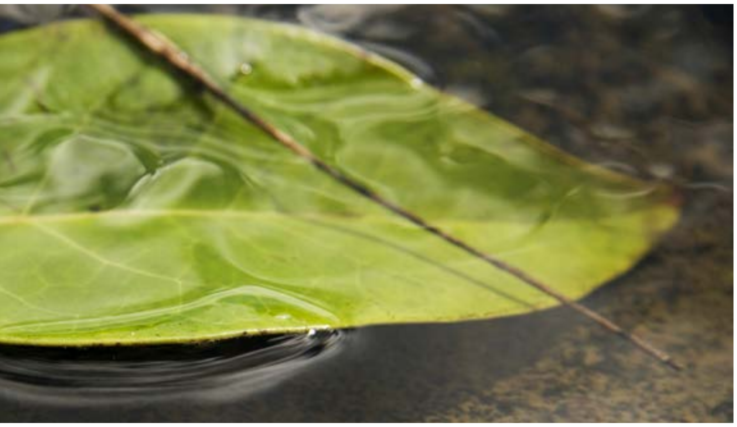


Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

OHIO REGION 05

FINAL

January 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

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- Kathleen D. White, PhD, PE, Institute for Water Resources - US Army Corps of Engineers
- Jeffrey R. Arnold, PhD, Institute for Water Resources - US Army Corps of Engineers
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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 Ohio 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.

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Water Resources Region 05	Projected Climate	Climate Vulnerability
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OHIO REGION 05

January 20, 2105

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Edited by:

Kathleen D. White PhD, PE, Institute for Water Resources - US Army Corps of Engineers
Jeffrey R. Arnold, PhD, Institute for Water Resources - US Army Corps of Engineers

Prepared by:

Chris Kurtz, PE, CDM Smith
Tim Cox, PhD, PE, CDM Smith
Frannie Bui, PE, CDM Smith
Lauren Klonsky, PE, CDM Smith
Jamie Lefkowitz, PE, CDM Smith
Alexandra Bowen, PE, CDM Smith
Lauren Miller, CDM Smith
Rebecca Jablon, AICP, LEED AP, CDM Smith
Quentin Smith, CDM Smith
Tim Feather, PhD, CDM Smith
Mark Dunning, PhD, CDM Smith
David Spector, CDM Smith

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Water Resources Region 05: Ohio Region

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 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 Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty one water resources regions included in this series of reports is 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 5, the Ohio Region, the boundaries for which are shown in **Figure 1.2**. The entire Ohio Region is within the USACE Louisville, Nashville, Huntington, and Pittsburgh district territories.

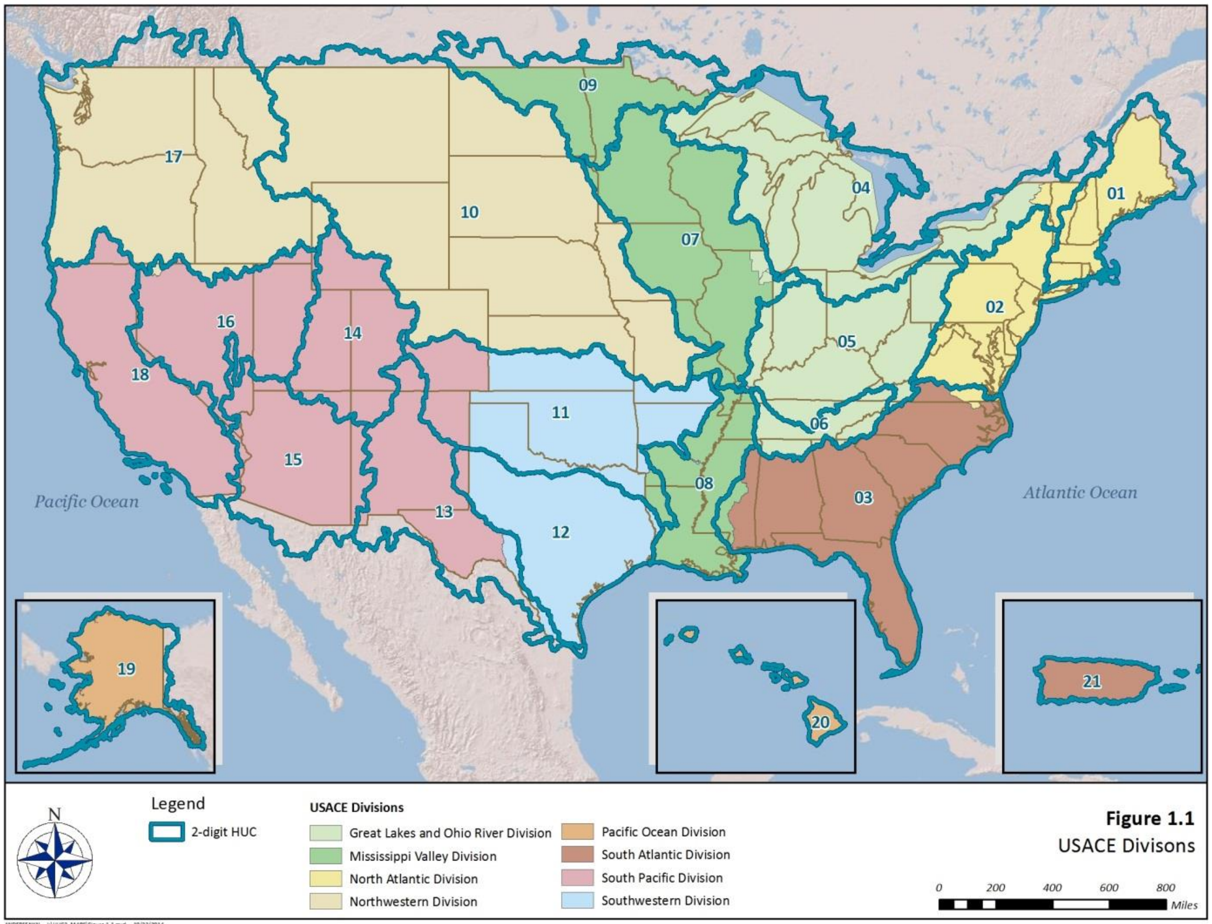


Figure 1.1. 2-digit Hydrologic Unit Code Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico

Figure 1.2. Water Resources Region 05: Ohio Region Boundary.

1.1. A Note on the 2-digit 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 U.S. Geological Survey (USGS) HUC (Water Resources Region), 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 HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Region scale both to be guides into the climate change literature and to support the informational analyses USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 03, both the 2-digit and 4-digit HUC boundaries are shown in **Figure 1.2**.

2. Observed Climate Trends

Observed climate trends within Water Resources Region 5 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 Water Resources Region 5 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 of the Water Resources Region 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 that the Ohio Region overlays a transition zone in historic temperature and precipitation trends. Studies of regional streamflow reviewed here present evidence of increased flows observed over the past 60 years.

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 Ohio Region and regional studies focused more specifically on the region. Results from both types of studies, relevant to the Ohio Region, are discussed below.

At a national scale, a 2009 study by Wang et al. 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 Ohio Region seasonal differences are evident. A positive warming trend is identified for most of the region in the winter (December to February) and spring (March to May). A transition from warming in the northern portion and cooling in the southern portion of the region is observed for the summer (June to August). In fall (September to November), a cooling trend is identified. The authors do not provide information on statistical significance of the presented observed trends. This study supports the hypothesis of the existence of a "warming hole" in the southeast U.S., exemplified by a region that has not experienced the same warming trend as the rest of the country (Meehl et al., 2012; Pan, 2004; Wang et al., 2009).

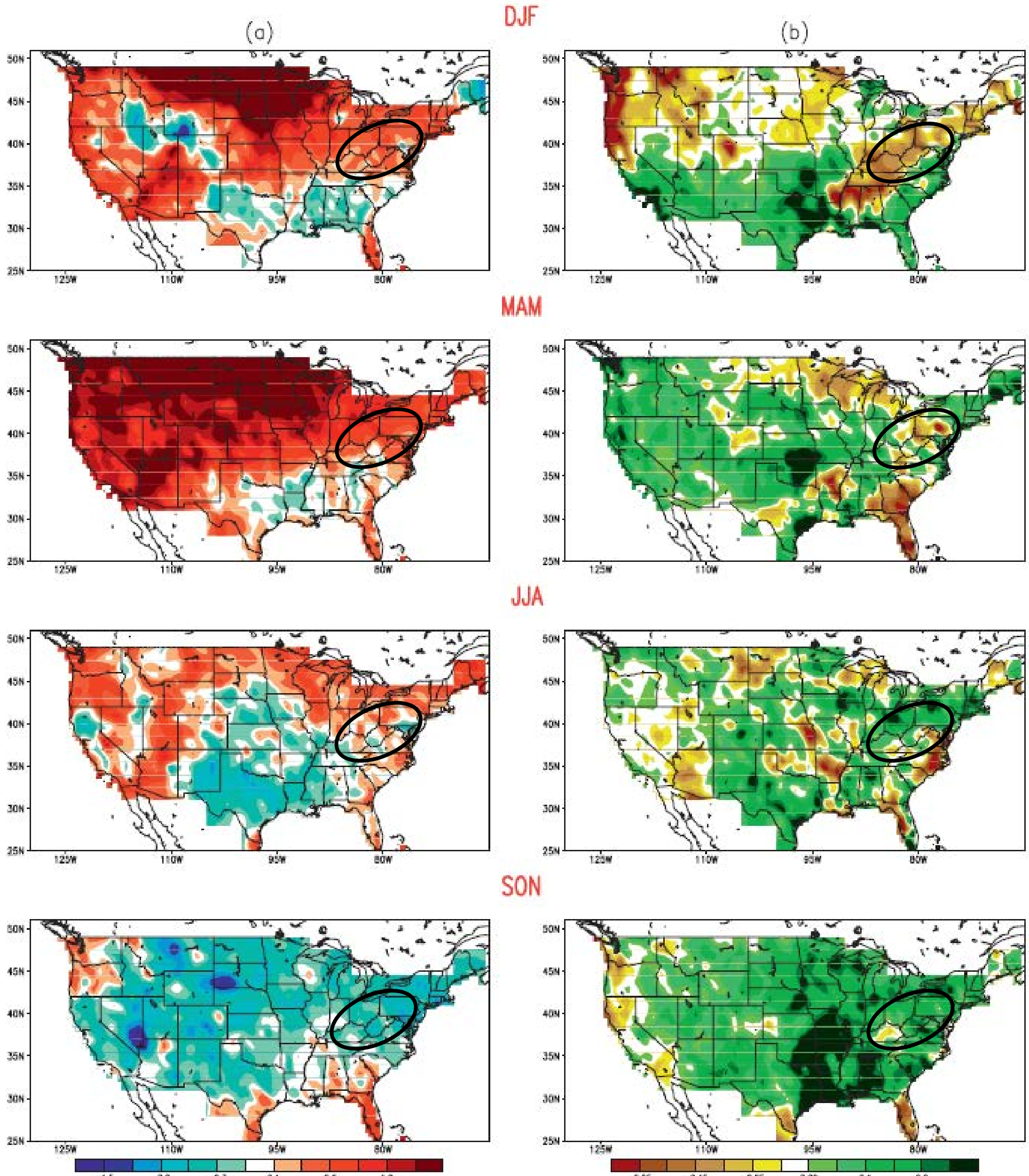


Figure 2.1. Linear trends in surface air temperature (a) and precipitation (b) over the United States, 1950 – 2000. The Ohio Region is within the black oval (Wang et al., 2009).

A later study by Westby et al. (2013), using data from the period 1949 to 2011, moderately contradicted these findings, presenting a general mild winter cooling trend for the entire Ohio Region for this time period. Their cooling trend, however, was 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. Water Resources Region 5 overlays three different NCA regions, therefore the nationwide summary was reviewed (Walsh et al., 2014) rather than the regional chapters. In comparing the temperature changes over the past 22 years with the 1901 to 1960 average, the NCA found temperature increases throughout the Ohio Region except for a small portion in the southeast (**Figure 2.2**). These findings corroborate the "warming hole" hypothesis and agree with Wang et al. (2009) that the Ohio Region spans a transition zone between warming and cooling trends. Details on statistical significance are not provided.

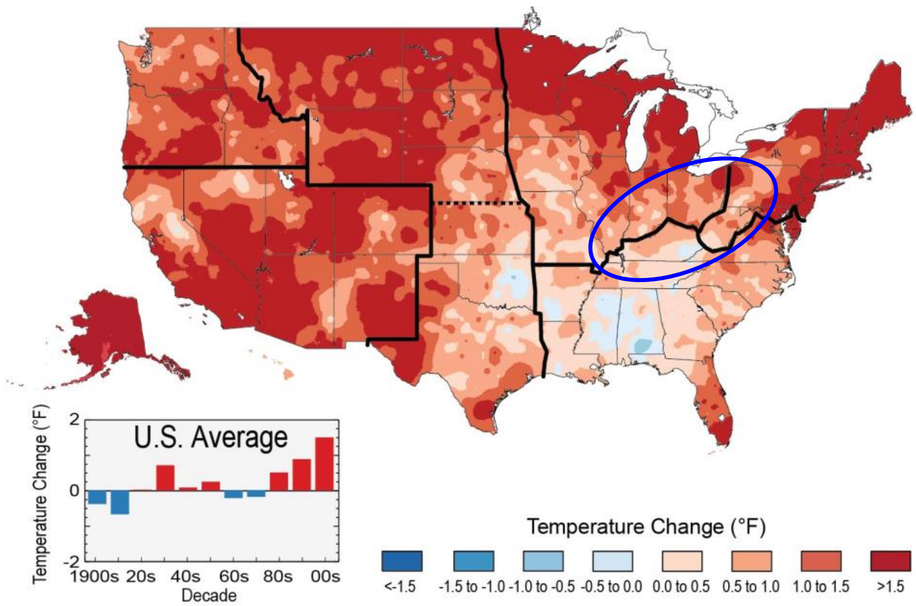


Figure 2.2. Temperature changes over the past 22 years (1991 – 2012) compared to the 1901 – 1960 average, and compared to the 1951 – 1980 average for Alaska and Hawaii (Walsh et al., 2014). The blue oval indicates the approximate Water Resources Region 5.

Meehl et al. (2012) also observed a transition zone between warming and cooling that overlaps with the Ohio Region. However, their analysis of observed climate data and model calculations for 1950 to 1999 found the cooling trend to extend further into the northeast during the winter and more limited to the southeast than Wang et al. (2009). 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. Their findings indicate additional evidence of a cooling trend in the southern portion of the Ohio Region and a warming trend in the northern portion of the Ohio Region. This is shown by an earlier arrival of spring in the northern portion of the region and a later arrival of spring in the southern portion (**Figure 2.3**).

Figure 2.3. Change in spring onset (first leaf date), in days for 2001 – 2010 compared to 1951 – 1960. The Ohio 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. They found a linear trend of between 0 and 0.4 °C per century for the Ohio Region (**Figure 2.4**). They also indicate a cooling trend in the southeast U.S., but the cooling region does not overlap with the Ohio Region in these findings.

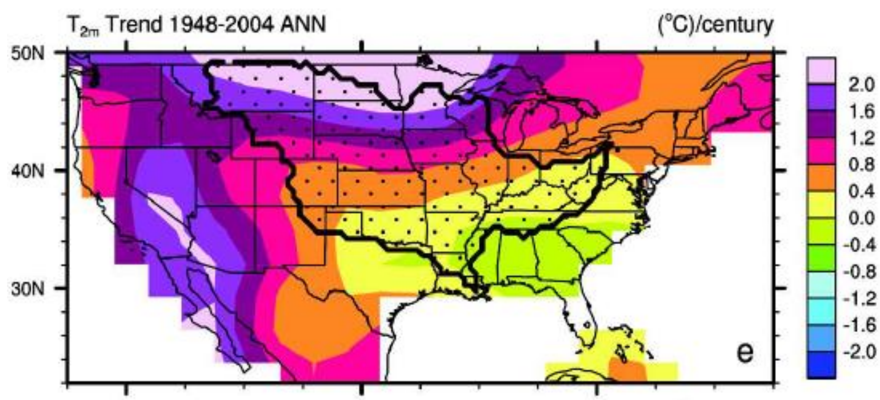


Figure 2.4. Linear trend from October 1948 to September 2004 in annual observed temperature (Qian et al., 2007).

Brown et al. (2010) used an extended period dataset (1893 to 2005) to evaluate for trends in climate extremes in the northeast, using a region that includes Pennsylvania and overlaps with the Ohio Region. The research indicates statistically significant (95% C.I.) upward trends in their index for summer days (number of days per year with daily maximum temperatures over 25 degrees Celsius) at the stations in Pennsylvania that overlap with the Ohio Region, for 1893 to 1950. Those stations showed no trend for their cold spell duration indicator (number of events per year with at least six consecutive days with temperatures below the 10th percentile) for 1893 to 1950. When the researchers examined the latter half of the 20th century, they found some stations with statistically significant decreases in the number of summer days in the Ohio Region and other stations with no change or an increase (though not statistically significant). Their analysis of cold spells showed a fairly consistent, though not statistically significant, decrease in the number of annual cold spells for the latter half of the century.

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. For the Ohio Region, they found a statistically significant (95% C.I.) increasing trend in the number of one-day extreme minimum temperatures for approximately one-third of the nine to ten stations in the Ohio Region. No significant trend was found at the other station in the Water Resources Region. No significant trends were found in the number of one-day extreme maximum temperatures at any stations in the Ohio Region.

Key point: There is general consensus that the Ohio Region spans a transition zone between a century-long warming trend toward the north and a cooling trend toward the south. However, there have been inconsistent findings about the geographic extent and seasonality of the warming and cooling zones in the region.

2.2. Precipitation

The third NCA report presents historical annual total precipitation changes for the country and by region. Water Resources Region 5 overlays three different NCA regions, therefore the nationwide summary was reviewed (Walsh et al., 2014) rather than the regional chapters. The NCA compared changes in precipitation totals for 1991 to 2012 relative to the 1901 to 1960 average (**Figure 2.5**). A small increase in annual total precipitation of 0 to 5% was observed throughout the region, with some areas in the western portion of the Ohio Region showing a larger 5 to 15% increase and a few spots in the southeastern portion showing a potential 5% decrease.

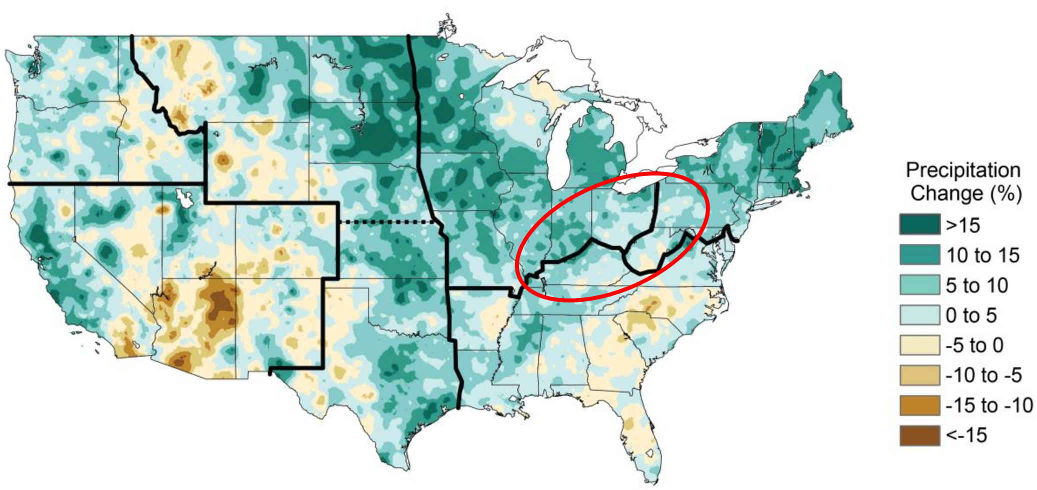


Figure 2.5. Observed changes in precipitation over the past 22 years (1991-2012) compared to the 1901-1960 average, and compared to the 1951-1980 average for Alaska and Hawai'I (Walsh et al., 2014). The red oval indicates approximate Ohio Region.

The NCA also reported on the observed change in very heavy precipitation for the U.S. Water Resources Region 5 is situated in an area with the highest percent change in very heavy precipitation from 1958 to 2012 (**Figure 2.6**), spanning the Southeast (27%), Midwest (37%), and Northeast (71%) regions. The NCA results indicate that more precipitation is falling in the Ohio Region now as compared with the first half of the 20th century, and that the precipitation is concentrated in larger events.

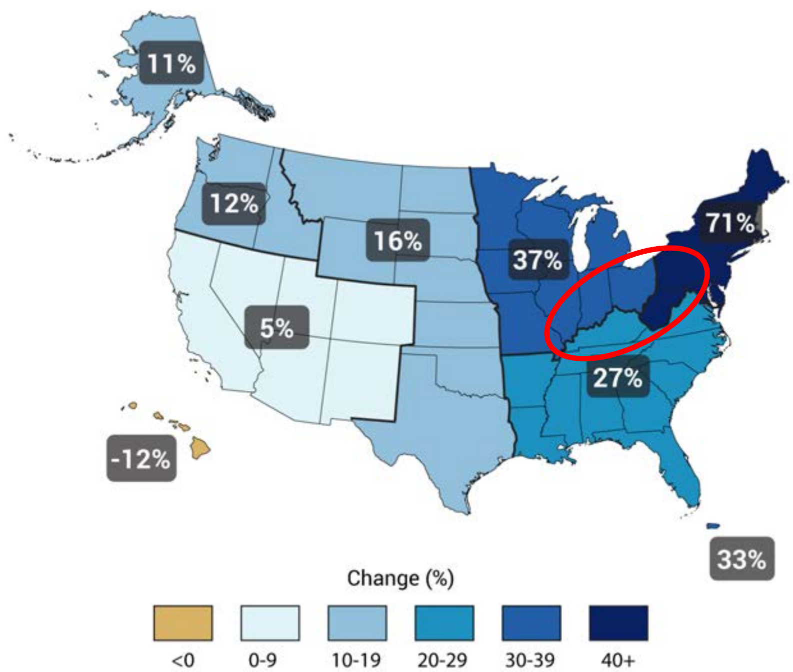


Figure 2.6. Percent changes in the amount of precipitation falling in the heaviest 1% of events from 1958 to 2012 for each region (Walsh et al., 2014). The red oval indicates approximate Water Resources Region 5.

Multiple authors have studied the trends in observed annual total precipitation for the entire U.S. and regions that include the Ohio Region. A 2011 study by McRoberts and Nielsen-Gammon 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 similar trends as the NCA report, showing a range of annual precipitation increase throughout most of the region up to 15% per century. They also report no change or a slight decrease in precipitation in the southeastern portion of the region.

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**). Their results are slightly contradictory to the McRoberts and Neilsen-Gammon and NCA report findings, possibly due to the different timeframes of comparison. They find an increase in annual precipitation throughout the Ohio Region, but with less of an increase in the northwestern portion (Ohio) and no decrease observed in the southeastern portion.

Walter et al. (2004) also found an increase in precipitation looking at records for a similar timeframe as Qian et al. (2007). The former authors report an increase of 1.76 mm/year for the entire Mississippi River watershed. Spatial variation is not provided so trends for the Ohio Region specifically cannot be determined.

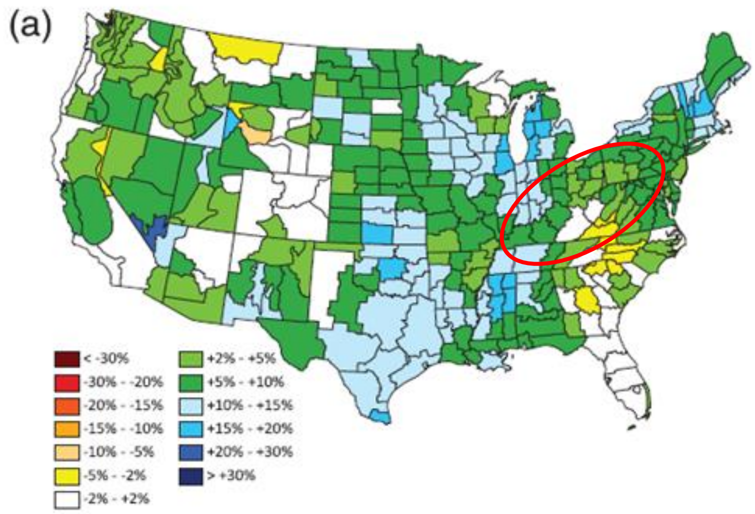


Figure 2.7. Linear trends in annual precipitation, 1895 – 2009, percent change per century. The Ohio Region is within the red oval (McRoberts and Nielsen-Gammon, 2011).

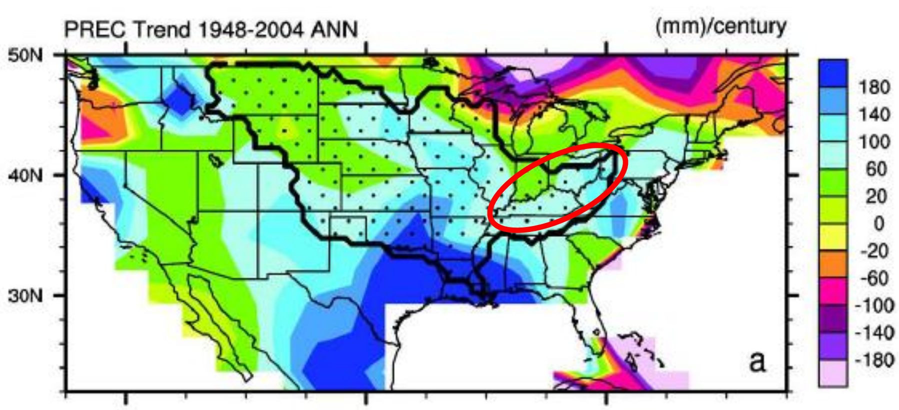


Figure 2.8. Linear trend from October 1948 to September 2004 in annual observed precipitation (Qian et al., 2007). The Ohio Region is within the red oval.

Pryor et al. (2009) performed statistical analyses 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 also reports an increasing trend of precipitation at stations throughout the Ohio Region. However, two stations show a decreasing trend and many stations did not show a statistically significant trend.

a) Annual precipitation

b) 90th percentile daily precipitation

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

d) Number of precipitation days per year

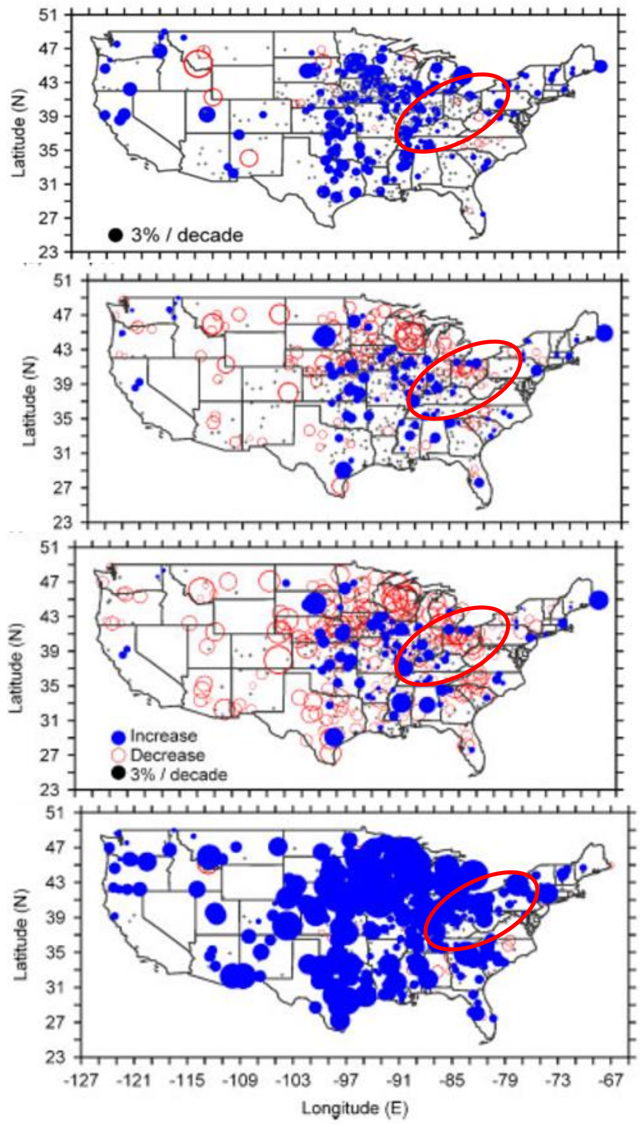


Figure 2.9. Historical precipitation trends (20th century). a.) annual totals, b.) 90th percentile daily, c.) precipitation intensity (annual total/number of precipitation days), and d.) number of precipitation days per year. Note that blue dots indicate positive trend, red circles indicate negative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

Grundstein (2009) identified statistically significant (95% C.I.) increasing trends in soil moisture for several climate division stations in the Ohio Region (**Figure 2.10**) based on annual data from 1895 to 2006. Soil moisture 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, was quantified for several of the stations.

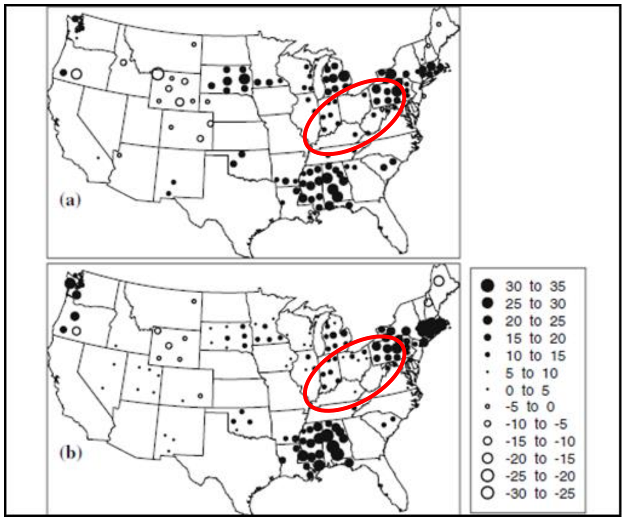


Figure 2.10. Statistically significant linear trends in (a) soil moisture index (unitless) and (b) annual precipitation (cm) for the continental U.S., 1895 – 2006. The Ohio Region is within the red oval (Grundstein, 2009).

The work of Small et al. (2006) included analysis of the Ohio Region specifically for annual and fall precipitation trends. These authors investigated for significant 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 fall (September through November) precipitation for several locations in the northeastern portion of the region (**Figure 2.11**). None of the stations showed significant trends for annual precipitation (panel b).

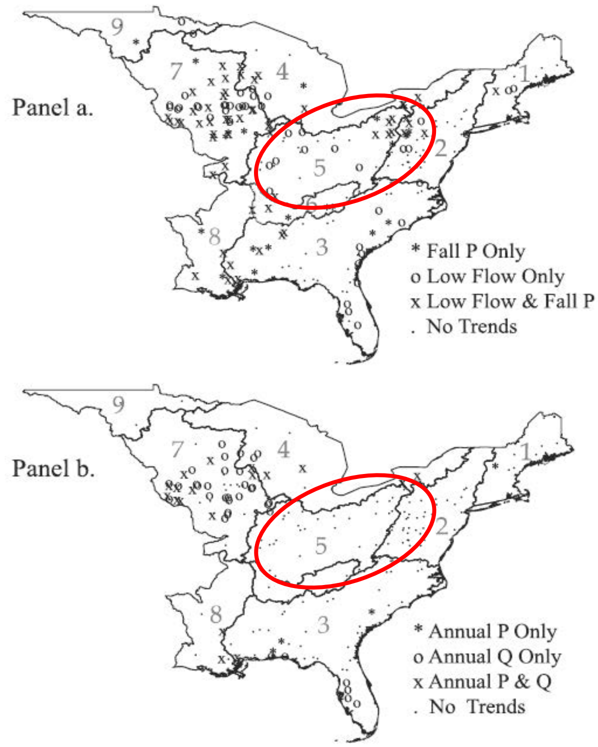


Figure 2.11. Historical trends in precipitation (P) and streamflow (Q), 1948 – 1997. The Ohio Region is within the red oval (Small et al., 2006).

In 2009 Wang et al. 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 similar period of record as Small et al. (2006) and Qian et al. (2007) (1950 – 2000). The authors identified generally positive significant trends in annual precipitation for most of the U.S. For the Ohio Region, the authors identified a mild decreasing trend in winter precipitation and mild increasing trends in precipitation for the other seasons (**Figure 2.1**). The spring trend in the northeast portion of the Water Resources Region 5 appears to lag the rest of the region, there still being a decreasing trend reported in March to May for that area. There is also a pocket of decreasing trend in Kentucky in the fall (September to November). The authors do not provide information on statistical significance of the presented observed trends.

A number of authors have studied historic trends for storm events. Palecki et al. (2005) examined historical precipitation data from across the continental U.S. They quantified trends in precipitation for the period 1972 to 2002 using NCDC 15-minute rainfall data. The Ohio Region spans three of the study's zones, making it difficult to draw conclusions about the Ohio Region based on their findings. They reported higher storm total precipitation in the southern and western portions of the Water Resources Region 5 for most seasons, finding statistically significant increases in their zone which overlaps the western portion but also covers a large area of plains outside of the Ohio Region. They reported lower storm totals in the northeast for most seasons. Pryor et al. (2009) reported a similar trend in 90^{th} percentile daily precipitation with increases toward the west of the Ohio Region and decreases toward the east (**Figure 2.9**).

Wang and Zhang (2008) used recent historical data and downscaled Global Climate Models (GCMs) to investigate changes in extreme precipitation across North America. They focused specifically on the changes in the frequency of the 20-year maximum daily precipitation event. The authors looked at both historical trends in observed data and trends in future projections. Statistically significant increases in the frequency of the 20-year storm event were quantified across the southern and central U.S., in both the recent historical data and the long-term future projections (described below). For the Ohio Region, there do not appear to be any significant changes in the recurrence of this type of storm event for the period from 1977 to 1999 compared to the period from 1949 to 1976. A portion of the region shows a small increase (0 – 25%) while a different portion shows a small decrease (0 – 25%) in frequency of occurrence.

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 Ohio 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 Ohio Region exhibited no significant trends.

Key point: A mild increasing trend in precipitation in the study region, in terms of both annual totals and occurrence of storm events, has been identified by multiple authors but a clear consensus is lacking. Results show increases in precipitation in some portions of the Ohio Region and show decreases in other portions. At least one study shows that rainfall may be concentrated in larger storms in the latter half of the 20th center as compared with the first half.

2.3. Hydrology

Studies of trends and nonstationarity in streamflow data collected over the past century have been performed throughout the continental U.S., some of which are inclusive of the Ohio Region. Xu et al. (2013) investigated trends in streamflow for many stations in the Ohio Region. This study used the Model Parameter Estimation Experiment (MOPEX) data set for the period 1950 – 2000. None of the stations in the Ohio Region show significant (at 95% C.I.) trends in streamflow in either direction.

Kalra et al. (2008) aggregated data (1992 – 2001) by Water Resources Region, and found significant (95% C.I.) trends upward at only two stations, for spring-summer flows, in the Ohio Region out of several dozen stations studied for all seasons. Further support is provided by Small et al. (2006) who also found no significant (95% C.I.) trends in annual flow at Ohio Region stream gages, using HCDC data for the period 1948 – 1997. They did, however, see an increasing trend in low flow in streams throughout the region (**Figure 2.11**).

Other authors have found trends in streamflow over the past 50 to 100 years in the Ohio Region. A recent study of unimpaired streamflow stations with data from 1951 to 2010 found five of 21 stations with increasing trends using annual records (Sagarika et al., 2014) (**Figure 2.12**). The increasing trend was seen in fall, spring, and summer at two to six stations within the Ohio Region. A decreasing trend was seen in two stations in winter and spring.

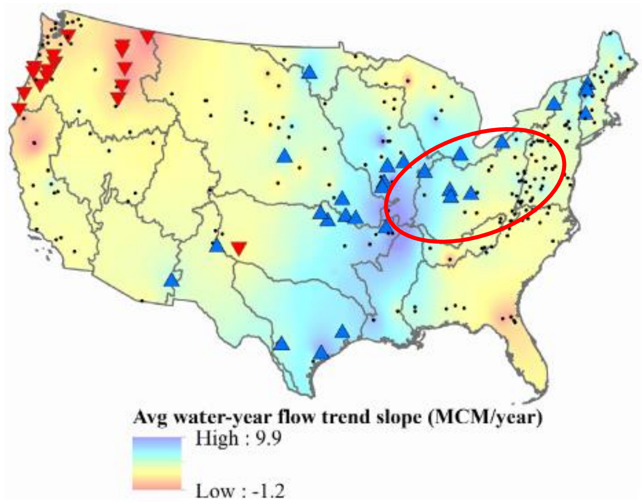


Figure 2.12. Map showing water-year trends. Upward-pointing triangles indicate statistically significant increasing trends at p = 0.10. The Ohio Region is within the red oval (Sagarika et al., 2014).

Qian et al. (2007) studied trends in precipitation, temperature, and modeled runoff throughout the Mississippi River watershed using data from 1948 to 2004. They found an increase in annual runoff of between 20 and 180 mm per century in the Ohio Region (**Figure 2.13**).

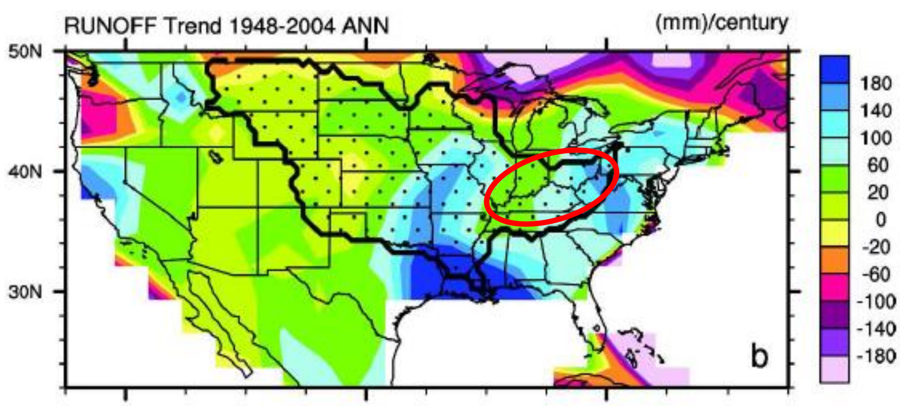


Figure 2.13. Linear trend from October 1948 to September 2004 in annual modeled runoff (Qian et al., 2007). The Ohio Region is within the red oval.

Walter et al. (2004) also found an increase in stream discharge from 1950 to 2010 for the entire Mississippi River watershed of 0.65 mm per year. The authors do not provide spatial results to determine if the increase was consistent through the Ohio Region, which is only a small portion of the entire Mississippi River watershed and could have experienced different streamflow trends than the western plains portion. These findings do, however, agree with Qian et al. both in upward direction and general magnitude (0.2 to 1.8 mm per year compared with 0.65 mm per year).

Key point: The studies reviewed were split on conclusions about streamflow trends in Water Resources Region 5 for the past 60 years. More authors indicated an upward trend in streamflow for the region than did not.

2.4. Summary of Observed Climate Findings

There is general consensus that the Ohio Region spans a transition zone between a century-long warming trend toward the north and a cooling trend toward the south. However, there have been inconsistent findings about the geographic extent and seasonality of the warming and cooling zones.

A mild increasing trend in precipitation in the study region, in terms of both annual totals and occurrence of storm events, has been identified by multiple authors but a clear consensus is lacking. Results show increases in precipitation in some portions of the Ohio Region and show decreases in other portions. Recent reports indicate that rainfall may be concentrated more in larger events now than in the past.

The studies reviewed were split on conclusions about streamflow trends in the Ohio Region for the past 60 years. However, more authors indicated an upward trend in streamflow for the region than did not.

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 Ohio 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.

Results of this review indicate moderate consensus in the scientific literature that average and extreme temperatures will increase overall in the Ohio Region, though the amount of the expected increase varies between studies. However, consensus is lacking on predicted changes in precipitation and streamflow. Both temperature and precipitation changes may vary within the region.

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 Ohio Region show a projected increase in winter and spring maximum air temperature from 2 to 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 ºC for summer temperatures and 2.5 to 3.5 ºC fall temperatures.

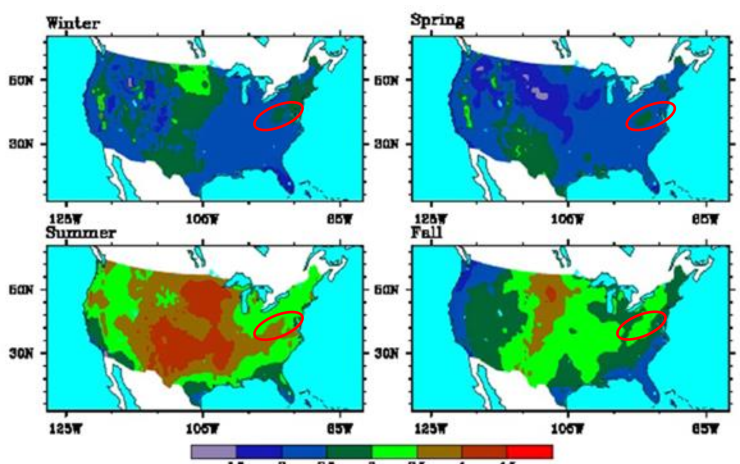


Figure 3.1. Projected changes in seasonal maximum air temperature, ºC, 2041 – 2070 vs. 1971 – 2000. The Ohio Region is within the red oval (Liu et al., 2013).

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. Portions of the Ohio Region are found in the Northeast (Pennsylvania, West Virginia, New York, and Maryland), Midwest (Ohio, Indiana, and Illinois), and Southeast (Kentucky, Tennessee, Virginia, and North Carolina) regions.

Results for all three 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 3.9 to 5.7 ºC and an expected increase in average daily minimum winter temperatures of 1.7 to 3.6 ºC. The 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.

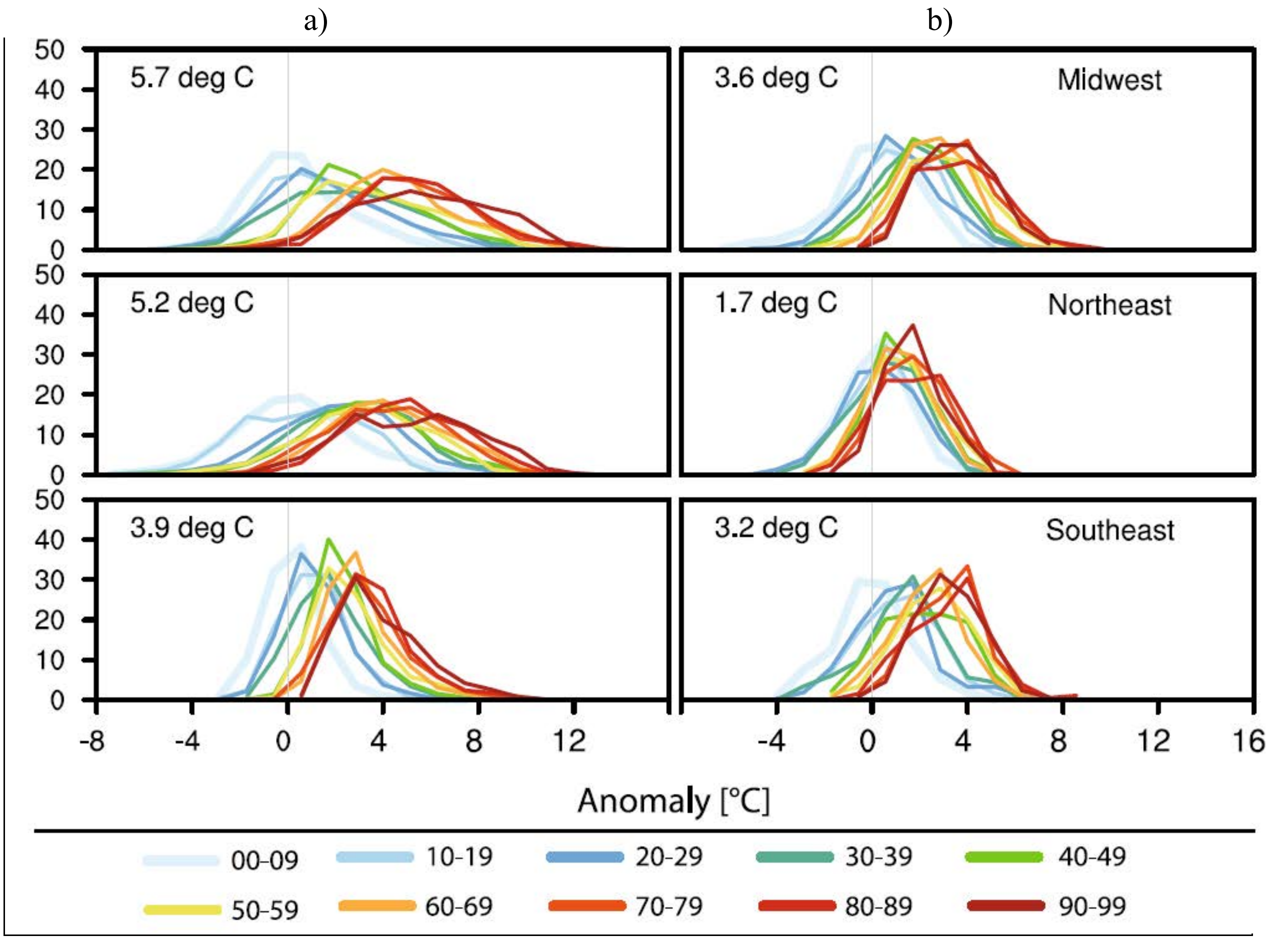
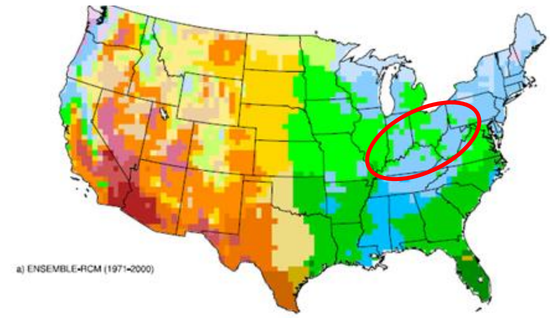


Figure 3.2. Probability distributions of GCM Projections of daily maximum temperatures for Years 2000 – 2100 by decade; Midwest, Northeast, and Southeast regions (a. average daily maximum temperature, summer months: Jun – Aug, b. average daily minimum temperatures, winter months: Dec – Feb). Colors indicate 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 Ohio Region has historically been primarily a cool and wet climate type, with some cool and moist areas. Future projections are both warmer and drier overall, showing a growth in cool and moist areas and the introduction of warm and moist as a dominant climate type, with a few areas remaining cool and wet by the period 2041 – 2070 (**Figure 3.3**).

a) Historical observed (1971 – 2000)



b) GCM projections (2041 – 2070)

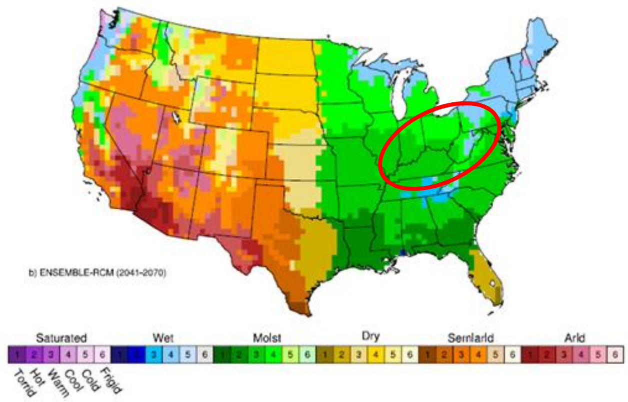


Figure 3.3. Revised Thornthwaite climate types projected by regional climate models. The Ohio Region is within the red oval (Elguindi and Grundstein, 2013).

Chien et al. (2013) examined the potential impacts of climate change on streamflow in four river basins in Illinois and Indiana, including the Wabash River watershed in Water Resources Region 5. Researchers used 9 downscaled GCMs and the A1B, A2, and B1 emissions scenarios for a total of 26 models (one GCM was not available with the A1B scenario). (A1B is "middle of the road", A2 is "worst case" and B1 is more optimistic, with a slower increase in global carbon emissions.) On average, the models predicted that mean temperature change from the period 1990-1999 to the period 2051-2060 was 3.2 ºC in the Wabash River basin, and 4.7 ºC to the period 2086-2095.

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 A1F), with a focus on summer heat wave occurrence and intensity. For the Ohio Region, comparing a 2090 planning horizon with a recent historical baseline, projections indicate a 3.5 to 6 ºC increase in three-day heat wave temperatures, with projected temperatures generally increasing from northeast to southwest. The annual number of heat wave days is projected to increase by 30 to 75 days; generally, greater increases are seen further south in the Ohio Region.

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 Ohio 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 Ohio Region. The projected duration of heat waves is variable and is projected to increase by 1 – 4 days per event through most of the region, with the area of the Ohio Region in Tennessee projected to stay the same or decrease by up to 2 per year. The projected frequency of heat wave events is also variable. Projections within the Ohio Region range from 1 to 7 additional events per year compared to the baseline period (2001 – 2004).

a) Intensity (ºC)

b) Duration (days/event)

c) Frequency (events/year)

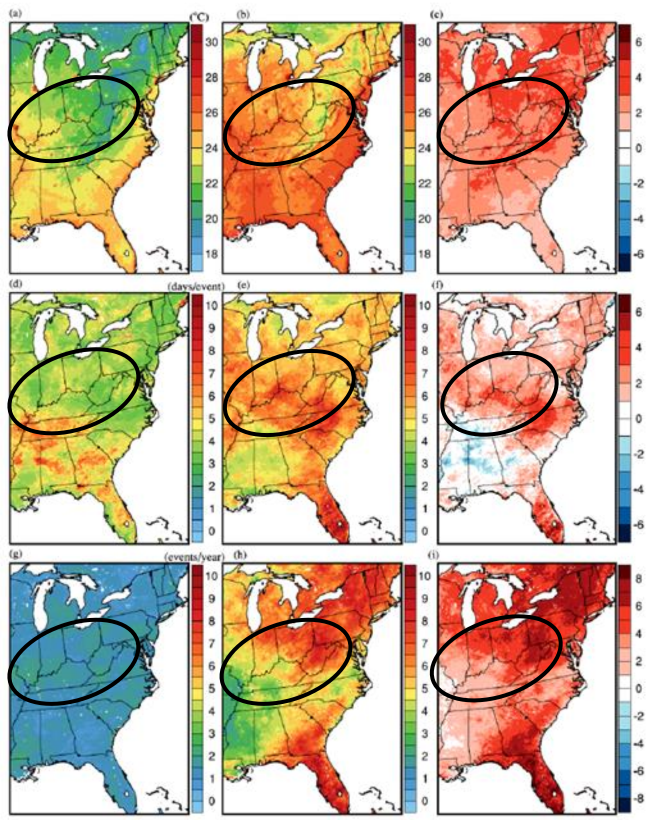


Figure 3.4. GCM Projections of heat wave patterns in the eastern U.S. (intensity, duration, frequency) for a 2058 planning horizon (compared to 2002 baseline); first column = baseline, second column = future, third column = difference between the two. The Ohio Region is within the black oval (Gao et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

The third NCA (Walsh et al., 2014) evaluated projected temperature changes based on CMIP5 (**Figure 3.5**). Emissions scenarios RCP 4.5 and RCP 6.0 show average temperature changes by the period 2071 – 2099 between 4 and 7 ºF in the Ohio Region. RCP 4.5 and RCP 6.0 are "middle of the road" emissions scenarios, most similar to B1 and A1B, respectively. The NCA also notes a projected increase in the frost-free season, defined as the number of days without freezing temperatures between spring and fall. The frost-free season in the Ohio Region may increase anywhere from 6 to 10 days (**Figure 3.6**).

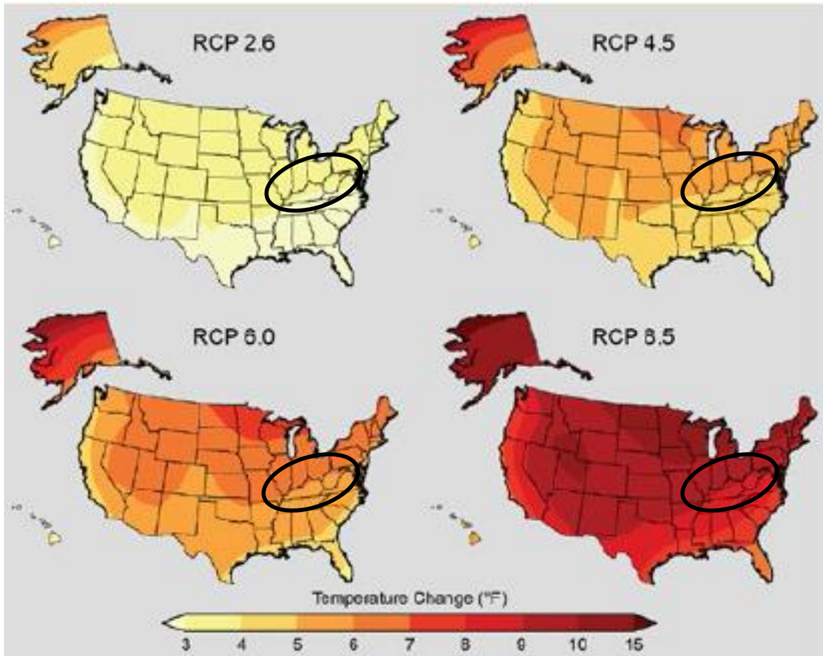


Figure 3.5. CMIP5 projections of temperature change in the United States. The Ohio Region is within the black oval (Walsh et al., 2014).

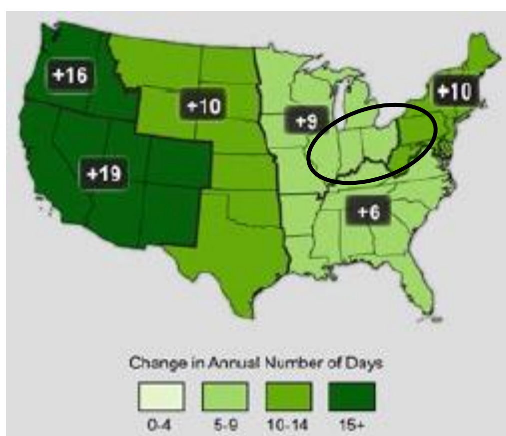


Figure 3.6. GCM projections of change in frost-free season length in the United States. The Ohio Region is within the black oval (Carter et al., 2014)

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 3.7**). In the Ohio Region, summer temperatures are projected to change very little – between -1 and 1 ºC – but fall temperatures are expected to rise by 4 to 8 ºC.

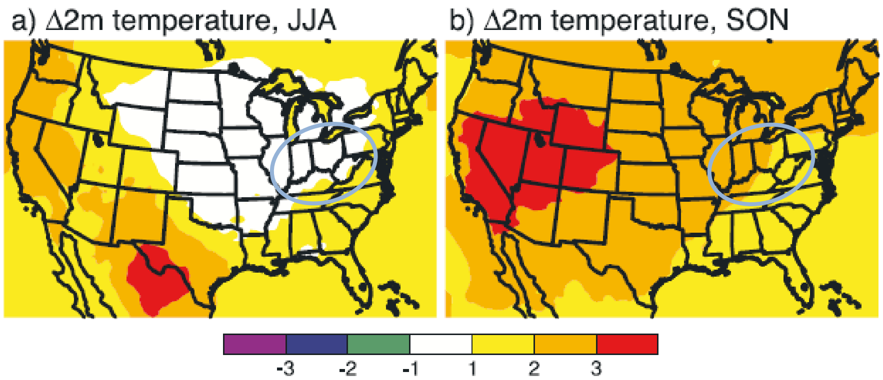


Figure 3.7 Projections of 2-meter air temperature change in the United States, ºC. Summer (June through August) projections are on the left and fall (September through November) on the right. The Ohio Region is within the blue oval (Leung and Gustafson, 2005).

Key point: Although there is a strong consensus that average and extreme temperatures will increase, the amount of projected increase varies between studies. Several studies also show considerable variation within the Ohio Region.

3.2. Precipitation

Similar to projections for the rest of the country, projections of future changes in precipitation in the Ohio Region are variable and there is a general lack of consensus in the literature. 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 140 mm per year for the Water Resources Region 5, with projections varying throughout the region. (**Figure 3.8**).

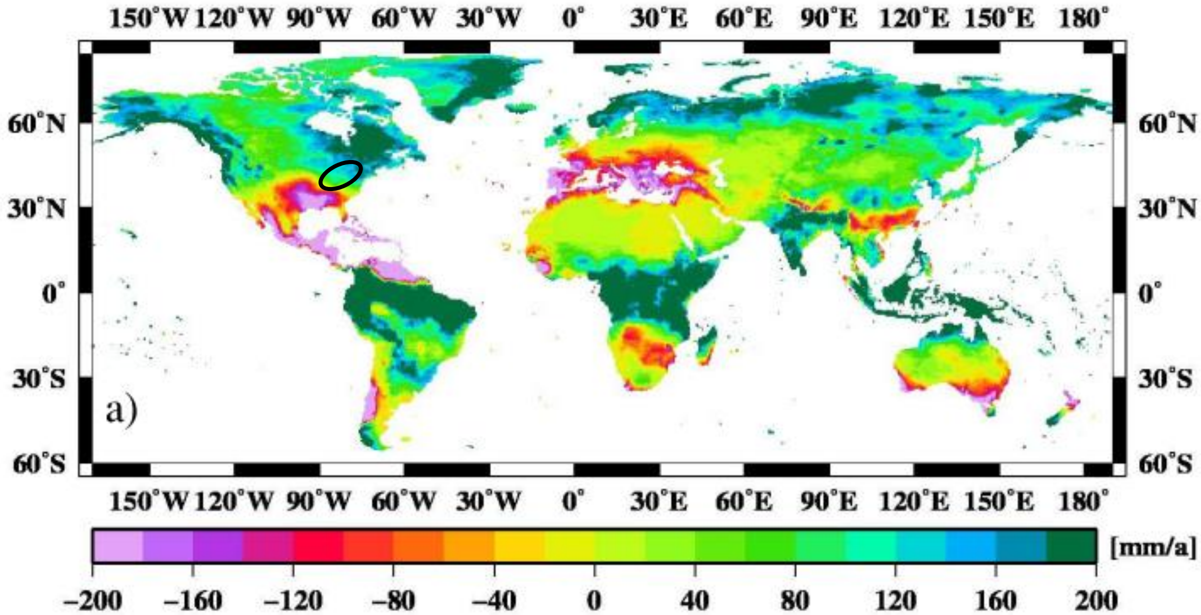


Figure 3.8. Projected (2071 – 2100) changes in annual precipitation compared to baseline, 1971 – 2000, conditions, mm/year. The Ohio Region is within the black oval (Hagemann et al., 2013).

The Liu et al. study (2013) of the U.S., described above, quantified significant increases in spring precipitation associated with a 2041 – 2070 planning horizon, relative to a recent historical baseline (1971 – 2000, centered around 1985) (**Figure 3.9**). Smaller increases are projected for winter and summer, with slight decreases projected in parts of the Ohio Region for fall.

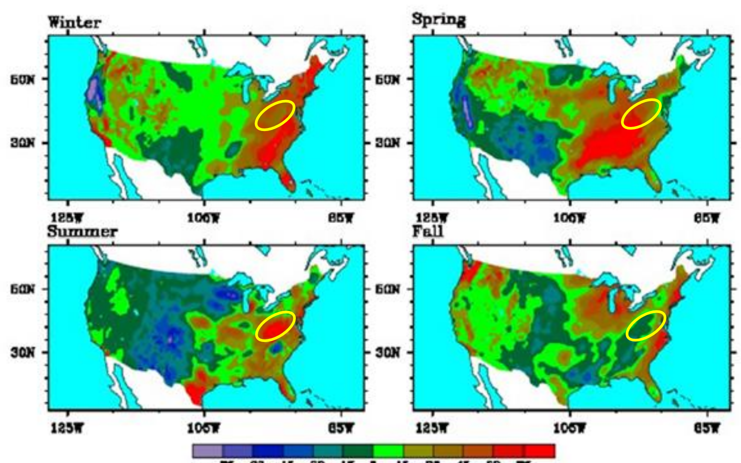


Figure 3.9. Projected changes in seasonal precipitation, 2055 vs. 1985, mm. The Ohio Region is within the yellow oval (Liu et al., 2013).

Leung and Gustafson (2005) study described above, projected changes in rainfall frequency. Within the Ohio Region, rain days are expected to increase by 1 to 4 days per year in the summer, but may decrease by more than 8 days per year in the fall (**Figure 3.10**).

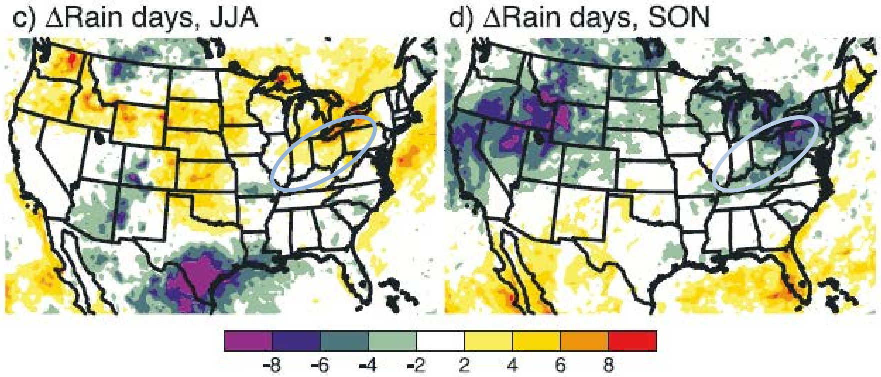


Figure 3.10. Projected changes in rainfall frequency, days per year. Summer (June through August) projections are on the left and fall (September through November) on the right. The Ohio Region is within the blue oval (Leung and Gustafson, 2005).

As described above, Chien et al. (2013) ran 26 GCMs in the Wabash River basin in Water Resources Region 5. The models predicted that annual precipitation from the period 1990 – 1999 to the period 2051 – 2060 changed by between -18.6% and 7.25%, and between -20% and 16.2% for the period 2086 – 2095.

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 an increase of up to 30% in the recurrence of the current 20-year 24-hour storm event for their future planning horizon (2050 – 2099) in the Ohio Region (**Figure 3.11**).

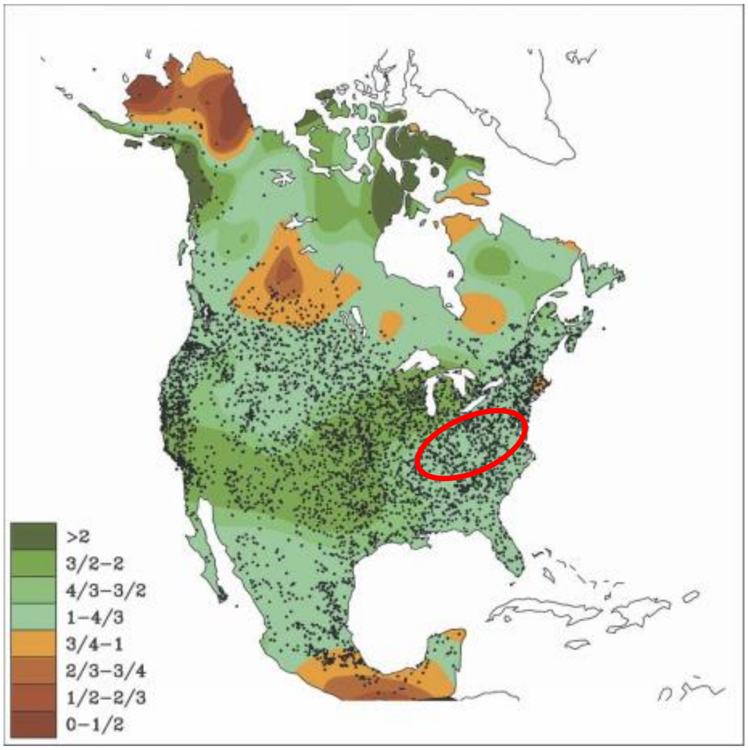


Figure 3.11. Projected risk of current 20-year 24-hour precipitation event occurring in 2070 compared to historical (1974). A value of 2 indicates this storm will be twice as likely in the future compared to the past. Black dots show the locations of stations. The Ohio Region is within the red oval (Wang 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. The study examined the magnitude of annual total precipitation (up to 200 mm per year), daily extreme precipitation events within the 95th percentile (up to 20 mm per day), and frequency of storm events (increases of up to 5 days per year), for the 2057 – 2059 planning horizon compared to current conditions (2001 – 2004). Within the Ohio Region, increases were projected overall for all three parameters, with some smaller areas projected to decrease (**Figure 3.12**).

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

b) Daily extreme storms (mm/day)

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

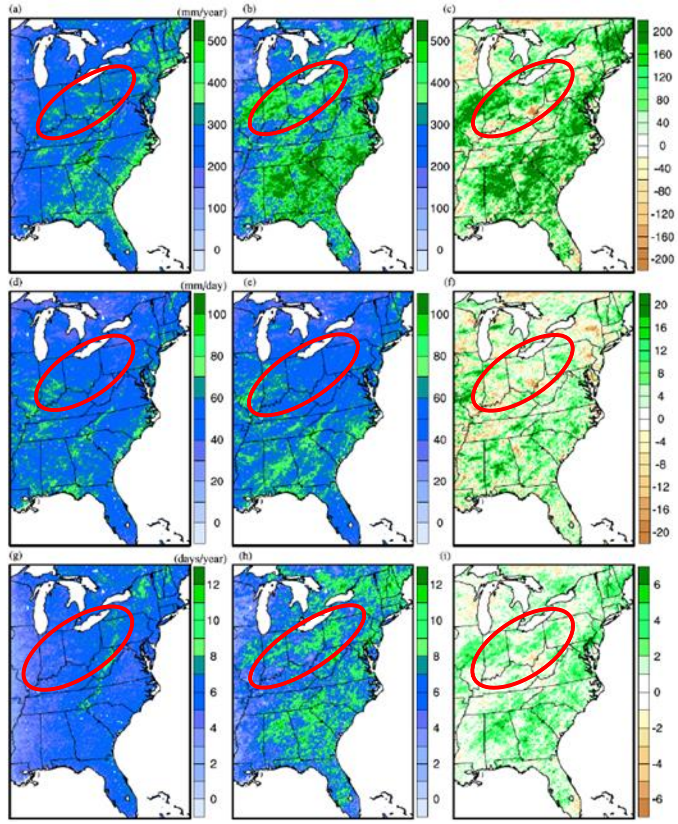


Figure 3.12. GCM projections of future precipitation patterns in eastern USA (annual extreme totals, daily extremes, frequency of events) for a 2057 – 2059 planning horizon (compared to 2001 – 2004 baseline); first column = baseline, second column = future, third column = difference between the two. The Ohio Region is within the red oval (Gao et al., 2012).

Section 3.1 noted a study by Elguindi and Grundstein (2013) modeling projected changes in the Thornthwaite climate index. This study indicated that the Ohio 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.

Lastly, the third NCA (Walsh et al., 2014) presents seasonal precipitation projections from CMIP5 (**Figure 3.13**). Projected changes in precipitation range from 0% to 10% for the RCP 2.6 scenario (rapid emissions reductions), and from 0% to 30% for the RCP 8.5 scenario (continued emissions increases), depending on the season.

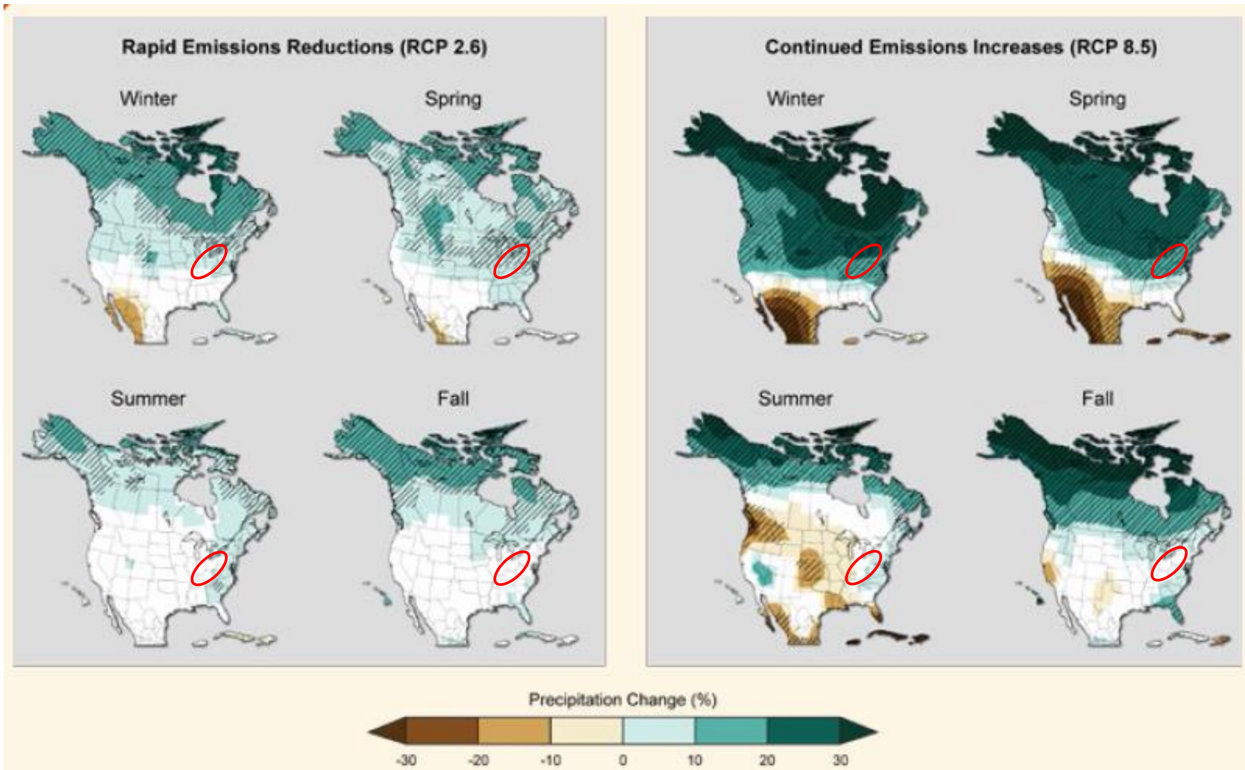


Figure 3.13. Percent change in total seasonal precipitation based on CMIP5 modeling. Stippling indicates greater than 80% agreement among the various models (Walsh et al., 2014). The Ohio Region is within the red oval.

Key point: Although precipitation is projected to increase in most studies surveyed, there are no clear trends in the literature indicating the magnitude or geographic distribution of future changes to average or extreme precipitation.

3.3. Hydrology

A number of global and national scale 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 3.14**), with projections within the Ohio Region ranging from a decrease of 25 mm per year to an increase of 25 mm per year. The authors also present more detailed results for selected 2- and 4- digit HUC regions, including the Ohio Region (**Figure 3.15**).

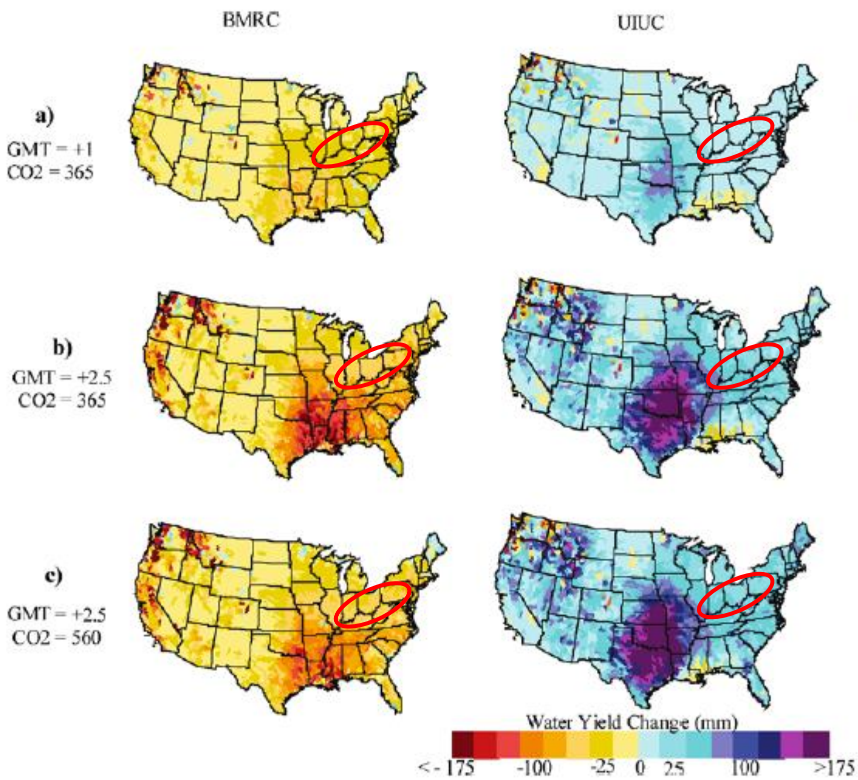


Figure 3.14. Projected change in water yield (from historical baseline), under various climate change scenarios based on 3 GCM projections. Global mean temperature increase (in ºC) and atmospheric CO_2 concentrations (ppm) are indicated on the left side for each of the three scenarios. The Ohio Region 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).

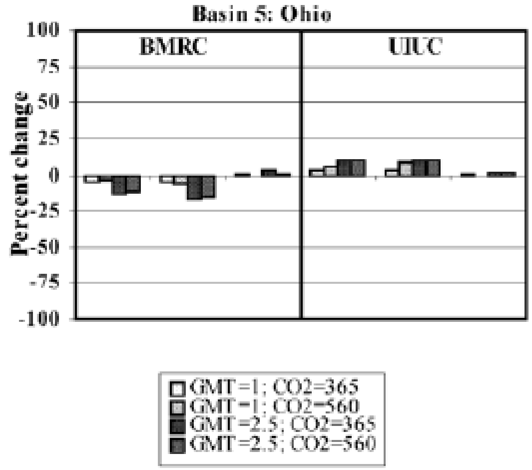


Figure 3.15. Projected percent change in water yield (from historical baseline), under various climate change scenarios based on 3 GCM projections for the Ohio Region. (Thomson et al., 2005).

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 CDMSmith (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 Ohio 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 3.16**), assuming an A2 emissions scenario. There is a small seasonal variation in projected changes in runoff, with slightly larger increases projected for winter (**Figure 3.17**).

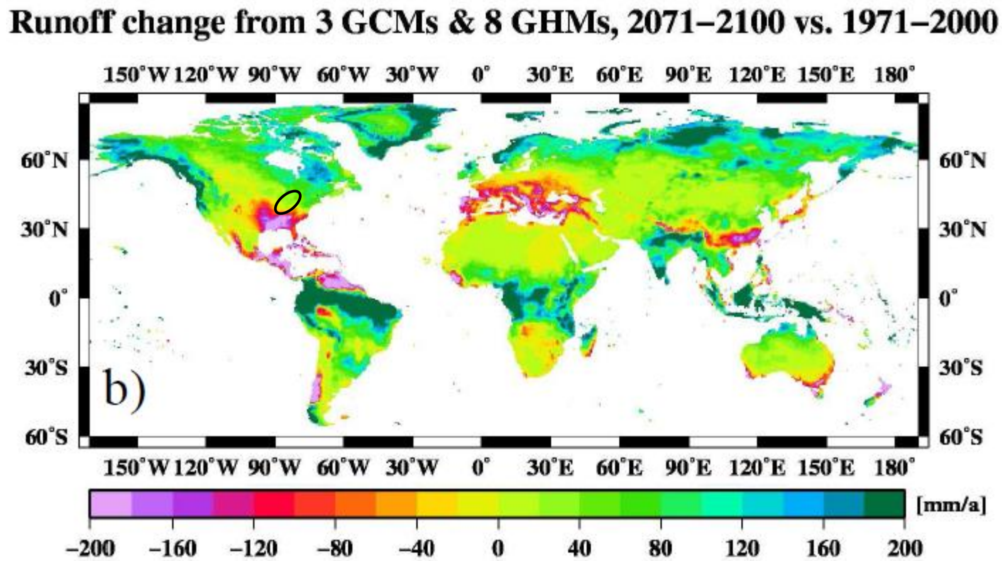


Figure 3.16. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Ohio Region is within the black oval (Hagemann et al., 2013).

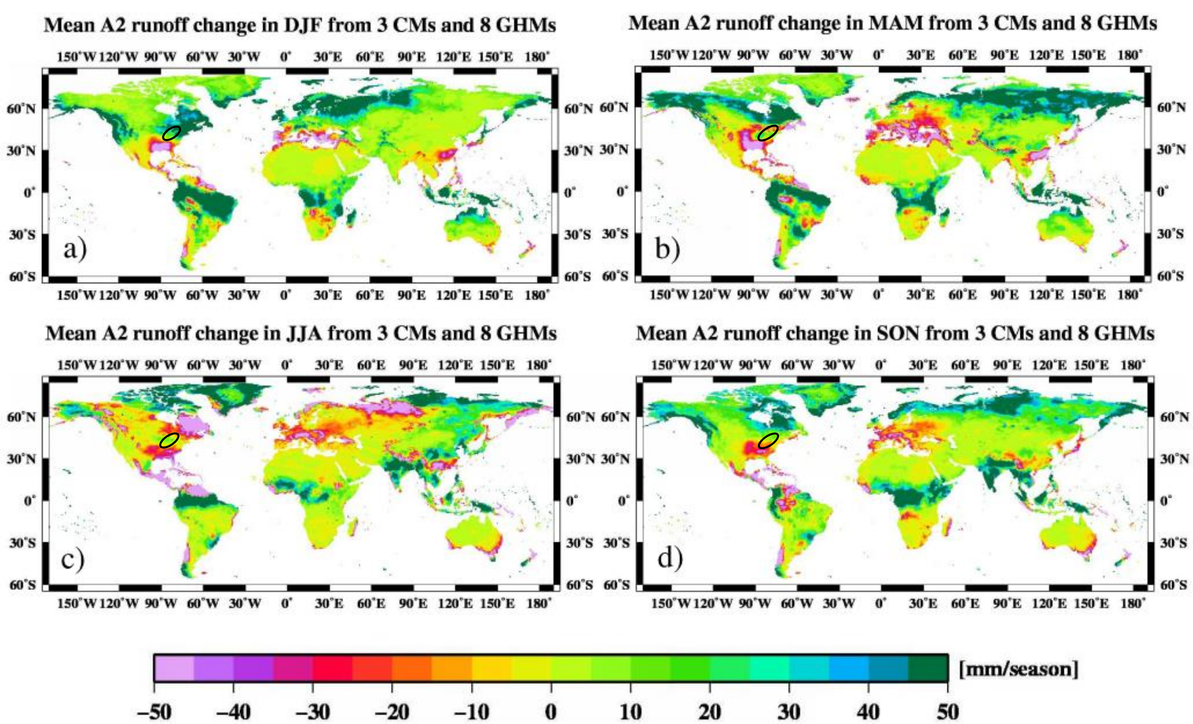


Figure 3.17. Ensemble seasonal (a. winter b. spring c. summer d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal

runoff, 2071 – 2100 vs 1971 – 2000. The Ohio Region is within the black oval (Hagemann et al., 2013).

Voisin et al. (2013) integrated climate change with a B1 emissions scenario into a series of water resources models. They linked a global climate model to several other models, including water resources, routing, land surface hydrology, and land surface models, and then downscaled the results for regional analysis. The study looked at results in the Upper Mississippi, Missouri, and Ohio River regions. (The Ohio River region includes Water Resources Region 5 as well as Water Resources Region 6, the Tennessee Region.) Results include simulated average monthly flows for the Ohio River at Metropolis, IL (**Figure 3.18**), indicating an increase in future streamflows. (Metropolis is located just downstream of the confluence of the Tennessee and Ohio Rivers; the drainage area to this location is all of Water Resources Region 5 and all of Water Resources Region 3.)

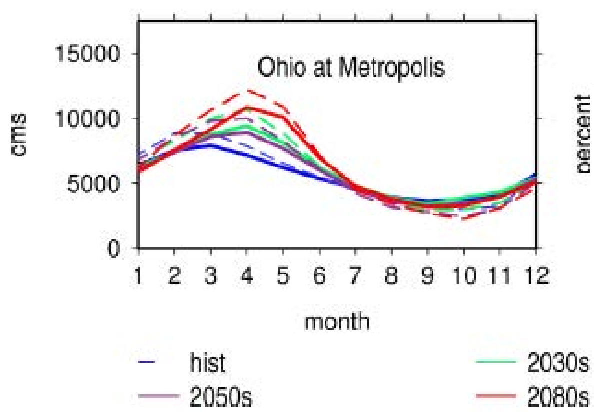


Figure 3.18. Projected average monthly natural (dashed) and regulated (solid) flows in the Ohio River at Metropolis, IL. (Voisin et al., 2013).

As described in Section 3.1, Chien et al. (2013) ran 26 GCMs in the Wabash River basin in Water Resources Region 5. Sixteen of the 26 models predicted a decrease in annual streamflow volume. On average, the models predicted that annual streamflows from the period 1990 – 1999 to the period 2051 – 2060 decreased by 41.4%, and by 44.6% by the period 2086 – 2095. The authors also noted a change in seasonal patterns, with streamflows increasing in winter but decreasing in summer (**Figure 3.19**)

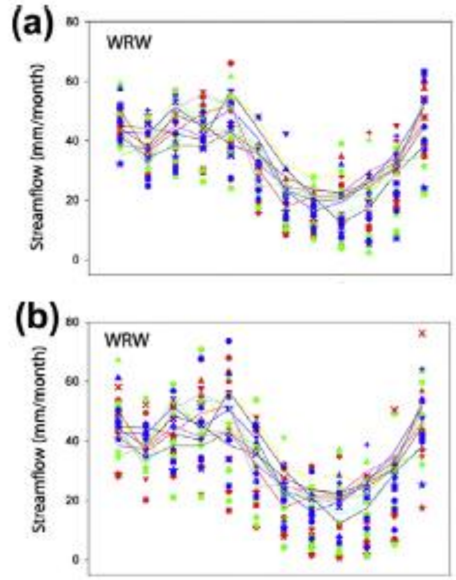


Figure 3.19. Modeled historical (solid lines, 1990 – 1999) and projected future (points) monthly streamflows for (a) 2051 – 2060 and (b) 2060 – 2095, in the Wabash River basin (Chien et al., 2013).

Key point: Projected changes in streamflow in the Ohio Region vary significantly across the peer-reviewed literature presented above.

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 8ºC by the latter half of the 21st century. The largest increases are generally projected for the summer months. 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 in the long-term future compared to the recent past.

Projections of precipitation in the study region are less certain than those associated with air temperature. Most studies project increases, but some predictions are for decreases, or for increases in some portions of the region and decreases in others. Similarly, while the projections tend toward more intense and frequent storm events than the recent past, some show a reduction in parts of the Ohio Region.

Similarly, clear consensus is lacking in the hydrologic projection literature. Projections generated by coupling GCMs with macro-scale hydrologic models in some cases indicate a reduction in future streamflows but in other cases indicate a potential increase in streamflows in the study region.

The trends and literary consensus of observed and projected primary variables noted above are summarized for reference and comparison in **Figure 3.20**.

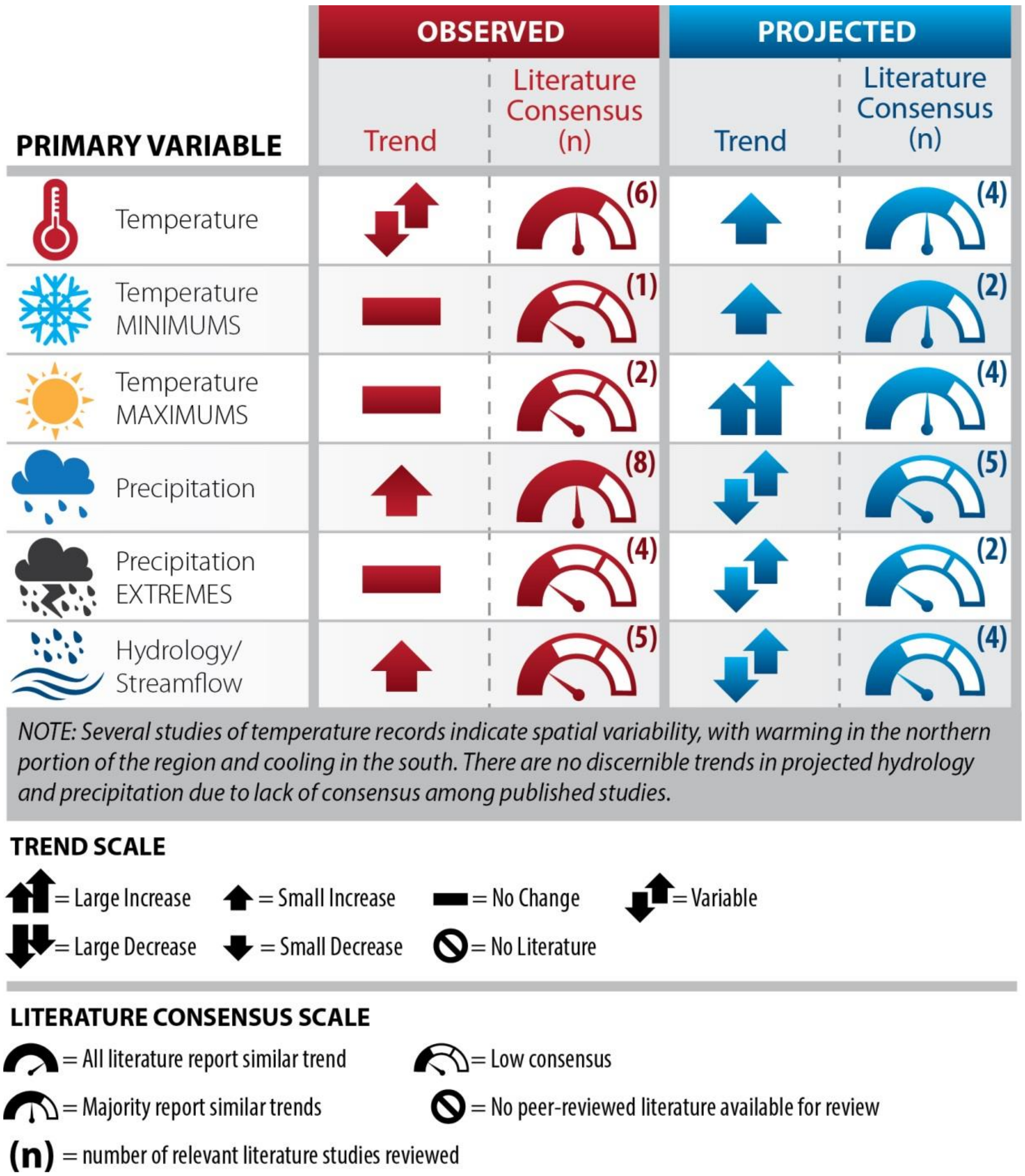


Figure 3.20. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The Ohio Region touches many states, including portions of Pennsylvania, West Virginia, New York, Maryland, Ohio, Indiana, Illinois, Kentucky, Tennessee, Virginia, and North Carolina. Climate impacts to this area may be affected by climatic conditions beyond this given region, especially by the climate impacts around the Tennessee River region. 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 Ohio Region is to maintain tributaries and over 2,500 miles of waterways. Millions of tons of cargo are transported on the Ohio River, primarily coal, chemicals, agricultural products, and petroleum products. This results in cost and emissions savings associated with bulk shipment of goods on barges rather than by truck or rail. By the end of the 21^{st} century, the frequency and intensity of large storm events and associated flooding are expected to increase. In addition, the Ohio Region may experience increases in ambient air temperature, which has implications for water levels and thus the ability for vessels to navigate the Ohio River and its tributaries.

USACE implements flood risk management projects in the region to limit flooding including dams, levees, and walls. The Ohio River region is already prone to flooding and increased precipitation is predicted for the region. 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 Ohio 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 several hydropower plants at USACE dams in the Ohio Region. By the end of the 21st century, annual precipitation and seasonal precipitation, especially in the spring (with smaller increases in the winter and summer), 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 and drought conditions, which would reduce the amount of power that may be generated by the hydropower plants.

Recreational facilities in the Ohio 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 Ohio 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 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	Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region: • 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:**
Increased Maximum Temperatures	Air temperatures are expected to increase 2-6°C in the latter half of the century with the number of heat wave days increasing as much as 75 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:**
Increased Annual Precipitation	By the middle 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:**
Streamflow Variability	Streamflow will have more extreme variability, which greatly depends on where the area of 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:**

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
Brown PJ, Bradley RS, Keimig FT (2010)	X	X																		
Carter LM, Jones JW, Berry L, Burkett JF, Murley JF, Obeysekera J, Schramm PJ, Wear D (2014)													X							
CDMSmith (2012)																X				
Chien H, Yeh PJF, Knouft JH (2013)											X			X		X				
Elguindi N, Grundstein A (2013)											X			X						X
Gao Y, Fu JS, Drake JB, Liu Y, Lamarque JF (2012)											X		X	X	X					
Grundstein A (2009)				X				X												
Grundstein A, Dowd J (2011)		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	X							
Leung LR, Gustafson GJ (2005)											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									
Palecki MA, Angel JR, Hollinger SE (2005)				X																
Pan Z (2004)	X																			
Pryor SC, Howe JA, Kunkel KE (2009)				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							
Schwartz MD, Ault TR, Betancourt JL (2013)	X								X											
Small D, Islam S, Vogel RM (2006)				X		X														
Thomson AM, Brown RA, Rosenberg NJ, Srinivasan R, Izaurralde RC (2005)											X					X				
Villarini G, Smith JA, Vecchi GA (2013)														X						
Voisin N, Liu L, Hejazi M, Tesfa T, Li H, Huang M, Liu Y, Leung LR (2013)																X				
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, Thorne P, Vose R, …, Somerville R (2014)	X			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					
Westby RM, Lee Y-Y, Black RX (2013)	X	X																		
Xu X, Scanlon BR, Schilling K, Sun A (2013)						X														

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Prepared by:

CDM Smith

www.cdmsmith.com