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National Climate Assessment

Historical Climate and Climate Trends in the Midwestern USA

WHITE PAPER PREPARED FOR THE U.S. GLOBAL CHANGE RESEARCH PROGRAM
NATIONAL CLIMATE ASSESSMENT
MIDWEST TECHNICAL INPUT REPORT

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At the request of the U.S. Global Change Research Program, the Great Lakes Integrated Sciences and Assessments Center (GLISA) and the National Laboratory for Agriculture and the Environment formed a Midwest regional team to provide technical input to the National Climate Assessment (NCA). In March 2012, the team submitted their report to the NCA Development and Advisory Committee. This white paper is one chapter from the report, focusing on potential impacts, vulnerabilities, and adaptation options to climate variability and change for the historical climate sector.

Contents

Introduction

The Midwestern USA, defined here as a region stretching from Minnesota, Iowa, and Missouri eastward to Michigan and Ohio ranks among the most important agricultural production areas of the world and contains a significant portion of the Great Lakes Basin, the largest supply of fresh water in the world with more than 20% of the global total (Quinn, 1988). The region spans a region of steep climate, geological, and vegetation gradients. Geological features transition from ancient, crystalline rocks overlain by glacial sediments in the north to a series of sedimentary rock strata covered by deep unconsolidated deposits across central sections to igneous/volcanic rock deposits within the Ozark Plateau in southern Missouri (Vigil et al., 2000). Changes in elevation are relatively minor, ranging from less than 500 feet above sea level along the Ohio River Valley to more than 1300 feet in the Superior Uplands of northern Minnesota, Wisconsin, and Michigan and across sections of the Ozark Plateau in Missouri and the Appalachian Plateau in eastern Ohio. Native vegetation varies greatly across the region, ranging from boreal forest in far northern sections to grassland across the central and western sections to hardwood forest in the south and east to savanna in between. This pattern is strongly related to soil type, which ranges from loess-dominated soils across most western and central sections of the region to alluvial soils near the major rivers to coarse-textured, highly heterogeneous soils in northeastern sections resulting from repeated glaciations to relatively old, highly-weathered soils in the southeast.

Controls on Regional Climate

The current climate of the Midwest region is chiefly governed by latitude, continental location, large scale circulation patterns, and in northeastern sections by the presence of the Great Lakes. Day-to-day and week-to-week weather patterns are generally controlled by the position and configuration of the polar jet stream in the winter and transition seasons, with somewhat less influence in the summer, when the region is also influenced by frequent incursions of warm, humid air masses of tropical origin (Andresen and Winkler, 2009).

The type and frequency of air masses moving through the westerlies is strongly dependent on the location of longwaves and the configuration of the jet stream across the Northern Hemisphere and the North American continent. Climate in the Midwest is a direct reflection of four primary airmass types from three different source regions: 1) northwestern Canada (continental polar), 2) Gulf of Mexico/southern United States (maritime tropical), 3) Hudson Bay/northeastern Canada (continental polar), and 4) northern Rockies/Pacific Northwest (maritime polar) (Shadbolt et al. 2006). Less frequently, airflow originates from the East Coast and western Atlantic and on occasion from the southwestern United States and Northern Mexico. The relative importance of the different airflow source regions varies with season.

Migratory midlatitude extratropical cyclones are an important component of regional climate, responsible for a significant portion of annual precipitation (Heideman and Fritsch 1988). Cyclogenesis is driven by upper-atmospheric circulation and cyclone tracks are dictated by the amplification and propagation of Rossby waves in the mid-latitudes. There are several principal areas of cyclogenesis in North America. Of particular importance for the Midwest are the Alberta and Colorado cyclogenesis regions, both of which are located on the leeward (downwind) side of the Rocky Mountains (Whittaker and Horn 1981). The Midwest also experiences a number of cyclones that form along the western Gulf Coast (Trewartha and Horn 1980, while approximately 20% of cyclones form within the region itself (Isard et al., 2000). Tropical cyclones, with origins in tropical and subtropical oceans, occasionally move into the region during the late summer and fall months following landfall in the southern or eastern USA and may bring widespread rainfall. Fortunately, wind or other related damage from these storms in the region is rare.

There are some existing statistical links between upper tropospheric flow and seasonal weather patterns across the region with global atmospheric teleconnection indices, but in general they are not as strong as in other regions of the USA (Hansen et al., 2001). For the El Niño/Southern Oscillation (ENSO), there is a tendency for an enhanced subtropical jet stream during negative phase (El Niño) winters across the southern United States, while the main polar branch of the jet stream retreats to a more northward than normal position across central Canada. As a result, the Midwest tends to experience weaker winds aloft, fewer storms and milder than average temperatures (Climate Prediction Center, 2005a). During positive phase (La Niña) events, jet stream flow tends to be relatively meridional across North America, with either much above or below normal temperatures and wetter than normal weather across southeastern sections of the Midwest. Statistical links with ENSO in other seasons (especially the transitional fall and spring seasons) are relatively weak or non-existent, although a tendency for wetter and cooler (drier and warmer) than normal weather has been observed over at least portions of the region during the summer months during negative (positive) phase events (Carlson et al., 1996). Recent studies suggest that the ENSO-related impacts in the Midwest may be modified on interdecadal time scales (approximately 21 year time periods) by the Pacific Decadal Oscillation (Birka et al, 2010). There are also established links with Midwestern weather patterns and the North Atlantic Oscillation (NAO). A positive NAO phase represents a deeper than normal low pressure system over Iceland and a stronger high pressure system near the Azores, whereas these systems are weaker than normal during a negative NAO phase (Rogers et al., 2004). Portions of the Midwest, especially eastern sections, tend to have above average temperatures (Climate Prediction Center,

2005) and above normal precipitation totals during winter and spring seasons with positive NAO phase (Kingston et al., 2006), although the link is not particularly strong (Rodionov, 1994; Hurrell, 1995). Leathers et al. (1991) demonstrated a link to temperature and precipitation in the USA to the Pacific North America pattern (PNA), mostly in the winter and nearby months. In the Midwest, both variables are generally negatively correlated with the PNA, which can be further related to changes in sea surface temperature in sections of the equatorial Pacific region. In a study of wintertime precipitation, Rodionov (1994) found negative correlation between the phase of PNA and precipitation totals. During the positive phase of PNA (with upper air ridging across western North America and troughing across the east), cyclonic activity across the region tends to be of northern origin and contains relatively less precipitation. During the negative phase, there is a greater frequency of cyclones of southern plains origin which tend to contain more Gulf of Mexico-origin moisture, resulting in greater precipitation totals across the Midwest (Isard et al., 2000). Rodionov (1994) also found that the position of the upper atmospheric trough across the eastern USA to be important, with a more westerly position being associated with a greater frequency of Colorado (central Rockies)-origin cyclones, and a decrease with an easterly position (and a corresponding increase in Alberta (northern Rockies)-origin) cyclones.

Finally, it is also important to consider the influence of smaller scale systems on the region's climate. Mesoscale convective weather systems in the form of clusters of showers and thunderstorms account for approximately 30% to 70% of the warm-season (April-September) precipitation over the Midwest region, with an even greater percentage during the June through August period (Fritsch et al., 1986). More recent studies have further identified links between precipitation spatial patterns and major land use boundaries in the region, with enhanced warm season convection along and near boundaries between agriculture- and forest-covered landscapes (e.g. Carleton et al, 2008).

Influences of the Great Lakes

The proximity of the Great Lakes has a profound influence on the weather and climate of northeastern sections of the region (Scott and Huff 1996). Overall, so-called 'lake effect' influences result in a cloudier, wetter, and more moderate climate in areas downwind of the lakes (e.g. Michigan, Ohio) than in areas upwind or away from the lakes. These influences are related to three major physical changes associated with air flowing across the surface of the lakes and onto nearby land surfaces: changes in friction/surface drag, changes in heat content, and changes in moisture content (Changnon and Jones, 1972). It is important to note that these modifications typically act in combination.

Arguably, the spatially most widespread lake effect-associated impact is a change in the amount and frequency of cloudiness, which in turn directly impacts insolation rates and air temperatures. In areas directly downwind of the lakes, given climatological source regions of relatively cold continental polar or arctic polar air masses in the interior sections of northern North America and the Arctic, a majority of lake-related cloudiness is associated with northwesterly wind flow across the region during the fall and winter seasons. Enhanced cloudiness results in mean daily insolation rates in that are less than 75% of rates in areas upwind of the lakes at the same latitude, ranking the region statistically among the cloudiest areas of the country (Andresen and Winkler, 2009). During the late spring and summer seasons when lake water temperatures are relatively cooler than air and adjacent land surfaces, the impact on cloudiness is symmetrically opposite, as the cooler water leads to relatively greater atmospheric stability, general low-level sinking motion, and to fewer clouds over and immediately downwind of the lakes.

Other modifications include moderated air temperatures, with a general reduction in temperatures in downwind areas during the spring and summer seasons and an increase during the fall and winter seasons. Combined with the enhanced cloudiness, daily and annual temperature ranges are also reduced. Changnon and Jones (1972) estimated that mean winter maximum and minimum temperatures in areas just east of the lakes are 6% and 15%, respectively warmer than locations upwind of the lakes, while mean summer maximum and minimum temperatures on the downwind side are 3% and 2% lower than those upwind, respectively. Climatological extreme minimum temperatures in areas within 30 miles of the shores of the Great Lakes are as much as 20°F warmer than those at inland locations at the same latitude across the state. The impact is somewhat less in the summer season, with extreme maximum temperatures in coastal areas are as much as 14°ºF cooler than those at inland locations across the state (Eichenlaub et al. 1990).

Given enough atmospheric lift and moisture, lake effect clouds may also produce precipitation. Altered precipitation patterns are among the most significant lake influences on regional climate. So-called lake effect snowfall greatly enhances the seasonal snowfall totals of areas generally within 150 miles of the downwind shores of the lakes (Norton and Bolsenga 1993). For example, Braham and Dungey (1984) estimated that 25-50% of the yearly snowfall totals on the eastern shores of Lake Michigan could be attributed to lake effect snowfall.

Current Regional Climate

General Description

As noted earlier, Midwestern climate conditions are largely determined by the region's location in the center of the North American continent. The generic Modified Koeppen classifications for the region range from Mesothermal, humid subtropical (Cwa) across far southern sections of the region to Microthermal humid continental hot summer (Dfa) across central sections to Microthermal humid continental mild summer (Dfb) across northern sections. Average annual temperature varies by about 20°F across the region (Figure 1) from less than 38°F in northern Minnesota to more than 60°F in the Missouri Bootheel. Seasonally, the greatest range in temperature across the region occurs during winter (December-February) with the least during the summer months (June- August). Seasonally, mean temperatures across the region typically peak in late July or early August and reach minima during late January or early February. Coldest overall temperatures tend to be observed in northern interior sections away from the lakes (Figure 2). Base 50°F seasonal growing degree day totals, a temperature-derived index of time spent above the 50 degree threshold, range from around 2000 in far northern Michigan and northeastern Minnesota to over 4000 in southern Missouri and Illinois.

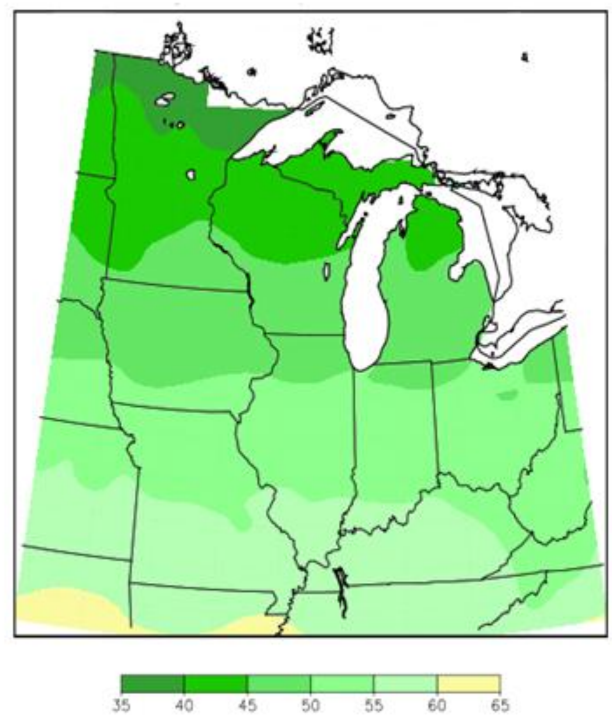

***Figure 1**. Average annual temperature (°F), 1981-2010. Figure courtesy of Midwestern Regional Climate Center.*

Average annual precipitation increases from northwest to southeast across the region (Figure 3) ranging from about 20 inches in northwest Minnesota to 47 inches in southern Missouri and along the Ohio River. Precipitation occurs in all months and seasons, but is generally greatest during the warm season and least during the winter months. The degree of seasonality increases from east to west across the region. Average summer rainfall exceeds 12 inches across most western sections, accounting for almost 50% of the annual total (Figure 4). Snowfall in the Midwest region is generally associated with either large, synoptic-scale weather disturbances or with the lake effect phenomenon, which may lead to highly varying snowfall totals over only short distances. Average annual snowfall varies from less than 10 inches in the far south to more than 200 inches in Michigan's Upper Peninsula, where seasonal snowfall totals and seasonal duration of snow cover are climatologically among the greatest of any location in the USA east of the Rocky Mountains.

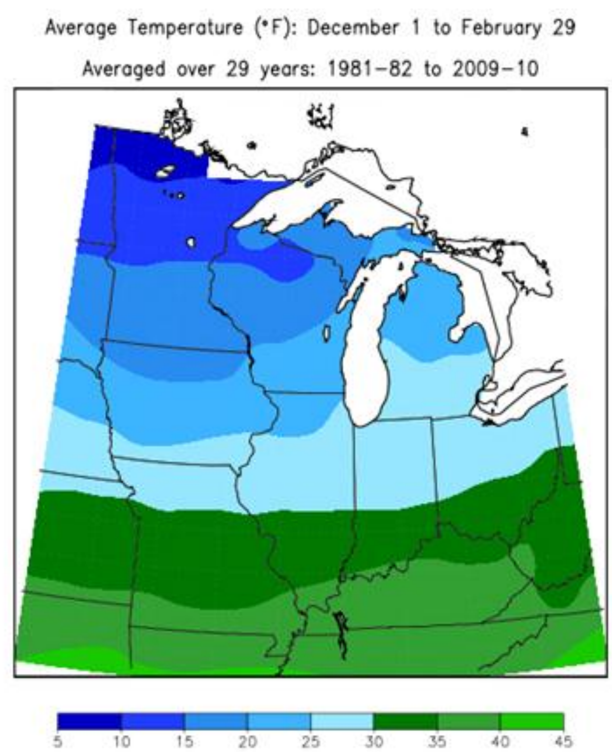

***Figure 2**. Average winter (December-February) temperature, 1981-2010. Figure courtesy of Midwestern Regional Climate Center.*

Vulnerabilities

Weather and climate have major influences on human and natural systems in the Midwest, although the overall impacts are relatively less than in other sections of the U.S. (Cutter and Finch, 2008). Agriculture is a major component of the Midwestern economy, with over $200B in farm gate value (NASS, 2012a). The region has over 400,000 farms and is responsible for a significant portion of total global corn and soybean production. The Midwest is also a major producer of fruits, vegetables, dairy and beef cattle, and pigs. Weather and climate remain among the most important uncontrollable variables involved in the region's agricultural production systems. Frequency and amount of rainfall, heat stress, pests, ozone levels, and extreme events such as heavy precipitation, flooding, drought, late spring or early fall freezes, and severe thunderstorms (high winds, hail) can seriously affect yields and/or commodity quality levels. The risks of significant losses from such events are often higher for smaller producers and for specialty crops.

The major urban centers in the region, which include Chicago, Cincinnati, Cleveland, Detroit, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis, are more sensitive to some weather and climate events due to the specific characteristics of the urban environment such as building density, land use, urban sprawl, and proximity to the Great Lakes. Extreme air and dew point temperatures can have large impacts on human health, particularly in the urban core where the urban heat island effect elevates summer afternoon temperatures and slows cooling at night. Severe storms, both winter and summer, result in major disruptions to surface and air transportation that often have impacts well beyond the region. During the winter, cities such as Chicago, Milwaukee, and Cleveland are susceptible to lake-enhanced snowfall during winter storms. Extreme rainfall causes a host of problems, including storm sewer overflow, flooding of homes and roadways, and contamination of municipal water supplies. Climate extremes combined with the urban pollution sources can create air quality conditions that are detrimental to human health.

The region serves as the nation's center for air and surface transportation; weather and climate extremes influence each form—commercial airlines, barges, trains, and trucks. Severe weather, including floods and winter storms, either stops or slows various forms of transportation for days and sometimes weeks. The Mississippi River, Ohio River, and the Great Lakes are used intensively for barge and ship transport; high and low water levels and ice cover, all determined largely by climate conditions, affect barge and ship traffic.

Human health and safety are affected by climate conditions. Temperature extremes and storms have impacts on human health and safety, including loss of lives. Tornadoes, lightning, winter storms, and floods combined annually lead to many fatalities. Over the recent 15 year interval (1996-2010), approximately 104 weather-related deaths occurred per year across the 8 Midwestern states while approximately 823 injuries occurred (www.weather.gov/om/hazstats.shtml). The occurrence of vector-borne diseases is modulated by climate conditions.

With several large urban areas, as well as miles of shorelines along the Great Lakes and other lakes, tourism is a large business sector in the Midwest. Climate conditions can greatly affect the number of tourists that decide to travel to and within the Midwest. Temperature extremes and precipitation fluctuations in the spring and summer affect fruit production, lake levels for fishing and other

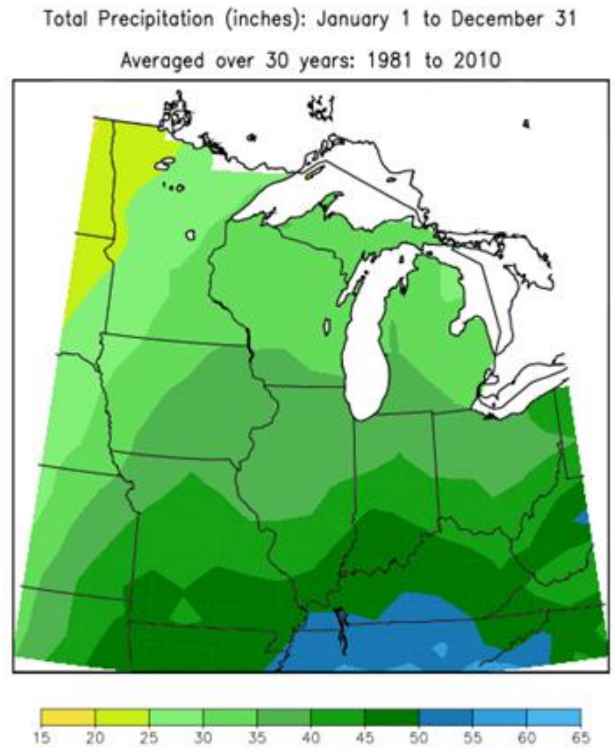

Figure 3. *Average annual precipitation, 1981-2010. Figure courtesy of Midwestern Regional Climate Center.*

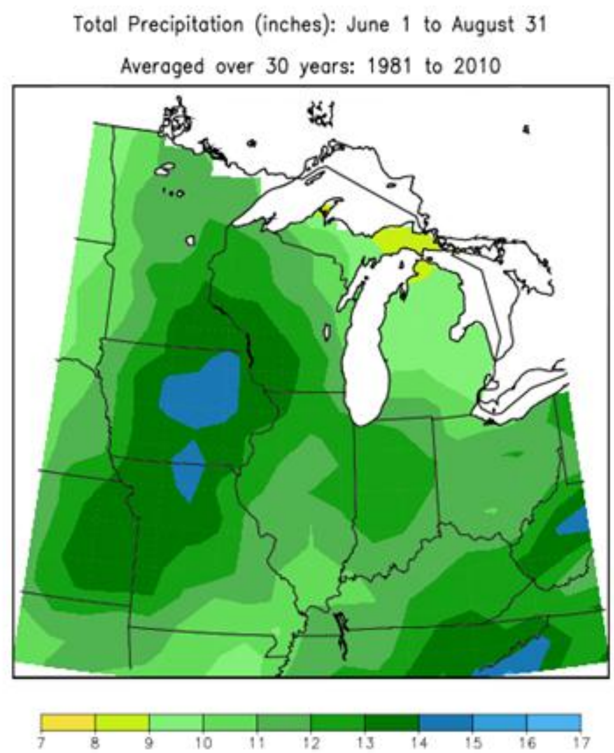

Figure 4. *Average summer (June-August) precipitation, 1981-2010.*

water activities, golf course maintenance, and state park visits, as well as attendance at sporting events and historical sites. In the winter, recreational activities such as skiing and snowmobiling are very dependent on the large annual fluctuations of snowfall and temperature across the region.

Specific major climate vulnerabilities include:

Regional Floods

Flooding is a major and important economic risk along Midwestern rivers. Some of the most costly flooding events in U.S. history have occurred along the Mississippi (1927, 1965, 1993) and the Ohio (1913, 1937, 1997) Rivers. The largest of these, the 1993 Mississippi River flood, is the second costliest flood in modern times (after Hurricane Katrina in 2005), with most of the losses occurring in the Midwest (Parrett et al., 1993). In a study across the central states of the U.S., Changnon et al. (2001) ranked Iowa first, Missouri fourth, and Illinois sixth in state losses due to flooding during the 1955-1997 period. In addition to agricultural losses and direct damage to homes and infrastructure, floods can cause national disruptions to transportation because of the region's role as the center of the surface and riverine systems. In the 1993 flood, bridges, railroads, and the river were all shut down for periods of weeks to months. A more recent flood event in eastern Iowa in 2008 led to massive flooding in Cedar Rapids, IA when the levels on the Cedar River exceeded the previous record by more than 11 feet and led to total damages on the order of $10B (Temimi et al, 2011). In response, the city created an award-winning redevelopment plan that will help mitigate against the impacts of floods in the future (http://www.cedar-rapids.org/city-news/flood-recovery-progress/floodrecoveryplans/pages/default.aspx).

Flooding along the Ohio River Valley during the winter season has been linked to upper tropospheric teleconnection patterns. La Nina (cool or negative phase) conditions in the Pacific have been shown to be significantly associated with wetter winter conditions and El Nino (warm or positive phase) with drier winters (Coleman and Rogers 2003). The Pacific-North American (PNA) teleconnection index is even more strongly linked to the Ohio River Valley winter moisture with zonal(meridional) flow being related to wet(dry) conditions. PNA mode was strongly zonal during the period leading up to the 1997 Ohio River flood as well as during the 1937 flooding event.

While many flooding events are due to persistent patterns in heavy rainfall like the ones above, another type of flooding occurs in the spring due to melting snowpacks. In the spring of 1997, record floods occurred along the Red River of the North and the Mississippi River in Minnesota and Iowa due to snowfall totals exceeding average by 150 to 250 percent (Kunkel 2003).

Severe thunderstorms

Severe thunderstorms can be accompanied by tornadoes, hail, lightning, and strong straight-line winds, causing property and crop damage and human injuries and death. Non-tornadic thunderstorms are the most frequently-occurring weather catastrophe type (as defined by the insurance industry) based on insurance losses in this region (Changnon 2010). The mean annual numbers of severe thunderstorms generally decrease from southwest to northeast across the region, with southwestern portions included in the nation's 'Tornado Alley' region of greatest severe weather frequency. Four states in the Midwest region, MO, IL, IA, and IN, ranked among the top 10 states with greatest frequency of hail catastrophes ($1M or greater damage) during the period 1949-2006, with relative rankings of 5th, 7th, 8th, and 9th, respectively (Changnon, 2008). Severe thunderstorm frequency varies by season across the region, with greatest frequency during late spring and early summer over southern sections and during mid-summer months across the far north. Most violent severe weather tends to occur during the spring.

Summer drought, heat, and excess rain

Since most agriculture in this region is rainfed, the Midwest is highly vulnerable to summer drought. As the nation's "breadbasket" and a major international food production area, droughts can have substantial economic ramifications both nationally and internationally. Large scale regional droughts were relatively common in the Midwest during the period of 1895 to 1965, but since 1965, only the summer droughts of 1988 and 2012 have had severe impacts across the entire region. Due to the potentially large areas impacted, regional droughts may contribute to large increases in world-wide commodity and food prices.

During the summer, convective events can produce excessive rain over localized areas. These events can produce flooding along small rivers and streams as well as in urban areas where drainage is not adequate. Despite typically being short-lived, these flash flooding events can leave behind much damage. Climatologically, the fraction of annual precipitation associated with the 10 largest events of the year increases from less than 0.3 across eastern Ohio to more than 0.5 across western sections of Minnesota, Iowa, and Missouri (Pryor et al., 2009a).

Heat waves

Major widespread heat waves occurred in the region during 1934, 1936, 1954, 1980, 1995, 1999, 2011, and 2012 (Westcott, 2011), The 1995 heat wave, which lasted only 4 days, resulted in over 700 fatalities in Chicago, the most deadly U.S. heat wave in decades. Maximum daily temperatures were equal to or greater than 90°F for seven consecutive days, and greater than 100°F for two days at the peak of the heat wave. Even more importantly, there was no relief at night, as nighttime minimum temperatures remained above 80°F during the hottest days. Heat waves also cause major power outages and disrupt a number of economic activities. Climatologically, the number of days with temperatures reaching 90°F or greater in the 9 largest urban areas of the region (Chicago, Cincinnati, Cleveland, Detroit, Des Moines, Indianapolis, Milwaukee, Minneapolis-St. Paul, and St. Louis) average from 7 (Milwaukee) up to 36 (St. Louis) days each year, while the number of days over 100°F range from one every two years up to an average of two per year. The factors that determine the region's climate favor occasional episodes of intense heat that are frequently accompanied by very high humidity. The heat index combines temperature and humidity to estimate how hot humans feel. Currently, southern Midwest states experience between 6 (Indiana and Iowa) and 18 (Missouri) days per year with a heat index over 95°F while northern states and states that border the Great Lakes such as Michigan and Ohio experience less than 3 days per year. Bentley and Stallins (2008) identified three predominant synoptic features associated with extreme dew point (and heat wave) events across the Midwest: 1) The development and propagation of low pressure from the high plains through the upper Great Lakes with the surface advection of low-level moisture from eastern Nebraska, Iowa, Missouri eastward into Illinois and Indiana. 2) Healthy agricultural crops and sufficient soil moisture content throughout the region and 3) Restricted low-level mixing in the boundary layer allowing near-surface moisture to become trapped. The episodic nature of these events contributes to vulnerability because the population does not become acclimated to the intense conditions as is the case in warmer regions of the country (Anderson and Bell, 2011). There is evidence that adoption of simple community adaptive responses can mitigate the impacts of heat waves (Palecki et al., 2001) and that the adverse impacts of heatwaves across the region have declined in recent decades due to improved health care, increased access to air conditioning, and infrastructural adaptations (Davis et al., 2002). In response to the 1995 heat wave, the City of Chicago put together an extreme weather operations plan that included mitigation steps for the city to take during heat waves. These were implemented during a 1999 heat wave that was nearly as hot as the 1995 event, but fatalities were far less numerous. The city has also put together an ambitious Climate Action Plan that outlines both adaptation and mitigation strategies. One strategy is an aggressive "green roof" campaign, which has resulted in the installation of seven million square feet of green roofing. Green roof tops have been shown to reduce temperatures in urban areas by as much as 5.5°F, but concerns exist that they also increase surface dew point temperatures, which lead to smaller decreases in the apparent temperature (Smith and Roebber 2011).

Winter storms

Major blizzards, snow storms, and ice storms create many problems for surface and air transportation. These in turn create numerous other impacts on the full spectrum of economic activities. Winter storms are the second-most frequent weather-related catastrophe in the region. The average annual incidence of snowstorms of 6" or greater snowfall in a 1-2 day period across the Midwest range from less than 0.5/year along the Ohio River to 1.0/year across most central sections of the region to 1.5 or more in northwestern Minnesota to more than 6/year along the lee sides of Lakes Superior and Michigan (Changnon et al., 2006). Major snowstorms are numerically most common in December in the lake effect snowbelt regions and during January and February elsewhere across the region.

Regional Climate Trends

Paleoclimate

Ideally, the search for climatological patterns and trends thus requires consistent, unbiased data from as many long term sources as possible, as the magnitude of such trends may be far less than changes experienced on an annual, daily, or even hourly basis. In general, the amount and quality of data available for climatological analysis in the Midwest region decreases quickly with time into the past. Routine instrumental observations began in during the middle 19th century across much of the region, but the number and quality of those data and as well as differences in technology with current observations before the latter half of the 19th century complicate their use in such analyses.

There are a number of paleoclimatic records in the region based on fossil, sediment cores, tree rings, and other such evidence which illustrate large shifts in climate over geologic time scales, ranging from humid tropical conditions during the Carboniferous and Devonian eras 400-300 million Years Before Present (YPB) to frigid, glacial conditions as recently as 12,000 YBP during the end of the Pleistocene era. These major shifts are thought to be the result many factors, including tectonic drift of the continents, changes in the composition of the earth's atmosphere, periodic changes in the earth's tilt and orbit around the sun (Milankovitch cycles), and catastrophic singular events such as the impact of large meteorites and major volcanic eruptions.

More substantial paleoclimatological evidence of regional changes in climate is available since the end of the last major glacial epoch about 12,000 years before present. During early portions of the Holocene era approximately 10,000 years before present (YBP), climate in the region warmed rapidly following the end of the last major glacial epoch, resulting in a relatively mild and dry climate (versus current and recent past conditions) which lasted until about 5,000 YBP. During this period, the levels of the Great Lakes fell until the lakes became terminal or confined about 7,900 YBP (Croley and Lewis, 2006) and vegetation in the region gradually transitioned from a dominance of boreal to xeric species (Webb et al. al., 1993). Beginning about 5,000 YBP, climate cooled and precipitation totals increased, possibly associated with a change in jet stream patterns across North America from mostly west - east or zonal to more north - south or meridional (Wright, 1992). The cooler, wetter climate favored the establishment of more mesic vegetation, which is among the primary vegetation types today. Given a more meridional jet stream flow (and an increase in frequency of polar and arctic-origin airmasses into the region), there is also evidence to suggest that the frequency and amount of lake effect precipitation increased relative to previous periods at about 3,000 YBP (Delcourt et al., 2002). Finally, during the late Holocene, the region experienced a period of relatively mild temperatures from approximately 800A.D. to 1300 A.D. (sometimes referred to as the 'Medieval Warm Period') followed by a period of relatively cool temperatures from about 1400A.D. until the late 19th Century (the 'Little Ice Age').

The mid-continent of North America was likely drier than present during the mid-Holocene, based on inferences from fossil-pollen data and estimates of past lake levels, and such conditions have often been explained by increases in the dominance (frequency and/or duration) of Pacific airmasses, zonal flow patterns, or enhanced westerlies (Schinker et al., 2006). The authors of this study also suggested that large-scale circulation patterns alone may not provide a full explanation of surface-moisture anomalies due to the dynamic interplay between surface conditions and atmospheric processes and that moisture availability (determined by atmospheric moisture flux and soil-moisture recycling) must also be considered.

Instrumental Record

Temperature

Although there is tremendous inter-annual variability in regional temperatures, and there are multiplepoints in time when temperature shifts occurred, mean temperatures have increased overall since 1900 (Figure 5). Based on data obtained from the CRUTEM3 data set (Brohan et al., 2006), a homogenized data set with spatial resolution of 5 × 5°, annual mean temperature over the Midwest increased by approximately 0.059°C per decade during 1900-2010 period, increased 0.12°C per decade for the period 1950-2010, and 0.26°C per decade for the period 1979-2010. The trends and temporal patterns are somewhat similar to overall global trends which include an increase in mean temperature of about 0.8°C since 1850 (IPCC, 2007).

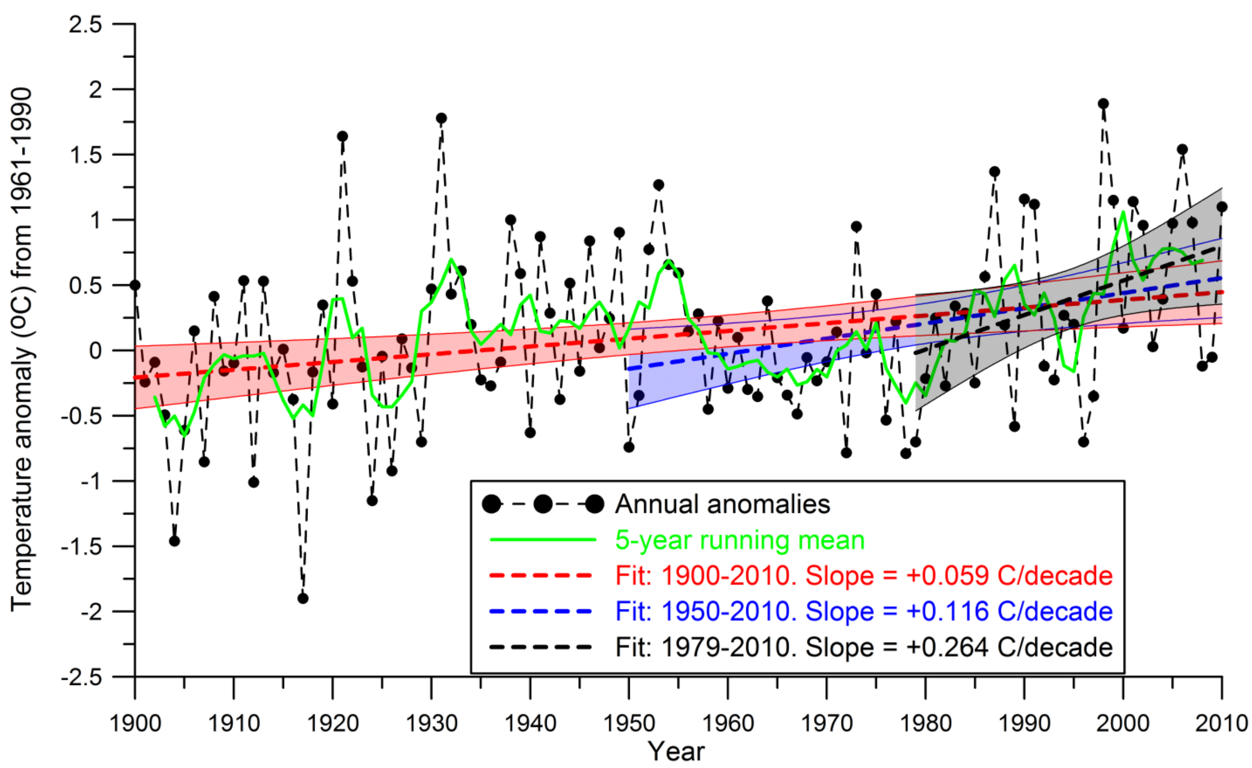

***Figure 5**: Annual temperature anomalies for the Midwest from the CRUTEM3 data set. The anomalies are relative to 1961-1990. The data have a spatial resolution of 5 x 5° thus the domain used to construct this figure is 35°N to 50°N and 95°W to 80°W. Data were downloaded from http://www.cru/uea.ac.uk/cru/data/temperature/#datdow. Also shown is a 5 year running mean and linear fits to the annual data for 1900-2010, 1950-2010 and 1979-2010. The shading represents the 95% confidence intervals on the fits. The slopes of the region-wide trend estimates are expressed in °C per decade and are shown for 3 time periods; 1900-2010, 1950-2010, and 1979-2010 (Pryor and Barthelmie 2011a).*

Precipitation

Overall, annual precipitation across the Midwest generally decreased from the late 1800's through the dust bowl years of the mid 1930's, followed by a general increasing trend beginning during the late 1930s that continues to the present (Groisman and Easterling, 1994; Andresen, 2012), with an overall increase in precipitation during the past century. In general, annual precipitation has increased since 1895 by 2.5 – 5.5 inches, or a range of 5-15%. The 1930's were the driest decade on record regionally, while the recent 2-3 decades were the wettest (Lorenz at al., 2009b). The increase in precipitation since the 1930's has occurred both as a result of an increase in the number of heavy precipitation events (Kunkel et al., 2003) as well as overall increases in the number of wet days and multiple wet day events. In northeastern sections of the region, for example, the number of both single and 2-day consecutive wet day frequencies has increased more than 30% between the 1930s and the present (Andresen, 2012; Grover and Sousounis, 2002). Climate modeling results suggest that wetland drainage across large areas of the region over time has resulted in significant changes in the regional energy (sensible and latent heat flux) and radiation (long-wave radiation) budgets, particularly from May to October. As a result, the climate has become warmer, and convective precipitation has decreased during summer months (Kumar et al., 2010).

Seasonality of Temperature, Precipitation Changes

The increases in temperature and precipitation during the past century have not been consistent across season or time of day. Trend statistics for precipitation and mean temperature by state and season are given in Tables 1a and 1b for the periods 1895-2010 and 1981-2010, respectively. While changes in precipitation and mean temperature have been generally consistent during both time frames across states within the region, a relatively greater proportion of the regional warming occurred during the winter and spring seasons during the 1895-2010 period, and during the summer and fall seasons during the last 3 decades. In some sections of the region (e.g. IL, IN, MI) mean summer temperatures actually decreased with time, possibly due to landscape cover type changes associated with intensified agriculture over time (Pan et al., 2004). Just as importantly, much of the warming in recent decades has been associated with warmer nighttime (i.e. minimum) temperatures (Lorenz et al., 2009a; Easterling et al., 1997). The latter results are consistent with the results of Zhang et al. (2000), who found largest increases in temperature across southern Canada between 1900 and 1998 had occurred in winter and early spring.

	Precipitation (in./year)					Temp (ºF/year)				
1895-2010	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
IA	0.040***	0.002	0.017***	0.020***	0.000	0.009**	0.014	0.014**	0.004	0.001
IL	0.039***	0.004	0.012	0.012*	0.010	0.004	0.005	0.011*	-0.001	-0.001
IN	0.049***	0.001	0.015*	0.020***	0.012	0.003	0.006	0.010*	-0.005	-0.001
MI	0.038***	0.003	0.004	0.016***	0.016***	0.001	0.008	0.007	-0.006	-0.008
MN	0.029***	0.003	0.008	0.008	0.010*	0.014***	0.022*	0.015**	0.008*	0.006
MO	0.027	0.005	0.010	-0.004	0.015*	0.005	0.008	0.010*	0.002	-0.004
OH	0.034***	-0.002	0.011*	0.008	0.015***	0.008***	0.011	0.014***	0.002	0.003
WI	0.022**	0.002	0.005	0.012*	0.003	0.009***	0.019*	0.013*	0.002	0.002
AVG	0.035	0.002	0.010	0.012	0.010	0.007	0.012	0.012	0.001	0.000

	Precipitation (in./year)					Temp (ºF/year)				
1981-2010	Annual	Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall
IA	0.075	0.031	0.044	0.079	-0.081*	0.007	-0.031	-0.010	-0.006	0.062
IL	0.078	0.029	0.053	0.051	-0.053	0.036	0.014	0.046	0.020	0.050
IN	0.196*	0.073	0.066	0.069	-0.011	0.033	0.005	0.058	0.016	0.040
MI	0.000	0.040	0.033	0.006	-0.076**	0.041	0.036	0.018	0.030	0.081***
MN	0.016	0.028**	0.023	-0.025	-0.003	0.028	0.007	-0.037	0.005	0.122***
MO	0.014	-0.007	0.073	0.013	-0.065	0.038	0.020	0.035	0.045	0.043
OH	0.222**	0.084***	0.066	0.057	0.017	0.042*	0.008	0.060	0.048	0.047
WI	-0.005	0.033	0.035	0.033	-0.104 ***	0.037	0.030	-0.005	0.015	0.100***
AVG	0.075	0.039	0.049	0.036	-0.047	0.033	0.011	0.021	0.022	0.068

Table 1 a, b. *Yearly trends in precipitation (inches/year) and mean temperature (ºF/year) for a) 1895-2010 and b) 1981-2010 periods. Asterisks denote significance at 0.10 (*), 0.05(**), and 0.01(***) levels respectively.*

Seasonal differences were also noted for regional precipitation trends. The majority of the increase in precipitation since the 1930's has occurred during spring, summer, and fall seasons, accounting for over 90% of the increase in the overall annual precipitation. In contrast, during the most recent three decades trends for fall precipitation were negative for all states except OH, while trends for almost all other seasons and states were positive. There were also relatively larger increases in winter precipitation (0.039 inches/year on average).

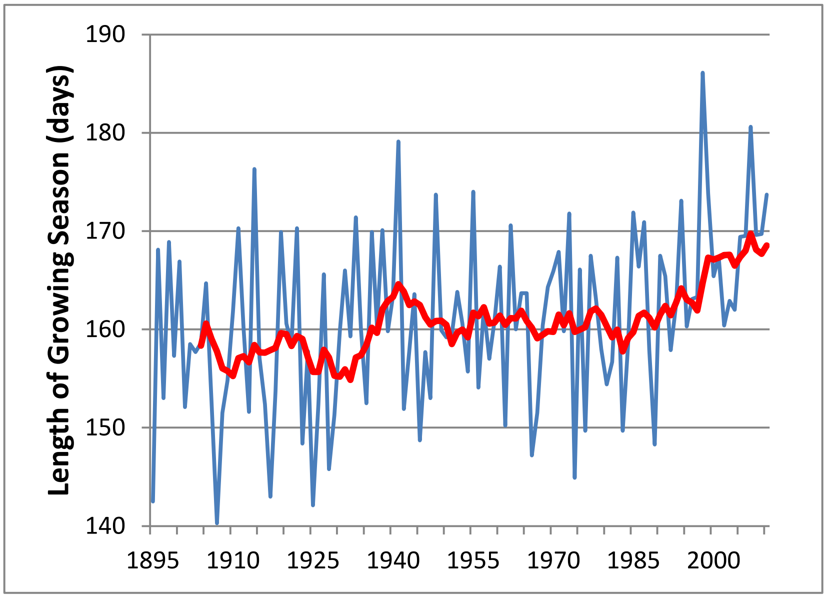

***Figure 6**: Length of the growing season, defined as the period between the last occurrence of 32° in the spring and first occurrence of 32°F in the fall. The red line is a 10-yr moving average. Based on data from the National Climatic Data Center for the cooperative observer network and updated from Kunkel et al. (2004).*

Growing Season

The growing season length has increased across the region during the past several decades. In an earlier study, Skaggs and Baker (1985) concluded that frost free growing season length had increased an average of 14 days between 1899 and 1992. Similarly, Robeson (2002) found the length of the growing season in Illinois to have increased by nearly one week 1906-1997, much of the change the result of earlier last spring freezes. The date of the first fall freeze in the study was virtually unchanged during the study period. These regional trends are consistent with larger, hemispheric trends (Linderholm, 2006) and have been confirmed with satellite data depicting phenological changes over large areas Zhou et al. (2001). Averaged across the 8-state region over time (Figure 6), the frost free growing season length averaged about 155-160 days prior to the 1930s, then increased to around 160 days during the 1930s into the 1980s. Since the 1980s, it has continued to increase and now averages about a week longer than during the 1930s to 1980s period. In some contrast to the findings of Robeson (2002), the increase in length across the region is the result of both earlier last spring freezes and later first fall freezes.

Longer growing seasons allow production of longer season crop types and varieties, many of which have potentially greater yields. This has resulted in profound changes in cropping systems and mixtures across the region, especially across northern sections (Parton et al., 2007). In North Dakota, for example, the number of planted acres of corn and soybean across the state increased from 300,000 and 200,000 in 1980 respectively to 3,200,000 and 4,550,000 respectively in 2012 (NASS, 2012b). Longer growing seasons have also resulted in changes to the typical crop production calendar. From 1981-2005, corn planting dates in major U.S. production areas advanced about 10 days earlier, with a concurrent lengthening of the period from planting to maturity of about 12 days and an average increase in corn yields of 0.9 – 2.2 bu/acre for each additional day of earlier planting (Kucharik 2006; Kucharik, 2008). While shifting climate played a major role in these changes, changes in agronomic technology such as improved cultivars and increasing capacity of agricultural implements were also found to be important (Sacks and Kucharik, 2011). Not all of the impacts associated with changing seasonality have been positive. Changing seasonality has also advanced the dates at which overwintering perennial natural and agricultural crops break dormancy, which leaves them more vulnerable to subsequent freezing temperatures. While the last freezing temperatures of the spring season have tended to also come earlier with time across the region, the rate of change is not as rapid as the date of initial greenup, which results in an overall longer period of freeze risk for many fruit crops such as cherries and apples (Winkler et al., 2012).

Ice Cover

Among the impacts resulting from the recent warmer winter temperatures is a reduction in the amount and duration of ice cover on lakes across the Midwest region including the Great Lakes. This trend is well documented in previous studies by Magnuson et al. (2000) and Magnuson et al. (2010) which suggest an increasingly later onset of first ice cover on inland lakes in the region by 6-11 days since the middle 19th century and an increasingly earlier breakup of ice in the spring from 2-13 days during the same period. While available for a much shorter period of record, satellite imagery provides a more comprehensive estimate of ice cover changes on the Great Lakes as shown in Figure 7 for the period 1973-2009 (Wang et al., 2010). Average ice cover area across the Great Lakes during this period peaked during the late 1970's before decreasing by more than one half during the 1-2 decades of record. These numbers are in good agreement with the results of Duguay et al. (2006), who documented similar decreases in ice cover duration as well as trends towards earlier lake ice break up in the spring season during the period 1951-2000 in nearby areas of Canada.

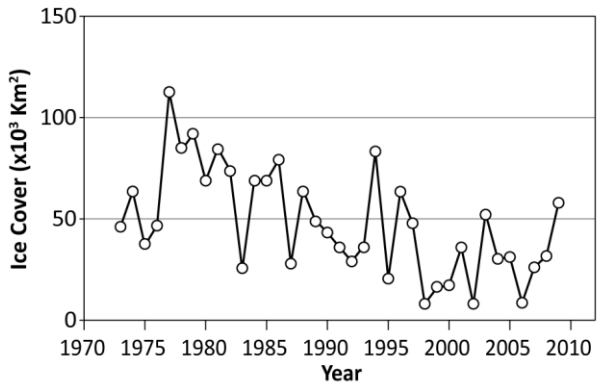

Figure 7*: Time series of annual average ice area coverage on the Great Lakes. From Wang et al. (2010).*

Snowfall

Trends in seasonal snowfall across the Midwest during recent decades have varied by location. Average seasonal snowfall totals plotted for the thirty-year periods 1961-1990 and 1981-2010 in Figures 8a and 8b reveal some interesting patterns. In general, mean seasonal snowfall decreased across far southern sections of the region between the two periods, remained about the same across central sections, and increased across the north, especially in areas downwind of the Great Lakes. These trends are consistent with a reduction in the number of synoptic snowfalls and an increase in the frequency of lake effect snowfalls, possibly both linked with milder wintertime temperatures and the warmer, more open waters of the Great Lakes during the past few decades (Burnett et al., 2003). Similarly, temporal trends in the frequency of major snowstorms varied widely across the region during 1901–2000, with downward trends across southern sections and upward trends across the north (Changnon et al., 2006). In terms of snow cover, Dyer and Mote (2006) found minimal changes in North American snow depth through January, with regions of decreasing snow depths beginning in late January and continuing through March and into April, implying an earlier onset of spring melt. As noted by Andresen (2012) in sections of the Great Lakes region, there are distinct connections with snow cover and trends

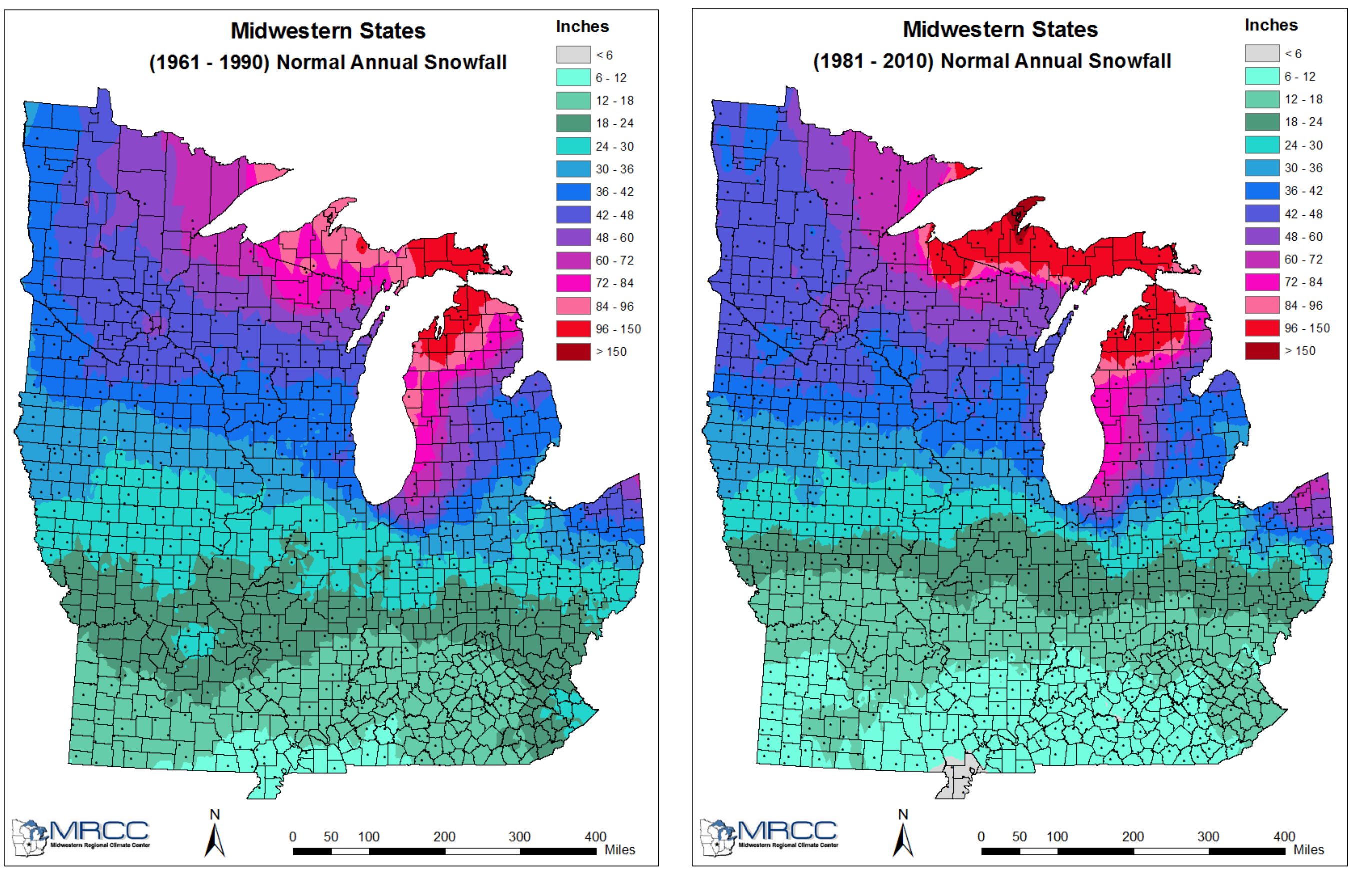

Figure 8*. Mean seasonal snowfall (inches) across the Midwest for a) 1961-1990 (left) and b) 1981-2010 (right) periods. Figures courtesy of Midwest Regional Climate Center.*

towards milder temperatures, with recent observations suggesting that milder winter temperatures are melting snow more quickly than in past decades even though more snow is falling.

Cloudiness

Given trends toward more annual precipitation and days with precipitation in recent decades, it is also logical to assume that cloudiness in the region has increased as well. Unfortunately, quality cloudiness and solar radiation observational records in the region are scarce. In an examination of observations obtained from U.S. military installations between 1976 and 2004, Dai et al. (2006) concluded that total cloud cover over most of the contiguous United States has increased during the period, including changes at Midwestern locations in the range of 1-3% per decade. While these findings are limited by the relative lack of data available for the study, they are consistet with the observed reduction in U.S. surface solar radiation from 1961 to 1990 reported by Liepert (2002) and average global decreases of 2.7% per decade noted by Stanhill and Cohen (2001). Besides the increasing frequency of precipitation, Minnis et al., (2004) attributed at least part of the recent increase in cloudiness to increases in high level cirriform cloudiness across the Midwest associated with jet aircraft contrails.

Humidity

The search for trends of humidity is complicated by the relative lack of quality observations and past changes in sensor technology. Most existing studies suggest that humidity levels across the Midwest have increased in recent decades. For example, Gaffen and Ross (1999) reported positive trends of both relative and specific humidity across the USA, although the relative humidity trends were weaker than specific humidity trends. Dai (2006) found relatively large changes of 0.5-2.0% per decade in surface relative humidity observations from 1976 to 2004 across the central USA while Changnon et al. (2006) reported a steady increase of the frequency of high dew point days during the period 1960-2000. In a very recent study, Schoof (2012) found increases in maximum dew point temperatures during the summer season across the Midwest which partially offset flat or decreasing maximum air temperatures and a wide variance in trends of resulting apparent temperatures. A likely cause of higher dew point temperatures during the growing season is the significant increase in plant density from earlier decades, which greatly enhances the transpiration of water from the soil to the atmosphere (Changnon et al. 2003).

Wind

Similar to humidity, there is a relative paucity of long-term records of near-surface wind speeds, which when coupled with inconsistencies manifest in different data sets, the highly uneven spatial coverage of surface observing stations, and issues pertaining to local land-cover change in the proximity of the observational sites, confound accurate assessment of wind climates and the presence or absence of temporal trends. In an analysis by Pryor et al. (2009b) based on North American Regional Reanalysis (NARR) 8-times per day output, 10m wind components at a resolution of ~ 32 × 32 km were extracted for 1979-2006 and analyzed to quantify mean temporal trends in a range of metrics of the wind speed distribution. In general, there

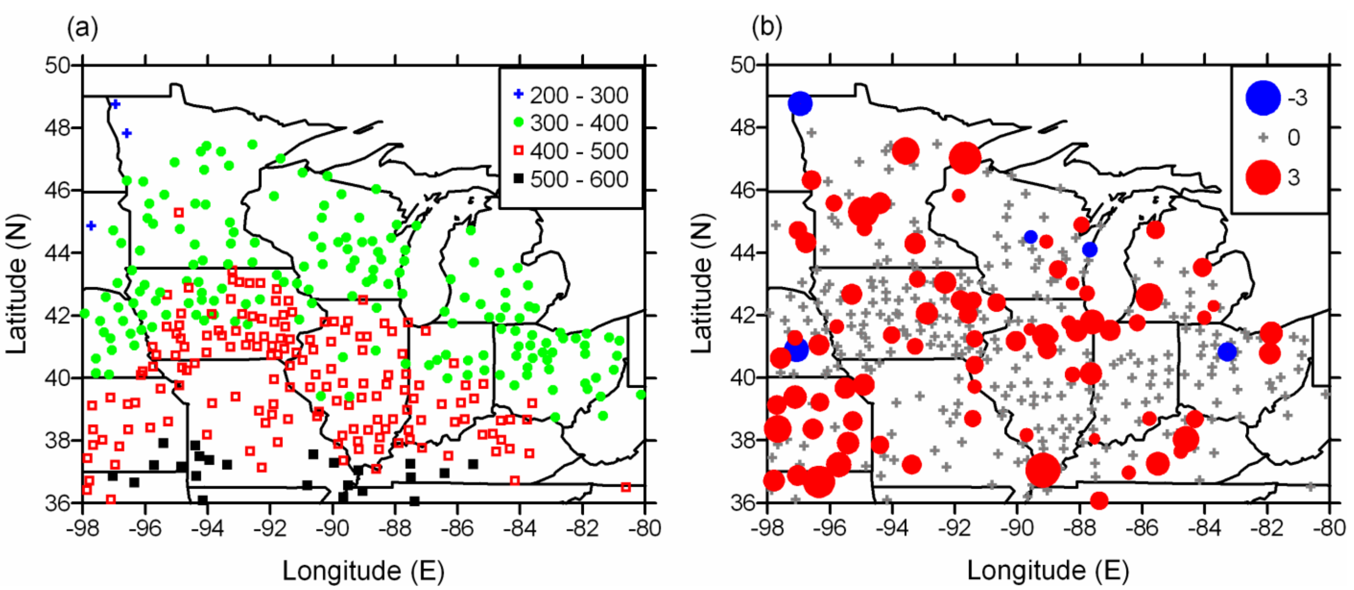

***Figure 9**: a) Mean sum of the top-10 wettest days in a year (mm) (1971-2000). b) Trend in sum of the top-10 wettest days in a year 1901-2000 expressed in a percent per decade. Red circle indicates the station showed a statistically significant increase through time; blue circle indicates a statistically significant decline. Plus symbol indicates trend was not significant (shown as 0 in the legend. The diameter of the dot scales linearly with trend magnitude (Pryor et al. 2009b).*

was no evidence of significant changes in either the central tendency or higher percentiles of the wind speed distribution over the period of record.

Extreme Precipitation

Intense precipitation events are an important part of annual hydrology in the Midwest, with over 30% of total annual precipitation obtained in the ten wettest days of the year in most areas of the region (Pryor et al., 2009a). In the western part of the region, as much as 50% of annual accumulated precipitation falls in 10 daily events. Spatial patterns in the total amount of precipitation in the 10 greatest rainfall events per year and the temporal trends of that sum are given in Figures 9a and b (from Pryor et al., 2009a). Both metrics closely mirror those present in the total annual precipitation with the highest values in the south of the region and lowest values in the north. In general, stations that exhibit significant changes in the metrics of extreme precipitation indicate trends towards increased values. Twenty-two percent of the stations considered in the study exhibited significant increases in the total accumulated precipitation during the top-10 wettest days of the year. Over the region as a whole, the occurrence of intense precipitation events has risen substantially in recent decades. In an update of an earlier study by Kunkel (2003), the number of 24 hour, once in 5-yr storms was found to have increased by about 4% per decade since the beginning of the 20th century (Figure 10). About 85% of the events occurred during the warm season

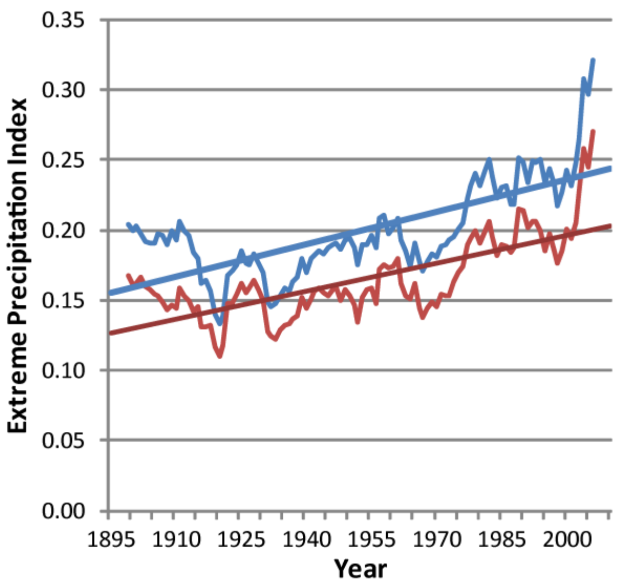

***Figure 10**. Time series of extreme precipitation index for the occurrence of 1-day, 1 in 5 year extreme precipitation events. The annual time series and linear trend (straight line) are shown in blue. A time series for the months of May through September is shown in red. Analysis is averaged for the states of IL, IN, IA, MI, MN, MO, OH, and WI. Based on data from the National Climatic Data Center for the cooperative observer network and updated from Kunkel et al. (2003).*

period of May through September and approximately 90% of the annual trend was due to increases during the warm season period. Synoptically, the risk of intense rainfall events in the region tends to be associated with a westward extension and strengthening of the Bermuda subtropical high across the western Atlantic Basin (Weaver and Nigam, 2008; Bell and Janowiak, 1995) as well as the development of a slow moving, cut-off-low system over the Rockies Mountain and Great Plain region which steadily advects low-level moisture into the Upper Mississippi region from the Gulf of Mexico (Gutowski et al., 2008). The trend towards heavier rainfall has resulted in an overall increased risk of flooding threat across the region (Markus et al., 2007), although in many urban areas the increased flood risk was found to be more strongly associated with land cover change factors than climatologic factors (Scharffenberg and Fleming, 2006; Changnon et al., 1996a).

Extreme Temperatures

Time series plots of 4-day cold waves and heat waves in the region from 1985 through 2010 are given in Figures 11 a) and b) after Kunkel (2003). Following relatively higher frequencies during the first few decades of the 20th century and from the late 1960's through the early 1990's, intense cold waves have been relatively infrequent, but similar to periods experienced from the early 1920s through 1960. The frequency of intense heat waves has also been relatively low in recent decades, especially relative to the 1930s Dust Bowl era which remains the most intense in the historical period of record.

Given recent upwards trends in temperature overall, a majority fraction of climate observing sites within the region recorded significant increases in warm extreme maximum temperature exceedences during the 1960-1996 period as well as increases in warm minimum temperatures and decreases in cold extreme maximum and minimum temperature exceedences (DeGaetano and Allen, 2002).

Drought

Given an increase in precipitation across the region during the past several decades, the incidence of drought has decreased with time. In a study across central sections of the Midwest, Mishra et al. (2010) found upward trends of precipitation and temperatures from 1916-2007 were associated with increases in total column soil moisture and runoff and decreases in frozen soil moisture. The authors also concluded that the study region has experienced reduced numbers of extreme and exceptional droughts with lesser areal extent in recent decades. A study by Andresen et al. (2009) suggests that a majority of the 10-15% increase in annual precipitation in Michigan during the past 50 years ended up as shallow aquifer recharge, which is in turn supported by observations of increasing base streamflow across the region (Johnston and Shmagin, 2008). In a study of Midwestern droughts during the 1950-1990 period, Changnon et al.(1996b) found that droughts in during the 1950-1970 period covered a relatively greater area of the Midwest region and lasted longer, while droughts during the 1971-1990 period impacted fewer basins and have been of shorter duration. The trend towards a wetter climate and decreasing drought frequency has also had a major impact on the region's agriculture industry in recent decades, with relative increases in crop yields due to less moisture stress and overall more favorable growing conditions (Andresen et al., 2001).

Synoptic Changes

The links between upper tropospheric flow, synoptic circulation patterns, and climatologic trends over the region are complicated. In general, synoptic patterns characterized by large amplitude long waves in the middle and upper levels of the hemispheric circulation across the region lead to anomalously cool or warm weather, and depending on the location of the upper air feature, and to relatively wet or dry conditions resulting from the influence of cyclones or anticyclones, respectively. In contrast, a flatter, more zonal pattern across the region is characterized more by more frequent, weaker cyclones and anticyclones Angel and Isard (1998). On a hemispheric scale, Agee (1991) found a positive correlation between increased (decreased) cyclone frequency and increased (decreased) hemispheric temperatures associated periods of warming and cooling mean temperatures between from 1900-1990 across the Northern Hemisphere. He associated the periods of warming with a flatter, relatively zonal pattern jet stream of short waves carrying more numerous yet weaker disturbances, and periods of cooling with stronger, less numerous disturbances. In the Midwest, Booth et al (2006) linked enhanced westerly upper air flow during the summer season with increases in the frequency of relatively dry Pacific-origin air masses, reductions in northward transport of Gulf of Mexico-origin moisture, and to drier than normal conditions across western sections of the region. There have also been important synoptic changes over time across the region. Grover and Sousounis (2002) suggest that upper tropospheric flow across the region during the fall season was relatively more meridional during the 1935-1956 period, and more zonal during the 1966-1995 period, which may have led to both greater frequency and total amounts of precipitation. The zonal flow was associated with greater baroclinicity across the Rocky Mountain region as well as a stronger subtropical jet and stronger low-level flow of moisture from the Gulf of Mexico. As noted earlier, other studies have linked extended droughts or wetter than normal periods in the Midwest to large scale oceanic sea surface temperature and circulation patterns in the Pacific and/or Atlantic Basins (e.g. McCabe et al., 2004).

In terms of mean pressure patterns, early studies of cyclone and anticyclone frequency and intensity across the region generally suggested a decrease in the frequency of cyclones and anticyclones during the second half of the last century (Agee, 1991; Zishka and Smith, 1980). More recent studies

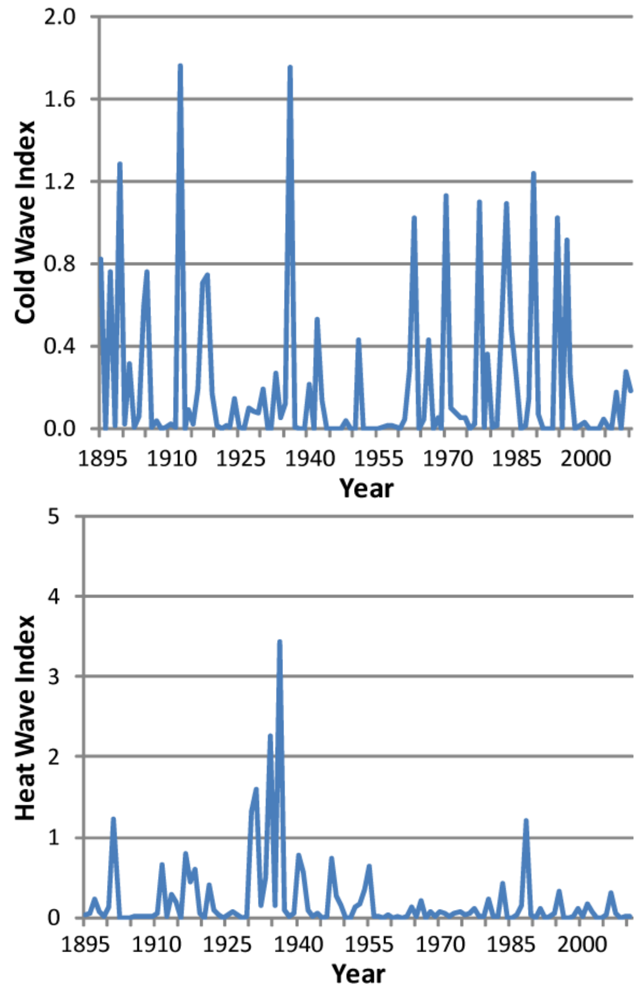

***Figure 11**: Time series of an index for the occurrence of a) cold waves (left) and b) heat waves (right) defined as 4-day periods colder and warmer than the threshold for a 1 in 5 year recurrence, respectively. Based on data from the National Climatic Data Center for the cooperative observer network and an update by Kunkel et al. (1999).*

suggest more complex trends. For example, Angel (1996) found a statistically significant increase in the frequency of strong cyclones over the Great Lakes region in November and December during the 20th century. A subsequent study by Polderman and Pryor (2004) reinforced these findings, reporting an increasing frequency of cyclones originating from Colorado and surrounding region along with a decrease in the frequency of Arctic (cold polar highs) outbreaks in the Midwest during their 1956-1999 study period. Results from the same study also linked record low lake levels of the Great Lakes with a polar jet stream displaced further south than normal, reduced winter cyclone activity, increased evaporation, and reduced ice cover on the lakes. Polderman and Pryor (2004) concluded that their results suggest that climate change is being manifested both in terms of changes in the frequency and surface manifestations of synoptic circulation patterns.

References

Agee, E.M., 1991. Trends in Cyclone and Anticyclone Frequency and Comparison of Periods of Warming and Cooling over the Northern Hemisphere. *J. Clim*. 4:263-267.

Anderson, G.B. and M.L. Bell, 2011. Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities. *Environ Health Perspect.* 119(2): 210–218.

Andresen, J.A., 2012. Historical Climate Trends in Michigan and the Great Lakes Region. In: Dietz T, Birdwell D (eds.) Proceedings of the international symposium on climate change in the Great Lakes region: Decision making under uncertainty, in press.

Andresen, J.A. and J.A. Winkler, 2009. Weather and Climate. Chapter 19 in Michigan Geography and Geology, R.J. Schaetzl, D. Brandt, and J.T. Darden. (eds). Pearson Custom Publishing, Boston, MA. ISBN: 0536987165.

Andresen, J.A., W.J. Northcott, H. Prawiranata, and S.A. Miller, 2009. The Influence of Land Cover Type on Surface Hydrology in Michigan. Chapter 11 in Understanding Climate Change: Climate Variability, Predictability, and Change in the Midwestern United States, S. C. Pryor, ed., ISBN 978-0-253-35344-3, Indiana University Press, Bloomington, IN.

Andresen, J.A., G. Alagarswamy, J.T. Ritchie, C.A. Rotz, and A.W. LeBaron, 2001. Assessment of the Impact of Weather on Maize, Soybean, and Alfalfa Production in the Upper Great Lakes Region of the United States, 1895-1996. *Agron. J.* 93: 1059-1070.

Angel, J.R. and S.A. Isard, 1998. The frequency and intensity of Great Lake cyclones. *J. Clim.* 11: 61-71.

Angel, J.R., 1996. Cyclone Climatology of the Great Lakes. Illinois State Water Survey,

Champaign IL, Miscellaneous Publication 172.

Assel, R. A., K. Cronk, and D. C. Norton, 2003. Recent trends in Great Lakes ice cover. *Climate Change*, 57: 185–204.

Bell, G. D., and J. E. Janowiak, 1995: Atmospheric circulation associated with the Midwest floods of 1993. *Bull. Amer. Meteor.Soc.* 76: 681–695.

Bentley. M.L. and J.A. Stallins, 2008. Synoptic evolution of Midwestern US Extreme dew point Events. *Int. J. Climatol.* 28: 1213–1225.

Birka, K., R. Lupo P. Guinan, and E. Barbieri, 2010. The interannual variability of midwestern temperatures and precipitation as related to the ENSO and PDO. *Atmósfera* 23: 95-128.

Booth, R.K., J.E. Kutzbach, S.C. Hotchkiss, and R.A. Bryson, 2006. A Reanalysis of the Relationship Between Strong Westerlies and Precipitation in the Great Plains and Midwest Regions of North America. *Clim. Change* 76: 427–441 DOI: 10.1007/s10584-005-9004-3

Braham Jr., R. R., and M. Dungey, 1984: Quantitative estimates of the effect of Lake Michigan on snowfall. *J. Appl. Meteor.* 23: 940–949.

Brohan, P., J.J. Kennedy, I. Harris, S. F. B. Tett, and P. D. Jones, 2006. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *J. Geophys. Res.* 111, D12106, doi:10.1029/2005JD006548, 2006.

Burnett A.W., M.E. Kirby, H.T. Mullins, and W.P. Patterson, 2003. Increasing Great Lake-effect snowfall during the twentieth century: A regional response to global warming? *J. Climate*16: 3535-3542.

Carlson, R.E., Todey, D.P., and S.E. Taylor, 1996. Midwestern corn yield and weather in relation to extremes of the southern oscillation. J. Prod. A. 9: 347-352.

Carleton, A.M., D.J. Travis, J.O. Adegoke, D.L. Arnold, and S. Curran, 2008. Synoptic Circulation and Land Surface Influences on Convection in the Midwest U.S. "Corn Belt" during the Summers of 1999 and 2000. Part II: Role of Vegetation Boundaries. *J. Clim.* 21:3617-3641.

Changnon, D., M. Sandstrom, and C. Schaffer, 2003: Relating changes in agricultural practices to increasing dew points in extreme Chicago heat waves. *Clim. Res.* 24: 243-254.

Changnon, D., M. Sandstrom, and M. Bentley, 2006. Midwestern High Dew Point Events 1960–2000. *Physical Geography* 27: 494-504.

Changnon, D., D. Fox, and S. Bork, 1996a: Differences in warm-season, rainstorm-generated stormflows for northeastern Illinois urbanized basins. *Water Resources Bulletin* 32: 1307-1317.

Changnon, D., 1996b. Changing temporal and spatial characteristics of Midwestern hydrologic droughts. *Physical Geography* 17: 29-46.

Changnon, S.A., 2010: Temporal distribution of weather catastrophes in the USA. Climatic Change, doi 10.1007/s10584-010-9927-1.

Changnon, S.A., 2008. Temporal and Spatial Distribution of Damaging Hail in the Continental United States. *Phys. Geog.* 29: 341-350.

Changnon, S.A., D. Changnon, and T.R. Karl, 2006. Temporal and Spatial Characteristics of Snowstorms in the Contiguous United States. *J. Appl. Meteor. Climatol.*, 45: 1141–1155.

Changnon, S.A., K.E. Kunkel, and K. Andsager, 2001: Causes for record high flood losses in the central United States. *Water International*, 26: 223-230.

Changnon, S.A. and D.M.A. Jones, 1972. Review of the Influences of the Great Lakes on Weather. *Water Resour. Res.* 8: 360-371.

Climate Prediction Center, 2005. North Atlantic Oscillation. http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.shtml. Accessed February, 2011.

Coleman, J.S.M. and J.C. Rogers, 2003: Ohio River Valley winter moisture conditions associated with the Pacific/North American teleconnection pattern. *J. Clim.* 16, 969-981.

Croley, T.E. and C.F.M. Lewis, 2006. Warmer and drier climates that make terminal great lakes. *J. Great Lakes Res.* 32:852-869.

Cutter, S.L. and C. Finch, 2008. Temporal and spatial changes in social vulnerability to natural hazards. *Proc. Nat. Acad. Sci.* 105: 2301–2306.

Dai, A., 2006: Recent climatology, variability, and trends in global surface humidity. *J. Clim.* 19: 3589-3606.

Dai, A., T.R. Karl, B. SUN, and K.E. Trenberth, 2006. Recent Trends in Cloudiness Over the United States: A Tale of Monitoring Inadequacies. *Bull Am. Met. Soc.* 87: 597-606.

Davis, R.E., Knappenberger, P.C., Novicoff, W.M., Michaels, P.J, 2002. Decadal changes in heat-related human mortality in the eastern United States. ***Climate Research*** 22: 175-184 **.**

DeGaetano, A.T. and R.J. Allen, 2002. Trends in Twentieth-Century Temperatrue Extremes across the United States. *J. Clim.* 15: 3188-3205.

Delcourt, P.A., P.L. Nester, H.R. Delcourt, C.I. Mora, and K.H. Orvis, 2002. Holocene Lake-Effect Precipitation in Northern Michigan. *Quarternary Res.* 57:225-233.

Duguay, C.R., T.D. Prowse, B.R. Bonsal, R.D. Brown, M.P. Lacroix, and P. Menard, 2006. Recent trends in Canadian lake ice cover. *Hydrological Processes* 20:781-801.

Dyer, J.L. and T.L. Mote, 2006. Spatial variability and trends in observed snow depth over North America. *Geophys. Res. Let.* 33, L16503, doi:10.1029/2006GL027258.

Easterling, D.R., B. Horton, P.D. Jones, T.C. Peterson, T.R. Karl, D.E. Parker, M.J. Salinger, V. Razuvayev, N. Plummer, P. Jamason and C.K. Folland, 1997. Maximum and minimum temperature trends for the globe. *Science* 277: 364-367.

Eichenlaub, V.L., Harman, J.R., Nurnberger, F.V., and H.J. Stolle, 1990. The Climatic Atlas of Michigan. Univ. of Notre Dame Press, South Bend, IN.
Fritsch, J. M., R.J. Kane, and R. J. Chelas, 1986. The Contribution of Mesoscale Convective Weather Systems to the Warm-Season Precipitation in the United States. *J. App. Met.* 25: 1333-1345.
Gaffen, D.J., and R.J. Ross, 1999: Climatology and trends of U.S. surface humidity and temperature. *J. Clim.* 12: 811-828.
Groisman, P.Ya. and D.R. Easterling, 1994. Variability and Trends of precipitation and snowfall over the United States and Canada. *J. Clim*. 7:184-205.
Grover, E.K. and P.J. Sousounis, 2002. The Influence of Large-Scale Flow on Fall Precipitation Systems in the Great Lakes Basin. *J. Clim.* 15: 1943-1956.
Gutowski, W.J., S.S. Willis, J.C. Patton, B.R. Schwedler, R.W. Arritt, and E.S. Takle, 2008. Changes in extreme, cold-season synoptic precipitation events under global warming. *Geophys. Res. Let.* Vol. 35, L20710, doi:10.1029/2008GL035516.
Hansen, J.W., J.W. Jones, A. Irmak, and F.S. Royce, 2001. ENSO impacts on crop production in the southeast US. Impact of climate variability on agriculture. American Society of Agronomy Special Publication 63, pp. 55–76
Heideman, K.F. and J.M. Fritsch, 1988. Forcing mechanisms and other characteristics of significant summertime precipitation. *Weather and Forecasting* 3:115-130.
Hurrell, J.W., 1995. Decadal trends in the North Atlantic Oscillation – Regional temperatures and precipitation. *Science* 269: 676–79.
IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.
Isard, S.A., J.R. Angel, and G.T. Van Dyke, 2000. Zones of origin for Great Lakes cyclones in North America, 1899-1996. *Monthly Weather Review* 128:474-485.
Johnston , C.A. and B.A. Shmagin, 2008. Regionalization, seasonality, and trends of streamflow in the US Great Lakes Basin. *J. Hydrol.* 362: 69– 88.
Kingston, D.G., D.M. Lawler, and G.R. McGregor, 2006. Linkages between atmospheric circulation, climate and streamflow in the northern North Atlantic: research prospects. *Prog. Phys. Geog.* 30: 143-174 DOI: 10.1191/0309133306pp471ra .
Kucharik, C.J., 2008. Contribution of planting date trends to increased maize yields in the central United States. *Agron. J.* 100: 328-336.
Kucharik, C.J., 2006. A multidecadal trend of earlier corn planting in the central USA. *Agron. J.* 98: 1544–1550.
Kumar, S., V. Merwade, W. Lee, L. Zhao, and C. Song, 2010. Hydroclimatological impact of century-long drainage in midwestern United States: CCSM sensitivity experiments. *J. Geophys. Res.* 115, D14105, doi:10.1029/2009JD013228.
Kunkel, K. E., D.R. Easterling, K. Redmond, and K. Hubbard, 2003: Temporal variations of extreme precipitation events in the United States: 1895–2000, *Geophys. Res. Lett.*, **30**, 1900, 10.1029/2003GL018052
Kunkel, K.E., 2003: North American Trends in Extreme Precipitation, *Nat. Hazards*, **29**, 291-305.
Liepert, B. G., 2002. Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. *Geophys. Res. Lett.,29:* 1421, doi:10.1029/2002GL014910.
Leathers, D.J., B. Yarnal, and M.A. Palecki, 1991. The Pacific/North American Teleconnection Pattern and United States Climate. Part 1: Regional Temperature and Precipitation Associations. *J. Clim.* 4:517-528.
Linderholm, H.W., 2004. Growing season changes in the last century. *Ag. For. Met.* 137: 1–14.
Lorenz, D.J.,S.J. Vavrus, D.J. Vimont, J.W. Williams, M. Notaro, J.A. Young, E.T. DeWeaver and E.J. Hopkins, 2009a. Wisconsin's Changing Climate: Temperature. Chapter 7 in *Regional Climate Variability and Change in the Midwest*, Midwest Assessment Group for Investigations of Climate, S.C. Pryor, ed. Indiana University Press, Bloomington, IN.
Lorenz, D.J., S.J. Vavrus, D.J. Vimont, J.W. Williams, M. Notaro, J.A. Young, E.T. DeWeaver and E.J. Hopkins, 2009b. Wisconsin's Changing Climate: Hydrologic Cycle. In *Regional Climate Variability and Change in the Midwest*, SC Pryor, editor. Indiana University Press, Bloomington, IN, pp. 135-144.
McCabe, G. J., Palecki, M. A., and J.L. Betancourt, 2004. 'Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States', *Proc. Nat. Acad. Sci.*101: 4136.
Magnuson, J.J., 2010: History and heroes: the thermal niche of fishes and long-term ice dynamics. *Journal of Fish Biology*, 77, 1731-1744, doi:10.1111/j.1095-8649.2010.02781.x.
Magnuson, J., D. Robertson, B. Benson, R. Wynne, D. Livingstone, T.Aria, R. Assel, R. Barry, V. Card, E. Kuusisto, N. Granin, T. Prowse, K. Stewart, and V. Vuglinski, 2000. Historical Trends in Lake and River Ice Cover in the Northern Hemisphere. *Science* 289: 1743-1746, DOI: 10.1126/science.289.5485.1743.
Markus, M., M. Hejazi, and S. McConkey, 2007. Impacts of Urbanization and Climate Variability on Floods in Northeastern Illinois. Proc. Gilbert F. White National Flood Policy Forum, 6-7 November, 2007, George Washington University, Washington, D.C.
Minnis, P., J. Ayers, R. Palikonda, and D. Phan, 2004. Contrails, Cirrus Trends, and Climate. *J. Clim.* 17: 1671-1685.
Mishra, V. K.A. Cherkauer, and S. Shukla, 2010. Assessment of Drought due to Historic Climate Variability and Projected Future Climate Change in the Midwestern United States *J. Hydromet.* 11: 46-68.
NASS, 2012a. Crop Values. 2011 Survey. U.S. Department of Agriculture, National Agricultural Statistics Service, Washington, DC. ISSN: 1949-0372.
NASS, 2012b. Acreage. National Agricultural Statistics Service, Agricultural Statistics Board, United States Department of Agriculture, ISSN: 1949-1522, Washington, DC. Available on the internet at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1000.
NOAA/NCDC. 1895-2010. Climatological Data. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC.
Norton, D.C. and S.J. Bolsenga, 1993. Spatiotemporal trends in lake effect and continental snowfall in the Laurentian Great Lakes, 1951-1980. *J. of Clim.* 6:1943-1956.
Palecki, M.A., S.A. Changnon, and K.E. Kunkel, 2001. The nature and impacts of the July 1999 heat wave in the Midwestern United States : Learning from the lessons of 1995. *Bull. Am. Met. Soc.* 82: 1353-1367.
Pan, Z.R., W. Arritt, E. S. Takle, W. J. Gutowski Jr., C. J. Anderson, and M. Segal, 2004. Altered hydrologic feedback in a warming climate introduces a "warming hole." *Geophys. Res. Lett.*, 31, L17109, doi:10.1029/2004GL020528.
Parrett, C., N. B. Melcher, and R.W. James, 1993. Flood Discharges s in the Upper Mississippi River Basin, 1993. U .S. Geological Survey Circular 1120-A. U.S. Geological Survey, Washington, DC.

Parton, W.J. M.P. Gutmann, and D. Ojima, 2007. Long-term Trends in Population, Farm Income, and Crop Production in the Great Plains. *BioScience* 57:737-747.

Polderman N.J. and S.C. Pryor, 2004. Linking synoptic-scale climate phenomena to lake-level variability in the Lake Michigan-Huron Basin. *J. Great Lakes Res.* 30: 419–434.

Pryor, S.C., J. A. Howe, and K. E. Kunkel, 2009a. How spatially coherent and statistically robust are temporal changes in extreme precipitation in the contiguous USA? *Int. J. Climatol.* 29: 31–45.

Pryor, S.C., R.J. Barthelmie, D.T. Young, E.S. Takle, R.W. Arritt, W.J. Gutowski Jr., A. Nunes, and J. Road, 2009b: Wind Speed trends over the contiguous USA. *J. Geo. Res*, **114**, D14105 doi:10.1029/2008JD011416.

Quinn, F.H., 1988. Great Lakes water levels, past, present, and future. In: The Great Lakes: Living with North America's Inland Waters. *Proc. Am. Water Res. Assoc. Annual Meeting*, Milwaukee, WI, pp 83-92.

Robeson, S.M., 2002. Increasing Growing Season Length in Illinois During the 20th Century. *Clim. Chng.* 52: 219–238, 2002.

Rogers, J.C., S.H. Wang, and D.H. Bromwich, 2004. On the role of the NAO in the recent northeastern Atlantic Arctic warming. *Geophys. Res. Let.*, VOL. 31, L02201, doi:10.1029/2003GL018728.

Rodionov, S.N., 1994. Association between Winter Precipitation and Water Level Fluctuations in the Great Lakes and Atmospheric Circulation Patterns. *J. Clim.* 7: 1693-1706.

Sacks, W.J. and C.J. Kucharik, 2011. Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. *Ag. and For. Met.*151: 882–894.

Scharffenberg. W. A. and Fleming, M. J. (2006). *Hydrologic Modeling System HEC-HMS User's Manual.* U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, California.

Schoof, J.T., 2012. Historical and Projected Changes in Human Heat Stress in the Midwestern USA Understanding climate change: Climate change impacts, risks, vulnerability and adaption in the Midwestern United States. Indiana University Press, in press.

Scott, R.W. and F.A. Huff, 1996. Impacts of the Great Lakes on regional climate conditions. *J. Great Lakes Research* 22:845-863.

Shadbolt, R.P., Waller, E.A., Messina, J.P., and J.A. Winkler, 2006. Source regions of lower-tropospheric airflow trajectories for the lower peninsula of Michigan: A 40-year air mass climatology. Journal of Geophysical Research 111: D21117, doi:10.1029/2005JD006657.

Schinker, J., P.J. Bartlein, and B. Shuman, 2006. Synoptic and dynamic climate controls of North American mid-continental aridity. Quaternary Sci. Reviews 25: 1401-1417 DOI: 10.1016/j.quascirev.2005.12.012.

Skaggs, R.H., Baker, D.G., 1985. Fluctuations in the length of the growing season in Minnesota. *Clim. Chng.* 7: 403–414.

Smith, K.R. and P.J. Roebber, 2011: Green Roof Mitigation Potential for a Proxy Future Climate Scenario in Chicago, Illinois. *J. Appl. Meteor. Climatol.*, 50: 507-522.

Stanhill, G. and S. Cohen, 2001. Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Ag. For. Met.* 107: 255–278.

Temimi, M.,T. Lacava, T. Lakhankar,V. Tramutoli, H. Ghedira, R. Ata, and R. Khanbilvardi, 2011. A multi-temporal analysis of AMSR-E data for flood and discharge monitoring during the 2008 flood in Iowa. *Hydrol. Process.* 25:2623– 2634.

Trewartha, G.T. and L.H. Horn, 1980. An Introduction to Climate. McGraw-Hill Pub., New York, NY.

Wang, J., X. Bai, G. Leshkevich, M. Colton, A .Cutes, and B. Lofgren, 2010: Severe ice cover on Great Lakes during winter 2008-2009. *Eos, Transactions, American Geophysical Union,* 91, 41-42.

Weaver, S. J., and S. Nigam, 2008. Variability of the Great Plains low-level jet: Large-scale circulation context and hydroclimate impacts. *J. Clim.* 21: 1532–1551.

Webb, T., P.J. Bartlein, S.P. Harrison, and K.H. Anderson, 1993. Vegetation, lake levels, and climate in eastern North America for the past 18,000 years. In 'Global Climates Since the last Glacial Maximum', H.E. Wright, J.E. Kutzbach, T.Webb, W.F. Ruddiman, F.A. Street-Perot, and P.J. Bartlein, eds., pp 415-467. Univ. of Minnesota Press, Minneapolis, MN.

Westcott, Nancy E., 2011: The Prolonged 1954 Midwestern U.S. Heat Wave: Impacts and Responses. *Wea. Climate Soc.* 3: 165–176. doi: http://dx.doi.org/10.1175/WCAS-D-10-05002.1

Whittaker, L.M. and L.H. Horn, 1981. Geographical and seasonal distribution of North American cyclogenesis, 1958-1977. *Monthly Weather Review* 109:2312-2322.

Winkler, J., J. Andresen, J. Bisanz, R. Black, G. Guentchev, J. Nugent, K. Piromsopa, N. Rothwell, C. Zavalloni, J. Clark, H. Min, A. Pollyea, H. Prawiranata, and R. Torre, 2012. Michigan's Tart Cherry Industry: Vulnerability to Climate Variability and Change. Chapter 9 in 'Climate change impacts, risk, vulnerability, and adaptation in the Midwestern United States', S.C. Pryor, ed. , Indiana University Press, Bloomington, IN, in press.

Wright, H.E., 1992. Patterns of Holocene climatic change in the Midwestern United States. *Quarternary Res.* 38:129-134.

Vigil, J.F., R.J. Pike, and D.G. Howell, 2000. A Tapestry of Time and Terrain. U.S. Geological Survey Geologic Investigations Series 2720. U.S. Geological Survey, Washington, DC.

Zhang, X., L.A. Vincent, W.D. Hogg, and A. Niitsoo, 2000. Temperature and Precipitation Trends in Canada During the 20th Century. *Atmos. Ocean* 38: 395-429.

Zhou, L., C.J. Tucker, and R.K. Kaufmann, 2001. Variation in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *J. Geophys. Res.* 106: 20069–20083.

Zishka, K.M. and P.J. Smith, 1980. The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950-1977. *Mon. Wea. Rev.* 108:387-401.