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Appendix A: Primary Impacts of Climate Change in the Chicago Region

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Introduction

Global warming, or more precisely global climate change, has emerged as a major scientific and public policy issue in the last few decades. This paper reviews the state of scientific knowledge regarding climate change in northeastern Illinois with a particular focus on variables of interest to municipalities. When scientists discuss climate change, they are referring to long-term and persistent changes in the climate of a location. Observed changes in climate are trends that are persistent for decades or longer. In contrast, weather is a short-term condition of the atmosphere. The results of the review suggest that changes have occurred in some climate variables, such as temperature and rainfall, over the past few decades in the Chicago region. A survey of climate projections for the Chicago area suggests further changes are in store.

The Region's Climate

The region's present-day climate is typically continental with cold winters, warm summers, and frequent short fluctuations in temperature, humidity, cloudiness, and wind direction. Four factors control the climate of northeastern Illinois: 1) the sun, 2) weather systems, 3) urban areas, and 4) Lake Michigan. The first two are the most significant. The sun, which is the primary energy source for virtually all weather phenomena, in large part, determines air temperatures and seasonal variations. Solar energy is three to four times greater in early summer than in early winter at Chicago's mid-latitude location, which results in warm summers and cold winters. The second major factor is weather systems, which result from varying air masses and passing storm systems. The polar jet stream, which is the focal point for the creation and movement of low-pressure systems that bring clouds, winds, and precipitation, is often located near or over Illinois.

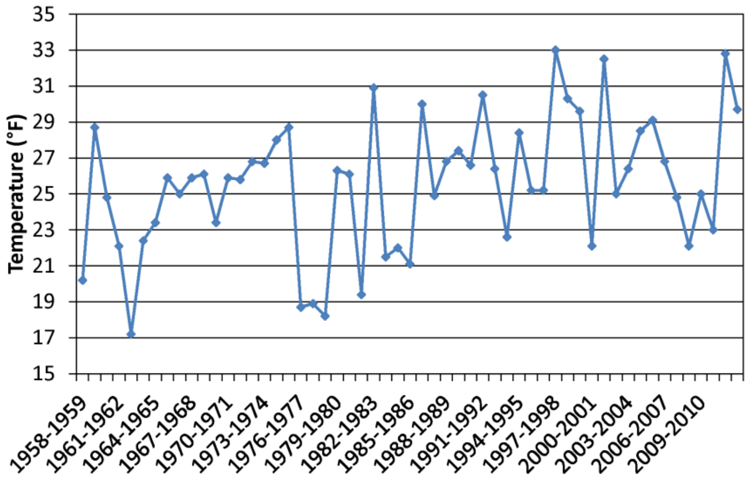
The other two controls are of lesser significance but they influence local climate conditions. Buildings, parking lots, roads, and industrial activities make the urban climate noticeably different from that of surrounding rural areas. On average, Chicago tends to be warmer by 2°F than outlying rural communities, especially at night. In some cases, these differences can be higher. This feature of the urban climate is called the "urban heat island effect".

Lake Michigan influences the climate of northeastern Illinois. The large thermal mass of the lake tends to moderate temperatures, causing cooler summers and warmer winters. The lake also tends to increase cloudiness in the area and suppress summer precipitation. In the winter, precipitation is enhanced by lake-effect snows that occur when winds blow from the north or northeast.

Climate Variability and Change

While observing trends in climate data, it is also important to understand the natural variability that is a fundamental component to climate. Climate variability refers to variations in climate on time scales of seasons to decades and is controlled by natural processes, like El Niño, La Niña, or the Atlantic Oscillation. Climate variability explains how one winter can be cold and snowy while the next is milder, or how one decade is exceptionally dry.

Figure 1. Average winter temperature (blue line) from Chicago O'Hare shows the large year-to-year variability that is characteristic of Chicago's climate.



Source: Midwestern Regional Climate Center

A common characteristic of continental climates is large variability in the weather experienced from one year to the next and northeastern Illinois' continental climate is no exception (figure 1). Large year-to-year variability has and always will be a characteristic of the Chicago regions' climate. In fact, some climate change studies have shown that year-to-year variability is more likely than not to increase in the future.[1]

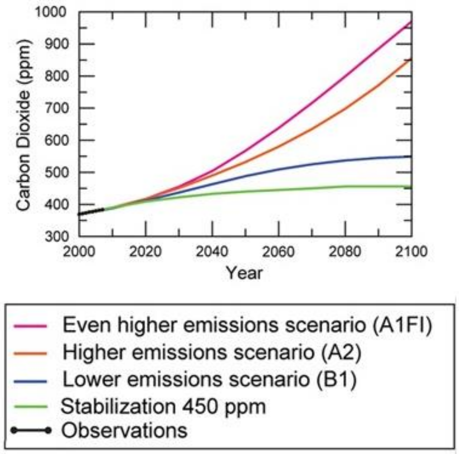
Due to the year-to-year variability in historical climate data for Chicago, observing changes in trends of certain climate variables becomes more difficult. The historical data often produces trends with low statistical significance. However, conclusions can still be drawn for most climate variables as to how the climate of Chicago has or has not changed over modern observational record.

Using and Interpreting Climate Model Projections

Climate models often show significant variation in projected values for the future. To interpret the myriad of projections, scientists often use a technique that involves gathering the results of several models to determine what the majority of models are predicting for the future, in order to determine the most likely scenario.

[1] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

Figure 2. Scenarios for atmospheric carbon dioxide concentration used in a majority of climate models.



Source: US Global Change Research Program, 2009

As for the reasons behind the variation, the range in projections for variables like precipitation and temperature are partially a result of the different carbon dioxide emissions scenarios underlying each climate model simulation. Low, intermediate, and high emissions scenarios are often used and each scenario represents a different level of carbon dioxide by the end of the century (figure 2). These different emissions represent different potential commitments to controlling carbon dioxide emissions.[2] Another source for the variation is that different climate models represent climate processes differently.

Given the nature of models as mathematical representations of Earth's climate system, there is inherent uncertainty. One source of uncertainty is that some of the processes at work in the earth-atmosphere system and their feedbacks are not yet fully understood, which makes it difficult for models to accurately represent these complicated climate processes. Correctly representing cloud and hydrological processes remains the single largest source of uncertainty in climate model simulations.[3] Therefore, precipitation projections often have a much larger range of projections and higher uncertainty than temperature projections. Finally, regional topography and regional circulation patterns are crudely represented in global climate models and even downscaled regional climate models may not fully capture these smaller-scale processes.[4]

Despite the uncertainties, scientists are confident that climate models provide reasonable estimates of future climate conditions, particularly at continental scales and above. This confidence comes from their ability to reproduced observed features of current and past climate changes. While it is not possible to precisely predict all aspects of future climate, many scientists agree that there is enough information about future climate trends and patterns to begin implementing robust adaptation strategies.

National Climate Assessment

Every four years, the United States Global Change Research Program completes a National Climate Assessment[5], which is required under the Global Change Research Act of 1990. The National Climate Assessment acts as a status report about climate change science and impacts around the country. The next assessment, which engaged over 240 authors in its creation, is

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[2] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

[3] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

[4] Winkler, J.A., R.W. Arritt, S.C. Pryor, 2012: Climate Projections for the Midwest: Availability, Interpretation and Synthesis. *In: U.S. National Climate Assessment Midwest Technical Input Report*.

[5] http://globalchange.gov/what-we-do/assessment

scheduled to be completed in 2013. Currently, it is in draft form and out for public review. The official release of the 2013 National Climate Assessment is expected in late 2013 or early 2014. Impacts and projections from the draft National Climate Assessment are incorporated into this study where applicable.

Primary Climate Change Impacts in Northeastern Illinois

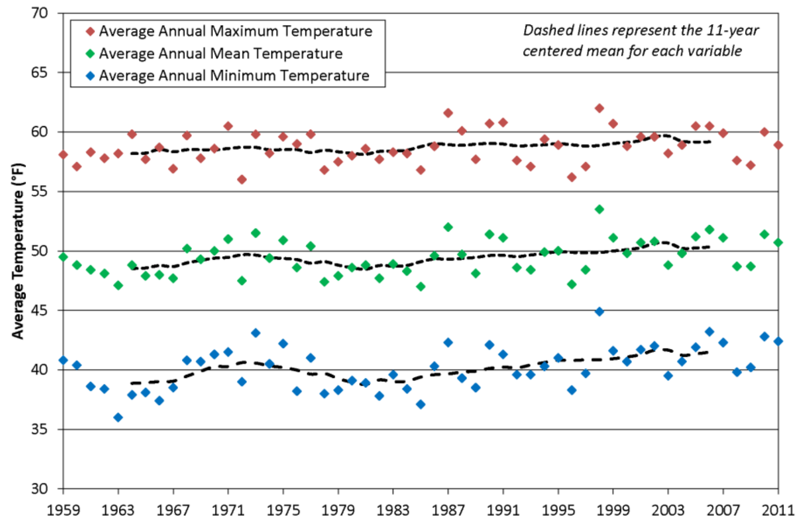
Temperature

Annual and Seasonal Temperature

Historical Trends

Annual trends for minimum, mean, and maximum temperature in Chicago have exhibited a slight warming trend since the late 1970's (figure 3), which is especially evident in the average minimum temperature. In fact, out of the climate variables analyzed in this study, an increase in minimum temperatures is the trend with the highest statistical significance. The trend of warming overnight low temperatures and consistent daytime maximum temperatures is not only evident in Chicago data, but in other locations in the Midwest as well. While it remains uncertain the specific reason for the warming trend in overnight lows, studies have found that it could be a result of increased humidity, increased cloudiness, or even a result of the local terrain or environmental changes surrounding the observation site.

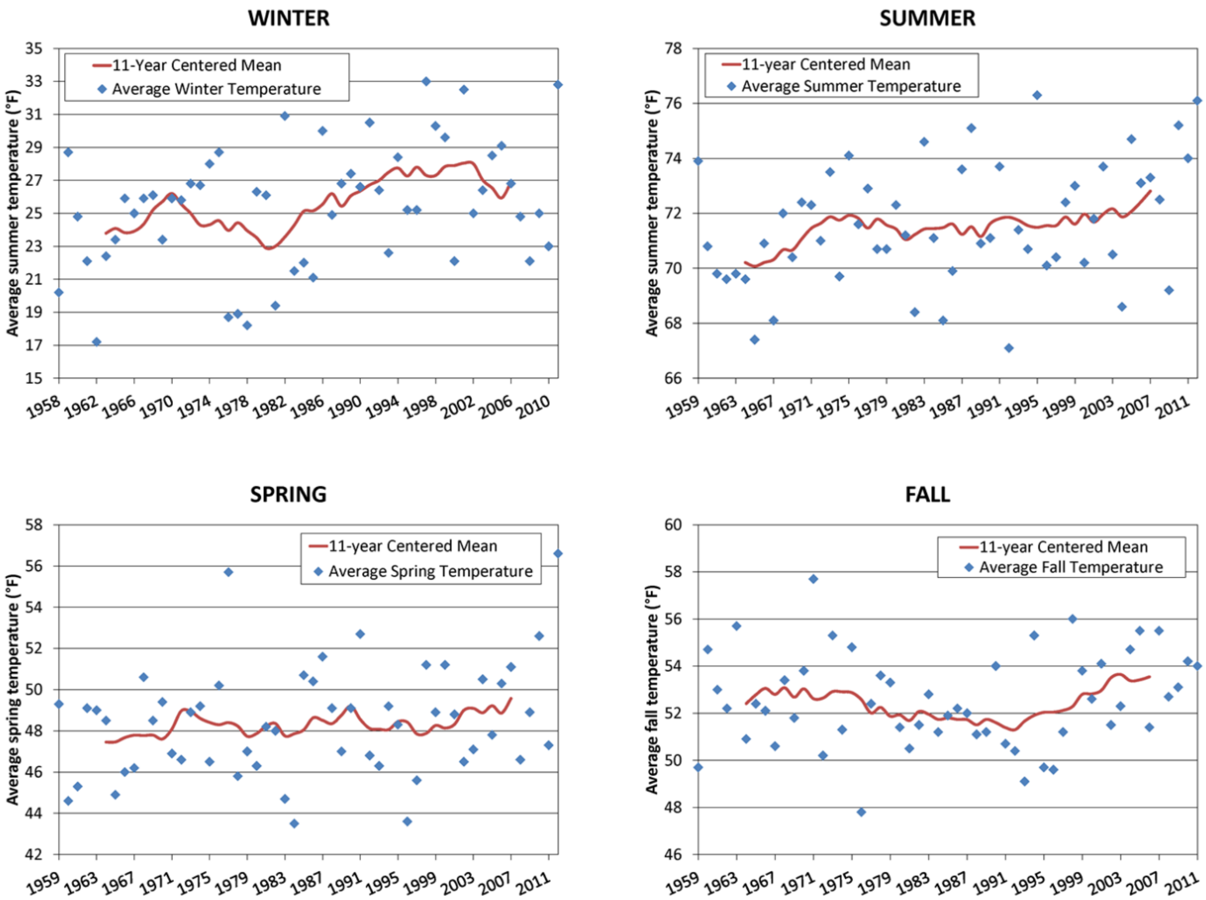
Figure 3. Average annual temperature trends for maximum temperature (red), mean temperature (green), and minimum temperature (blue) for Chicago O'Hare. The dots represent the average annual temperature and the black dotted line represents the 11-year centered mean.



Source: Midwestern Regional Climate Center

The slight increase in annual temperature since the 1970's in the Chicago region does not appear to be uniform throughout the year, meaning there are seasonal differences in the observed temperature trends. The winter and summer seasons have experienced slight warming trends since the late 1950's, while the trends in fall and spring are less apparent (figure 4).

Figure 4. Seasonal temperature trends at Chicago O'Hare in winter (top left), summer (top right), fall (bottom right), and spring (bottom left). The blue dots represent the average annual temperature and the red line represents the 11-year centered mean.



Source: Midwestern Regional Climate Center

Future Projections

Consistent with global projections, climate model studies for Chicago and surrounding regions are in general agreement that it is very likely annual temperatures will increase by mid-century and later. However, the degree of warming can differ substantially from one study to the next. Compiling information from several studies for Chicago and surrounding regions, a majority of studies project annual temperatures to be 5-9°F higher than they are today by the end of the 21st century. Some studies project slightly lower warming of only 2-5°F by the end of the century while some project higher, on the order of 9-13°F. In the near future (2010-2039), Hayhoe et al. (2010) estimates annual temperatures in Chicago may rise by 2-3.5°F and by mid-century (2040-2069) by 2.5-9°F.[6]

Future warming in the Chicago region may not be consistent throughout the year as well, with some seasons experiencing more warming than others. Some studies suggest a larger increase in summer temperatures compared to other seasons, with summer temperatures ranging 5-19°F

[6] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

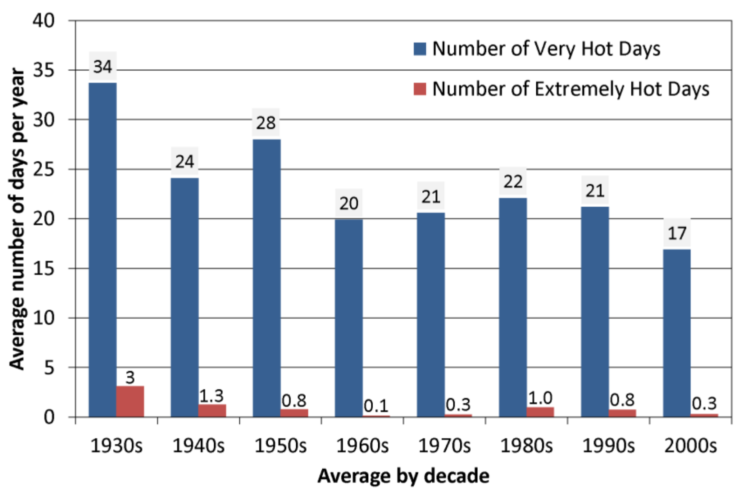
warmer than they are today by the end of the century.[7,8] One study shows that over the short term, greater increases are projected for the winter months and smaller increases in temperature for the spring and summer. However, by the middle of the century, the seasonality is projected to reverse and greater temperature increases will occur in summer as compared to winter and spring.[9]

Extreme Heat in Chicago

Historical Trends

A "very hot day" is defined as a day in which the maximum temperature is greater than or equal to 90°F, whereas an "extremely hot day" is defined as a day in which the maximum temperature is greater than or equal to 100°F.

Figure 5. The average number of very hot days (90°F, blue) and the average number of extremely hot days (100°F, red) per year (average by decade) at Chicago Midway.



Source: Midwestern Regional Climate Center

Over the modern observational record, the average number of very hot days at Chicago Midway is around 23 days per year (about 3-5 fewer days per year outside of the city). Some of the hottest decades in Chicago's history were the 1930's through the 1950s, when the average number of very hot days were around 25-35 per year, much higher than the average of 17 days per year in the 2000s (figure 5).

For desert climates like Phoenix, Arizona, reaching temperatures of 100°F or higher is a very normal part of their year. However, for continental climates like Chicago, the occurrence of 100°F temperatures is much less frequent. In fact, the average number of extremely hot days at Chicago Midway is around 1 day per year (less frequent outside of the city). The historical record indicates that the 1930s experienced the highest frequency of extremely hot days, averaging 3 days per year while the most recent decade only experienced 0.3 days per year, indicating that 100°F temperatures did not occur every year in the decade (figure 5). At Chicago Midway, the years with the highest number of extremely hot days were 1934 and 1936, when there were eleven days at or above 100°F.

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[7] Cherkauer and Sinha, 2010. Hydrologic impacts of projected future climate change in the Lake Michigan region. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 33-50.

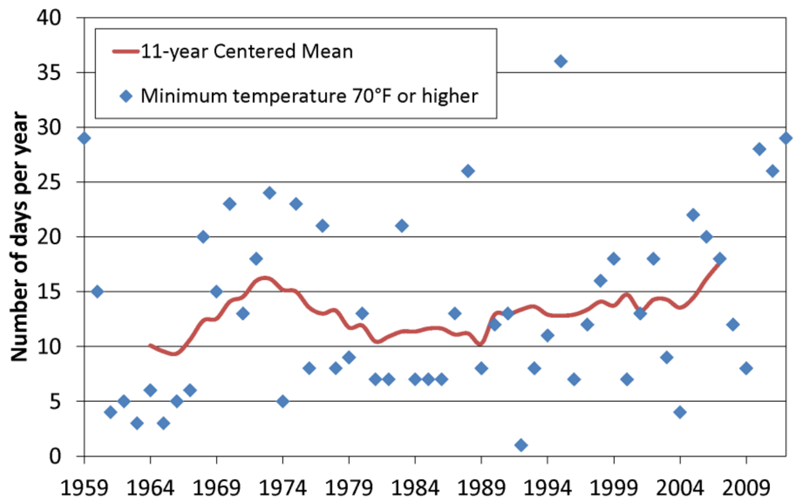
[8] Winkler, J.A., R.W. Arritt, S.C. Pryor, 2012: Climate Projections for the Midwest: Availability, Interpretation and Synthesis. *In: U.S. National Climate Assessment Midwest Technical Input Report*.

[9] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

Hot daytime temperatures are not the only concern during summer months. Several locations in the Midwest have shown a trend in the last few decades towards higher overnight minimum temperatures, particularly in the summer months when overnight temperatures over 70°F are becoming more common. When overnight temperatures stay elevated, humans, livestock, and vegetation experience increased heat stress, which can be harmful.

While not statistically significant, since the early 1990s, the Chicago region has experienced a slight increase in the frequency of days per year with a minimum temperature over 70°F (figure 6). The most recent years (2010-2012) have experienced over 25 days each year when overnight temperatures did not drop below 70°F, which is about 12-15 days above average.

Figure 6. Number of days per year with minimum temperature 70°F or greater at Chicago O'Hare. The blue dots represent the number of days per year and the red line represents the 11-year centered mean.



Source: Midwestern Regional Climate Center

Future Projections

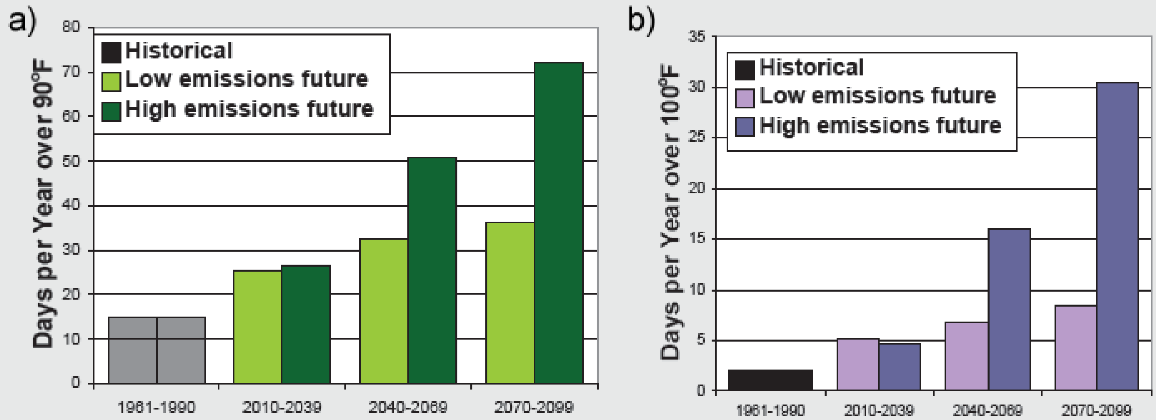
While the modern observational record does not show an increasing trend in extreme heat in Chicago, the majority of climate models project an increase in annual temperature in the region. Studies are also predicting that the number of very hot and extremely hot days is likely to increase as well. Simulated frequency of very hot days in Chicago increases from the current level to 36 days by the end of the century under a low emissions scenario, similar to the 1930s, and 72 days under a high emissions scenario (figure 7a). Climate models project that extremely hot days, which are currently an infrequent event in Chicago, may occur just over 30 days per year by the end of the century under a high emissions scenario and 8 days each year under a low emissions scenario (figure 7b).[10]

The average high temperature of the hottest day of the year in Chicago is expected to increase from the present-day value of around 99°F to 107°F under low emissions and 117°F under higher emissions.[11]

[10] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

[11] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

Figure 7. Projected frequency of 90°F and 100°F days per year in Chicago under a low emissions scenario (light green and light purple) and a high emissions scenario (dark green and dark purple) for 2010-2039, 2040-2069, and 2070-2099.



Source: Climate Change and Chicago: Projections and Potential Impacts (Chapter Two). *Chicago Climate Action Plan*: November 2007.

In the future, models project that overnight low temperatures over 80°F will change from being almost non-existent today to occurring about 2 to 14 days per year (on average) by the end of the century. Overnight low temperatures over 80°F have the potential to have even more harmful effects on humans, livestock, and vegetation. Since humidity is strongly correlated with minimum overnight temperatures, future projections of higher dew points should lead to an increased frequency of very warm nights.[12] Higher overnight temperatures could have harmful implications like an increase in heat stress during heat waves in the summer months in the Chicago region.

Humidity and the Heat Index

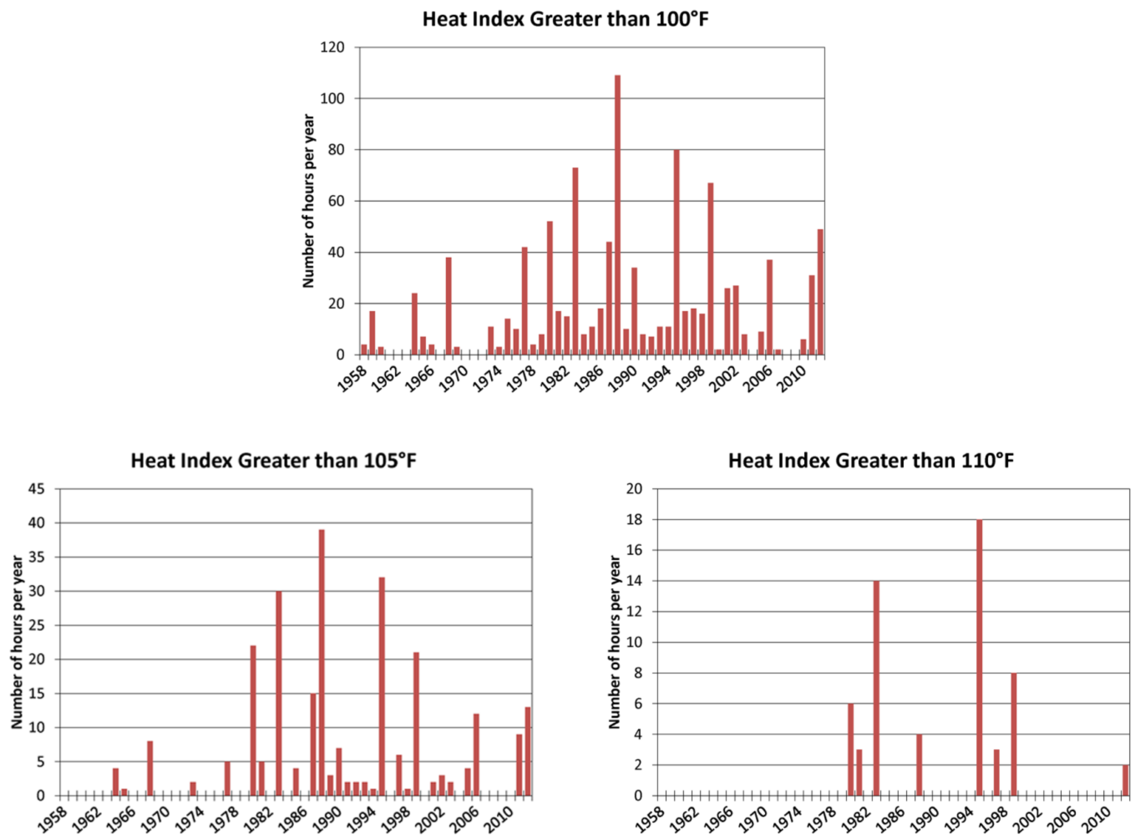
Historical Trends

Hot summertime temperatures in Chicago are often accompanied by high humidity, making it feel much warmer than it actually is. The saying – "it's not the heat, it's the humidity" – is often true during Chicago's summer. The high humidity often results in oppressive heat index values and dangerous heat waves during the summer months. The *heat index* is an index that combines air temperature and relative humidity to measure the human-perceived equivalent temperature (i.e. how hot it actually feels). Using the National Weather Service definition, heat wave warnings are issued in Chicago if the heat index is projected to be between 100°F and 105°F for three consecutive days, between 105°F to 110°F for two consecutive days, or any time the heat index is above 110°F.

[12] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

The Chicago region has been afflicted by severe heat waves in its history, with one of the worst occurring in July 1995, which caused over 700 deaths in the Chicago region.[13] During this event, heat index values soared to over 120°F for six consecutive hours and temperatures remained over 80°F for 57 consecutive hours at Midway Airport. On average, there are 19.5 hours per year with heat index values over 100°F in Chicago, with the most occurring in 1988 when there were 109 hours (figure 8). Of much less frequent occurrence, there have only been 8 years since 1958 that the heat index has gone above 110°F for one hour or more at O'Hare. The maximum number of hours was in 1995, when there were 18 hours above the 110°F heat index threshold.

Figure 8. Number of hours per year when the heat Index values at Chicago Midway were greater than 100°F (top), 105°F (bottom left), and 110°F (bottom right).

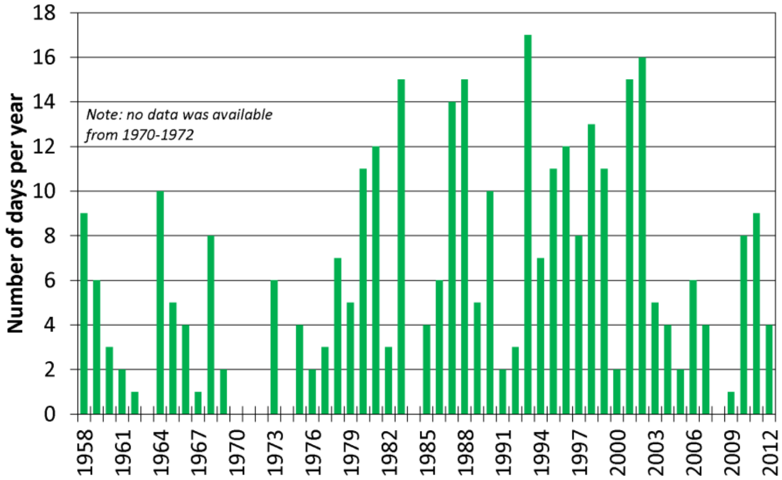


Source: Illinois State Water Survey; Chicago O'Hare data from the National Climatic Data Center

[13] Changnon, S.A., K.E. Kunkel, and B.C. Reinke, 1996. Impacts and Responses to the 1995 Heat Wave: A Call to Action. *Bulletin of the American Meteorological Society*, Vol. 77, No. 7.

To gauge the humidity in the atmosphere, the dew point temperature is frequently used and more accurate than other measures like relative humidity. During summer in Illinois, a dew point temperature in the 50s is generally comfortable. Most people begin to feel the humidity when dew point temperature reaches the 60s. Dew point temperatures in the 70s are rare and cause significant discomfort. During the peak of the July 1995 heat wave, dew point temperatures were in the upper 70s and lower 80s, unprecedented for the Chicago area.

Figure 9. Number of days per year with dew point temperature greater than 75°F.



Source: Illinois State Water Survey with data from the National Climatic Data Center

Figure 9 shows the number of days per year with a dew point greater than 75°F, which is very high humidity for northeastern Illinois. The years with the peak number of days per year occurred in the 1980s through the early 2000s. Since the early 2000s, number of days per year with high humidity at O'Hare have reduced to about half of what they were during peak years. However, there has been a 35% increase in the number of days per year with the dew point greater than 75°F when comparing the 1961-1990 normal to the most recent 1981-2010 normal.

Future Projections

Studies have projected that the region will experience higher dew points in the future, leading to hot days feeling even hotter due to this increased humidity.[14,15] As a result of higher temperatures and humidity in Chicago, the frequency, duration, and intensity of heat waves are likely to increase substantially in the future.[16,17] One study projects an increase of between 166 to 2,217 excess deaths per year from heat wave-related mortality in the City of Chicago by 2081-2100, depending on the climate model.[18]

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[14] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

[15] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

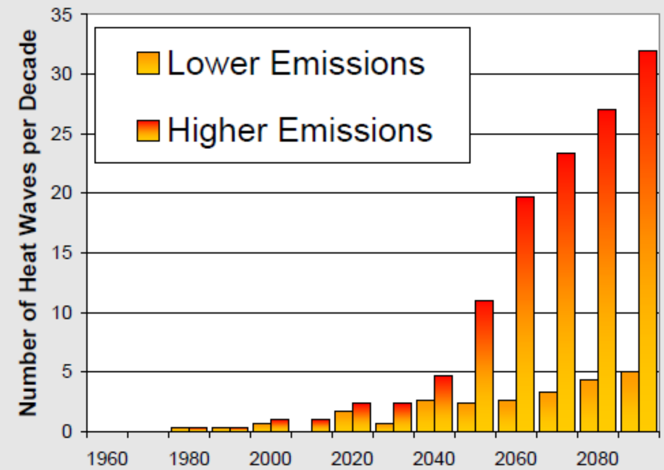
[16] Hayhoe, K., S. Sheridan, L. Kalkstein, and S. Greene, 2010. Climate change, heat waves, and mortality projections for Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 65-73.

[17] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

[18] Peng, R.D., J.F. Bobb, C. Tebaldi, L. McDaniel, M.L.Bell, and F. Dominici, 2011. Toward a Quantitative Estimate of Future Heat Wave Mortality under Global Climate Change. *Environmental Health Perspectives*, 119, 701-706.

Hayhoe et al. (2010) found that 1995-type heat waves are projected to occur 2 to 5 times per decade by mid-century and by the end of the century, they could be as frequent as every other year under low emissions and several per summer under high emissions (figure 10). Vavrus and Van Dorn (2010) projects that the average duration of consecutive 100°F days rises from 0.7 days today to 2.4 days under low emissions and 5.3 days under high emissions by the end of the century.

Figure 10. Total number of 1995-like heat wave events projected to occur each decade, as simulated by three climate models under higher (A1FI) and lower (B1) emissions scenario.



Source: Climate Change and Chicago: Projections and Potential Impacts (Chapter Two). *Chicago Climate Action Plan*: November 2007.

In addition, the amount of time during the year when heat waves occur, the "heat wave season", is expected to extend as well. Currently, there is a 69-day window during the summer when temperatures 90°F or greater occur. By the end of the century, that window may extend to 108 days under low emissions and 138 days under high emissions.[19]

By the end of the century under a low emissions scenario, Chicago summers could feel like those of Atlanta, Georgia, with day-to-day summer heat index values averaging 94°F and under a high emissions scenario, summers could feel like those of Mobile, Alabama, with summer heat index values averaging 105°F.[20]

Most likely, there will not be a steady increase in the frequency of heat waves with time. Vavrus and Van Dorn (2010) find that summers with infrequent or nonexistent extreme heat are still projected to occur throughout the late 21st century. However, occasional summers are expected to have a great many more hot, humid days than in the present climate.

Extreme Cold in Chicago

Historical Trends

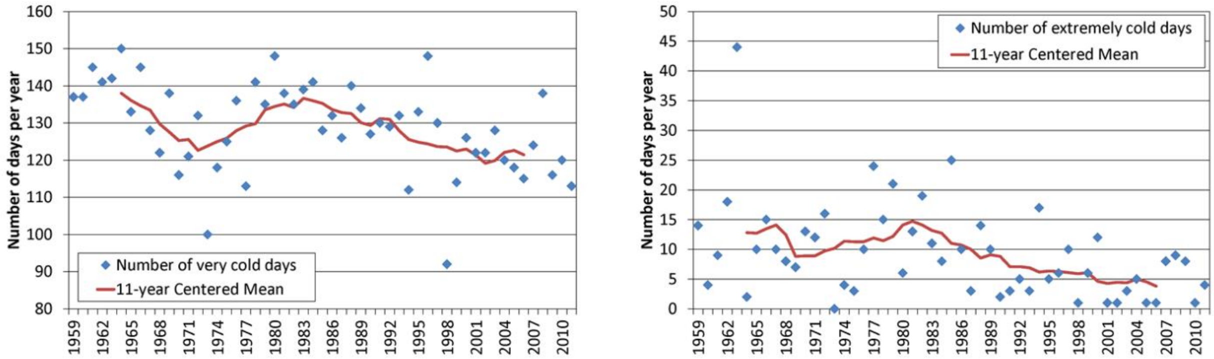
Not only does the Chicago region deal with hot and humid summers, but it also can experience very harsh wintertime conditions. A "very cold day" is defined as a day when the minimum temperature was less than or equal to 32°F and an "extremely cold day" is defined as a day when the minimum temperature is less than or equal to 0°F.

[19] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

[20] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

Typically, Chicago experiences about 128 very cold days per year and only about 9 extremely cold days per year. Looking at both thresholds, there has been a steady decrease in the number of these days per year (figure 11).

Figure 11. The number of very cold days (left) and extremely cold days (right) per year at Chicago O'Hare. The blue dots represent the number of days per year and the red line shows the 11-year centered mean.



Source: Midwestern Regional Climate Center

Future Projections

As the climate warms, it is expected that the frequency of freezing temperatures (less than or equal to 32°F) will continue to decrease. In fact, by mid-century, it is expected that there will be 22 fewer days per year with a minimum temperature below 32°F.[21] Not surprisingly, it is expected that Chicago will continue to see a decrease in the number of extremely cold days per year as well. A composite of global climate models indicate that by the end of the century, the United States will experience a 90% reduction in the frequency of extreme cold-air outbreaks, with the decline possibly even greater in the Great Lakes region.[22] For Chicago, the simulated occurrence of extremely cold days declines by 50% under a low emissions scenario and by 90% (meaning only about one day per year) under a high emissions scenario by the end of the 21st century.[23]

Heating and Cooling Degree Days

Historical Trends

A heating or cooling degree day is a measurement designed to reflect the demand for energy needed to heat or cool a building and is derived from measurements of outside air temperature. For this analysis, a base temperature of 65°F was used. To calculate the number of heating degree days for a given day, the average daily temperature is subtracted from 65°F and for the number of cooling degree days, 65°F is subtracted from the average daily temperature.

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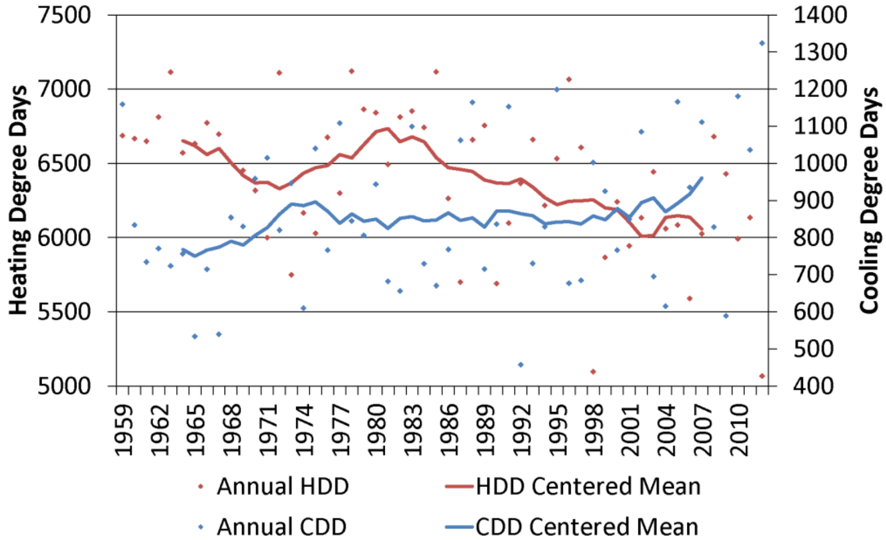
[21] Kunkel, K.E., Steven, L.E., and Stevens, S.E., 2012. Climate of the Midwest. *U.S. Guidance document prepared for the US National Climate Assessment*.

[22] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

[23] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

The number of heating degree days in the Chicago region have decreased since the early 1980's (figure 12), meaning that there is less demand for the energy needed to heat buildings during the colder months. At the same time, while the number of cooling degree days per year maintained an average of about 850 since the late 1950's, there has been an increase over the last ten years (figure 12).

Figure 12. The number of heating degree days (left axis) and cooling degree days (right axis) per year at Chicago O'Hare. The dots represent annual values, while the lines represent the 11-year centered mean.



Source: Midwestern Regional Climate Center

Future Projections

A recent study[24] found that the magnitude of the projected changes in cooling degree days are anticipated to be larger than the changes in heating degree days, which is not currently reflected in the historical data. However, as temperatures in the summer months are anticipated to warm more significantly than other seasons in the future, the observed trend may indeed shift to what is projected by this study for the Chicago region. By 2041-2070, this study anticipates a 66% increase in cooling degree days when averaged across the Midwest, which equates to about 570 additional cooling degree days here per year. This study finds that based on a mean of multiple models, heating degree days may decrease by 15% across the Midwest.

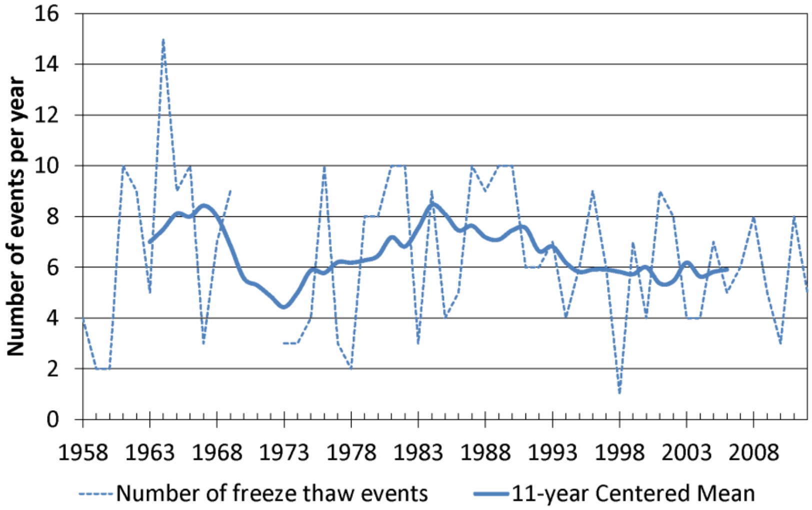
Freeze-Thaw Cycles

Historical Trends

Historical data indicates that the frequency of freeze-thaw events in Chicago average around 6.5 events per year. Overall, there is no significant trend in the number of freeze-thaw events per year in Chicago (figure 13). However, the year-to-year variability in the number of events has become smaller since the late 1990s. Over the past couple of decades, Chicago has experienced between 4 to 8 events per year compared to earlier data when the range was anywhere from 2 to 10 events.

[24] Kunkel, K.E., Steven, L.E., and Stevens, S.E., 2012. Climate of the Midwest. *U.S. Guidance document prepared for the US National Climate Assessment.*

Figure 13. The number of freeze-thaw events per year at Chicago O'Hare, calculated by counting days with a minimum temperature of 25.7°F or greater and a maximum temperature of 43.3°F or less. The blue dashed line shows the number of freeze thaw events each year while the solid blue line is the 11-year centered mean.



Source: Illinois State Water Survey with data from the National Climatic Data Center

A study by Baker & Ruschy (1995)[25] studied the effectiveness of several different thresholds for freeze-thaw events and found that the thresholds of 25.7°F for minimum temperature and 43.3°F for maximum temperature best represented the actual occurrence of freeze-thaw events in any given year at 1-centimeter bare soil. Therefore, these thresholds were used to examine the number of freeze-thaw events per year.

Future Projections

It is not clear how climate warming might affect the frequency of soil freeze-thaw cycles. However, given that a reduced or absent snowpack can make soils more vulnerable to fluctuations in ambient air temperature, climate warming and less snowy winters may contribute to an increased frequency of soil freeze-thaw cycles.[26] A study analyzed the historical and future frequency of freeze-thaw cycles in Canadian locations. Harrow, Ontario was the closest location in the study to Chicago. Based on data from 1961-1990, Harrow typically received about 6-7 annual freeze-thaw cycles (comparable to Chicago) and is expected to experience around 11-12 freeze-thaw cycles annually by 2050.

Precipitation

Annual and Seasonal Precipitation Trends

Historical Trends

Based on the 1981-2010 normal, Chicago O'Hare typically receives around 37 inches of precipitation per year. Since the late 1950's, there has been a statistically significant increasing trend in the total annual precipitation at O'Hare (figure 14). There was a slight decrease from the mid-1980s until the mid-1990s, but since then, there has been an increasing trend in annual precipitation.

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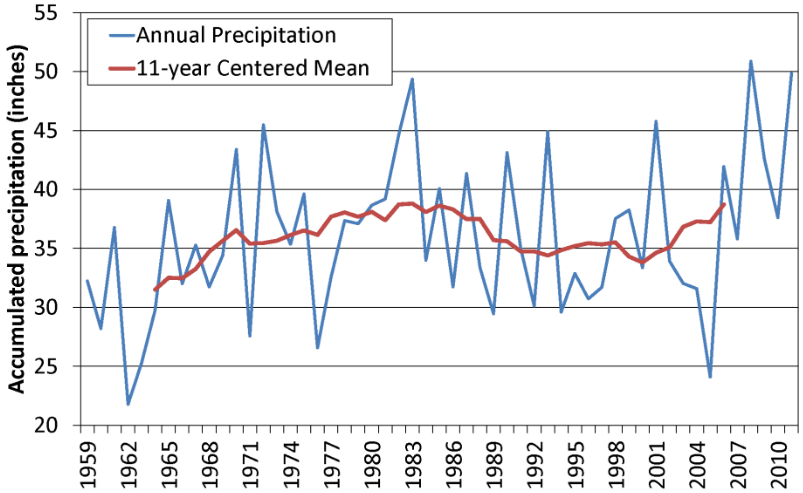
[25] Baker, D.G. and D.L. Ruschy, 1995. Calculated and Measured Air and Soil Freeze-Thaw Frequencies. *Journal of Applied Meteorology*, Vol. 34: 2197-2205.

[26] Henry, H.A.L., 2008. Climate change and soil freezing dynamics: historical trends and projected changes. *Climate Change,* Vol. 87: 421-434.

Chicago typically receives the most precipitation in the summer season (33%) followed by spring (27%), fall (25%), and winter (15%). While no season shows a statistically significant trend, precipitation in the summer and winter does appear to have increased slightly since the late 1950s.

Figure 14. Average annual precipitation at Chicago O'Hare. The blue line shows accumulated precipitation annually (inches) while the red line shows the 11-year centered mean.

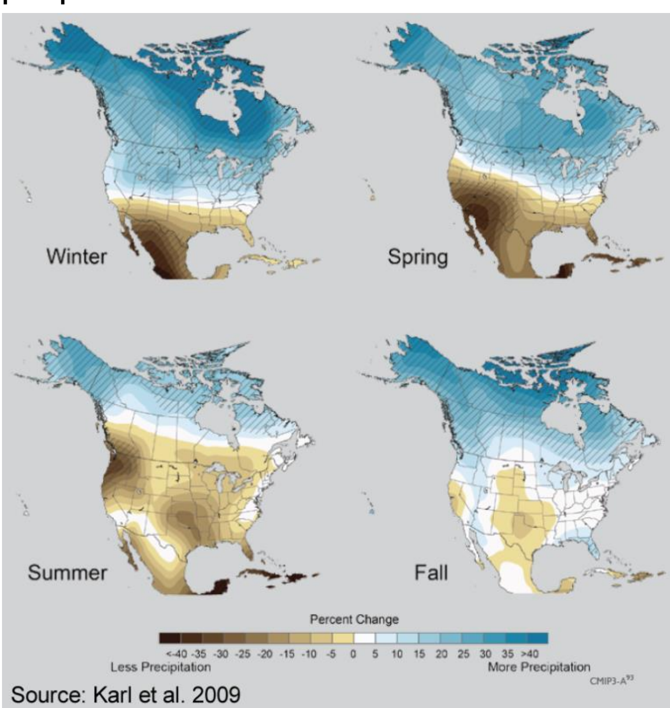


Source: Midwestern Regional Climate Center

Future Projections

The degree of uncertainty surrounding precipitation projections in climate models remains high. However, looking at several studies for Chicago and the surrounding region, there is some agreement regarding future precipitation trends for the region. A significant number of models project that annual precipitation will increase in the region with seasonal differences expected. However, some models do project that there could be a decrease in annual precipitation. Based on projections for annual precipitation from the IPCC (Intergovernmental Panel on Climate Change), near-term changes (2010-2039) could be on the order of -2% to+7%, mid-century changes (2040-2069) on the order of -2% to +10%, and end of the century changes (2070-2099) on the order of -1% to +19%.[27]

Figure 15. Projected changes in North American precipitation by 2080-2099. The brown shades represent less precipitation while the blue shades represent more precipitation.



A majority of model studies indicate that even if precipitation increases in the future, the increase most likely will not occur uniformly in all seasons (figure 15).[28] Several studies indicate that

[27] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

[28] Karl, T.R., J.M. Melillo, and T.C. Peterson, 2009. Global Climate Change Impacts in the United States. *Cambridge University Press*.

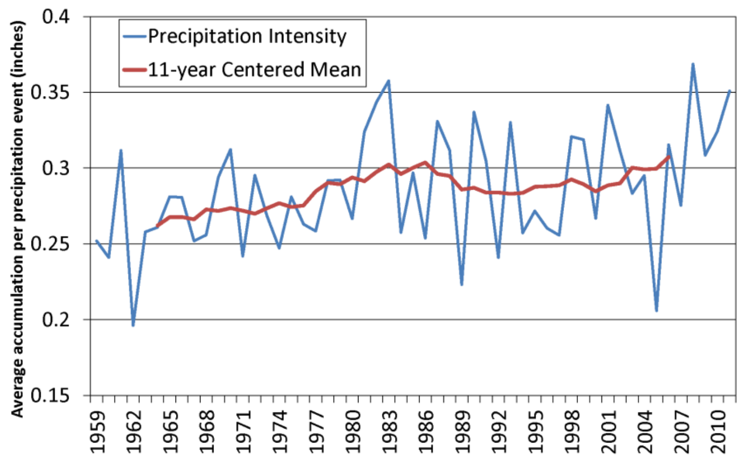
increases in winter and spring precipitation are likely and it is likely that there will be little change in summer and fall precipitation.[29,30] Another study indicates that by the end of the century, it is possible that there will be precipitation increases for all seasons except for summer by the end of the century, with maximum increases in the spring (between 14% and 42%).[31] Overall, there is little confidence in the sign (positive or negative) of change in the mean precipitation for the summer season.[32]

Heavy Precipitation Events

Historical Trends

Historical data shows that Chicago has experienced an increase in precipitation intensity over the last few decades, meaning that more precipitation is associated with each event (figure 16). To calculate precipitation intensity, total annual precipitation is divided by the number of days with measurable precipitation (greater than or equal to 0.01").

Figure 16. Precipitation intensity, or the average accumulation per event, for Chicago O'Hare. The blue line shows the average precipitation intensity annually and the red line shows the 11-year centered mean.



Source: Midwestern Regional Climate Center

Used as the typical standard rainfall amount to size drainage systems, the 24-hour, 10-year storm in the northeastern Illinois is 4.47" (based on rainfall frequencies from Bulletin 70[33]), meaning that in a stationary climate, there is a 10% chance of 4.47" of rain in 24 hours occurring any given year, or an average of once in every 10 years. Used as the typical basis for flood protection, the 24-hour, 100-year storm in northeastern Illinois is 7.58", meaning that in a stationary climate, there is a 1% chance of 7.58" of rain in 24 hours occurring any given year, or on average once in every 100 years.

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[29] Climate Change and Chicago – Projections and Potential Impacts: Executive Summary. *Chicago Climate Action Plan*: September 18, 2008.

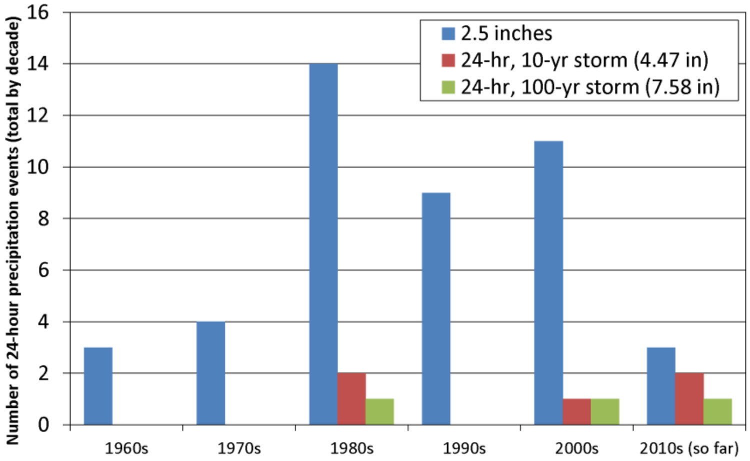
[30] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

[31] Cherkauer and Sinha, 2010. Hydrologic impacts of projected future climate change in the Lake Michigan region. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 33-50.

[32] Winkler, J.A., R.W. Arritt, S.C. Pryor, 2012: Climate Projections for the Midwest: Availability, Interpretation and Synthesis. *In: U.S. National Climate Assessment Midwest Technical Input Report*.

[33] http://www.isws.illinois.edu/atmos/statecli/RF/download.htm

Figure 17. The number of times per decade that certain threshold precipitation events were exceeded at Chicago O'Hare. Thresholds included 2.5" (blue), 24-hr, 10-yr storm or 4.47" (red), and 24-hr, 100-yr storm or 7.58" (green).



Source: Illinois State Water Survey with data from the National Climatic Data Center

Historical analysis of heavy precipitation events in Chicago indicate that the rare 24-hour, 100-year storm, which on average occurs once in every 100 years, has been met or exceeded three times at Chicago O'Hare since the 1980s (figure 17). In addition, the 24-hour, 10-year storm has already been exceeded twice in the 2010s, which is more frequent than the expected occurrence of only once every 10 years. This is especially significant considering there are seven more years remaining in the decade.

Kunkel et al. (2012)[34] studied daily extreme precipitation events (those exceeding the threshold for a 1-in-5 year occurrence) in the United States from 1908-2009. This study found that there has been a statistically significant upward trend in the number of extreme precipitation events caused by frontal systems, which is the most common cause of extreme precipitation in the central United States.

Future Projections

Vavrus and Van Dorn (2010) found that the intensity of precipitation events is expected to continue to increase in the future, meaning that more precipitation may be associated with each event. Other studies have come to this same conclusion that heavy precipitation events are likely to increase in the future, although at different rates depending on what threshold is used to define "heavy" precipitation.

Wuebbles and Hayhoe (2004)[35] estimate that both 24-hour and 7-day rainfall events will double by the end of the next century in the Midwest. Kunkel et al. (2012)[36] found that the number of days with precipitation greater than one inch increases by over 30% in the northern portion of the Midwest by the end of the century.

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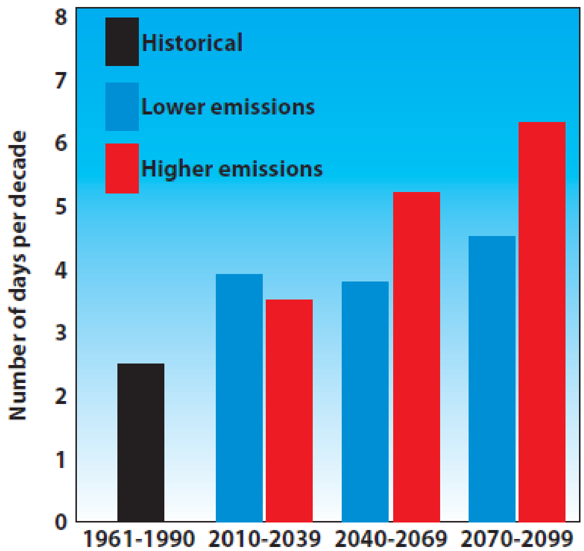
[34] Kunkel, K.E., D.R. Easterling, D.A.R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012. Meteorological Causes of the Secular Variations in Observed Extreme Precipitation Events for the Conterminous United States. *J. Hydrometeorology*, Vol. 13, 3, 1131.

[35] Wuebbles, D.J. and Hayhoe, K., 2004. Climate change projections for the United States Midwest. *Mitigation Adaptation Strategies Global Change*. Vol. 9 (4), 335-363.

[36] Kunkel, K.E., Steven, L.E., and Stevens, S.E., 2012. Climate of the Midwest. *U.S. Guidance document prepared for the US National Climate Assessment*.

Figure 18. Projected number of days per decade with heavy precipitation (more than 2.5" per day) under a low emissions scenario (blue) and high emissions scenario (red) for 2010-2039, 2040-2069, and 2070-2099.



Source: Chicago Climate Action Plan, *Climate Change and Changes in Precipitation*

A few studies have looked at future projections for extreme precipitation specifically for Chicago. Hayhoe et al. (2010)[37] projects that in Chicago, the number of days per decade with heavy precipitation (defined as more than 2.5 inches per day) should increase in the future from the average 2 to 3 per decade based on the 1961-1990 period (figure 18). In the near future (2010-2039), these events may occur 3 to 4 days per decade while by the end of the century (2070-2099), there may be 4.5 days per decade under low emissions and up to 6.5 days under high emissions. Vavrus and Van Dorn (2010)[38] projects that the most extreme events in Chicago (classified as those with more than about 1.5 inches per day) will to increase by more than 25% under a low emissions scenario to over 60% in a high emissions scenario by the end of the century. When looking specifically at the frequency of thunderstorms in the Chicago region, Trapp et al. (2007)[39] found that thunderstorm frequency is likely to increase by the end of the 21st century in the Chicago area.

Periods of Drought

Historical Trends

Drought in northeastern Illinois has become less frequent in recent decades when compared to the historical record (figure 19). The Palmer Drought Severity Index (PDSI) in northeastern Illinois shows periods of significant drought prior to the 1970s, with the summer of 1934 being the most severe drought in the region in recent history. Negative numbers represent periods of drought. The longest period of drought for the region began in the spring of 1962 and continued through the end of 1964, resulting in 34 consecutive months of negative PDSI values. After the early 1970s, periods of non-drought, or wetter conditions, have dominated. The longest period of non-drought conditions was from the summer of 1977 to the spring of 1985, when there were 93 consecutive months with positive PDSI values. Prior to 2012, northeastern Illinois had been in a non-drought pattern since early 2006.

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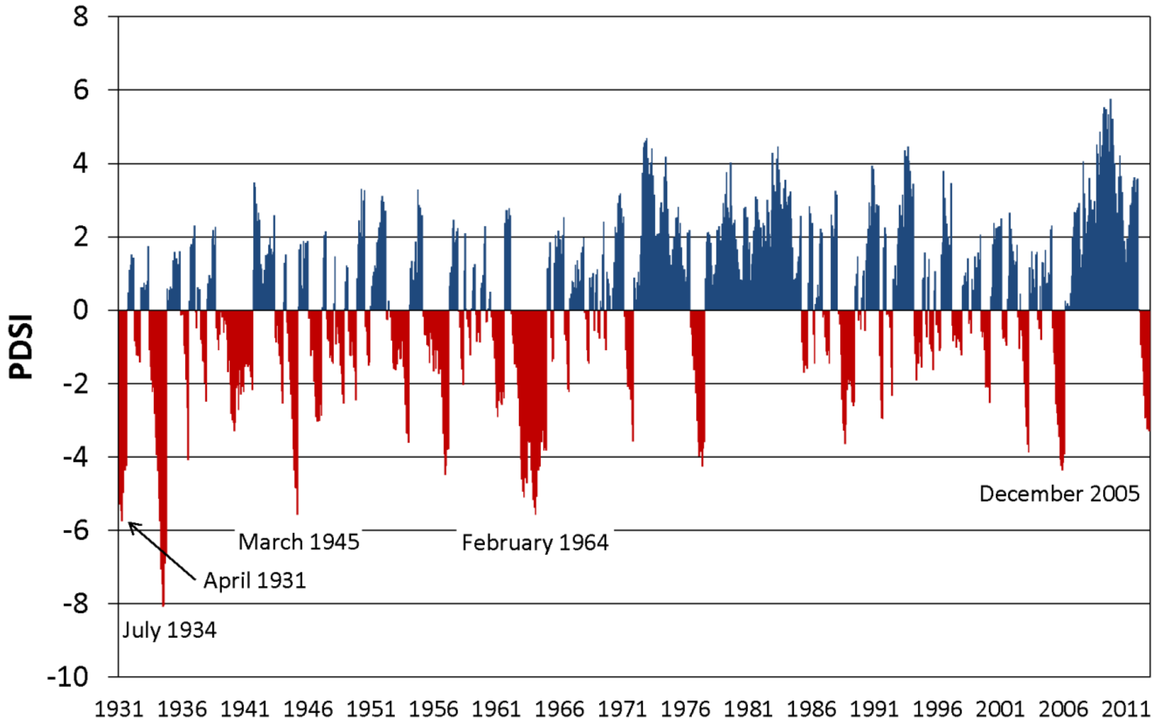
[37] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

[38] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

[39] Trapp, R.J., Diffenbaugh, N.S., Brooks, H.E., Baldwin, M.E., Robinson, E.D., Pal, J.S., 2007. Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proceedings of the National Academy of Sciences.*, Vol. 104 (50), 19719–19723.

Figure 19. The Palmer Drought Severity Index (PDSI) for northeast Illinois. The negative values (red) indicate periods of drought while the positive values (blue) show wet periods.



Source: Midwestern Regional Climate Center

Future Projections

Many studies have suggested that both floods and droughts will increase in frequency in the future in the Midwest.[40] Studies have found that the expected increase in heavy precipitation is larger than the simulated gain in total annual precipitation, meaning that along with an increase in heavy precipitation events, there would also be a decrease in the number of light events.[41] A decrease in the occurrence of light events would result in longer periods of dry conditions, and possibly drought, in between wet precipitation events.

[40] Lofgren, B. and A. Gronewold, 2012: *Water Resources. In: U.S. National Climate Assessment Midwest Technical Input Report*.

[41] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

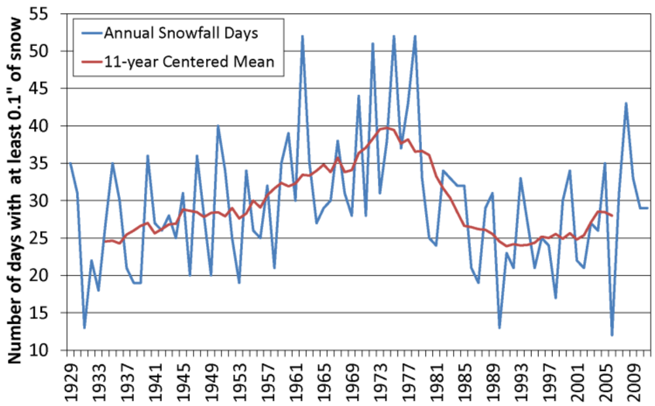
Snowfall

Trend in Snowfall Days

Historical Trends

During the cold-season months, Chicagoans are quite familiar with cold, blustery days that bring snowfall to Chicago and surrounding areas. Based on the climate record at Chicago Midway, the average number of snowfall days (defined here as days with snowfall greater than or equal to 0.1") per year is 29.4 days. Overall, the number of snowfall days has varied greatly over the historical record at Chicago Midway, resulting in no significant positive or negative trend (figure 20). There is an obvious increasing trend from the late 1920's to the very snowy decade of the 1970's, with a sharp decrease after the 1970s. In recent years, it appears that the trend may have started to level out or even a slight increasing trend again, making it uncertain how this trend may continue into the future.

Figure 20: The number of snowfall days (at least 0.1" of snow) at Chicago Midway. The blue line represents the number of days annually while the red lines shows the 11-year centered mean.



Source: Midwestern Regional Climate Center

Future Projections

Hayhoe et al. (2010)[42] found that over the next few decades, little change is expected in the number of snow days per year for more northern states in the Midwest (including the Chicago region). However, by the end of the century, on average the number of snow days per year is expected to decrease. Decreases on the order of 30% to 50% are expected under a low emissions scenario and 45% to 60% under the higher emissions scenario.

Winter Precipitation: More Falling as Rain than Snow?

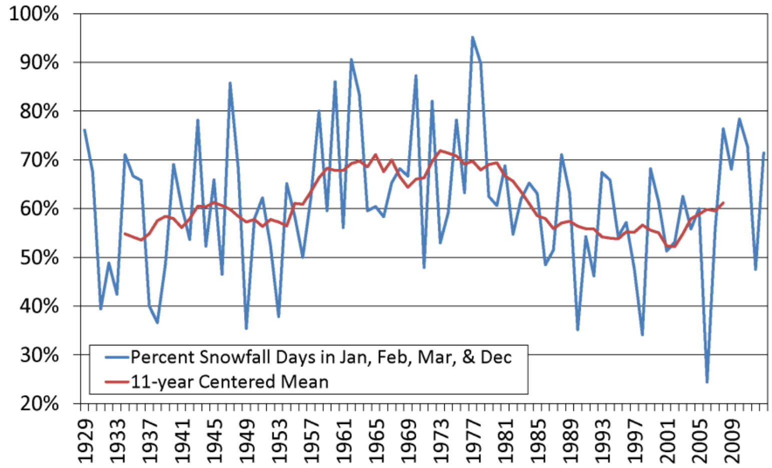
Historical Trends

Typically in Chicago, about 60% of precipitation days during the snowiest months (December, January, February, and March) are days with snowfall, meaning the remaining 40% are typically rainfall days. Some studies have found that for the Chicago region, more precipitation has already been falling as rain and less as snow over the last few decades.[43] Looking at climate data from Chicago Midway, the ratio of snowfall days to precipitation days has been quite variable over the record and there is not a statistically significant trend in either direction (figure 21).

[42] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

[43] Hayhoe, K., J. VanDorn, T. Croley II, N. Schlegal, and D. Wuebbles, 2010. Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 7-21.

Figure 21. The percent of snowfall days in the snowiest months at Chicago Midway (December-March). The blue line shows the percent annually and the red line shows the 11-year centered mean.



Source: Midwestern Regional Climate Center

In this figure, low values show years that had a greater percentage of precipitation fall as rain instead of snow and vice versa for higher values. Since the snowy decade of the 1970's, the data shows that more precipitation has been falling as rain instead of snow. However, in most recent years, the decreasing trend has leveled out or even began increasing again, meaning that there has been a greater percentage of snowfall days.

Future Projections

As winter temperatures increase, studies have found that more winter precipitation is likely to fall as rain instead of snow.[44] However, because winter precipitation is projected to increase overall, the total amount of snowfall is not expected to change much under a low emissions scenario. However, average winter snowfall could drop by about 10 inches under a higher emissions scenario by the end of the century in the Chicago area.

Snowfall Intensity

Historical Trends

In order to determine whether the Chicago region is currently experiencing a shift to more intense snowfall events (i.e. more snow during each event), a variable called "snowfall intensity" is used, which is simply the total annual snowfall divided by the number of days with measurable snowfall (days with snow greater than or equal to 0.1").

While the trend is not strong enough to be statistically significant, there is a steady upward trend in the intensity of snowfall events since the early 1930s (figure 22). Changnon (2007) examined the frequency and intensity of severe winter storms and generally found an increase in intensity over time and a decrease in frequency, with these effects most concentrated in the eastern United States.[45]

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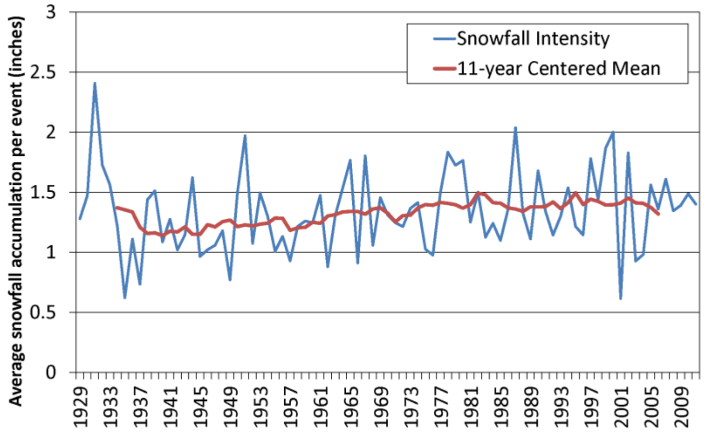
[44] Climate Change and Chicago – Projections and Potential Impacts: Chapter Two – Climate. *Chicago Climate Action Plan*: November 7, 2007.

[45] Lofgren, B. and A. Gronewold, 2012: *Water Resources. In: U.S. National Climate Assessment Midwest Technical Input Report*.

Future Projections

Even though climate models have indicated that the number of snowfall days may decrease in the future, precipitation intensity is expected to increase due a higher moisture-capacity of the atmosphere[46]. Therefore, it is expected that a higher accumulation of snowfall will be associated with snow events when they occur.

Figure 22. Snowfall intensity (total annual snowfall divided by the number of days with measurable snowfall) at Chicago Midway. The blue line shows the average annual snowfall intensity and the red line shows the 11-year centered mean.



Source: Midwestern Regional Climate Center

Lake-Effect Snow Events

Historical Trends

Due to the close proximity to Lake Michigan, winter precipitation in Chicago and surrounding areas is enhanced by lake-effect snows that occur when winds blow from the north or northeast. These winds allow air to pass over the relatively warm lake, boosting storm system energy and water content, leading to increased snowfall. Several studies have looked at the trend in 20th century lake-effect snowfall in the Great Lakes region and many of these studies have found an increasing trend in lake-effect snow.[47] However, one recent study by Bard and Kristovich (2012) found a distinct trend reversal in lake-contribution snowfall during the latter half of the 20th century, beginning around 1980. The exact reason for the reversal is unknown at this time.

Future Projections

Studies looking at future projections for lake-effect snow have shown varying results. Burnett et al. (2003)[48] found an increasing trend in lake-effect snowfall in the Great Lakes region during the 20th century and states that given the projected increases in future global temperature, areas downwind of the Great Lakes may experience increased lake-effect snowfall for the foreseeable future. However, another study by Kunkel et al. (2002)[49] looked at longer-term trends in lake-effect snow based on predicted large-scale weather patterns and found that eventually, lake-

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[46] Vavrus, S. and J. Van Dorn, 2010. Projected future temperature and precipitation extremes in Chicago. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 22-32.

[47] Bard, L. and D.A.R. Kristovich, 2012. Trend Reversal in Lake Michigan Contribution to Snowfall. *J. Applied Meteorology and Climatology*, Vol. 51, 2058-2046.

[48] Burnett, A.W., M.E. Kirby, H.T. Mullins, W.P. Patterson, 2003: Increasing Great Lake–Effect Snowfall during the Twentieth Century: A Regional Response to Global Warming?. *J. Climate*, Vol. 16, 3535–3542.

[49] Kunkel, K.E., N.E. Westcott, and D.A.R. Kristovich, 2002: Effects of climate change on heavy lake-effect snowstorms near Lake Erie. *J. Great Lakes Res.*, Vol. 28, 521-536.

effect snow would be replaced by lake-effect rain, especially for the southern-most lakes like Lake Michigan.

Wind

Historical Trends

Wind climates, particularly wind extremes, represent a major vulnerability to the Midwest region. Unfortunately, the lack of long-term wind speed records, combined with several other data issues, make it difficult to assess the presence or absence of temporal trends in historical wind data in this region.[50] In addition, the most damaging wind events for the Chicago region typically occur at such a small, localized scale that there is no data recording the wind speeds during the event. Therefore, it makes it difficult to obtain observational data and analyze the trends for these damaging wind events.

A study by Pryor and Ledolter (2010)[51] found that in general, there was no evidence of significant changes in the tendency of wind speed over the 1979-2006 time period. Researchers at Iowa State University found that across the country and particularly in the Great Lakes, wind speeds are decreasing, which could not only impact the wind power industry, but also agriculture, pollution in major cities, and ventilation during heat wave events.[52]

Future Projections

Wind climates and wind extremes are somewhat difficult for climate models to simulate because wind, especially extremes, typically occurs at scales below those captured by global and regional climate models or they involve processes that are not well understood. However, the current suite of climate projections suggests little change in wind resources or wind extremes to the middle of the current century.[53]

Plant Hardiness Zone

Historical Trends

Based on the 2012 USDA Plant Hardiness Zone map, a majority of Cook County is classified as zone 6a, while the surrounding counties are zone 5b, indicating that the surrounding counties have a slightly colder average annual minimum temperature (figure 23)[54]. The difference in zones between the City of Chicago and surrounding counties reflect the impact of the urban heat island of Chicago.

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[50] Andresen,J., S. Hilberg, K. Kunkel, 2012: Historical Climate and Climate Trends in the Midwestern USA. In: *U.S. National Climate Assessment Midwest Technical Report.* http://glisa.msu.edu/docs/NCA/MTIT_Historica.pdf

[51] Pryor, S.C., and J. Ledolter (2010), Addendum to "Wind speed trends over the contiguous United States," *J. Geophys. Res., 115*, D10103.

[52] http://www.sciencedaily.com/releases/2009/06/090625202010.htm

[53] Winkler, J.A., R.W. Arritt, S.C. Pryor, 2012: Climate Projections for the Midwest: Availability, Interpretation and Syntehsis. In: *U.S. National Climate Assessment Midwest Technical Input Report. http://glisa.msu.edu/docs/NCA/MTIT_Future.pdf*

[54] http://planthardiness.ars.usda.gov/PHZMWeb/

Figure 23. **The Plant Hardiness Zones in Illinois from the USDA.**

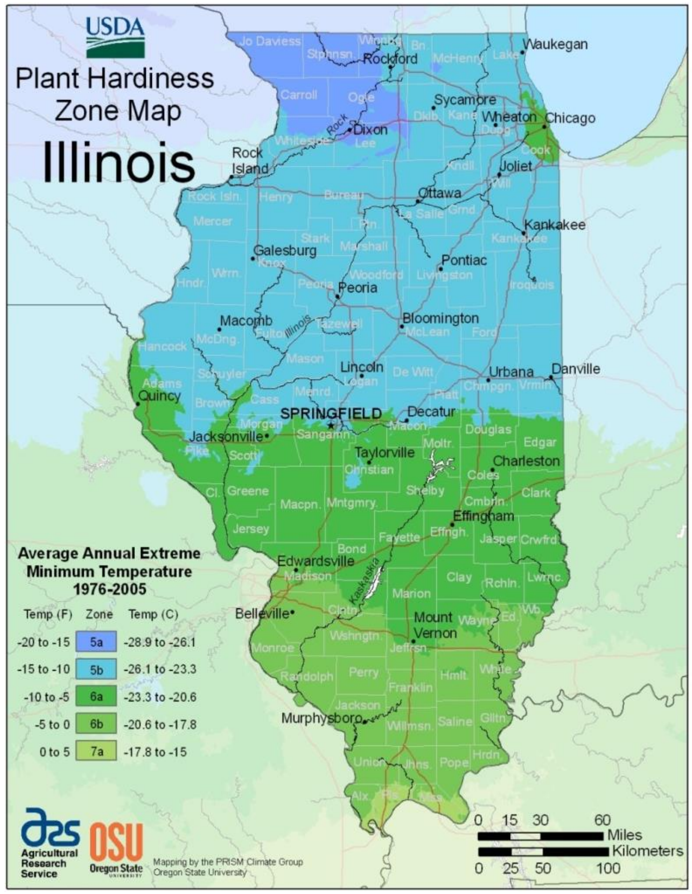
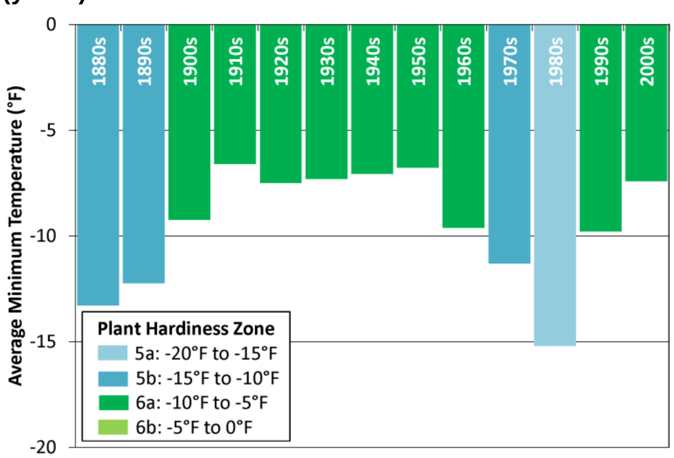


Figure 24 shows Plant Hardiness Zone by decade for the Chicago region, beginning with the 1880s. Except for the colder decades of the 1970s and 1980s when the zone shifted to 5b and 5a, respectively, the region has been consistent in its history as being classified as zone 6a, indicating an average annual minimum temperature between -10°F and -5°F.

Future Projections

In general, Plant Hardiness Zones are projected to move northward as regional temperatures warm.[55] According to Hellmann et al. (2010), within the next few decades, the geographic region near southwestern Lake Michigan (outside of the City of Chicago) will shift from its current zone of 5b (-15°F to -10°F) to zone 6a (-10°F to -5°F), similar to the zone in the City of Chicago or far central Illinois. By mid-century (2040-2069), the zone is projected to be 6a (-10°F to -5°F) under the low emissions scenario or 6b (-5°F to 0°F) under the high emissions scenario, which is similar to that of southern Illinois. Finally, by the end of the century (2070-2099), the Chicago region's zone is projected to be 6b (-5°F to 0°F) under a low emissions scenario (similar to southern Illinois) or 7a (0°F to 5°F) under a high emissions scenario (similar to the Tennessee River Valley).

Figure 24. The Plant Hardiness Zones (bars) by decade, which is determined by the average minimum temperature (y-axis).



Source: Midwestern Regional Climate Center

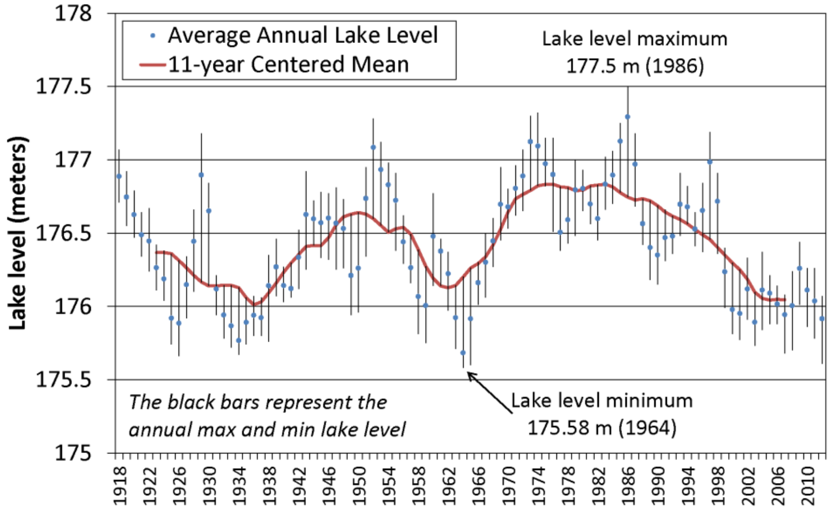
[55] Hellmann, J.J., K.J. Nadelhoffer, L.R. Iverson, L.H. Ziska, S.N. Matthews, P. Myers, A.M. Prasad, and M.P. Peters, 2010. Climate change impacts on terrestrial ecosystems in metropolitan Chicago and its surrounding, multi-state region. *Journal of Great Lakes Research*, Supplement 2, Vol. 36, 74-85.

Lake Michigan

Lake Levels

Historical Trends

Figure 25. Annual lake levels (in meters) for Lake Michigan-Huron. The blue dots represent the average annual lake level, the black bars represent the annual maximum and minimum lake level, and the red line represents the 11-year centered mean.



Source: Great Lakes Environmental Research Laboratory (NOAA)

Several climatic factors control the level of Lake Michigan, including precipitation, evaporation, runoff, outflow, ice cover, air temperature, and other factors. Ultimately, the major factors influencing the level of Lake Michigan are the balance between the input of water to lake (via precipitation and runoff) and the output of water from the lake (via evaporation and outflow). If there is more precipitation and runoff than evaporation and outflow, lake levels are likely to rise. However, if evaporation and outflow are greater than precipitation and runoff, then lake levels are likely to decrease.

Historical annual lake level data was obtained from GLERL, the Great Lakes Environmental Research Laboratory[56], for the Lake Michigan-Huron basin. The level of Lake Michigan-Huron (the two lakes are hydraulically connected so they behave like one larger lake) has been quite variable since observational records began in the late 1910's, exhibiting no significant trend in one direction or another (figure 25). On average, the level of the lakes has varied between about 176 meters and 177 meters, with annual maximum and minimum levels just outside of that. The highest-recorded lake level on Lake Michigan-Huron was 177.5 meters, which occurred in 1986, and the lowest-recorded lake level was 175.58 meters, which occurred in 1964 (2012 was near the record low at 175.61 meters).

Despite the high variability, the observational record shows that since the late 1970s, there has been a steady decline in the levels of Lake Michigan-Huron. In fact, the levels of Lake Michigan-Huron during the fall of 2012 have been near the all-time record low level set in 1964 due to recent dry conditions. With the high variability in the lake level record, it is difficult to determine what may happen to lake levels in the future based solely on observational record.

[56] http://www.glerl.noaa.gov/

Future Projections

With a warmer climate, increased air temperatures could contribute to greater amounts of evaporation from the surface of the lake, potentially contributing to lower lake levels. In addition, a continued trend towards less ice cover on the lakes in the wintertime will allow for more evaporation off the surface of the lake, also contributing to lower levels. However, precipitation plays a role as well.

If precipitation remains constant, increasing temperature should lead to a decrease in lake levels. In addition, any future decreases in annual precipitation are likely to lead to substantial declines in lake levels. However, in the case of increasing precipitation, there will be a counterbalance to the effects of rising temperatures, leading to smaller declines in lake levels or perhaps even small increases in lake levels.[57]

Despite the uncertainty, several model studies have shown greater potential for a decline in Lake Michigan-Huron by the end of the century (Table 1).[58,59,60,61,62,63] Typically, these studies project that by the end of the century, Lake Michigan-Huron levels could be anywhere from almost one meter higher than they are today to 2 to 2.5 meters lower, with a majority of those models favoring a decrease in lake levels. However, despite the favorability towards lower lake levels in the future of most studies, table 1 shows that several studies do show the potential for higher lake levels, especially if annual precipitation increases more than expected.

Table 1. Projected Great Lakes/Lake Michigan-Huron levels by the end of the century, based on results from several studies.

Study	Projected End of the Century Lake Level	Basin
Bruce (1984)	Significantly lower lake levels likely	Great Lakes basin
Hartmann (1990)	-0.13 meters to -2.5 meters	Great Lakes basin
Lofgren et al. (2002)	+0.35 meters to -1.4 meters	Lake Michigan-Huron
Angel and Kunkel (2010)	+0.88 meters to -1.81 meters	Lake Michigan-Huron
NCAR Model	+0.16 meters to -0.99 meters	Lake Michigan-Huron
Hayhoe et al. (2010)	0 meters to -0.55 meters	Lake Michigan
Lofgren et al. (2011)	+0.41 meters to -2.11 meters	Lake Michigan-Huron

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Glossary

11-year centered mean: a continuous average of data over 11 years, utilized to smooth the year-to-year variability in order to observe trends; also known as a moving or running average

24-hour, 10-year storm: calculated to be the level of storm (within a 24-hour period) expected to be equaled or exceeded every 10 years on average or a storm that has a 10% chance of being equaled or exceeded in any single year; typically used to size drainage systems

24-hour, 100-year storm: calculated to be the level of storm (within a 24-hour period) expected to be equaled or exceeded every 100 years on average or a storm that has a 1% chance of being equaled or exceeded in any single year; typically used as a basis for flood protection

Climate change: long-term (decades or longer) and persistent changes in climate trends

Climate model: mathematical representations of Earth's climate system, used to get a picture of what the atmosphere and climate may look like some time in the future in response to natural and anthropogenic (human) processes

Climate normal: a three-decade average of climatological variables, like temperature and precipitation; the most recent climate normals are from 1981-2010

Climate variability: short-term (seasons to decades) variations in climate trends

Cooling degree day: a measurement designed to reflect the demand for energy needed to cool a building; the number of cooling degree days for a given day is calculated by subtracting a base temperature of 65°F from the average daily temperature

Dew point: depicts how much water vapor is present in the atmosphere; it is the temperature below which water vapor in a volume of humid air will condense into liquid water

Drought: an extended period of months or years when a region notes a deficiency in its water supply whether surface or underground water; based on the Palmer Drought Severity Index, when the index is less than zero

Extremely cold day: a day in which the minimum temperature is less than or equal to 0°F

Extremely hot day: a day in which the maximum temperature is greater than or equal to 100°F

Freeze-thaw cycle: fluctuations of air temperature across the freezing point (32°F). The thresholds used in this study for the occurrence of freezing and thawing events in the bare soil at 1-centimeter are a shelter minima and maximum limits set at -3.5°C (25.7°F) and 6.3°C (43.3°F), respectively.

Heat index: an index that combines air temperature and relative humidity in an attempt to determine the human-perceived equivalent temperature (i.e. how hot it actually feels)

Heat wave (NWS definition): as defined by the National Weather Service, heat warnings in Chicago are issued if the heat index is projected to be between 100°F and 105°F for three consecutive days, between 105°F to 110°F for two consecutive days, or any time the heat index is above 110°F

Heating degree day: a measurement designed to reflect the demand for energy needed to heat a building; the number of heating degree days for a given day is calculated by subtracting the average daily temperature from a base temperature of 65°F

Plant Hardiness Zone: a geographically defined area in which a specific category of plant life is capable of growing, as defined by climatic conditions, including its ability to withstand the minimum temperatures of the zone

Precipitation intensity: used to determine how intense precipitation was during a particular storm or time period; determined by dividing total precipitation by a time period (i.e. average annual precipitation intensity would be the total annual precipitation divided by the number of days with measurable precipitation)

Snowfall intensity: used to determine how intense snowfall was during a particular storm or time period; determined by dividing total snowfall by a time period (i.e. average annual snowfall intensity would be the total annual snowfall divided by the number of snowfall days)

Snowfall day: a day with snowfall greater than or equal to 0.1"

Very hot day: a day in which the maximum temperature is greater than or equal to 90°F

Very cold day: a day in which the minimum temperature is less than or equal to 32°F

Methods and Data

In the Chicago region, the stations with the longest and most complete historical climate record are Chicago Midway Airport and Chicago O'Hare Airport. Daily data from Chicago Midway is available from February 1928 to present and hourly data is available from October 1928 to present. Daily and hourly data from Chicago O'Hare is available from November 1958 and is considered the official station for Chicago, Illinois by the National Oceanic and Atmospheric Administration (NOAA). To best represent the seven county region in northeastern Illinois for this project, Chicago O'Hare Airport was selected as the station to examine historical climate data trends for the region for most climate variables. Due to inconsistencies in the snowfall record at Chicago O'Hare, the snowfall analysis is done using daily data from Chicago Midway Airport. Finally, the Chicago ThreadEx station (1871-present) was created as part of the ThreadEx project[64], which addressed the fragmentation of station information over time due to station relocations for the express purpose of calculating daily extremes of temperature and precipitation. Therefore, this study uses the Chicago ThreadEx station when daily extremes for plant hardiness zone are analyzed.

[64] http://threadex.rcc-acis.org/

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