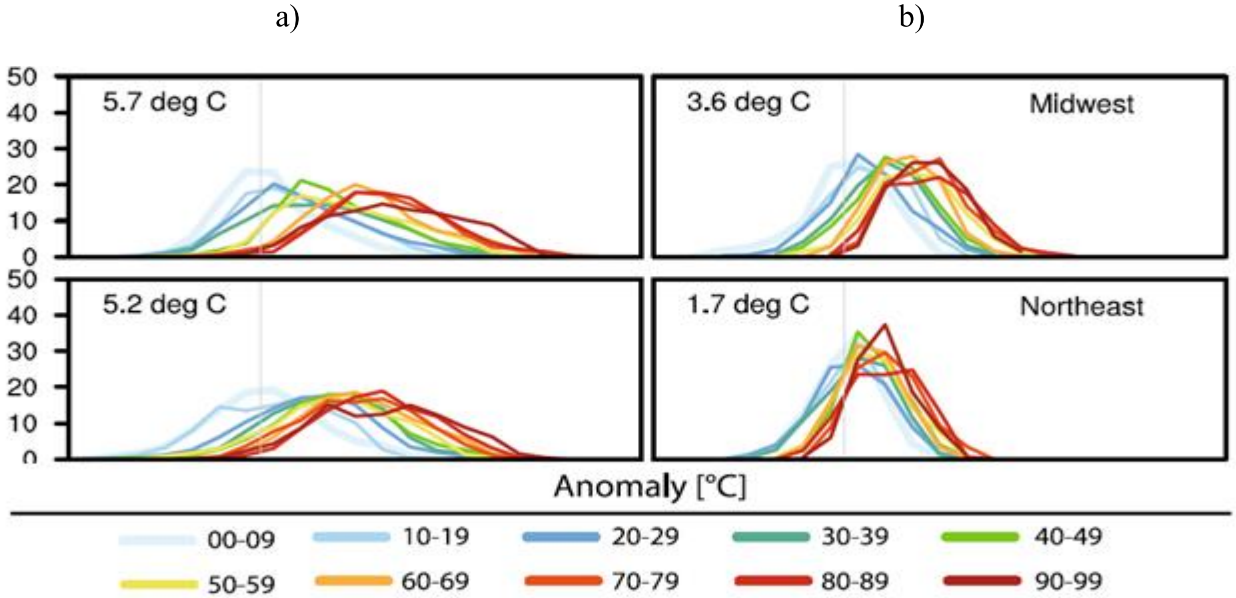

Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade; Midwest, and Northeast regions (a. average daily maximum temperature, summer months: June – August, b. average daily minimum temperatures, winter months: December – February). Colors indicate the decade of the 21st century. Probabilities on the vertical axis are in 0.01%. The value in the upper left–hand corner of each box is the expected anomaly during the 2090s (Scherer and Diffenbaugh, 2014).

Elguindi and Grundstein (2013) present results of regional climate modeling of the U.S. focused on the Thornthwaite climate type – a measure of the combination of relative temperature and precipitation projections. The Great Lakes Region has historically been primarily a cool and wet climate type, with some cold and wet areas and a moist and cool region in central Michigan. Future projections are both warmer and drier overall, with moist and cool as the dominant climate type with smaller wet and cool areas by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971 – 2000)

b) GCM projections (2041 – 2070)

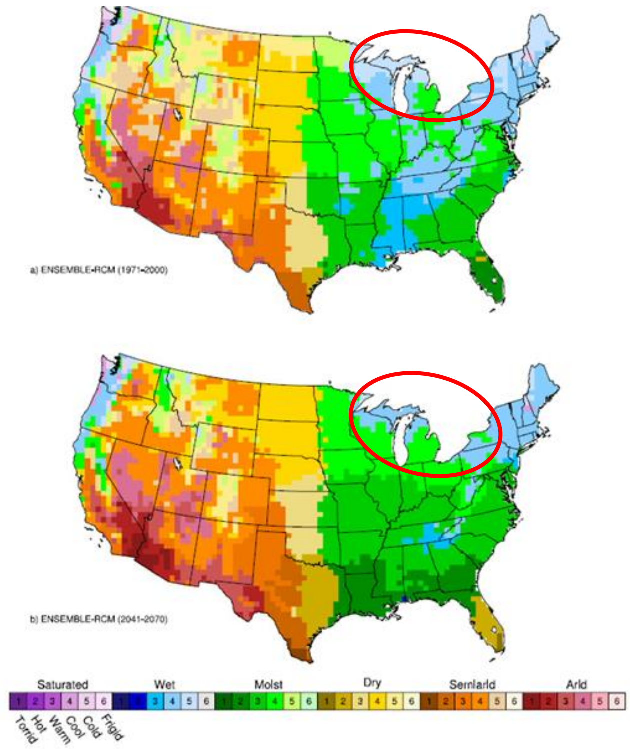

Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. The Great Lakes Region is within the red oval (Elguindi and Grundstein, 2013).

Projections of changes in temperature extremes have been the subject of many recent studies, including by Kunkel et al. (2010). In this study, two different downscaled GCMs were applied to the continental U.S., assuming high greenhouse gas emissions scenarios (A2 and A1B), with a focus on summer heat wave occurrence and intensity. For the Great Lakes Region, comparing a 2090 planning horizon with a recent historical baseline, projections indicate a 3 to 6 ºC increase in three–day heat wave temperatures, and a projected increase in the annual number of heat wave days of 30 to 50 days.

Gao et al. (2012) focus on future extreme climate events in the eastern U.S. using data from the 5th (and most recent) release of the Coupled Model Intercomparison Project (CMIP5, http://gdo–dcp.ucllnl.org/downscaled_cmip_projections). They applied a single GCM downscaled to a high resolution grid (4 km x 4 km) that included the entire Great Lakes Region. The analysis compared present (2001 – 2004) conditions to future projected conditions (2057 – 2059). CMIP5 uses several defined representative concentration pathways (RCPs) in place of previous emissions scenarios (e.g. A1B1). Gao et al. (2012) used RCP 8.5, which assumes intensive future fossil fuel use and high greenhouse gas emissions. Results (**Figure 3.4**) show projected increases in heat wave intensity, duration, and frequency for the study region.

Extreme heat wave temperatures are projected to increase by 2 to 5 ºC in the Great Lakes Region when compared to the baseline period (2001 – 2004). The projected duration of heat waves is projected to increase by 0 – 2 days per event throughout the region and the projected frequency of heat wave events is projected to increase by 4 – 8 days per year.

a) Intensity (ºC)

b) Duration (days/event)

c) Frequency (events/year)

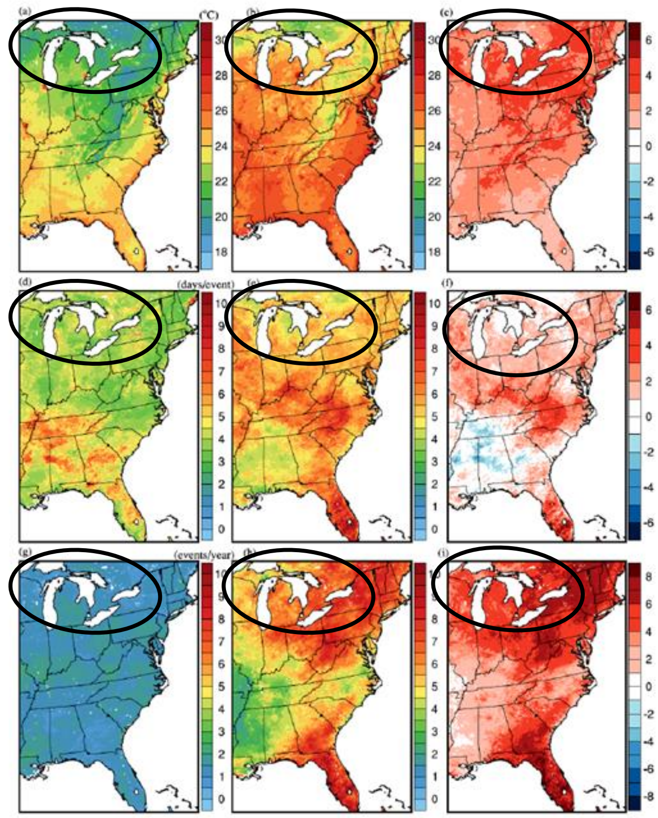

Figure 3.4. GCM Projections of heat wave patterns in the eastern U.S. (intensity, duration, frequency) for a 2058 planning horizon (compared to 2002 baseline); first column = baseline, second column = future, third column = difference between the two. The Great Lakes Region is within the black oval (Gao et al., 2012).

The third NCA reviewed projected temperatures by region. The Midwest region (Pryor et al., 2014) includes a significant portion of the Great Lakes Region, including all areas in Michigan, Ohio, Indiana, Wisconsin, and Minnesota. The authors reviewed projected changings in average and extreme temperatures (**Figure 3.5**) under an A2 emissions scenario (assuming a continued rise in emissions), comparing 2041 – 2070 with 1971 – 2000. The Great Lakes portion of the Midwest region is projected to show an increase in average annual temperature of 4.1 ºF (2.3 ºC) or greater. Days above 95 ºF (35 ºC) will increase by 5–10 days for much of the region, though could increase by anywhere from 0 – 15. The frost–free season is expected to increase by 19 days or more, and the number of cooling degree days is projected to increase by 225–300 through much of the region, ranging from 150 – 275 in some areas.

Leung and Gustafson (2005) used a downscaled GCM under an A1B emissions scenario and examined projected changes in 2045 – 2055 in the average 2–meter temperature (**Figure 3.6**). In the Great Lakes Region, summer temperatures are projected to change very little – between 0 and 2 ºC – while fall temperatures are expected to rise by 1 to 3 ºC.

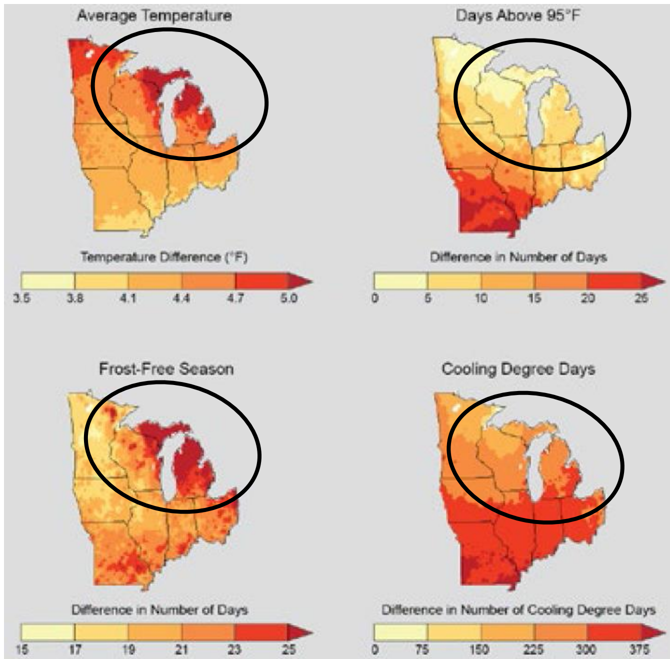

Figure 3.5. CMIP5 projections of temperature change in the Midwest. The portion of the Great Lakes Region that falls within the Midwest region is within the black oval (Pryor et al., 2014).

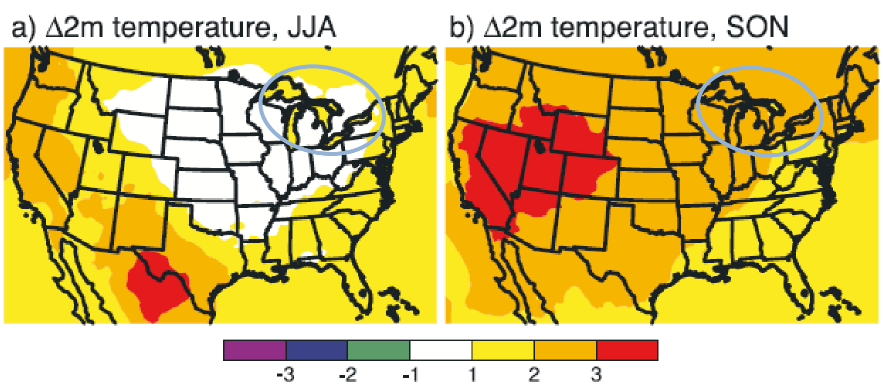

Figure 3.6 Projections of 2–meter air temperature change in the United States, ºC. Summer (June through August) projections are on the left and fall (September through November) on the right. The Great Lakes Region is within the blue oval (Leung and Gustafson, 2005).

Angel and Kunkel (2010) studied the impacts of climate change on water levels in the Great Lakes. They used 23 GCMs and 3 emissions scenarios – B1, A1B, and A2 (low, moderate, and high, respectively) – and applied them to the Great Lakes drainage basin, which includes nearly all of the Great Lakes Region. Average temperatures were projected to increase throughout the basin for all scenarios. By 2094, the projected temperature increase ranged from 1.5 – 4.0 ºC for the B1 scenario, 2.0 – 5.0 ºC for A1B, and 3.5 – 7.0 ºC for A2.

Key point: There is a high level consensus within the literature for slight to moderate warming over the next century, throughout the region and across all seasons.

3.2. Precipitation

From a global analysis using three bias–corrected global GCM projections and eight hydrologic models, Hagemann et al. (2013) project a typical increase in annual precipitation of around 180 mm per year for the Great Lakes Region (**Figure 3.7**).

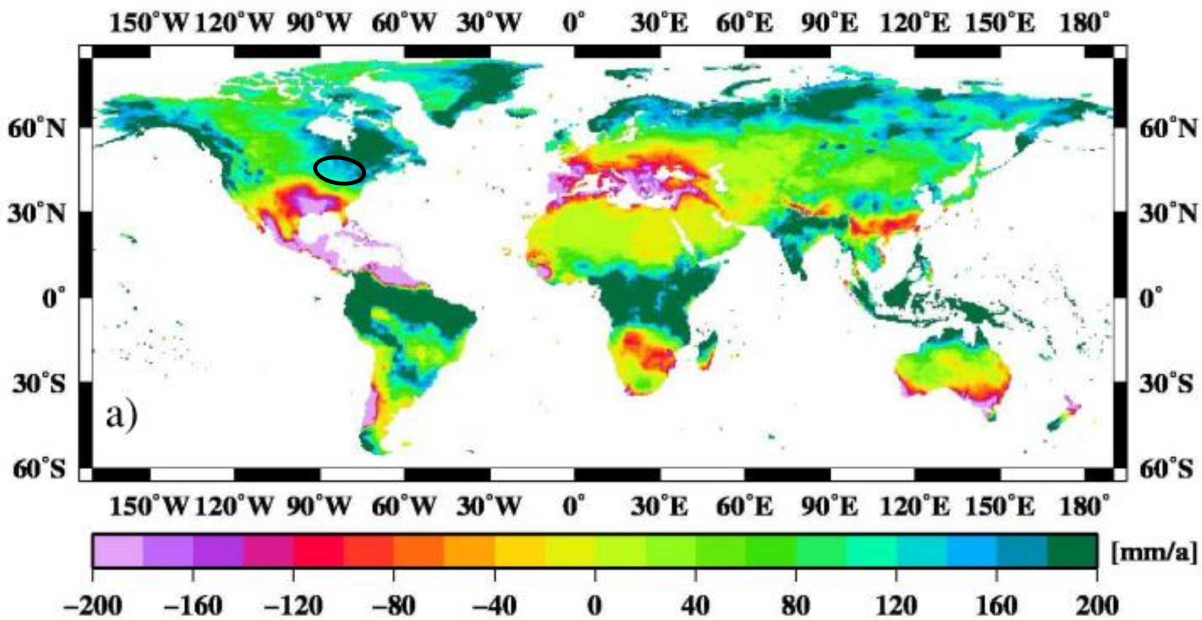

Figure 3.7. Projected (2071 – 2100) changes in annual precipitation compared to baseline, 1971 – 2000, conditions, mm/year. The Great Lakes Region is within the black oval (Hagemann et al., 2013).

The Liu et al. (2013) of the U.S., described above, predicted increases throughout the region for all seasons except summer, during a 2041 – 2070 planning horizon, compared to a recent historical baseline (1971 – 2000) (**Figure 3.8**). Winter, spring, and fall show typical increases of 30 – 45 mm with some areas of the region anywhere from 0 – 75. Projections are variable within the region for summer, showing anywhere from a decrease of 60 mm to an increase of 30 mm, with decreases generally appearing in the western portion of the region.

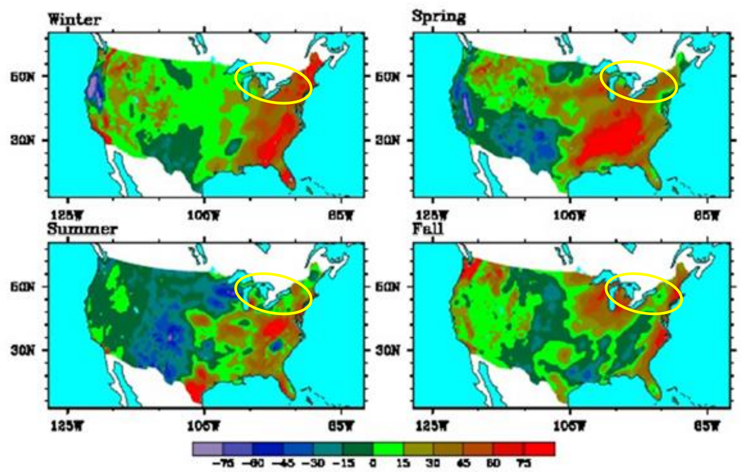

Figure 3.8. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Great Lakes Region is within the yellow oval (Liu et al., 2013).

The Leung and Gustafson (2005) study, described above, projected changes in rainfall frequency. Within the Great Lakes Region, rain days are expected to increase in the summer and decrease in the fall (**Figure 3.9**). The magnitude of the change is variable within the region. In the summer, some areas have no projected change while others show an increase of greater than eight summer rain days per year. Similarly, some areas have no projected change in the number of fall rain days, while others may decrease by more than eight days per year.

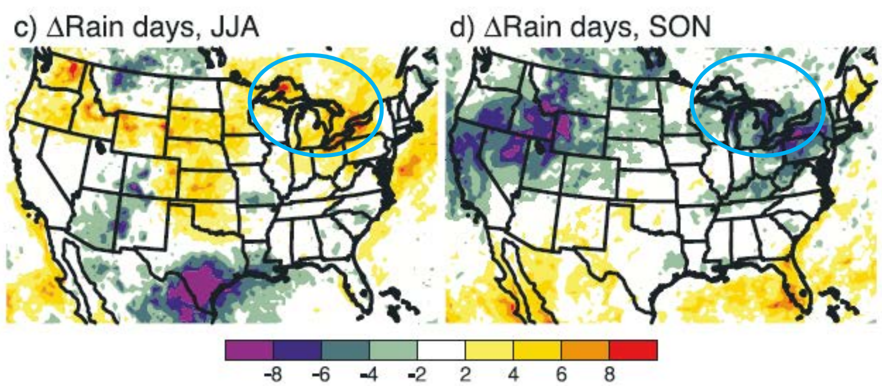

Figure 3.9. Projected changes in rainfall frequency, days per year. Summer (June through August) projections are on the left and fall (September through November) on the right. The Great Lakes Region is within the blue oval (Leung and Gustafson, 2005).

Future projections of extreme events, including storm events and droughts, are the subject of studies by Wang and Zhang (2008) and Gao et al. (2012). In addition to the historical data trend analyses by Wang and Zhang (2008) described above, these authors also used downscaled GCMs to look at potential future changes in precipitation events across North America. The GCMs, which used the A2 emissions scenario, projected that the recurrence of the historical 20–year 24–

hour storm event for their future planning horizon (2050 – 2099) in the Great Lakes Region would increase, occurring twice as often in some parts of the region (**Figure 3.10**).

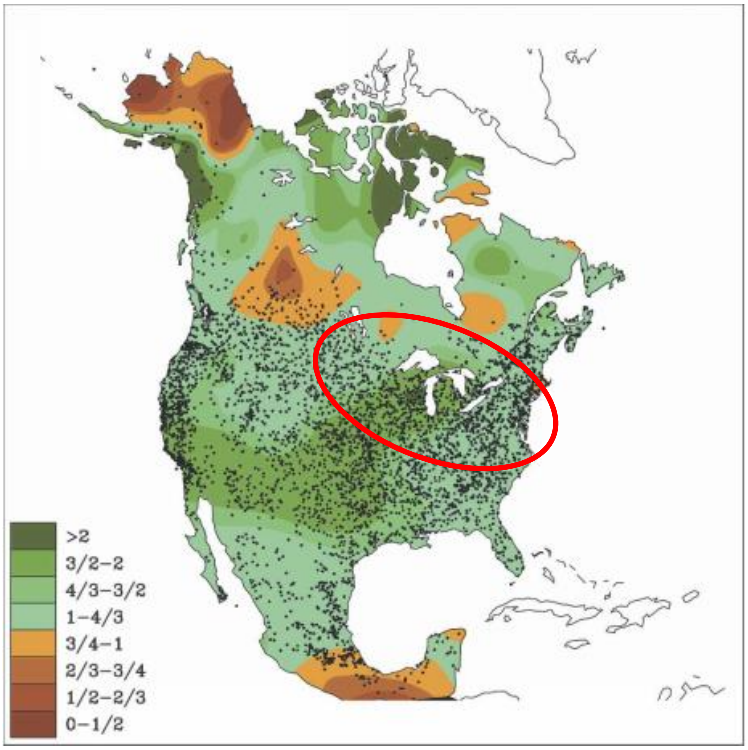

Figure 3.10. Projected risk of current 20–year 24–hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The Great Lakes Region is within the red oval (Wang and Zhang, 2008).

The GCM applied in the Gao et al. (2012) study for the eastern U.S. generally projects increases in extreme precipitation events throughout the eastern U.S. (**Figure 3.11**). The study examined the magnitude of annual total precipitation from extreme events above the 95^{th} percentile, average daily precipitation from extreme events, and frequency of storm events, for the 2057 – 2059 planning horizon compared to current conditions (2001 – 2004). All three parameters showed variability within the Great Lakes Region, with increases expected overall but decreases expected in some areas.

Section 3.1 noted a study by Elguindi and Grundstein (2013) modeling projected changes in the Thornthwaite climate index. This study indicated that the Great Lakes Region will be drier overall. However, the Thornthwaite index is not a direct measure of precipitation; a drier Thornthwaite index may indicate higher evaporation rather than lower precipitation.

a) Annual total of extreme events (mm/yr.)

b) Daily extreme storms (mm/day)

c) Frequency of storm events (days/yr.)

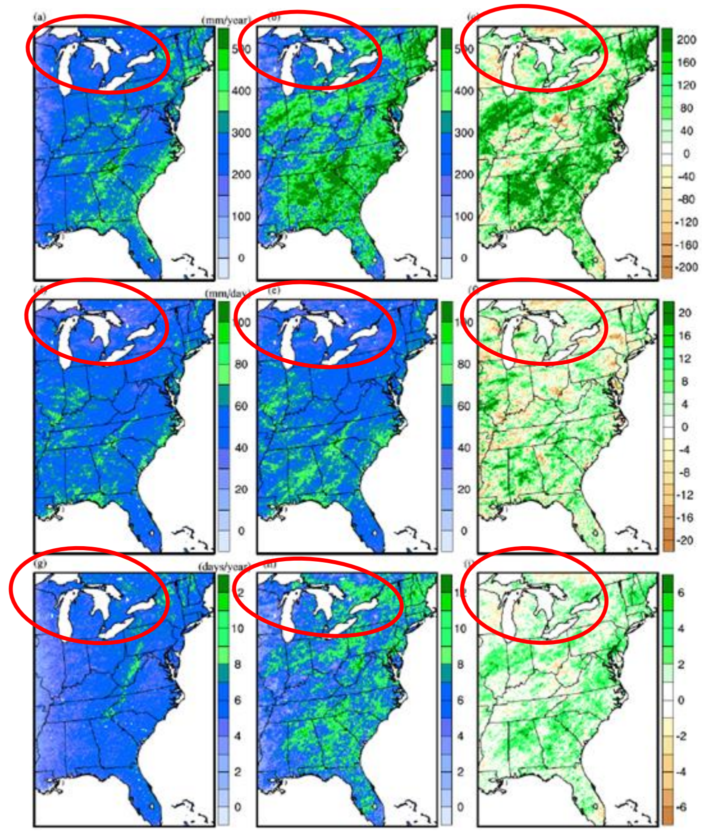

Figure 3.11. GCM projections of future precipitation patterns in the eastern U.S. (annual extreme totals, daily extremes, frequency of events) for a 2057 – 2059 planning horizon (compared to 2001 – 2004 baseline); first column = baseline, second column = future, third column = difference between the two. The Great Lakes Region is within the red oval (Gao et al., 2012).

Schuster et al. (2012) studied projected changes in precipitation and flooding in several cities in Wisconsin, including Milwaukee and Green Bay in the Great Lakes Region. They used 14 different downscaled, debiased GCMs under an A1B emissions scenario. For those two cities, they found an 11.5% increase in the 100–year 24–hour storm volume and a 9.7% increase in the 10–year 24–hour storm volume, comparing 2046 – 2065 to 1961 – 2000. They also noted a 42.9% increase in the frequency of events exceeding 7.6 centimeters.

As noted above, Angel and Kunkel (2010) studied the potential impacts of climate change to Great Lakes levels using 23 GCMs and B1, A1B, and A2 emissions scenarios. Within the Great Lakes drainage basin, while some simulations showed a reduction in average precipitation over time, most showed an increase, up to 15 cm per year by 2050.

Lastly, the third NCA (Walsh et al., 2014) presents seasonal precipitation projections from CMIP5 (**Figure 3.12**). Projected increases in total seasonal precipitation range from 0% to 10% for the RCP 2.6 scenario (rapid emissions reductions), and from 0% to 20% for the RCP 8.5

scenario (continued emissions increases). The exception is summer under the RCP 8.5 scenario, which shows decreases of up to 10%.

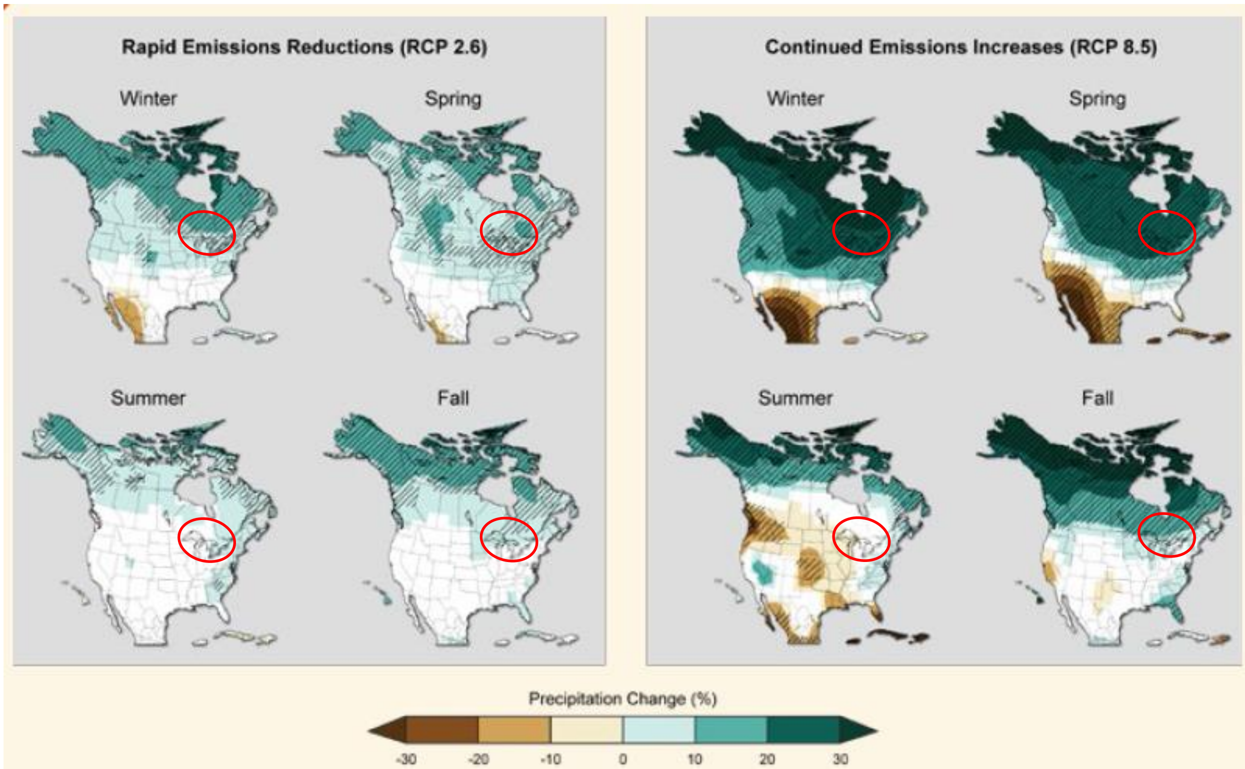

Figure 3.12. Percent change in total seasonal precipitation based on CMIP5 modeling. Stippling indicates greater than 80% agreement among the various models (Walsh et al., 2014). The Great Lakes Region is within the red oval.

Key point: Projections generally show an increase in average annual precipitation as well as the frequency and magnitude of storm events. However, there is considerable uncertainty in the magnitude of potential future increases.

3.3. Hydrology

A number of studies have attempted to project future changes in hydrology, relying primarily on a combination of GCMs and macro–scale hydrologic models. Thomson et al. (2005) used three GCMs, in combination with a hydrologic model applied at the 8–digit HUC scale, to quantify potential changes in water yield (considered to be a surrogate for streamflow) across the United States. The modeling included two future temperature scenarios and two future CO_2 concentration scenarios (used to model the 'CO_2–fertilization' effect in the hydrologic model). For most of the United States, projected water yield differs significantly between the different GCMs evaluated (**Figure 3.13**), with projections within the Great Lakes Region ranging from a decrease of 50 mm per year to an increase of 25 mm per year.

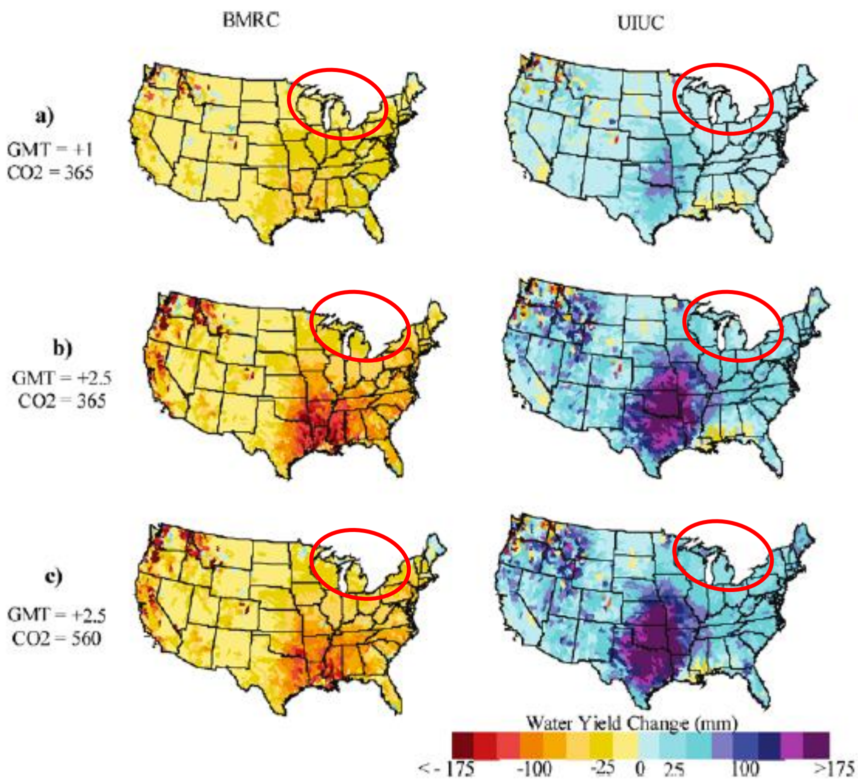

Figure 3.13 Projected change in water yield (from historical baseline), under various climate change scenarios based on 3 GCM projections. Global mean temperature increase (in ºC) and atmospheric CO_2 concentrations (ppm) are indicated on the left side for each of the three scenarios. The Great Lakes Region is within the red oval. The GCM in the third column is a variation on the GCM in the second column (Thomson et al., 2005).

The results presented by Thomson et al. (2005), described above, highlight the significant uncertainties associated with global climate modeling, particularly with respect to hydrologic parameters. Additional uncertainty is generated when these climate models are combined with hydrologic models that carry their own uncertainty. This comparison and quantification of uncertainty is the subject of a study by Hagemann et al. (2013). In this study, the authors apply three GCMs, across two emission scenarios to seed eight different hydrologic models for projecting precipitation, ET, and runoff on a global scale. Their findings, in agreement with CDM Smith (2012), indicate that the uncertainty associated with macro–scale hydrologic modeling is as great, or greater, than that associated with the selection of climate models. Study projections from Hagemann et al. (2013), for the Great Lakes Region show an overall increase in runoff by up to 80 mm per year for their future planning horizon (2071 – 2100) compared to the recent historical baseline (1971 – 2000) (**Figure 3.14**), assuming an A2 emissions scenario. There is seasonal variation in projected changes in runoff, with larger increases projected for winter and smaller increases or decreases projected for spring (**Figure 3.15**).

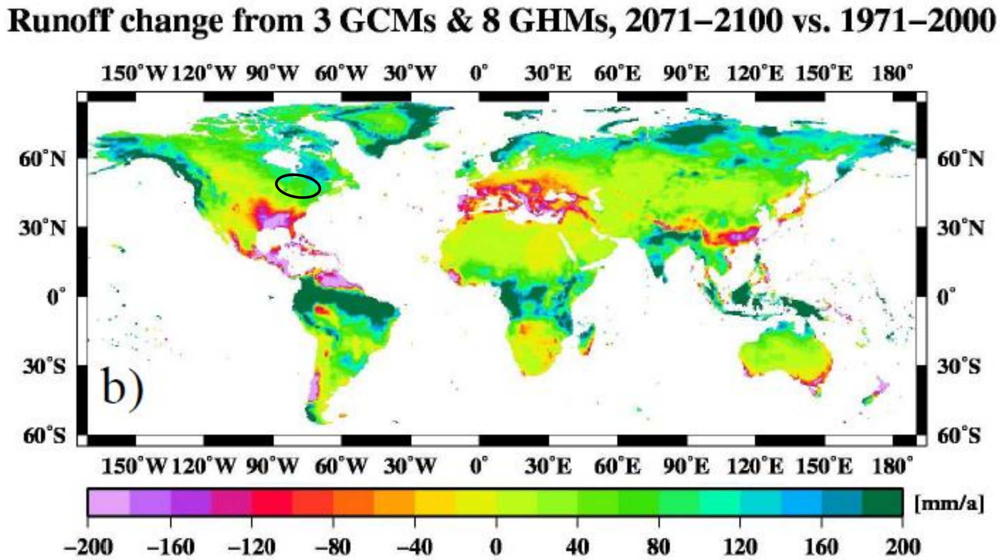

Figure 3.14. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Great Lakes Region is within the black oval (Hagemann et al., 2013).

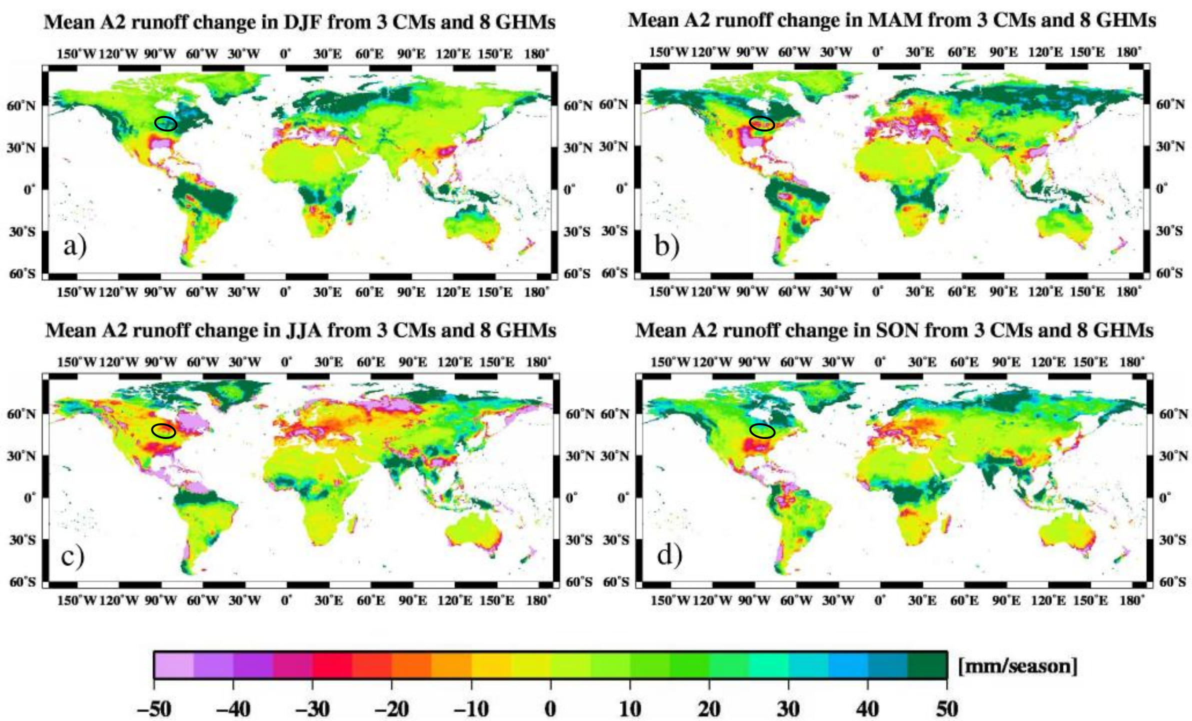

Figure 3.15. Ensemble seasonal (a. winter b. spring c. summer d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071 – 2100 vs 1971 – 2000. The Great Lakes Region is within the black oval (Hagemann et al., 2013).

As noted above, Angel and Kunkel (2010) analyzed the potential impact of climate change on water levels in the Great Lakes. They used 23 GCMs and three emissions scenarios (B1, A1B, and A2) to estimate climatic changes in the Great Lakes drainage basin, then applied the results to a hydrologic model to estimate impacts on water levels. The authors completed a total of 565 model runs, 75% of which showed average water levels remaining the same or declining. The authors noted significant uncertainty regarding projected water levels. Depending on the emissions scenario, the median projected decline in lake levels was: 0.07 – 0.18 m for 2020 – 2034; 0.23 – 0.24 m for 2040 – 2064; and 0.25 – 0.41 m for 2080 – 2094, when compared with the average lake level from 1970 – 1999.

Key point: Significant uncertainty exists in projected runoff and streamflow, with some models projecting increases and other decreases. Changes in runoff and streamflow may also vary by season. Projections of water levels in the Great Lakes also have considerable uncertainty, but overall lake levels are expected to drop over the next century.

3.4. Summary of Future Climate Projection Findings

There is strong consensus in the literature that air temperatures will increase in the study region over the next century. The projected increase in mean annual air temperature ranges from 0 to 7 ºC by the latter half of the 21st century. Reasonable consensus is also seen in the literature with respect to projected increases in extreme temperature events, including more frequent, longer, and more intense summer heat waves.

Projections of precipitation in the study area are less certain than those associated with air temperature. Most studies project increases, but other studies project decreases, and some project variability within the region or by season. Similarly, while the projections tend toward more intense and frequent storm events than the recent past, some show a reduction in parts of the Great Lakes Region.

Significant uncertainty exists in hydrologic projections for this region. Projections generated by coupling GCMs with macro–scale hydrologic models in some cases indicate a reduction in future streamflow but in other cases indicate a potential increase in streamflow in the study region. Projections of water levels in the Great Lakes are generally expected to decline, but some modeling scenarios show an increase or no change.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.16**.

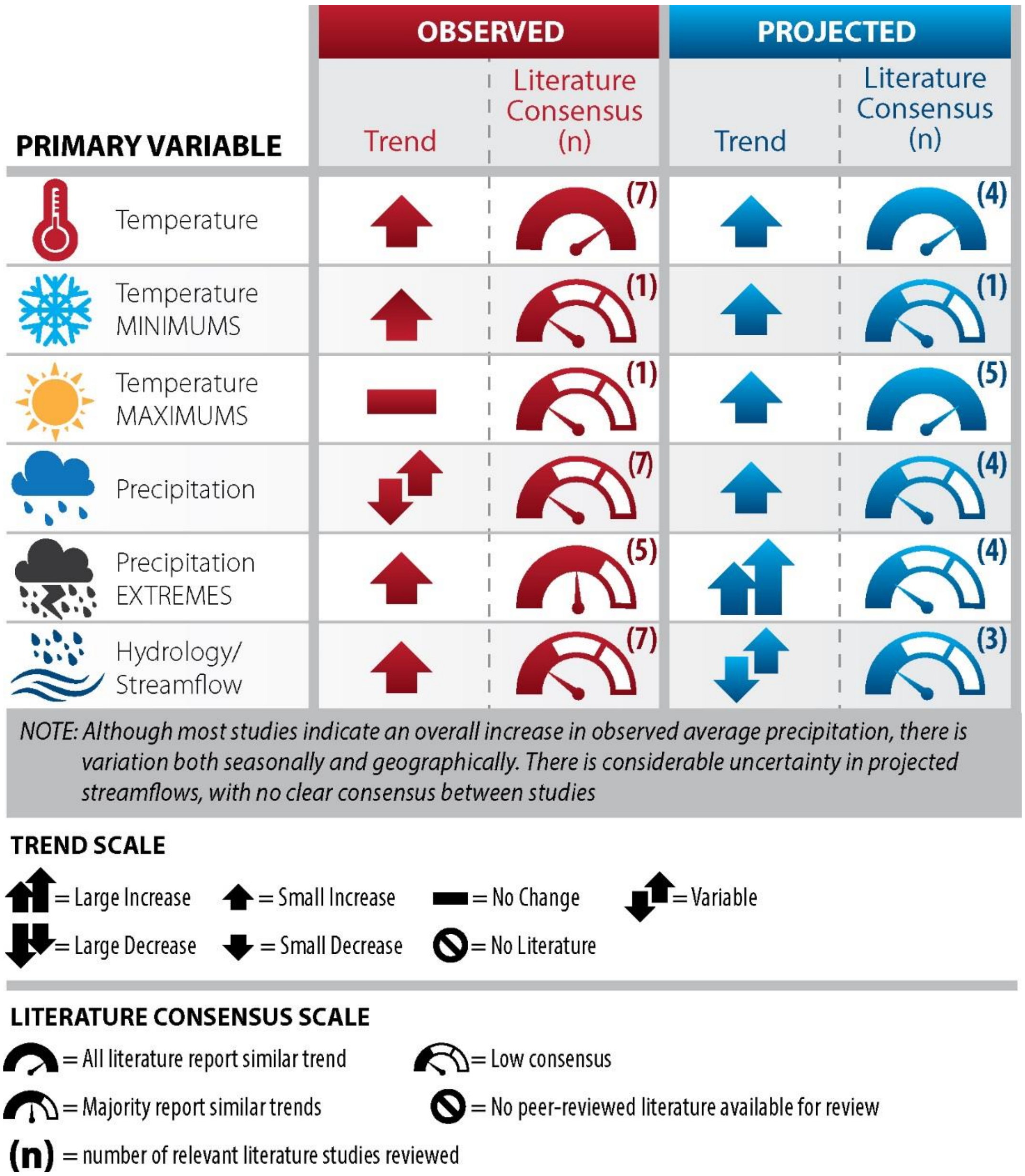

Figure 3.16. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The Great Lakes Region touches many states, including portions of Pennsylvania, New York, Ohio, Michigan, Indiana, Vermont, and Wisconsin. Climate impacts to this area may be affected by climatic conditions beyond this given region, especially from impacts to the Great Lakes in Canada. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Water Supply
- Ecosystem Restoration
- Hydropower
- Recreation
- Emergency Management
- Regulatory
- Military Programs

The navigation mission in the USACE Great Lakes Region is to maintain 140 harbors, 2 operational locks, 104 miles of breakwaters and jetties, and over 600 miles of maintained navigation channels. The Great Lakes navigation system connects all the way to the Atlantic Ocean, by the Gulf of St. Lawrence. The Great Lakes Region may experience increases in ambient air temperature and changes to seasonal precipitation. Overall, the lake levels are expected to drop, which has implications for water levels and thus the ability for vessels to navigate the Great Lakes Region.

USACE implements flood risk management projects in the region to limit flooding; such projects include dams and levees. An increase in annual precipitation is predicted for the region, as are the frequency of extreme storm events. This may cause increased runoff and may cause flash floods if the storms are intense. Flood risk management projects may be very important for reducing the residual flooding impacts due to increased precipitation and extreme storm events.

USACE also maintains and operates several fresh water supplies to maintain water quality in the region; this is a drinking water source for millions of people. The contrast between increasing mean air temperatures along with increased frequency and magnitude of heat waves will make managing competing water needs a challenge, especially when water demand is high and water supply is low.

USACE implements ecosystem restoration projects in the Great Lakes Region. Increased ambient air temperatures will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures are associated with the growth of nuisance algal blooms and influence wildlife and supporting food supplies.

In addition, possible changes to seasonal precipitation patterns may pose complications to planning for ecosystem needs and lead to variation in flows. This may be particularly true during dry years, when water demands for conflicting uses may outweigh water supply. During wet years, flooding may raise particular ecological concerns and may threaten ecosystems.

There are some hydropower plants in the Great Lakes Region at USACE-owned dams. Annual precipitation and seasonal precipitation, especially in the winter (with smaller increases in the spring), are expected to increase in the region. This may be beneficial for hydropower plants in the region, as flooding and increased river flows may lead to increased power generation. However, in extreme cases excess flooding may present some operational issues at these projects. Conversely, there may also be times during any given year where flows and reservoir levels are reduced due to high temperatures, which would reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the Great Lakes Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature along extended heat wave days and the possible increase in extreme storm events have the potential to decrease the number of visitors to USACE's recreational facilities. Periods of extreme high heat poses human health concerns and higher water temperatures can result in algal blooms and other water quality issues which may cause health risks for those involved in aquatic activities. An increase in extreme storm events may make recreational activity difficult, dangerous, or impossible.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize. Increased precipitation and the possible increase of extreme storm events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Great Lakes Region. USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing for reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulations or an increase in the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services include the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. The interrelationships between business lines must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. **Figure 4.1** summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
Increased Ambient Temperatures	By mid-century, increased ambient air temperatures are expected to create the following vulnerabilities on the business lines in the region: • Loss of vegetation from increased periods of heat and variable streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Variable flows, have implications for maintain water levels in the rivers and lakes. • Risk of wildfires during hot and dry conditions may cause an increased risk of wildfires, especially in heavily forested and dry areas. Flora and fauna that are not drought resistant can also be impacted by longer drought conditions, which may reduce opportunities for recreational wildlife viewing. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management
Increased Maximum Temperatures	Air temperatures are expected to increase 2-2.5°C by mid century, with the number of days per year over 95°F increasing by 5-10 days. This is expected to create the following vulnerabilities on business lines in the region: • Increased water temperatures leading to water quality concerns, particularly for the dissolved oxygen (DO) levels, growth of nuisance algal blooms and influence wildlife and supporting food supplies. • Increased evapotranspiration. • Human health risk increases from extended heat waves, impacting recreational visitors and increasing the need for emergency management. **BUSINESS LINES IMPACTED:** Recreation, Water Supply, Ecosystem Restoration
Increased Annual Precipitation	By the end of the century, annual precipitation is expected to increase in the region which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management, Emergency Management
Increased Storm Intensity and Frequency	Extreme storm events may become more frequent and intense over the coming century which are expected to influence the following vulnerabilities on business lines in the region: • Increased runoff during an event, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Change in engineering design standards to accommodate new extreme storms magnitudes. • Increased flash flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management, Emergency Management
Streamflow Variability	Streamflow may have more variability in the region. This may result in: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. • Loss of vegetation from increased periods of drought and reduced streamflows may have impacts on vegetation within the region, which is important for sediment stabilization in the watershed. Loss of non-drought resistant vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Decrease in flows may result from periods of drought and reduced streamflow has implications for maintain water levels in the rivers. **BUSINESS LINES IMPACTED:** Navigation, Recreation, Water Supply, Ecosystem Restoration, Hydropower, Flood Risk Management, Emergency Management

NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables

= Navigation = Flood Risk Management = Ecosystem Restoration = Hydropower = Recreation = Water Supply = Emergency Management

Figure 4.1. Summary of projected climate trends and impacts on USACE business lines

Appendix A: References Climate/Hydrology Summary Table

	Observed										Projected									
References	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Angel JR, Kunkel KE (2010)											X			X		X				
CDM Smith (2012)																X				
Elguindi N, Grundstein A (2013)											X			X						X
Gao Y, Fu JS, Drake JB, Liu Y, Lamarque JF (2012)													X		X					
Grundstein A (2009)				X				X												
Grundstein A, Dowd J (2011)	X	X	X																	
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, ..., Voss F, Wiltshire AJ (2013)														X		X				
Kalra A, Piechota T, Davies R, Tootle G (2008)						X														
Kunkel KE, Liang X-Z, Zhu J (2010)													X							
Leung LR, Gustafson GJ (2005)											X	X	X	X	X					
Liu Y, Goodrick SL, Stanturf JA (2013)													X	X	X					
McRoberts DB, Nielsen-Gammon JW (2011)				X																
Meehl GA, Arblaster JM, Branstator G (2012)	X	X	X																	
Milly PC, Dunne KA, Vecchia AV (2005)											X									
Novotny EV, Stefan HG (2007)						X														
Palecki MA, Angel JR, Hollinger SE (2005)				X	X															
Pryor SC, Howe JA, Kunkel KE (2009)				X																
Pryor SC, Scavia D, Downer C, Gaden M, Iverson LN, R., Patz J, Robertson GP (2014)	X										X	X	X							
Qian T, Dai A, Trenberth KE (2007)	X			X		X														
Sagarika S, Kalra A, Ahmad S (2014)						X														
Scherer M, Diffenbaugh N (2014)											X	X	X							
Schuster ZT, Potter KW, Liebl DS (2012)														X						
Schwartz MD, Ault TR, Betancourt JL (2013)	X								X											
Small D, Vogel RM, Islam S (2006)				X		X														
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005)																X				
Villarini G, Serinaldi F, Smith JA, Krajewski WF (2009)						X														
Villarini G, Smith JA, Vecchi GA (2013)				X																
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, ..., Lenton T, Kennedy J, Somerville R (2014)	X			X	X									X						
Walter MT, Wilks DS, Parlange J-Y, Schneider RC (2004)				X		X														
Wang H, Schubert S, Suarez M, Chen J, Hoerling M, Kumar A, Pegion P (2009)	X	X	X	X																
Wang J, Zhang X (2008)				X	X									X	X		X			
Westby RM, Lee Y-Y, Black RX (2013)	X	X																		

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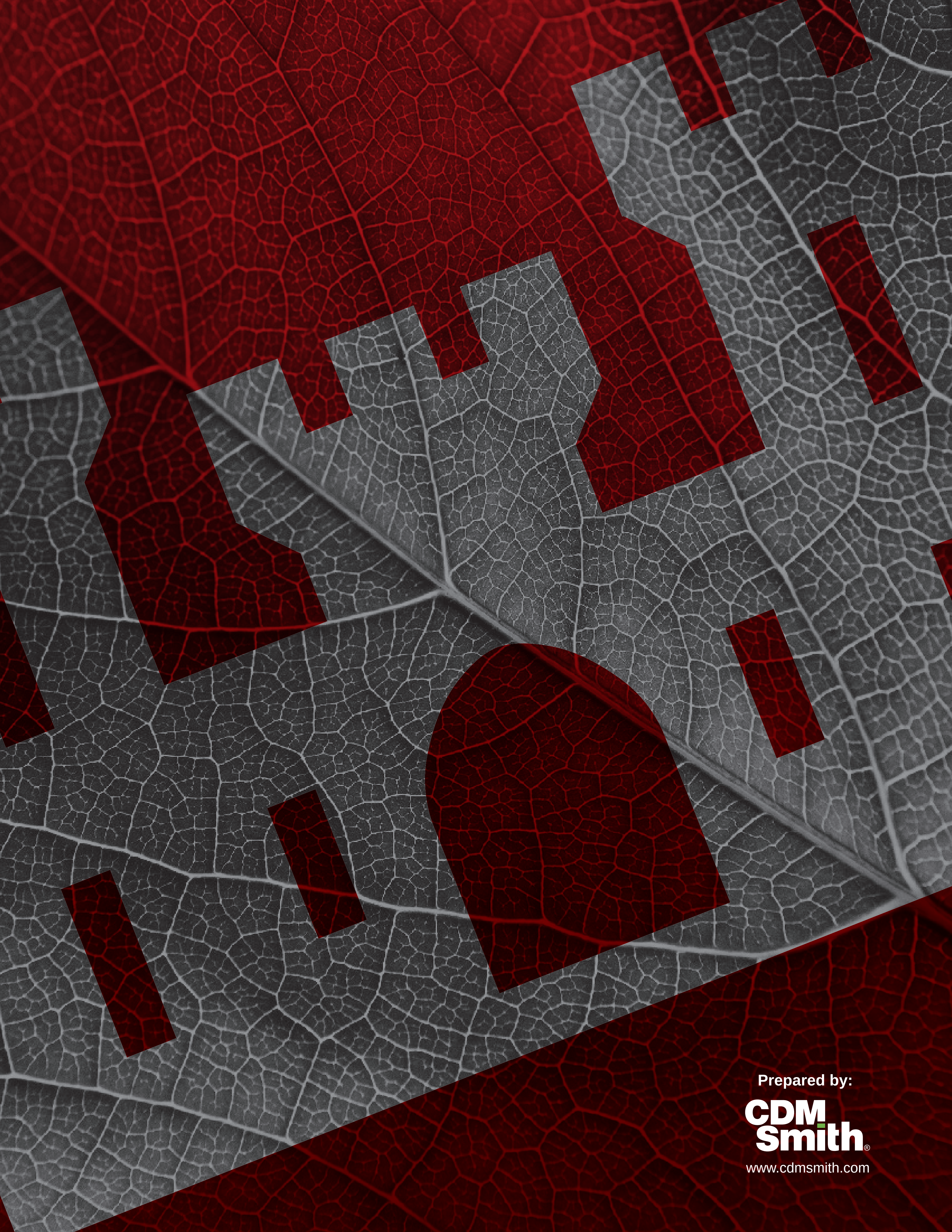

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