CHICAGO CLIMATE ACTION PLAN

# CLIMATE CHANGE AND CHICAGO

PROJECTIONS AND POTENTIAL IMPACTS

CHAPTER TWO – CLIMATE

11-07-2007

**This research was commissioned by the Chicago Climate Task Force in the development of the Chicago Climate Action Plan. It does not represent official City of Chicago policy.**

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**CHAPTER**
***Two***

# CLIMATE

Climate in Chicago is largely determined by its location in the middle of continental North America. Situated in the heart of the Midwest, Chicago is 800 miles due west of New York City, 900 miles north of New Orleans, and more than 2000 miles due east of northern California. Far from the moderating effects of the oceans, Chicago's weather conditions vary widely over the course of a year. Sudden changes of weather, large daily temperature ranges, and unpredictable precipitation patterns are all staples of Chicago weather.

Chicago typically has four distinct seasons, although those seasons can be highly variable and year-to-year variations can be large. In the winter, the absence of significant mountain barriers to the north allows bitterly cold air masses from the Arctic to move southward into the region. In January, the coldest month, high temperatures average 31°F, while low temperatures average 16°F. The coldest temperature ever recorded in Chicago was on January 20, 1985, where temperatures dropped to -27°F with a wind chill of -83°F. The polar jet stream is often located near or over the region during the winter, as well. As a result, frequent storm systems in the winter bring cloudy skies, windy conditions, and frequent precipitation. In winter, most of precipitation tends to fall as snow. The snowiest winter ever recorded in Chicago was 1929-30, with 114.2 inches of snow in total. On average, Chicago receives 38 inches of snow each winter, with most of that falling in December, January and February.

**CHICAGO WEATHER RECORDS**

Coldest temperature: –27°F with a wind chill of –83°F on January 20, 1985.

Most snow in a year: 114.2 inches of snow during the winter of 1929–30

Highest temperature: 105°F at Midway Airport on July 17, 1995

Most rain in a day: 6.49 inches on August 14, 1987

In contrast, Chicago summers are characteristically hot and humid due to a semi-permanent high pressure system in the subtropical Atlantic that draws warm, humid ocean air into the area. July is the warmest month of the year, where daytime temperatures average 84°F and nighttime temperatures, 66°F. There are typically about 18-21 days each summer with daily maximum temperature over 90°F. According to the National Weather Service, the highest official temperature ever recorded was on July 17, 1995, where daytime temperatures at Midway Airport soared to 105°F during the major heat wave that year. Summer also tends to be the rainiest season, with short-lived rainfall and thunderstorms more common than prolonged rainy periods. Chicago's highest one-day rain total was 6.49 inches, on August 14, 1987.

Although Chicago is far from the oceans, it is located on the western shore of Lake Michigan, the second largest of the Great Lakes. The Great Lakes have a substantial impact on climate. Because large bodies of water lose and gain heat more slowly than surrounding land masses, the surface water temperatures of the lakes tend to be warmer than the land during the late fall and early winter. Conversely, the water is much colder than the surrounding land in the late spring and summer. This has a moderating influence on air temperatures near the shores of the lakes.

Chicago often experiences microclimatic effects from Lake Michigan, especially during summer months. Very often during the summer a local lakeshore breeze will bring much cooler air into Chicago than experienced by other Midwest cities. However, the effect is so local that only the immediate shoreline region is affected. The lake breeze also depends on the direction of the prevailing wind; part of the reason why temperatures during the 1995 heat wave were so high was likely due to the lack of lake breeze during that time.

## Climate is changing

“Climate,” which refers to the average conditions in a given location, is relatively consistent over time scales of decades to centuries. Year-to-year weather patterns average out to give a picture of what a typical or “climatological” year might look like. For example, although winter temperatures from 1928 (when the observational record began at Midway Airport) to the present have ranged from as cold as 18$^{o}$F in 1936, to as warm as 34$^{o}$F in 2002, the climatological average winter temperature in Chicago over that time period was 27$^{o}$F.

Over longer time scales, however – on the order of centuries to millennia – climate or "average" conditions in the Midwest can be very different than today. During the last ice age that ended about 10,000 years ago, temperatures were approximately 10°F to 15°F cooler than today. Northeastern Illinois, including Chicago's location, looked radically different, covered by glaciers over a mile thick. When the glaciers retreated, they left behind them deposits of rock, stone and silt that can be seen today.

Until recent decades, both smaller short-term and larger long-term changes in mean climate in the Chicago region were driven primarily by natural variations in the climate system. Many of these are cyclical, returning again and again in recognizable patterns. For example, the El Niño and La Niña phenomenon, manifested by the changing temperature of ocean currents off the coast of Peru, recurs every two to five years. This cycle drives weather patterns that affect conditions in many parts of the world, including Chicago (Figure 2.1). When the warm-water El Niño dominates, Chicago sees warmer-than-average conditions all year round, particularly in summer and fall daytime maximum temperatures. Precipitation in spring and summer tends to be slightly below average, while autumns and winters are wetter than normal. In contrast, during a cool-water La Niña event, Chicago winter and spring temperatures are warmer than average, but summer and autumn months are cooler. Fall precipitation is also significantly lower than average. There are several other natural cycles in the Earth's atmosphere and ocean that regularly affect climate in the Midwest from year to year. These include the Arctic Oscillation, the North Atlantic Oscillation, and the Pacific-North American Pattern, all of whom have similar effects to the El Nino phenomenon – i.e., causing specific seasons to be warmer or cooler (or wetter or drier) than normal.

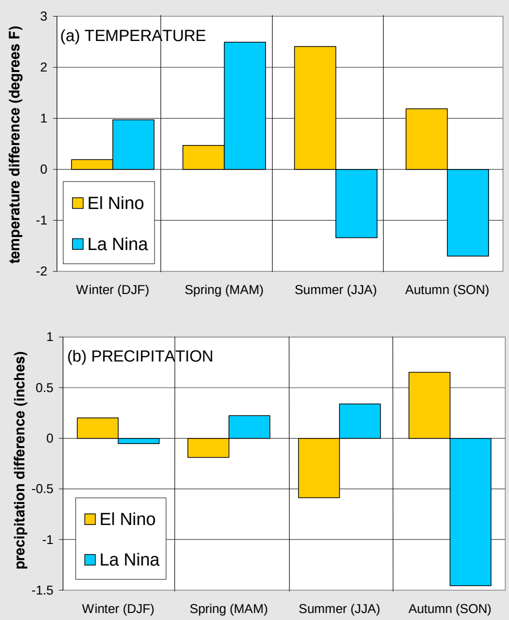


**Figure 2.1.** Observed differences in Chicago's seasonal average temperature and precipitation during El Nino and La Nina years as compared to the 1950-2000 average for each season. Temperature differences are in degrees F while precipitation differences are in units of inches per season.

In terms of other causes for natural climate change, major volcanic eruptions, while not cyclical, generally occur at least several times each century. Although the eruptions may be far removed from Chicago, a truly powerful volcano can spew dust all the way up into the stratosphere, where it can circle the globe for several years, reflecting solar radiation back to

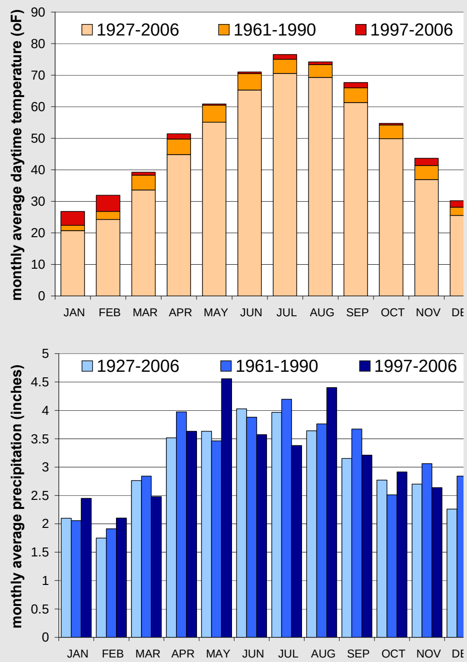


**Figure 2.2.** Monthly average (a) temperature (in degrees F) and (b) precipitation (in inches) observed at the Chicago Midway weather station. Averages are shown for the entire period of record (1927-2006), for the historical reference period used here to define Chicago's climatology (1961-1990), and for the last ten years of record (1997-2006).

space and cooling the underlying regions. For example, the 1992 eruption of Mt. Pinatubo in the Philippines was followed by five years of lower-than-average annual temperatures in Chicago.

Ultimately, however, energy from the sun is what makes life possible on earth and drives its dominant natural climate changes. The most noticeable climate cycle related to the sun is that of the seasons – as the angle between the Earth's spin axis and its orbital plane change over the course of a year, the length of day and the angle of the sun in the sky changes. These result in small but significant differences in the amount of radiation reaching the surface of the Earth in each hemisphere. These differences grow stronger with latitude, to the point where high latitude locations such as the poles experience nearly continuous daylight in summer and weeks of blackness during winter. Over longer time periods (on the scale of centuries to millennia), periodic shifts in the parameters of the earth's orbit around the sun cause more sustained variations in the amount of solar radiation the earth receives. In particular, periodicities in the parameters of the Earth's orbit around the Sun combine to create a 100,000-year cycle of ice ages and warmer interglacial periods that is strongly reflected in ice core records of temperature over the last 700,000 years.

In the past, most climate variations in the Chicago area and around the world have been driven by natural factors such as changes in solar radiation, dust from volcanic eruptions, and natural cycles of the earth-ocean-atmosphere system. Over the last 50 years, however, the story is very different. The extensive community of scientists studying this issue have now concluded that it is very likely (implying a greater than 90% certainty) that most of the observed changes in climate since mid-century have been due to emissions of heat-trapping gases from human activities[1].

Since the Industrial Revolution, we have become increasingly dependent on coal, gas, and oil to supply our energy needs. Electricity, transportation, manufacturing, waste treatment, agriculture, heating and cooling – all of these produce emissions of carbon dioxide, methane, and nitrous oxide. These gases trap heat in the atmosphere that would otherwise escape to space, increasing the temperature at the earth's surface. Over the rest of this century, human-induced warming is projected to raise global temperatures by an additional 3 to $7^{o}F$[2].

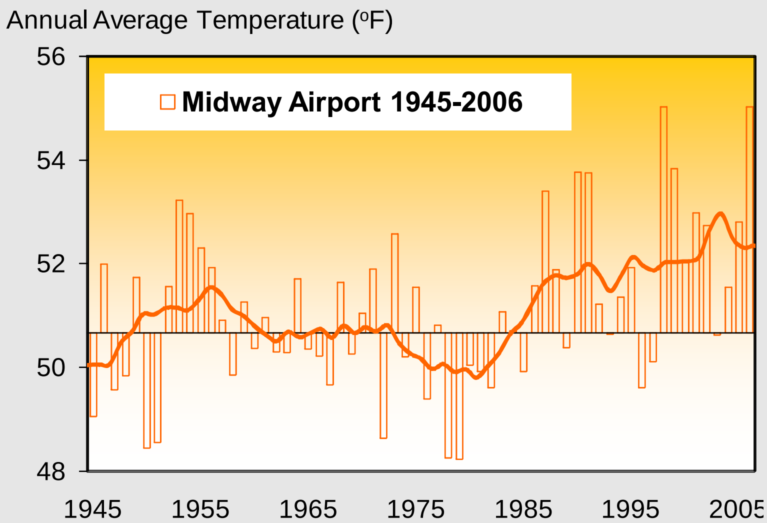


**Figure 2.3.** Annual average observed temperatures at the Chicago Midway weather stations from 1945 to the present. The 10-year running mean is indicated by the solid line.

Human-induced climate change is already causing warmer temperatures and changing weather patterns around the globe. Trends such as these, occurring over as short a time span as a few decades, are generally easier to detect at the global scale than on a regional basis. The finer the spatial scale, the higher the year-to-year variability and the more difficult it is to detect a long-term trend (see, for example, the annual temperature values in Figure 2.3). However, careful analyses of Chicago's weather records do reveal some significant shifts in temperature, total precipitation, and extreme events over the last century.

Comparing average monthly temperatures over the time period during which Chicago weather stations have been regularly recording daily temperatures (1926 to 2006) with average temperatures over the historical reference period (1961-1990) and over the last 10 years (1997-2006), Chicago temperatures have warmed by about 5$^{o}$F (Figure 2.2). Since the 1970s temperatures have increased steadily (Figure 2.3), particularly in winter. In the last four years, annual average temperatures have all been from 2-4$^{o}$F above the long-term average and up to 7$^{o}$F above average during the winter.

The recent warmth is comparable in magnitude to warm periods during the 1930s and 1950s. However, the warm periods in the past were much more regional in scale. They don't display the same large-scale "fingerprint" of today's warming, with global-scale changes consistent with what would be expected from increasing greenhouse gas levels in the atmosphere. Thus, they are unlikely to have been primarily anthropogenic, or human, in origin.

Other temperature and precipitation-based indicators show trends consistent with a warming climate. These include:

- A scarcity of cold waves during the 1990s, in contrast to the frequent cold waves lasting a week or more that characterized the late 1970s and early 1980s.[3]

- A number of extreme heat waves bringing record high temperatures (1995, 1999, 2006)[4]
- A progressive advance in the date of last spring freeze, with current dates being approximately 1 week earlier than the beginning of the 1900's. Growing seasons have also begun to lengthen as the length of the growing season in Illinois has become roughly one week longer during the twentieth century, and first bloom dates are coming earlier in spring. [5,6,7,8]
- Increased risk of potato late blight and other pests due to warmer and wetter growing season in the upper Great Lakes. [9]
- A doubling in the frequencies of heavy rain events (defined as occurring on average once per year during the past century) since the early 1900s. Also an increase in the number of individual rainy days, short-duration (one to seven days) heavy rain events, and week-long heavy rain events. Although the frequency of individual events is highly variable, the climatic shift to more multi-day periods of heavy rain appears to be the major reason that hydrologic flooding in Iowa, Missouri and Illinois has increased since the 1920s.[10,11,12,13]
- Formation of ice on inland lakes later in the year, and a shorter overall duration of winter lake ice, with some years being nearly entirely ice-free. [14,15,16]
- Recent decreases in ice and snow cover and duration across the Great Lakes, much more rapid than any changes that have occurred over at least the last 250 years. [17]
- Changes in the hydrological cycle, with a decrease in spring snow cover, followed by earlier dates for spring melt, and peak streamflow and lake levels. [18]
- Increases in fall precipitation resulting in increased annual mean and low flow of streams, without any changes in annual high flow. [19]
- Increasing lake-effect snow during the twentieth century which may be a result of warmer Great Lakes surface waters and decreased ice cover. [20]
- A shift in the timing and range of the seasonal cycle for Lake Michigan-Huron, with greatest changes occurring during winter and spring as snowmelt and runoff shifting to earlier in the year. The winter increase seems to be occurring at the expense of decreasing spring runoff, suggesting a hydrologic response to a warming climate. [21,22]

- A significant decrease in Lake Michigan annual maximum ice concentration, from its long-term (1963-2001) average of 33% to the most recent 4-year average (1998-2001) of 23%, setting a new record low. [23]
- An increase in Great Lakes near-shore water temperatures (measured at Sault Ste. Marie and Put-In-Bay) of almost 0.2°F per decade since 1920, accompanied by an increase in the duration of summer stratification[1] of more than two weeks. [24]

Most of these recently-observed changes are still within the range of natural variability for the region. For that reason, it is not yet possible to definitively attribute these observed trends in Chicago's climate to human-induced climate change. However, the patterns of change are very similar to those seen elsewhere around the globe, strongly suggesting a connection to human-driven climate change. Furthermore, model simulations of the past century show similar trends in temperature, extreme rainfall events, and related climate indicators, many of which are projected to be amplified in coming decades as emissions of heat-trapping gases continue to grow and the influence of human activities on global climate intensifies.

## Climate data and models

To examine past changes in climate, we rely on daily and hourly records of temperature, precipitation, humidity, snow, cloudiness and other relevant climate variables observed at 14 National Weather Service weather stations in and around the Chicago metropolitan region. These stations (Figure 2.4) were selected based on the length of their records, requiring at minimum 40 continuous years of data up to 1990. Weather data from these stations can be used to estimate trends in seasonal and annual temperatures and precipitation, as well as day-to-day variations in extreme-heat days or heavy rainfall events. To define climate trends for the city of Chicago itself, we average the observations taken at three of those stations, Chicago Midway Airport, Chicago O'Hare Airport, and the University of Chicago (Figure 2.3), in order to account for spatial differences in temperature and precipitation across the city.

[1] Duration of summer stratification is based on the last occurrence of a 39°F surface water temperature in spring and the first occurrence of a 39°F temperature in fall, marking the maximum potential duration of summer thermal stratification. The longer the duration of summer stratification, the longer the warm period.

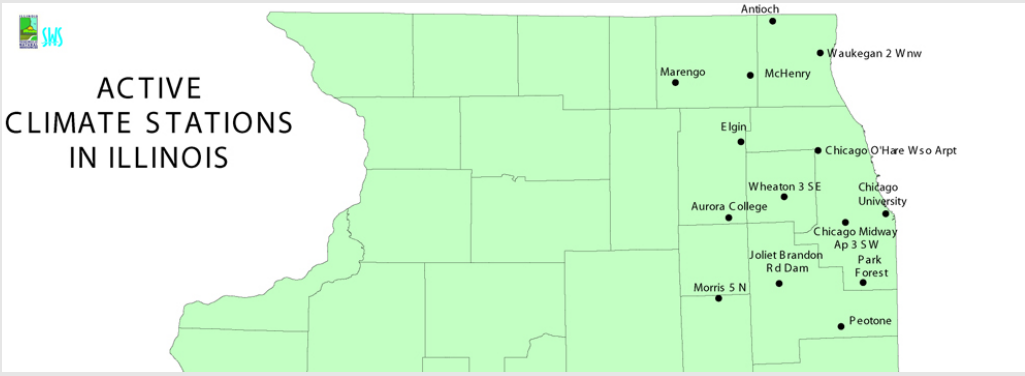


**Figure 2.4.** NWS weather stations used for the Chicago analysis meeting the minimum data length requirements of 40 continuous years of coverage up to at least 1990. (Source: Midwestern Climate Center,

http://www.sws.uiuc.edu/atmos/statecli/General/sites_available_in_illinois.htm).

To examine future changes in climate, we rely on climate model projections of how these same climate variables might be altered over the coming century. Climate model simulations are based on assumptions about population, energy use, and technology, called *emission scenarios*. The emissions of heat-trapping gases that would occur under those assumptions are then used as input to *global climate models*. Climate models treat the earth-ocean-atmosphere system as a series of grids, with each individual grid cell or box being somewhere on the order of 100 to 300 miles on each side. This resolution is too coarse to study climate change for a single location, such as Chicago. For that reason we also use advanced *statistical downscaling* methods that relate projected large-scale changes from climate model output to local conditions on the ground.

## Emission scenarios

Forecasts of changes in future climate due to emissions from human activities begin with the development of emission scenarios. These scenarios are not predictions, but represent plausible future conditions under particular assumptions. Based on a consistent set of assumptions, projections of population, demographics, technological developments, economic growth, energy supply and demand, and land use are developed. These projections are used as input to complex socio-economic models that estimate emissions of heat-trapping and other important gases resulting from human activities in a number of sectors, including agriculture, commercial & residential, forestry, industry, transportation, and other sectors of the economy.

The reference standard for emission scenarios are those developed by the Intergovernmental Panel on Climate Change (IPCC). The basis for the climate analyses presented in this report is the 'high emissions' and 'low emissions' scenarios from the latest IPCC Special Report on Emission Scenarios[25]. These scenarios use a variety of projections for future population, demographics, technology, and energy use to estimate possible future changes in heat-trapping gas emissions. This wide range of plausible futures can then be used to assess the differences in the extent and severity of the global warming that would result from alternative emissions choices that societies may make.

In this study, we use the SRES A1fi (fossil-intensive) and the B1 scenarios to represent possible higher- and lower-emissions choices, respectively, over the rest of the century (Figure 2.5a). Although these span the range of possible futures simulated by the IPCC emission scenarios, depending on the choices made over coming decades, emissions could end up being higher than A1fi (if the world continues to depend on fossil fuels without significant efficiency improvements), or lower than the B1 scenario (if substantial legislation is enacted to promote alternative energy sources and reduce emissions). The difference between the A1fi (higher) and B1 (lower) scenarios, however, is sufficient to illustrate the potential range of changes that could be expected and how these depend on the future emissions choices we make.

The higher-emissions scenario (A1fi) represents a world with fossil fuel-intensive economic growth and a global population that peaks mid-century and then declines. New and more efficient technologies are introduced toward the end of the century. In this scenario, atmospheric carbon dioxide concentrations reach

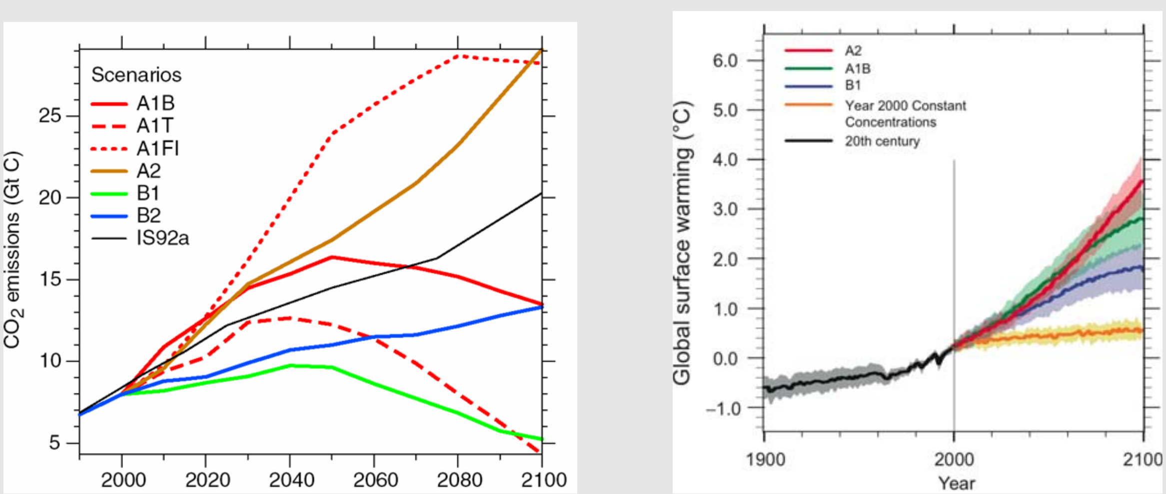


**Figure 2.5.** (a) Carbon dioxide emissions and (b) projected future global temperature changes corresponding to the IPCC SRES emission scenarios. (Sources: Nakicenovic, 2000; IPCC WG1 2007).

940 parts per million (ppm) by 2100—more than triple and almost four times pre-industrial levels. The lower-emissions scenario (B1) also represents a world with high economic growth and a global population that peaks mid-century and then declines. However, this scenario includes a shift to less fossil fuel-intensive industries and the introduction of clean and resource-efficient technologies. Emissions of heat-trapping gases peak around mid-century and then decline. Atmospheric carbon dioxide concentrations reach 550 ppm by 2100—about double pre-industrial levels.

## Climate models

Large, three-dimensional, coupled atmosphere-ocean General Circulation Models (AOGCMs) of the Earth's climate system are the reference standard for global change research. These models incorporate the latest understanding of the physical processes at work in the atmosphere, oceans, and the earth's surface. Models are constantly being enhanced as our understanding of climate improves and as computational power increases. As output, they produce gridded projections of precipitation, temperature, pressure, cloud cover, humidity, and a host of other climate variables at daily, monthly, and annual scales.

Because of the complexity of these models, they are generally designed and run by large research teams at supercomputing centers. Over time, the number of global climate models has grown. By 2006, 16 international climate modeling teams submitted historical and future simulations from 23 different climate models to the Intergovernmental Panel on Climate Change's Fourth Assessment Report[26]. Although some models were more successful than others at reproducing observed trends over the past century, all future simulations agreed that both global and regional temperatures will increase over the coming century in response to increasing emissions of heat-trapping gases from human activities (Figure 2.5b).

For the Chicago region, projections from these IPCC models also indicate that temperatures will continue to warm over the rest of the century (Figure 2.6). Specifically, over the near-term (2010-2039) annual temperatures are projected to rise by 1 to 2$^{o}$C. By mid-century (2040-2069), temperatures are likely to warm by 1.5 to 5$^{o}$C. By the end of the century (2070-2099), annual temperatures are likely to be anywhere from 2 up to 7$^{o}$C warmer than during the historical reference period 1961-1990. This range is partially a function of the different emission scenarios underlying each climate model simulation. In contrast to lower emissions (blue and green symbols in Figure 2.6), higher emissions (as

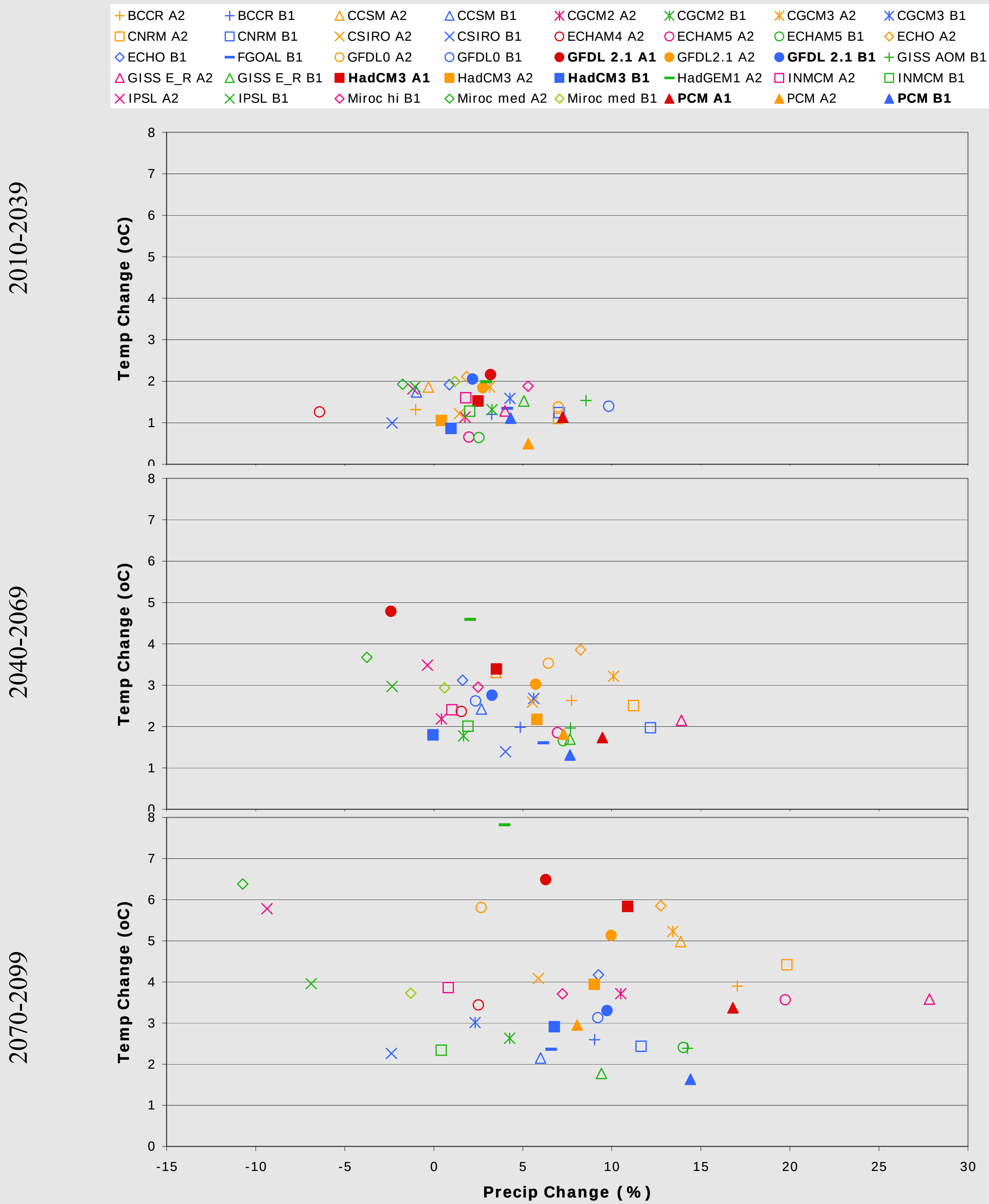


**Figure 2.6.** Projected change in annual average temperature (°C) and precipitation (%) over Chicago relative to the 1961-1990 average values, as simulated by 21 IPCC AR4 climate models, for the SRES higher (A1fi), mid-high (A2), and lower (B1) emission scenarios. Projections are shown for the near-term period (2010-2039), mid-century (2040-2069) and end-of-century (2070-2099). Model simulations used in this assessment to estimate climate impacts on Chicago are indicated by the solid shapes.

indicated by the red, orange and pink symbols) imply greater temperature changes, particularly towards the end of the century. However, the models also differ in their “climate sensitivity”. Climate sensitivity is defined as the temperature change resulting from a doubling of atmospheric carbon dioxide concentrations relative to pre-industrial times. It determines the extent to which temperatures will rise under a given increase in atmospheric concentrations of heat-trapping gases. Because many of the processes at work in the earth-atmosphere system and their feedbacks are not yet fully understood, these are represented somewhat differently in different global climate models. Hence, some models suggest a larger temperature increase in response to a given emissions scenario, while others show a small increase under the same scenario.

Different climate models also tend to represent cloud processes and the hydrological cycle differently. This produces a range in projected changes in precipitation over time, as well. Over the near-term, most models estimate annual precipitation changes ranging from decreases of a few percent to increases of up to +7% (Figure 2.6). By mid-century the range is broader, from –2 up to +10%. By the end of the century, only two models show decreases in precipitation; all the others indicate likely increases, up to 20% annually.

| | Annual | Winter (DJF) | Spring (MAM) | Summer (JJA) | Autumn (SON) |
|---|---|---|---|---|---|
| Projected change in temperature (ºC relative to 1961-1990 average) | | | | | |
| near-term (2010-2039) | 1 to 2 | 1 to 2 | 0.5 to 2 | 0.5 to 3 | 1 to 2 |
| mid-century (2040-2069) | 1.5 to 5 | 1.5 to 4.5 | 1.5 to 3.5 | 1.5 to 7.5 | 1.5 to 4.5 |
| end-of-century (2070-2099) | 2 to 7 | 2 to 6.5 | 2 to 5.5 | 2 to 10.5 | 2 to 6.5 |
| Projected change in precipitation (% relative to 1961-1990 average) | | | | | |
| near-term (2010-2039) | -2 to +7 | -4 to +14 | -2 to +13 | -13 to +7 | -7 to +8 |
| mid-century (2040-2069) | -2 to +10 | 0 to +20 | +1 to +23 | -36 to +9 | -7 to +11 |
| end-of-century (2070-2099) | -1 to +19 | +3 to +33 | +2 to +40 | -47 to +14 | -6 to +20 |

**Table 2.1.** Projected changes in temperature (in degrees C) and precipitation (in percentage) relative to 1961-1990 average as simulated by the full range of IPCC climate models. The range is defined as two standard deviations about the mean value based on available climate

On a seasonal basis, larger temperature increases are generally projected for summer and, to a lesser extent, for winter, as opposed to spring and fall (Table 2.1). Nearly all model simulations show precipitation increasing during winter and spring by the end of the century, but results are split for the summer months. Although many models suggest potentially large decreases in precipitation of up to almost –50% in summer, some also show modest increases of up to 14%.

Regional climate impacts assessments such as this one require climate projections as input to a wide range of impact models, to estimate the potential impacts of climate change on the region's hydrology, lake levels, trees, birds, mammals, air quality, human health, etcetera. Due to the enormous time commitment involved in completing all these simulations, it is virtually impossible to do so for each of the individual climate model simulations submitted to the IPCC's Fourth Assessment Report and shown in Figure 2.6. Instead, estimates of climate change impacts on the Chicago region must be based on a limited number of climate model simulations that are, to the extent possible, representative of the range of future projections.

To this end, a set of 3 climate models and 6 simulations were selected for this report. Their selection was based on several criteria, both scientific and practical, consisting of the following: (1) only well-established models were considered, that were already extensively described and evaluated in the peer-reviewed scientific literature; (2) only models that had participated in the Coupled Model Intercomparison Project[27] or otherwise been evaluated and shown to adequately reproduce key features of the atmosphere/ocean system, including seasonal circulation patterns, the Jet Stream, atmosphere-ocean heat fluxes, El Niño, etc.[28]; (3) simulations that had output saved at the daily (rather than monthly) time scales required for many of the impact analyses; (4) models with simulations available covering the full range of SRES scenarios (from A1fi to B1) in order to identify significant differences between higher and lower emissions futures; (5) where possible, models that were compatible with previous regional analyses[29]; and finally (6) models with a variety of climate sensitivity and hydrological parameterizations so as to capture a large part of the possible range of changes in both annual and seasonal temperature and precipitation over the coming century as shown in Figure 2.6 and Table 2.1.

Based on these criteria, three global climate models were selected for use in this analysis: the U.S. National Atmospheric and Oceanic Administration's Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1, the United Kingdom

Meteorological Office's Hadley Centre Climate Model, version 3 (HadCM3), and the National Center for Atmospheric Research's Parallel Climate Model (PCM)[30]. The primary characteristics of these models are described in Table 2.2. GFDL and HadCM3 have medium to medium-high climate sensitivities, while PCM has low climate sensitivity. This means that, for a given increase in heat-trapping gases in the atmosphere, GFDL will produce the highest temperature change, and PCM the lowest, with HadCM3 lying in the middle between these two. In this way we explicitly include the scientific uncertainty in determining the response of the climate system to increasing emissions from human activities, while the socio-economic uncertainty is incorporated by estimating changes that would result from a higher and lower emissions scenario.

| Model | Host Institution | Resolution | Reference |
|---|---|---|---|
| GFDL CM2.1 | National Ocean and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory (USA) | 1.8 degrees | Delworth et al., 2006 |
| HadCM3 | U.K. Meteorological Office, Hadley Centre (U.K.) | 2.5 x 3.75 degrees | Pope et al., 2000 |
| PCM | National Center for Atmospheric Research (USA) | 2.8 degrees | Washington et al,. 2000 |

**Table 2.2.** Description of the three global climate models used in this analysis.

## Downscaling

Global models provide a "coarse-scale" resolution, with geographic grid cells ranging in size from 50 to 250 miles per side. In general, this type of resolution is too coarse to capture the kinds of fine-scale changes we are already experiencing and are likely to continue experiencing in Chicago and across northern Illinois. For that reason, two statistical downscaling techniques were also used to transform the global climate model output into higher-resolution projections on the order of tens rather than hundreds of miles.

Statistical downscaling relies on historical instrumental data for calibration at the local scale. A statistical relationship is first established between AOGCM output for a past time period and observed temperatures and precipitation. This relationship is averaged over a relatively long period of time, such as 30 or 40 years, to remove year-to-year fluctuations. The historical relationship between AOGCM output and monthly or daily climate variables at the regional scale is then used to downscale both historical and future AOGCM simulations to that

**Gridded Downscaling Technique**

Monthly AOGCM temperature and precipitation fields were statistically downscaled to daily values for regions with a resolution of 1/8. Downscaling used an empirical statistical technique that maps the probability density functions for modeled monthly and daily precipitation and temperature for the climatological period (1961–1990) onto those of gridded historical observed data, so the mean and variability of both monthly and daily observations are reproduced by the climate model data. The bias correction and spatial disaggregation technique is one originally developed for adjusting AOGCM output for long-range streamflow forecasting (Wood et al., 2002), later adapted for use in studies examining the hydrologic impacts of climate change, and compares favorably to different statistical and dynamic downscaling techniques.

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Wood AW, Maurer EP, Kumar A, Lettenmaier DP (2002) Long-range experimental hydrologic forecasting for the eastern United States. J. Geophys. Res. 107, Art. No. 4429.

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**Station-Level Downscaling Technique**

This method uses a deterministic statistical approach to rescale AOGCM grid-cell temperature values on based on simple monthly regression relations. AOGCM-simulated time series were first modified so that the overall probability distributions of simulated daily values approximated the observed probability distributions of air temperatures at weather stations in each city (Dettinger et al. 2004). The regression relations derived from the historic observed and model-simulated time series were then applied to future simulations, such that rescaled values share the weather statistics observed at the selected stations. At the daily resolution addressed by this method, the need to extrapolate beyond the range of the historically observed parts of the probability distributions was rare even in the future simulations (typically, <1% of the future days), as most of the climate changes involve more frequent warm days rather than warmer-than-ever-observed days.

Reference:


Dettinger, M. D., D. R. Cayan, M. K. Meyer, and A. E. Jeton. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099. Climatic Change 62:283-317


same regional scale. Unlike regional climate modeling, statistical downscaling assumes that the relationships between large- and small-scale processes remain fixed over time—an assumption that may not always be justified for precipitation. However, statistical downscaling has a substantial time and cost advantage; hundreds of years of model simulations can be downscaled using the same computing resources required to run only a few years of regional-model downscaling.

Two statistical methods are used to downscale AOGCM-based monthly temperature and precipitation fields for the A1fi and B1 emissions scenarios. The first method[31] produces monthly and daily temperature and precipitation projections on a regular one-eighth-degree grid covering the entire states of Illinois, Indiana, Michigan, and Wisconsin, while the second approach[32] produces daily temperature and precipitation projections for each of seven Chicago-area stations: O'Hare, Midway, University, Aurora, Elgin, Joliet, Park Forest, and Wheaton.

# Future temperature changes

## Seasonal and annual temperatures

Over the coming century, temperatures in Chicago are projected to continue to rise. Through the next few decades, the amount of climate change that will occur is largely entrained by past emissions; hence, no difference is seen between a lower vs. a higher emissions scenario over that time.

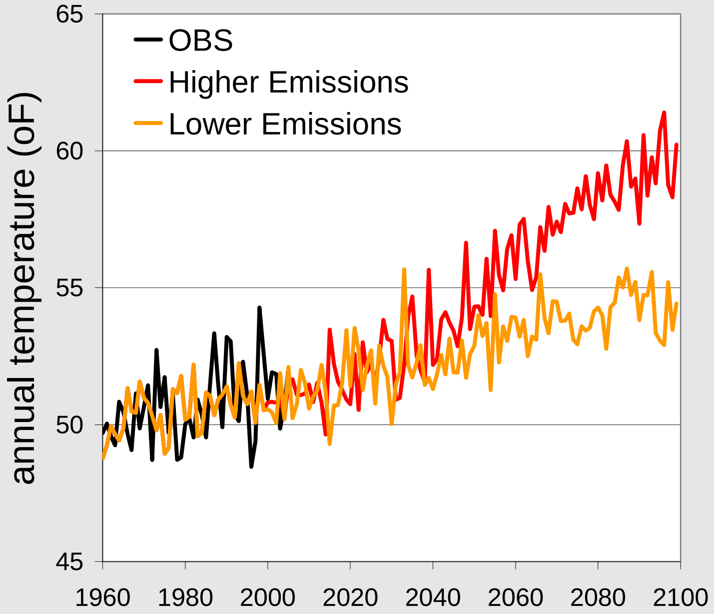


**Figure 2.7.** Observed and model-simulated historical and projected future annual average temperatures for Chicago. Model simulations show the average of the GFDL, HadCM3 and PCM models for the higher (A1fi) and lower (B1) emissions scenarios.

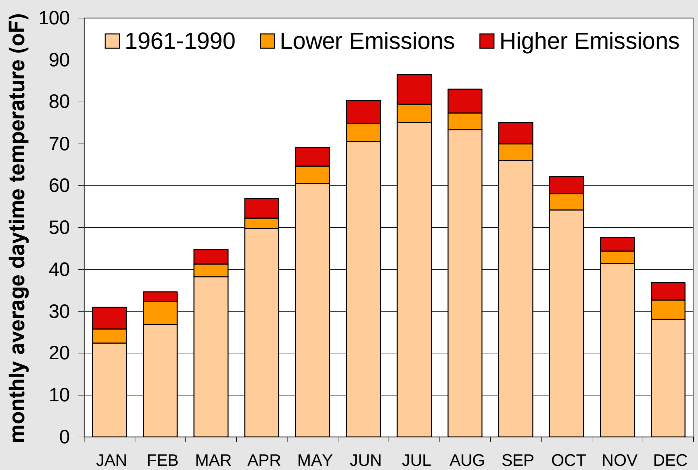


**Figure 2.8.** Monthly average temperatures for Chicago for the historical reference period 1961-1990 and for end-of-century (2070-2099) under the higher (A1fi) and lower (B1) emissions scenarios

However, by mid-century and beyond, the magnitude of temperature change that can be expected depends more and more on whether Chicago and the rest of the world follows a higher or lower emissions scenario (Figure 2.7). By the end of the century, temperature increases of 3-4°F are projected under the lower emissions future and 7-8°F under the higher emissions scenario.

Largest increases are projected to occur in summer months (Figure 2.8). Similar to annual changes, temperature changes for nearly all the months of the year are more than double the lower emissions scenario under the higher one.

## Extreme heat and heat waves

One of the most important changes in future extreme events is likely to be the altered characteristics of hot weather. Year-to-year variability increases, resulting in an increased frequency of very hot summers over time, rather than a gradual increase in mean summer temperatures. This suggests that different mitigation strategies may be needed to alleviate the resulting heat stress conditions than if such oppressively hot days were to rise in proportion to a more gradual rise in mean summer temperature. The seasonal range of day-to-day temperatures is also changing, with the difference between warmer and colder days in winter becoming smaller, while the difference between hotter and cooler spring and summer days becomes greater. The difference between "apparent temperature" (how hot it actually feels due to both humidity and temperature) and actual air temperature during heat waves is expected to increase as the climate warms. In other words, hot days will feel even hotter due to increased humidity, creating more dire heat stress conditions in the future than suggested when we consider projected increases in air temperature alone.

Future heat waves in Chicago are projected to become more frequent, intense, and long-lived, while the time of year during which they occur should expand. Future heat waves will also likely last longer: the average duration of consecutive 90°F days rises from 2.9 in the late 20th century to an average of 5.3 under the lower and 9.8 under the higher emissions scenario, while the corresponding values for consecutive 100°F days rise from 0.7 days today to 2.4 days under the lower and 5.3 days under the higher. Thus, the length of future heat waves is expected to increase by approximately 2 to 3 times for moderately hot conditions and by 3 to 8 times for intensely hot weather.

In addition, Chicago can expect a much longer heat-wave "season" (length of time during the year when hot weather usually occurs). Under recent climatic conditions, there is typically a 69-day window during the summer when 90°F weather occurs. This window is projected to widen considerably, due to the combination of hot weather beginning earlier in the year and terminating later, leading to a late-21st century heat wave season of 108 (lower) to 138 (higher) days for 90°F weather (more than one to two months longer). This expanded interval of potentially hot days will require more sustained vigilance by the health-care sector to respond to heat-stress ailments.

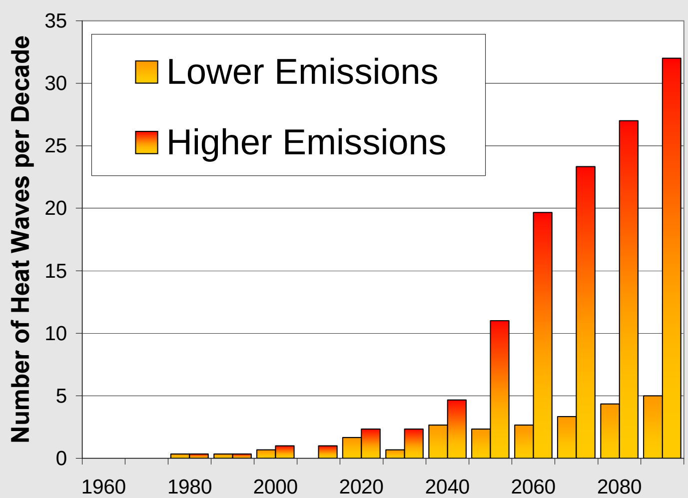


**Figure 2.9.** Total number of 1995-like heat wave events projected to occur each decade, as simulated by three climate models under the higher (A1fi) and lower (B1) emissions scenario.

The most severe heat wave Chicago has experienced in recent decades occurred in 1995, when almost 700 deaths were attributed to heat-related causes. The heat wave of 1995 was characterized by more than 7 consecutive days with maximum daily temperatures greater than 90°F and nighttime minimum temperatures greater than 70°F, where two days of those days had daytime maximum temperatures over 100$^{o}$F and nighttime temperatures that remained above 80$^{o}$F.

Taking these characteristics as the definition of a “1995-like” heat wave, we can calculate the likely frequency of such an event occurring in future decades. Averaging results from the three different climate models used here, historical simulations suggest a 1-in-3 chance of having a 1995-like heat wave once during the 1980s and/or during the 1990s. By mid-century, however, there are projected to be as many as 2 such heat waves each decade under the lower emissions scenario and almost 5 per decade – that’s every other year – under the higher emissions scenario. By the end of the century, under the lower scenario there are likely to be 1995-like heat waves every other year under the lower emissions scenario and over three such heat waves *each* year under the higher emissions scenario.

These results have serious implications for health and suggest that more heat-stress ailments can be expected in the future. More extreme heat in a warmer future climate is one of the most common results from climate models and is consistent with observed global trends during recent decades[33].

In addition to increasingly frequent heat wave events, characterized by multiple consecutive hot days, the absolute number of hot days in Chicago will probably rise substantially by the end of this century as well. The number of days where maximum temperatures exceed 90$^{o}$F is likely to increase from 15 days per year to 36 under the lower and 72 under the higher emissions scenario. The number

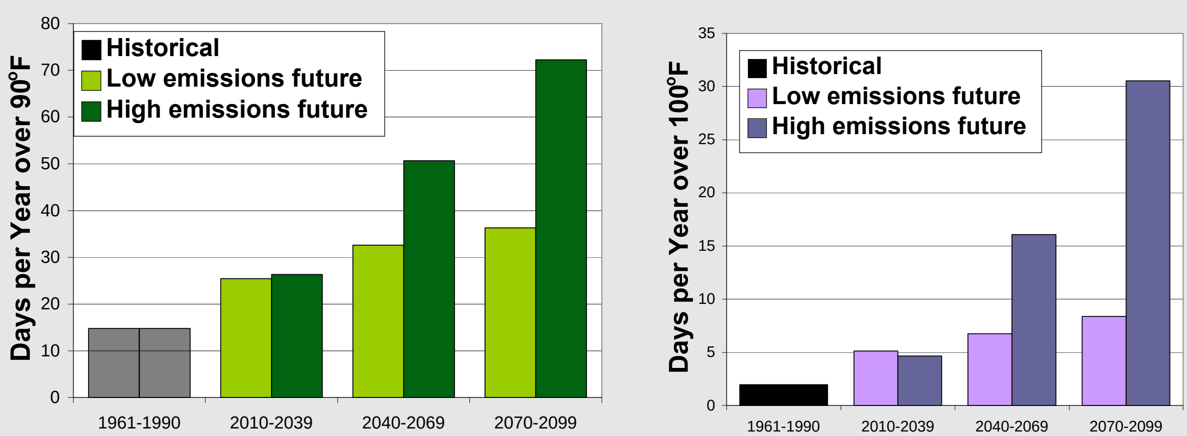


**Figure 2.10.** Projected frequency of 90$^{o}$ and 100$^{o}$F days per year in Chicago.

of days per year with temperatures exceeding 100$^{o}$F is projected to rise from only 2 days per year currently to 8 under the lower and 31 days under the higher (Figure 2.10).

The models also project corresponding increases in the average high temperature of the hottest day of the year from 99$^{o}$F at present to 107$^{o}$F (lower emissions) and 117$^{o}$F (higher emissions), representing significantly more intense heat waves.

The increase in extreme summertime air temperatures will probably be accompanied by greater humidity, due to the ability of warmer air to contain more moisture. The effect of warmer temperatures and higher humidity on cloud formation is included in the climate models used here. However, cloud processes still remain the single largest source of uncertainty in climate model simulations. It is very unlikely that greater cloudiness could completely offset the warming from increased greenhouse gases; however, cloud feedbacks are likely to affect the specific magnitude of a future warming trend by either enhancing it (thorough positive feedbacks) or diminishing it through negative ones.

The compounding effect of humidity is likely to exacerbate heat-related ailments, both by accentuating heat stress during the day and by promoting higher temperatures at night. The projected “apparent temperature” (the temperature perceived by people based on the combination of heat and humidity) has been estimated for O’Hare to quantify this reinforcing effect. The expected annual number of days exceeding 90$^{o}$F *apparent temperature* is approximately 7 days more than the corresponding exceedences of 90$^{o}$F air temperature alone by the end of this century (11 to 18% greater), while the number of 100$^{o}$F readings for apparent temperature is between 3-8 days greater than 100$^{o}$F air temperature readings for the low emissions-high emissions scenarios (30-40% greater). Because humidity is strongly correlated with minimum overnight temperatures, the higher dewpoints projected for the future should lead to an increased frequency of very warm nights and an associated rise in heat stress due to the strong relationship between nighttime temperatures and mortality during heat waves[34]. The models project that overnight low temperatures above 80$^{o}$F will change from being almost non-existent at present to occurring on average 2 to 14 days per year by the late 21st century.

The effect of increasing summer temperatures under climate change favors not only a greater average number of hot days per year, but also an increased probability of occasional summers with extremely oppressive conditions. The increase in very hot days accompanying a warming climate may be expressed largely as an increased frequency of severely hot summers, rather than as a steady increase in heat waves with time, as illustrated by the most conservative of the climate model simulations (PCM, for the lower emissions scenario) of apparent temperatures exceeding 100°F (Figure 2.11). In this scenario, summers with infrequent or non-existent extreme heat are still projected to occur throughout the late 21st century, but occasional summers are expected to have a great many more hot and humid days than in the present climate. If this projection accurately reflects how the Chicago area climate will respond to greenhouse warming, then different mitigation strategies may be needed to alleviate the resulting heat stress conditions than if such oppressively hot days rise in tandem with the more gradual rise in mean summer temperature.

## Extreme cold

According to the Centers for Disease Control and Prevention, excessive cold still accounts for approximately 750 deaths per year in the U.S.[35], despite the warming climate of the past several decades. Other impacts from extreme cold include agricultural losses, increased transportation expenses and hindrances, excess morbidity, and greater heating costs[36].

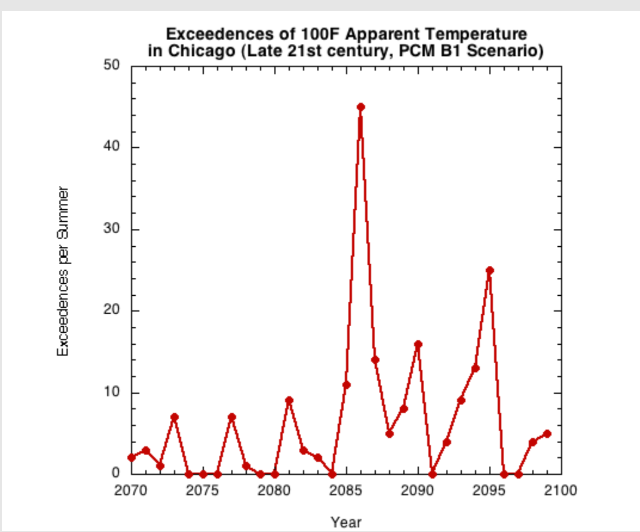


**Figure 2.11.** Days per summer of 100°F or higher apparent temperature at O'Hare, as projected in the late 21st century in the PCM's low-emissions scenario.

The frequency and severity of extreme cold in Chicago is expected to decline significantly during this century, consistent with a pronounced moderation of average winter conditions. Mean wintertime temperature is projected to rise from its late 20th century value by 4 to 7°F by the end of this century. Extreme cold should moderate even more, with models projecting the coldest day of the year to become 7 to 14°F warmer (Figure 2.12). The frequency of severe cold is also expected to decline, as models indicate that the number of extremely cold days (the coldest 5 to 10% of all days in the present climate) will fall by about 30 to 70% by the end of the century.

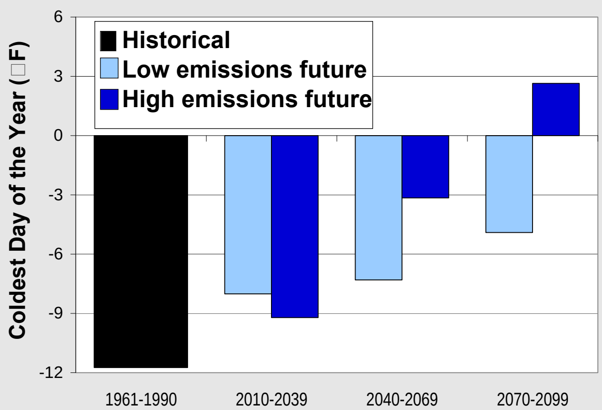


**Figure 2.12.** Projected average minimum temperature reached during the year.

These local changes are in agreement with projected regional and national trends of decreases in bitter cold weather. A composite of global climate models indicates nearly a 90% reduction in the frequency of extreme cold-air outbreaks over the U. S. by the late 21st century, based on a middle-of-the-road emissions scenario[37]. The decline is to be even larger over the Great Lakes region, consistent with a dramatic reduction in the occurrence of extreme high-pressure cells originating in the Arctic[38].

## Growing season

Finally, the length of the frost-free or "growing" season is projected to continue to expand, with the date of last (spring) frost moving earlier in the year by about 30 days under the higher scenario and 20 days under the lower by the end of the century. Significant decreases in the number of frost days per year and the annual frost depth are also expected, with larger changes towards the end of the century and under the higher vs. the lower emissions scenario (Figure 2.13).

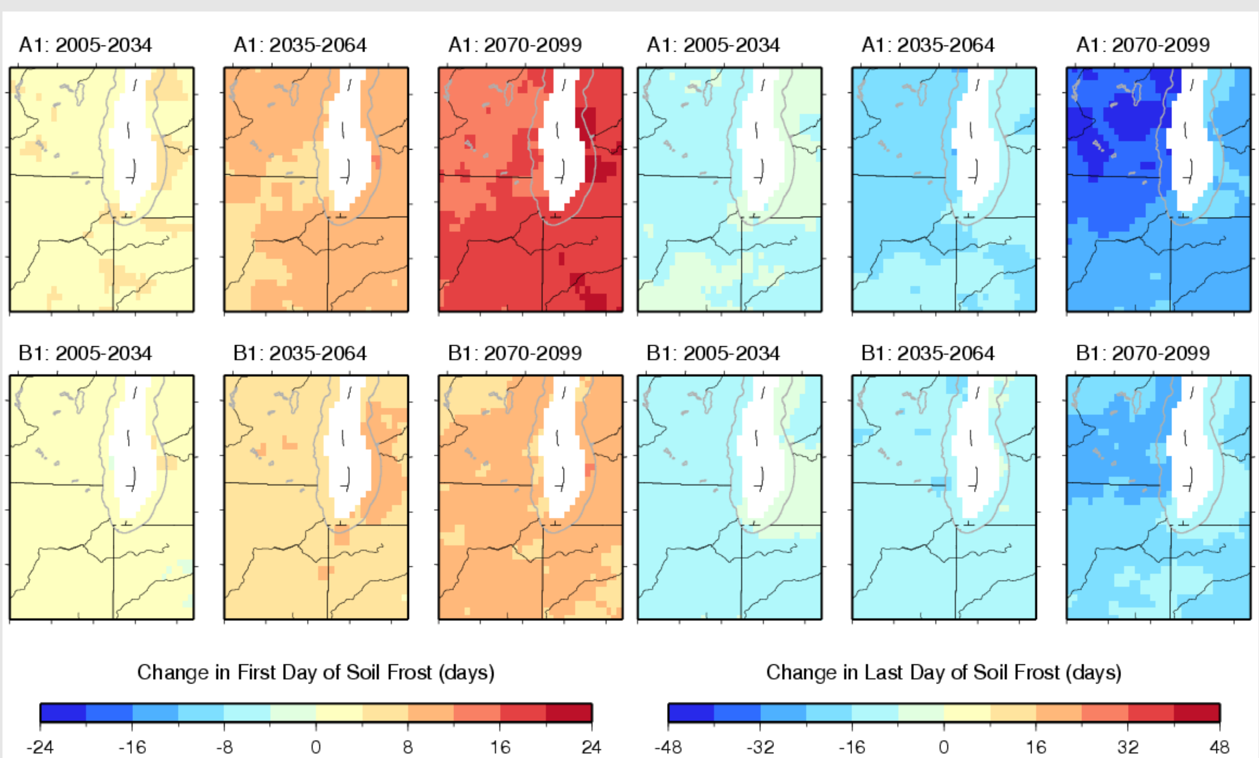


**Figure 2.13.** Projected change in the date of the first day of soil frost in autumn and the last day of soil frost in spring.

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