Regional climate change projections for Chicago and the US Great Lakes

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Assessing regional impacts of climate change begins with development of climate projections at relevant temporal and spatial scales. Here, proven statistical downscaling methods are applied to relatively coarse-scale atmosphere–ocean general circulation model (AOGCM) output to improve the simulation and resolution of spatial and temporal variability in temperature and precipitation across the US Great Lakes region. The absolute magnitude of change expected over the coming century depends on the sensitivity of the climate system to human forcing and on the trajectory of anthropogenic greenhouse gas emissions. Annual temperatures in the region are projected to increase 1.4 ± 0.6 °C over the near-term (2010–2039), by 2.0 ± 0.7 °C under lower and 3 ± 1 °C under higher emissions by midcentury (2040–2069), and by 3 ± 1 °C under lower and 5.0 ± 1.2 °C under higher emissions by end-of-century (2070–2099), relative to the historical reference period 1961–1990. Simulations also highlight seasonal and geographical differences in warming, consistent with recent trends. Increases in winter and spring precipitation of up to 20% under lower and 30% under higher emissions are projected by end-of-century, while projections for summer and fall remain inconsistent. Competing effects of shifting precipitation and warmer temperatures suggest little change in Great Lake levels over much of the century until the end of the century, when net decreases are expected under higher emissions. Overall, these projections suggest the potential for considerable changes to climate in the US Great Lakes region; changes that could be mitigated by reducing global emissions to follow a lower as opposed to a higher emissions trajectory over the coming century.

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Introduction

This analysis describes projected climate changes in the US Great Lakes region, and Chicago in particular, over the coming century. As the typical resolution of an atmosphere–ocean general circulation model (AOGCM) is too coarse to study climate change for a single location or even a region, we apply advanced statistical downscaling methods that relate projected large-scale changes from climate model simulations to local conditions on the ground. The US Great Lakes region is defined as encompassing the states of Illinois, Indiana, Michigan, Minnesota, Ohio, and Wisconsin. Although the Great Lakes also border New York, this state was not included in the analysis.

At the synoptic scale, climate in the Great Lakes region reflects its midlatitude location in the interior of the North American continent. In the winter, the absence of significant mountain barriers to the north allows Arctic air masses to move southward into the region. The polar jet stream is often located near or over the region during the winter. As a result, frequent storm systems in the winter bring cloudy skies, windy conditions, and precipitation. In contrast, summers are characteristically hot and humid due to a semipermanent high-pressure system in the subtropical Atlantic that draws warm, humid ocean air into the area. Summer also tends to be the rainiest season, with short-lived convective rainfall and thunderstorms more common than prolonged rainy periods.

At the mesoscale, large water bodies such as the Great Lakes are responsible for microclimates characterized by moderated temperature and/or elevated precipitation. Microclimate examples include the land/lake breeze that cools the shorelines of large cities such as Chicago and Toronto during hot summer months, as well as the record snowfalls experienced by Buffalo and its surrounding area during the winter.

In the past, most climate variations in the Great Lakes region 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. The Intergovernmental Panel on Climate Change (IPCC, 2007) has now concluded, however, that it is very likely that most of the observed temperature increase over the last 50 years was driven by emissions of greenhouse gases and other radiatively active substances from human activities.
A number of temperature and precipitation-based indicators in the Great Lakes demonstrate trends consistent with a warming climate (see Table 1). Attribution of regional-scale climate trends to anthropogenic influences is difficult; as the spatial scale decreases, the signal-to-noise ratio increases (Hegerl et al., 2007). It is not yet possible to definitively attribute these observed trends in the Great Lakes region to human-induced climate change, as most observed changes are still within the range of natural variability for the region, and some (such as the observed trends in temperature extremes) have not been observed over sufficiently long time scales. However, the similarity of these patterns of change to others seen elsewhere around the globe strongly suggests a connection to human-driven climate change (Hegerl et al., 2007; Lemke et al., 2007; Rosenzweig et al., 2007, 2008). Furthermore, model simulations of the impact of anthropogenic emissions on climate over 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 greenhouse gases and other radiatively active species continue to grow and the influence of human activities on global climate intensifies (Meethel et al., 2007; Tebaldi et al., 2006).

Over the coming century, global temperatures are expected to continue to increase, by an estimated 1.5 to 6 °C in response to increasing emissions of greenhouse gases from human activities (IPCC, 2007). This range is due to uncertainties inherent in predicting the human choices and activities that will determine future greenhouse gas emissions, as well as the scientific uncertainty regarding how natural sources and sinks of greenhouse gases will change, and the response of Earth’s climate system to these changes.

The objective of this work is to clearly describe the derivation of a consistent set of climate change scenarios for the Chicago and the US Great Lakes region. Data and methods summarizes the data, models, and methods used. Climate projections for Chicago and the Great Lakes shows how annual and seasonal temperature and precipitation are likely to be affected by climate change in the near future (2010–2039), by midcentury (2040–2069), and towards the end of the century (2070–2099). These projections are used to develop “migrating climate” estimates for two states (Michigan and Illinois), as well as the city of Chicago. This analysis consists of quantifying projected future climate conditions in a given location, then searching for present-day analogues to those conditions today. In Projected changes in lake levels, projections of changes in temperature and precipitation are used to develop corresponding estimates of changes in mean Great Lakes levels. Finally, Discussion and conclusions addresses the implications

Table 1
Observed trends in temperature and precipitation-based indicators in the Great Lakes consistent with increasing temperatures.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Time perioda</th>
<th>Reference(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Increases in annual temperatures at both rural and urban locations, from an average of 0.16 °C (0.28 °F) per decade for Illinois to 0.27 °C (0.49 °F) per decade in Minnesota</td>
<td>1950–2009</td>
</tr>
<tr>
<td></td>
<td>Increases in annual average temperatures for Chicago (average of Chicago Midway, O’Hare, and University of Chicago weather stations) of 0.25 °C (0.46 °F) per decade. A progressive advance in the date of last spring freeze in Illinois, with current dates approximately 1 week earlier, and a lengthening of the growing season, roughly 1 week longer</td>
<td>1945–2007</td>
</tr>
<tr>
<td></td>
<td>Increases in fall precipitation resulting in increased annual mean and low flow of streams, without any changes in annual high flow</td>
<td>1948–1997</td>
</tr>
<tr>
<td></td>
<td>Increasing lake effect snow during the 20th century which may be a result of warmer Great Lakes surface waters and decreased ice cover</td>
<td>1931–2001</td>
</tr>
<tr>
<td></td>
<td>A doubling in the frequencies of heavy rain events (defined as occurring on average once per year during the past century) and an increase in the number of individual rainy days, short-duration (1–7 days) heavy rain events, and week-long heavy rain events</td>
<td>1931–1996</td>
</tr>
<tr>
<td></td>
<td>Changes in the hydrological cycle, with a decrease in spring snow cover, followed by earlier dates for spring melt, and peak stream flow and lake levels</td>
<td>1960–2000</td>
</tr>
<tr>
<td></td>
<td>Decreases in ice and snow cover and duration across the Great Lakes, more rapid than any changes that have occurred over at least the last 250 years</td>
<td>1975–2004</td>
</tr>
<tr>
<td></td>
<td>An increase in hydrologic flooding in Iowa, Missouri, and Illinois, at least partially a result of more frequent midday periods of heavy rain</td>
<td>1920–2001</td>
</tr>
<tr>
<td></td>
<td>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. Winter increase occurring at the expense of decreasing spring runoff, suggesting hydrologic response to warming climate. 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</td>
<td>1860–1998</td>
</tr>
<tr>
<td></td>
<td>An increase in Great Lakes near-shore water temperatures (measured at Sault Ste. Marie and Put-In-Bay) of 0.1 °C per decade, accompanied by an increase in the duration of summer stratification of more than two weeks</td>
<td>1906–1993</td>
</tr>
<tr>
<td>Temperature extremes</td>
<td>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</td>
<td>1900–1996</td>
</tr>
</tbody>
</table>

a Where multiple studies or datasets are referenced, the time period shown is inclusive of all studies.

of these results for the Great Lakes region in general, and Chicago in particular.

Data and methods

Observations

We examine past changes in climate specific to the Great Lakes region using daily and hourly records of temperature, precipitation, humidity, and snow recorded by local weather stations. Station-level historical climate observations for the US Great Lakes region were obtained from three primary sources: the database maintained by the Midwestern Regional Climate Center at the Illinois State Water Survey, which provides observations from over 300 stations throughout the Midwest/Great Lakes region dating back over a century (Kunkel et al. 1998); the Global Historical Climatology Network (Vose et al., 2003) produced jointly by the US Department of Energy’s Carbon Dioxide Information Analysis Center (CDIAC) and the National Oceanographic and Atmospheric Administration’s National Climatic Data Center (NCDC); and the NCDC/National Weather Service high-resolution daily station data set (available online at http://cdo.ncdc.noaa.gov/pls/plclimprod/poemain.accessrouter?datasetabbv=SOD).

A second level of analysis focused on changes observed at 14 stations in and around the Chicago metropolitan region (Fig. 1). These stations were selected based on the length of their records, requiring at minimum 40 continuous years of data up to 1990. To define climate trends for the city of Chicago itself, we average the observations at three of those stations, Chicago Midway Airport, Chicago O’Hare Airport, and the University of Chicago, to account for spatial differences in temperature and precipitation across the city.

Historical simulations

Historical simulations correspond to the Coupled Model Intercomparison Project’s “20th Century Climate in Coupled Models” or 20C3M scenarios (Covey et al., 2003). These represent each modeling group’s best efforts to simulate observed global climate over the past century, including changes in solar radiation, volcanic eruptions, human emissions of greenhouse gases and other radiatively active species, and secondary changes in tropospheric ozone and water vapor.

Although the 20C3M simulations are all intended to represent the same historical total-forcing scenarios (including both natural variability as well as the effect of human emissions on climate), simulations by individual modeling groups do not necessarily have identical boundary conditions. Therefore, some differences between model simulations themselves as well as between simulations and observations identified here may also be a result of differing input conditions.

Future emissions scenarios

Socioeconomic models are driven by projections of global and regional population, demographics, technological developments, economic growth, energy supply and demand, and land use. These in turn estimate the resulting emissions of greenhouse gases and other radiatively active species resulting from human activities in a number of economic sectors, including agriculture, commercial and residential, forestry, industry, and transportation. These scenarios can then be used to assess the differences in the extent and severity of the global warming that would result from alternative emissions pathways over the coming century.

Emissions scenarios are not predictions, but rather represent plausible future conditions under particular assumptions. The reference

Fig. 1. 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. Region shown is the northeast corner of Illinois, with county boundaries indicated (Source: Midwestern Climate Center, http://www.sws.uiuc.edu/atmos/stateclim/General/sites_available_in_illinois.htm).
standard for emission scenarios are those developed by the Intergovernmental Panel on Climate Change (IPCC). The emissions scenarios considered here consist of the IPCC Special Report on Emission Scenarios (Nakicenovic et al., 2000) A1fi (fossil-intensive, higher), A2 (mid–high), and B1 (lower) emission scenarios. In particular, we use the Special Report on Emission Scenarios (SRES) A1fi and the B1 scenarios to simulate the consequences of higher and lower emissions choices, respectively.

The SRES A1fi scenario represents a world with fossil fuel-intensive economic growth and a global population that peaks midcentury and then declines. New and more efficient technologies are introduced toward the end of the century. In this scenario, atmospheric carbon dioxide concentrations reach 940 parts per million (ppm) by 2100—almost four times preindustrial levels. The lower–emissions scenario (B1) also represents a world with high economic growth and a global population that peaks midcentury 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 preindustrial levels.

It is important to note that, as broadly separated as they are, the SRES scenarios still do not cover the entire range of possible futures. The SRES scenarios were developed during the 1990s, when the growth rate of carbon emissions averaged 1.1% per year (Raupach et al., 2007). Post-2000, the growth rate increased to over 3% per year. If recent emission growth rates continue and sufficient fossil fuel supplies exist to support that growth, CO2 emissions are on a pathway to quickly exceed any existing scenarios, including A1fi (Raupach et al., 2007).

On the other hand, significant reductions in emissions could stabilize CO2 levels below the lowest SRES emission scenario (e.g., Meinschansen et al., 2006). Such policy options were not considered in the SRES scenarios, although the new Representative Concentration Pathways (RCPs; Moss et al., 2008) currently under development for the IPCC Fifth Assessment Report at least partially address this issue. The RCPs are expressed in terms of carbon dioxide equivalent concentrations in the atmosphere, rather than direct anthropogenic emissions.

Although AOGCM simulations are not yet available for the RCPs, it is still possible to place SRES-based projections into the context of these new scenarios by converting the SRES emission scenarios to carbon dioxide equivalent (CO2-eq) concentrations using the standard formulation of the carbon cycle component of the MAGICC model (Wigley, 2008). Specifically, the highest RCP 8.5 corresponds closely to the higher SRES A1fi emissions scenario, with end-of-century CO2-eq concentrations of 1360 parts per million (ppm) for RCP 8.5 as compared to 1465 ppm for A1fi. In contrast, the lowest RCP 2.6 projects a future where emissions are reduced significantly below even the lowest of the SRES scenarios, with CO2-eq concentrations rising to nearly 500 ppm then falling to 450 ppm by the end of the century. The mid–low RCP 4.5 corresponds most closely to SRES B1, with CO2-eq concentrations of nearly 600 ppm by the end of the century as compared to 640 ppm for B1.

This is an important comparison as it enables the projections presented here, for the Great Lakes region, to be placed in the context of the next generation of climate scenarios. It also reveals that the substantial difference between the SRES A1fi and B1 scenarios, although conservative in comparison to the RCPs in its estimate of the lower end of the range of future emissions, is still sufficient to illustrate the potential range of changes that could be expected, and how these depend on energy and related emission choices made over coming decades.

Climate projections

Emissions scenarios are used as input to three-dimensional, coupled global AOGCMs capable of simulating the impact of these emissions on the climate system. Currently, 18 modeling groups have submitted historical and future simulations from 25 different AOGCMs to the Intergovernmental Panel on Climate Change's Fourth Assessment Report (IPCC AR4; Meehl et al., 2007). Although some of these models are more successful than others at reproducing observed trends over the past century, all future simulations agree that both global and regional temperatures will increase over the coming century in response to increasing emissions of greenhouse gases from human activities (Meehl et al., 2007).

Two distinct climate model ensembles are used to generate the projections presented here. First, we compare projected Great Lakes region-wide average temperature and precipitation change across 40 simulations (one from each AOGCM with A2 and/or B1 simulations available in the IPCC AR4 database at the time of the analysis). This comparison enables us to quantify the mean and the range of changes projected by all AOGCMs for the three future time periods of interest. Second, we select a subset of 3 AOGCMs for further analysis focusing on the Great Lakes region, and the city of Chicago.

Our emphasis on this subset of 6 simulations from 3 AOGCMs (one each for the SRES A1fi and B1 emission scenarios) arises from the focus of our larger project (see remainder of papers in this special issue). The purpose of this project was to estimate the potential impacts of climate change on a broad variety of regional impacts in Chicago and the Great Lakes, including hydrology, ecology, air quality, and human health. Many of these analyses require high-resolution climate projections as input to quantitative modeling. Given the level of effort involved in conducting these simulations, it is virtually impossible to do in a timely manner for more than a subset of climate projections. Nor is it even desirable, for two reasons: first, some AOGCMs are clearly better than others at simulating processes important to regional climate and variability (e.g., Chapman and Walsh, 2007; Stoner et al., 2009); and second, daily output corresponding to higher SRES A1fi emissions scenario is not available from all of the IPCC AR4 models. Reliance on the lower SRES A2 emissions scenario for which more daily outputs are available would, for a given AOGCM, underestimate the upper bound of the temperature change envelope by approximately 25%.

Selection of a subset of AOGCM simulations for impact analyses was therefore based on the following criteria, both scientific and practical: (1) only well-established models were considered, which were already extensively described and evaluated in the peer-reviewed scientific literature; (2) only models that had participated in the Coupled Model Intercomparison Project (Covey et al., 2003) 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. (e.g., Vrac et al. 2006; Stoner et al., 2009); (3) simulations that had sufficient output fields saved at the daily 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) to identify significant differences between higher and lower emissions futures; (5) where possible, models that were compatible with previous or concurrent regional analyses (US GCRP, 2009; UCS, 2009); and finally, (6) models with a range of climate sensitivity and hydrological parameterizations, to capture a large part of the possible range of changes in the temporal and spatial distribution of temperature and precipitation over the coming century.

The subset of AOGCMs selected for use in the impacts analyses consisted of the US National Atmospheric and Oceanic Administration’s Geophysical Fluid Dynamics Laboratory (GFDL) CMZ.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). Together, these three models span approximately the lower two-thirds of the IPCC’s range of estimated climate sensitivity (IPCC, 2007). Primary references and characteristics of these models are described in Table 2.

A variety of studies relating to weather and climate prediction has demonstrated that combining models generally increases the skill, reliability, and consistency of model forecasts (Tebaldi and Knutti, 2007). To quantify how projections based on this subset of three AOGCMs may differ from those based on a larger multimodel ensemble, Fig. 2
compares the spatial patterns of change as simulated by statistically downsampled projections from 16 AOGCMs (USGCRP, 2009) to those resulting from the subset of three AOGCMs only. Projections are shown for the period 2070–2099 relative to 1971–2000, for annual average temperature and precipitation. This comparison reveals that, over the Great Lakes region, the three-AOGCM average displays a very similar pattern of change to that resulting from a much larger model ensemble.

**Statistical downscaling**

Typical AOGCM resolution is too coarse to capture the nuances of regional-scale change. For that reason, downscaling techniques are often used to transform AOGCM output into higher-resolution projections on the order of tens rather than hundreds of square 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 “training period,” and observed climate variables of interest (here, daily maximum and minimum temperature and precipitation). This relationship is averaged over a climatological period of two decades or more to remove year-to-year fluctuations. The historical relationship between AOGCM output and monthly or daily climate variables at the regional scale is then tested using a second historical “evaluation period” to confirm the relationship is robust. Finally, the historical relationship between AOGCM output and monthly or daily climate variables at the regional scale is used to downscale both historical and future AOGCM simulations to that same regional scale.

Unlike regional climate modeling, statistical downscaling assumes that the relationships between large- and small-scale processes remain

<table>
<thead>
<tr>
<th>Model</th>
<th>Host institution</th>
<th>Horizontal spatial resolution (°)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFDL CM2.1</td>
<td>National Ocean and Atmospheric Administration,</td>
<td>1.8</td>
<td>Delworth et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Geophysical Fluid Dynamics Laboratory (USA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HadCM3</td>
<td>UK Meteorological Office, Hadley Centre (UK)</td>
<td>2.5 × 3.75</td>
<td>Pope et al. (2000)</td>
</tr>
<tr>
<td>PCM</td>
<td>National Center for Atmospheric Research (USA)</td>
<td>2.8</td>
<td>Washington et al. (2000)</td>
</tr>
</tbody>
</table>

Fig. 2. Projected change in annual average (a) temperature and (b) precipitation as simulated under the SRES A2 (mid–high) emissions scenarios compare a 16-model AOGCM average to the average of the subset of 3 AOGCMs used for the impact analyses presented in this volume, for the period 2070–2099. Temperature projections are in units of degrees Celsius and precipitation in units of percentage change relative to the 1971–2000 average and have been statistically downscaled to a spatial resolution of one-eighth degree, after USGCRP (2009).
fixed over time—an assumption that may not always be justified, particularly for precipitation. However, analysis of 37 stations in the state of Illinois comparing future projections downscaled using both statistical and dynamical (regional climate model) methods suggests that this relationship only breaks down for the most extreme precipitation events above the 99th percentile of the distribution (Vrac et al., 2007). Analysis for the Northeast (Hayhoe et al., 2008) further indicates that, in areas of variable topography such as mountains and coastlines, statistical methods trained to match historical spatial patterns may perform better than regional climate models that are limited by their convection schemes. In addition, 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 or dynamical downscaling.

For these reasons, two statistical methods are used to downscale AOGCM-based monthly temperature and precipitation fields for the A1fi and B1 emissions scenarios. In the first method, monthly AOGCM temperature and precipitation fields are statistically downscaled to daily values across the Great Lakes region with a resolution of 1/8th degrees. This downscaling approach uses an empirical statistical technique that maps the probability density functions for modeled monthly and daily precipitation and temperature for the climatological period (1961–1990; Maurer et al., 2002) onto those of gridded historical observed data, so the mean and variability of both monthly and daily observations are reproduced by the climate model outputs. The bias correction and spatial disaggregation technique is one originally developed for adjusting AOGCM output for long-range stream flow forecasting (Wood et al., 2002; Van Rheenan et al., 2004), later adapted for use in studies examining the hydrologic impacts of climate change. The method compares favorably to regional climate model simulations (Wood et al., 2004).

The second approach downscales to individual weather stations using an asynchronous quantile regression method that can determine relationships between two quantities not measured simultaneously, such as an observed and a model-simulated time series. The method assumes that,

![Fig. 3. May–September daily maximum temperature distributions for Chicago Midway station, binned at 0.5 °C intervals, in units of average number of days per year. (a) Comparison of observed (black) with model-simulated statistically downscaled distributions for the period 1961–1990. Observed standard deviation is 2.17. Modeled values are 2.01, 2.09, and 2.05 for GFDL CM2.1, HadCM3, and PCM models, respectively. (b) Comparison of three-model average simulated historical (1961–1990) and projected future (2070–2099) distributions for the SRES A1fi higher (red) and B1 lower (orange) emission scenarios. Future distributions suggest a shift in the mean (and broadening of the standard deviation or σ) of the distribution from 25.9 °C (σ = 5.52) in 1961–1990 to 28.6 °C (σ = 5.96) under lower and 32.2 °C (σ = 6.73) under higher emissions by end-of-century.]

![Fig. 4. Projected change in annual average temperature (°C) and precipitation (%) over the US Great Lakes region relative to 1961–1990 climatological values, as simulated by 21 IPCC AR4 AOGCMs for the SRES A1fi (higher; red), A2 (mid–high; orange, pink), and B1 (lower; green blue) emissions scenarios. Legend shows the acronym given to each AOGCM; full names and provenance provided in Meehl et al. (2007). Projections are shown for the near-term period (2010–2039), midcentury (2040–2069), and end-of-century (2070–2099). The subset of AOGCMs selected for this analysis are indicated by solid shapes. All simulations indicate a projected increase in temperature that becomes progressively greater under higher emissions scenarios and towards the end of the century. Although precipitation projections for summer and fall are mixed, consistent increases in winter and spring precipitation are projected, with larger changes under higher emissions as compared to lower, and by end-of-century as compared to closer time periods.]

although the two time series are independent, they describe the same variable, at approximately the same location, and therefore must have similar probability density functions (PDFs). The two independent time-varying variables $X(t)$ and $Y(t)$ are regressed using only their statistical distributions $F(x)$ and $G(y)$. The method determines the function $Y = u(X)$ by matching the quantiles of $x$ and $y$ of the distributions of $X$ and $Y$ for each probability level (O'Brien et al., 2001). Using 2 m daily model-simulated maximum and minimum air temperature and precipitation from the AOGCM as the predictor and daily observed maximum and minimum temperatures and precipitation as the predictand, the resulting regression model can then force the PDFs of the simulated fields to match those of the observed data.

AOGCM-simulated time series are first modified, so overall probability distributions of simulated daily values approximate observed probability distributions of air temperatures at weather stations in each city (as shown for the Chicago Midway station in Fig. 3(a)). The regression relationships derived from the historic observed and model-simulated time series are then applied to future simulations, such that

![Fig. 5. Projected increase in (a) winter (Dec–Jan–Feb) and (b) summer (Jun–Jul–Aug) average temperature as simulated under the SRES A1fi (higher) and B1 (lower) emissions scenarios by the average of 3 AOGCMs for near-term (2010–2039), midcentury (2040–2069), and end-of-century (2070–2099). Temperature projections are in units of degrees Celsius relative to the 1961–1990 average and have been statistically downscaled to a spatial resolution of one-eighth degree.](image-url)
precipitation in water balances to estimate the Great Lakes levels used simple constant changes in air temperature or factors are used to calculate lake ice extent during winter months. The climate variables used as input include daily maximum, minimum, cloud cover), precipitation, and wind speed. Air temperature change of 5 °C (9 °F) and 3 to 10 ft under temperature change of 1–4 °C (2–7 °F) and 3 to 10 ft under temperature change of 5–6.5 °C (9–12 °F), relative to the 1971–2000 average lake levels. These estimates represent the ultimate response of lake levels to a specific change in temperature and precipitation that must be maintained over many decades while lake levels respond, not the instantaneous response in a given year. Equilibrium projections emphasize the importance of mitigating climate change to prevent major long-term drops in lake levels but do not provide information regarding the magnitude of changes that should be expected over the coming century while climate is continuously changing.

Fig. 6. Observed and model-simulated historical and projected future annual average temperatures for Chicago, in degrees Celsius. Model simulations show the average of the GFDL 2.1, HadCM3, and PCM models for the SRES A1B (higher) and B1 (lower) emission scenarios. Observations are the average of temperatures recorded at the three long-term Chicago “urban” weather stations: Midway Airport, O’Hare Airport, and the University of Chicago. Thin lines show year-to-year values while thick lines indicate the 10-year running mean.

Lake-level modeling

To estimate future lake levels and changes in ice cover, we use the Advanced Hydrologic Prediction System (AHPS), a model developed by the National Oceanic and Atmospheric Administration’s Great Lakes Environmental Research Laboratory (GLERL; Croley, 2006). The AHPS consists of daily runoff models for each of the 121 watersheds, lake thermodynamic models for each of the major water bodies, hydraulic models for the four connection channels and five water body outflow point with operating plans for Lakes Superior and Ontario included, and simultaneous calculations of water balances on all of the lakes. The lake water balance is determined by over-lake precipitation, runoff to the lake, and lake evaporation.

The runoff portion of the AHPS is handled by the Large Basin Runoff Model (LBRM), which is an interdependent tank-cascade model. The runoff model has been calibrated to each of the 121 watersheds contributing to the Great Lakes by minimizing root mean square error between daily model outflows and adjusted outflow observations. Simulated weekly and monthly outflow values compare well with observations (Croley and Assel, 2002). The parameters represent present-day hydrology and are not changed in the simulations.

Evaporation is handled by GLERL’s Lake Thermodynamic Model, which includes reflection and short-wave radiation, net long-wave radiation, and advection. Energy conservation accounts for heat storage, while both mass and energy conservation drive ice formation and decay. The evaporation model has been calibrated to each of the seven lake surfaces by minimizing root mean square error between daily model surface temperatures and observations. The model enables one-dimensional modeling throughout of spatially averaged water temperatures over the lake depth and can be used to follow thermal development and turnovers in the lake.

For future scenarios, the AHPS takes changes in average monthly values for each variable between the historical reference period 1961–1990 and each future time period, near-term (2010–2039), mid-century (2040–2069), and end-of-century (2070–2099). Monthly climate variables used as input include daily maximum, minimum, and average air temperature, humidity, solar radiation (used to back-calculate cloud cover), precipitation, and wind speed. Air temperatures are used to calculate lake ice extent during winter months. The AHPS then simulates moisture storages and runoff from the 121 watersheds draining into the Great Lakes, and evaporation from each of the Great Lakes. When combining these components as net water supplies, an estimate of lake levels can be obtained.

Previous projections of climate change impacts on lake levels

Early studies examining the potential impacts of climate change on Great Lakes levels used simple constant changes in air temperature or precipitation in water balances to estimate the “steady-state” changes that would be expected to occur for a given change in temperature and/or precipitation, with mixed results as they were often based on just one or two simulations from early-generation IPCC AOGCMs. For example, one study found both increases and decreases in annual mean net basin supply, negative (−11%) in the mid-21st century and positive (+15%) in the late 21st century (Lofgren, 2004). In contrast, a second study (Croley, 2003) found only a likely decrease in net basin supply for all future time periods (up to −21% for a scenario significantly hotter and drier than today). A third study used two AOGCMs to estimate future levels for Lake Michigan (Lofgren et al., 2002). One model estimated Lake Michigan’s level would fall by 1.38 m, whereas the other model actually showed an increase of 0.35 m by end-of-century. Not surprisingly, simulations that predicted a rise in lake level were based on simulations showing a larger increase in precipitation and smaller increase in temperatures than simulations that resulted in a decrease in lake levels.

Taking these estimates to the extreme, a fourth study (Croley and Lewis, 2006) then calculated the magnitude of the climate changes that would be required to create “terminal” Great Lakes (i.e., lakes with no outlet). Using a steady-state version of the same AHPS model, they estimate that lakes Michigan–Huron would become terminal for a precipitation decrease greater than 63%, a temperature increase greater than 14 °C, or a combined temperature/precipitation change of 4.5T + P = 63. Neither of these conditions are likely to occur over this century; however, if human-driven climate change were to continue unchecked, at least the temperature threshold would likely be met at some point in the future.

As AOGCM simulations become increasingly more accessible for use as input to hydrological modeling, a clearer signal is emerging regarding the likely direction of mean lake level change. The most comprehensive study has been conducted by Angel and Kunkel (2010), using over 500 simulations from the full set of IPCC AR4 AOGCMs to simulate changes in Great Lake levels. For lakes Michigan–Huron, median changes by end-of-century were estimated at −0.25, −0.28, and −0.41 m for the B1, A1B, and A2 emission scenarios, respectively. The authors also noted that projected values were highly variable due to differences in emission scenarios as well as uncertainty in model simulations.

In terms of the long-term effects of climate change on lake levels, on time scales of centuries, Kunkel et al. (available online at: http://www.ssw.uiuc.edu/wsp/climate/ClimateTom_scenarios.asp) used a series of steady-state relationships between lake levels, temperature, and precipitation calculated by the “terminal lakes” from the AHPS steady-state model to estimate that Lake Michigan levels could drop by about 0 to 3 ft under temperature change of 1–4 °C (2–7 °F) and 3 to 10 ft under temperature change of 5–6.5 °C (9–12 °F), relative to the 1971–2000 average lake levels. These estimates represent the ultimate response of lake levels to a specific change in temperature and precipitation that must be maintained over many decades while lake levels respond, not the instantaneous response in a given year. Equilibrium projections emphasize the importance of mitigating climate change to prevent major long-term drops in lake levels but do not provide information regarding the magnitude of changes that should be expected over the coming century while climate is continuously changing.

rescaled values share the weather statistics observed at the selected stations (Fig. 3(b)). This approach was used to produce daily temperature and precipitation projections for each of the 14 Chicago-area weather stations shown in Fig. 1.
Climate projections for Chicago and the Great Lakes

The Great Lakes region is already experiencing long-term climate trends; many observed over the last few decades, some over the last century and beyond (Table 1). Although they cannot be definitively attributed as yet, these changes are consistent with human-induced warming at the global scale (Hegerl et al., 2007; Rosenzweig et al., 2007, 2008). Annual average temperatures are rising, accompanied by a reduction in snow and ice cover, a longer growing season, and increased frequency of extreme rainfall events (Table 1). All of these changes are expected to continue in the future, with the amount of change depending on future greenhouse gas emissions as well as on the sensitivity of the Earth’s climate system to anthropogenic emissions (Meehl et al., 2007; USGCRP, 2009). Temperature changes are expected to be greater under a higher emission scenario as compared to a lower, and by end-of-century as compared to earlier time periods (Fig. 4). Here we discuss projected changes in annual and seasonal temperature and precipitation. Corresponding changes in heatwaves and temperature extremes and hydrology are discussed elsewhere in this issue (Hayhoe et al., 2010; Cherkauer and Sinha, 2010).

Fig. 7. Projected change in (a) spring (Mar–Apr–May) and (b) summer (Jun–Jul–Aug) average precipitation as simulated under the SRES A1fi (higher) and B1 (lower) emissions scenarios by the average of the subset of 3 AOGCMs used for the impact analyses presented in this volume. Precipitation projections are in units of percentage change relative to the 1961–1990 average and have been statistically downscaled to a spatial resolution of one-eighth degree.
Annual and seasonal temperature

Projections from the full suite of IPCC AR4 models for the SRES A1fi, A2, and B1 scenarios (Fig. 4) indicate that, over the near-term (2010–2039), annual temperatures in the region are projected to rise by an average of 1.4±0.6 °C, where the uncertainty is defined as the standard deviation of the 40 simulations shown in Fig. 4. Due to the inertia of the climate system and the lack of differentiation between scenarios over the near term, no significant difference can be expected between higher vs. lower emissions over this time period. By midcentury (2040–2069), annual average temperatures are projected to increase by 2±0.7 °C under lower emissions and 3±1 °C under higher. By the end of the century (2070–2099), annual average temperatures for the US Great Lakes region are likely to increase by 3±1 °C under lower emissions and 5±1.2 °C under higher emissions, relative to the historical reference period 1961–1990.

The range in projected temperatures is a function of the different emission scenarios underlying each climate model simulation as well as the climate sensitivity of each individual AOGCM. In contrast to lower emissions (blue and green symbols in Fig. 4), higher emissions (as indicated by the red, orange, and pink symbols) imply greater temperature change, particularly towards the end of the century. Similarly, models with greater climate sensitivity suggest a larger temperature increase in response to a given emissions scenario, while others with a smaller sensitivity simulate a smaller temperature increase under the identical emissions scenario.

At the same time, however, region-wide annual average temperature projections mask significant variability in the temporal and spatial distribution of warming. Winter and summer temperature change simulated by the subset of three AOGCMs is shown in Fig. 5. Over the short term, relatively greater increases are projected for winter months and smaller increases in spring and summer, consistent with observed trends. After the middle of the century, this seasonality is projected to reverse, with greater temperature increases in summer as compared to winter and spring. By the end of the century, for example, projected increases in region-wide summer temperatures average at least a degree higher than changes in winter.

There are also important geographic differences across the Great Lakes region. Temperature increases are projected to be generally greater for more southerly states such as Illinois and Indiana and slightly smaller for more northerly states of Minnesota and Wisconsin. Temperature increases for spring, summer, and fall are strongest for more southern states. The opposite pattern is seen in winter, where temperature increases are greatest for northern states such as Wisconsin and Minnesota. A similar effect has already been observed in the US Northeast, where winter temperatures are rising at twice the rate of the annual average (Hayhoe et al., 2007).

For the city of Chicago by the end of the century, temperature increases of 1.5–2 °C are projected under the lower emissions future and 4.4–5.5 °C under the higher emissions scenario (Fig. 6). Towards the end of the century, greater increases are projected to occur in summer months. Temperature projections for Chicago incorporate its current urban heat island (UHI) effect but do not attempt to estimate the effect of any potential changes in the city’s UHI, such as the moderating effect of adaptation efforts such as the city’s Green Roofs program (more information available online at: http://egov.cityofchicago.org/).

Annual and seasonal precipitation

Different AOGCMs tend to represent cloud processes and the hydrological cycle differently. This produces a range in projected changes in precipitation exceeding that of temperature.

Over the near-term, most models estimate annual precipitation changes over the Great Lakes region ranging from decreases of a few percent to increases of up to +7%, well within the range of interannual variability (Fig. 4). By midcentury, the range is slightly broader, from −2 up to +10%. By the end of the century, only two models show decreases in precipitation; all the others indicate increases of up to 20% annually across the region.

Although climate change is expected to bring the Great Lakes region no more than slight increases in annual average precipitation, as with temperature these relatively small changes in annual average values mask much larger shifts at the subannual scale. Spring and summer precipitation change simulated by the subset of three AOGCMs is shown in Fig. 7. Relatively large increases in winter and spring precipitation are projected to occur across the region, with larger changes under higher emissions as compared to lower (∼+30% vs. ∼+20%), and by end-of-century as compared to closer time periods. For summer, AOGCM simulations range from modest increases up to potentially large decreases in precipitation of −50%. Precipitation increases in winter and spring tend to be larger for states directly south of the Great Lakes, including Illinois, Indiana, and Ohio (Fig. 7).

This increase in winter and spring precipitation has implications for the number of rain and snow days. As winter temperatures have warmed across the region, more precipitation has been falling as rain and less as snow over the last few decades. Since 1980, almost 3 out of 4 winters have seen below-average snowfall. Over the next few decades, little change is expected in the number of snow days for more northern states, including the city of Chicago; although more southern states could lose between 2 and 4 snow days each year. By end of century, however, on average across the region the number of snow days per year is expected to decrease. Decreases on the order of 30% to nearly 50% are expected under lower emissions, depending on location, and 45% to 60% under higher (Fig. 8).

Migrating climates

A tangible measure of how climate change may affect Great Lakes states and the city of Chicago is provided by a “migrating state/city” analysis. First used in an earlier assessment of climate change impacts on the Great Lakes (Kling et al., 2003), a migrating climate analysis consists of quantifying projected future climate conditions in a given location, then searching for present-day analogues to those conditions today. In that report, summer conditions in the state of Illinois by end-of-century were projected to be similar to those of East Texas today, while winter conditions were estimated to be more like southern Missouri or northern Arkansas feel today. The original projections were based on projected changes in seasonal average temperature and precipitation under a midrange emissions scenario.

![Fig. 8. Projected change in the average number of snow days per year across the US Great Lakes region, by state. Average number of days for the period 1961–1990 are compared to 2070–2099 average under the SRES A1fi (higher) and B1 (lower) emissions scenarios. Values shown are the average of the subset of 3 AOGCM simulations, statistically downscaled to one-eighth degree.](http://egov.cityofchicago.org/)
Here, following the approach of Kling et al. (2003), we first use average summer temperature and rainfall to characterize summer climate conditions for the states of Michigan and Illinois (Fig. 9) and the city of Chicago (Table 3). This time, however, we project changes under higher and lower future emissions scenarios. In both these cases, projected changes in average summer temperature and rainfall under climate change are expected to make the states feel as if they are shifting south and westward over time. Within a decade or two, summer in central Illinois is likely to feel more like southern Illinois does today, while Michigan summers may feel more like those of Indiana do today.

Fig. 9. Projected changes in summer average temperature and rainfall for Illinois and Michigan indicate that summers in these states will feel progressively more like summers currently experienced by states to their southwest under both SRES A1fi higher (red) and B1 lower (yellow) future emissions scenarios. Both states are projected to warm considerably and have less summer rainfall.
Projected “climate migration” of the city of Chicago in winter (DJF) and summer (JJA): estimated using the approach of Kling et al. (2003) based on changes in seasonal average temperature and precipitation; and using a new approach, based on winter average temperature and snowfall amount, and summer average heat index (after UCS, 2006) derived from daily maximum temperature and humidity. Changes are those projected under the SRES A1fi higher and B1 lower emissions futures for the near-term (2010–2039), midcentury (2040–2069), and end-of-century (2070–2099).

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<td>Winter (DJF)</td>
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<td>Seasonal T/P</td>
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<td>Lower</td>
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<td>Cleveland, OH</td>
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<td>Summer (JJA)</td>
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<td>Seasonal T/P</td>
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<td>Springfield, IL</td>
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<td>Heat index</td>
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Over the rest of the century, both Illinois and Michigan summers are expected to become progressively hotter and drier, particularly under higher emissions. By the end of the century, Illinois summers would feel like East Texas does today under the A1fi higher emissions scenario, and like Arkansas under the B1 lower scenario. Michigan summers would feel like western Oklahoma does under higher emissions, and like Missouri under lower.

Although average summer temperature and precipitation are typically used to characterize climate at a given location, there are other climatic indicators that may more clearly communicate the effects of climate change on a city or region in terms that matter more directly to its inhabitants. For the city of Chicago, we therefore employed a second approach to estimate the city’s “migrating climate,” first used in UCS (2006). Summers were characterized by average June–July–August heat index values that combine maximum daily temperatures with humidity to more accurately simulate how hot a summer would “feel” to city inhabitants. This produces an average summer June–July–August heat index value of 34 °C (93.5 °F) under the lower and 40.5 °C (105.5 °F) under the higher emissions future before the end of the century. Although using a heat index vs. an average temperature value makes little difference over the near term (both analyses show Chicago feeling more like Springfield, IL, does today; Table 3), comparing midcentury and end-of-century projected increases in Chicago’s average summer heat index to historical summer heat index values reveals greater changes than those estimated from temperature alone. Based on its average summer heat index values, by the end of the century, Chicago would be expected to feel more like Atlanta, GA, does today under lower emissions, and like Mobile, AL, under higher.

In contrast to summer, the defining characteristics of winter in Chicago are its snow, its wind, and its cold temperatures. The ability of climate models to simulate future changes in wind speeds and direction at the local level, such as for Chicago, is limited. This means that we are unable to produce robust estimates of projected changes in wind chill, for example. Instead, we estimate how average winter snowfall and temperatures might be altered in the future due to climate change. Comparing future projections with present-day winter snow and temperature estimates for cities across the eastern US reveals that Chicago can be expected to migrate nearly due east from its current location, maintaining almost the same amount of average winter snowfall that it does today (Table 3). This is because winter precipitation is projected to increase as temperatures warm, maintaining the total amount of snowfall at similar levels to that observed historically over much of the coming century. Thus, although summers may feel like the South, winters are expected to feel more like those of northern Ohio or central Pennsylvania do today, with no significant reduction in snow or ice. Under the higher emissions scenario, by midcentury, the migration is projected to be occurring nearly twice as fast as under the lower emissions scenario, with Chicago winters becoming more like those of northern Virginia by the end of the century.

Care must be taken when interpreting these results, as local climate is sensitive to regional topography and other characteristics. Although summer temperature and precipitation may feel like that of East Texas or Oklahoma, or winters like Pennsylvania, that does not mean that all other characteristics of those states will automatically transfer. Michigan and Chicago will still experience the moderating effect of the Great Lakes on their climates, while Illinois will still own its flat land and rich soils. Ecosystems typical of these regions, while sensitive to climate changes, can take decades to centuries to adjust to climate change, as will infrastructure (Smith et al., 2004; Fischlin et al., 2007). Hence, it is important to acknowledge that this analysis is illustrative of climate conditions only, not of other aspects of the physical environment that characterize those locations.

Projected changes in lake levels

As the largest concentration of freshwater in the world, the Great Lakes represent an invaluable resource for the region. They are the mainstay of the region’s water supply, recreational activities, shipping industry, and natural ecosystems. As no study of climate change in the Great Lakes is complete without projections of how the lakes themselves will be affected, our last analysis applies the projected temperature and precipitation changes described above to estimate the net impact on long-term ice cover and lake levels for the Great Lakes.

Climate factors controlling lake levels

The Great Lakes have tremendous capacity for water and heat storage, creating a significant inertia when responding to changes in climate. Precipitation causes major long-term variations in lake levels (Quinn and Croley, 1981; Quinn, 1985). From 1900 through 1939, for example, annual precipitation across the region was generally below average. From about 1940 until recently, however, precipitation has been above the long-term average based on the period of record.

Variations in air temperature also influence lake levels. Warming air temperatures lead to warmer lake temperatures, altering water circulation patterns, particularly the timing and duration of summer stratification. At higher air temperatures, plants tend to use more water, resulting in more transpiration, and there are higher rates of evaporation from both the ground surface and the lake. This yields less runoff for the same amount of precipitation than would exist during a low temperature period when there is less evaporation and transpiration.

Warmer air temperatures also reduce the duration and extent of ice cover on the lake. Coupled with the higher lake evaporation due to the enhanced ability of warmer air to hold water vapor, lake levels tend to drop with increasing air temperature. The net effect of climate change on lake levels will be a complex balance between the timing and magnitude of all changes in environmental factors that influence the water cycle in the Great Lakes basin.
In the future, warming temperatures due to climate change are expected to continue the observed downward trend in both winter average ice cover as well as the extent of peak ice coverage. Our simulations of average February ice cover indicate that Lake Michigan could experience ice-free winters as soon as 2020 and that annual average ice cover could fall to near zero before midcentury, consistent with observed trends.

Here, we use a transient version of the AHPS model to estimate actual year-to-year changes in Lake Michigan levels for the three time periods used in this analysis: near-term (2010–2039), midcentury (2040–2069), and end-of-century (2070–2099) under the lower B1 and higher A1fi emission scenarios. As such, these projections encompass a more narrow range of climate simulations, but a wider range of emission scenarios that complement the analysis of Angel and Kunkel (2010). Looking at the drivers of lake-level changes, most climate models project a significant increase in winter/spring precipitation over the region, while all suggest an increase in both annual and seasonal temperatures (Fig. 4). This increase in precipitation largely counteracts the effects of warming temperatures, such that there is little net change in lake levels under a lower emissions scenario. Under the higher emissions scenario, much larger temperature increases do cause a net drop in lake levels by end-of-century on the order of 1.5 ft (Fig. 10).

Sensitivity experiments indicate that the main drivers of change are temperature and precipitation, with smaller contributions from wind and humidity. Temperature caused the lake levels to drop but these effects are very much mitigated by slight increases in precipitation, with some additional assistance from wind and humidity. As the various climatic influences cancel each other out to some degree, particularly under a lower emissions scenario, projected changes are relatively small as compared to previous estimates. For that reason, little to no significant change in lake level is projected under a lower emissions scenario, and about 1.5 ft for most of the Great Lakes under the higher scenario by end-of-century according to the transient runs (Fig. 10). Note, however, that these are average changes in lake levels; decadal-scale variability on the order of several feet would still be likely to occur as it has in the past.

Discussion and conclusions

A number of long-term climate changes have already been observed across the Great Lakes region (Table 1). While it is not possible to definitively attribute these trends to anthropogenic warming, the observed trends in temperature, precipitation, and related variables such as ice and snow cover are certainly consistent with those observed at the global scale and simulated by AOGCMs to be the result of increasing human emissions of greenhouse gases and other radiatively active gases and particulates.

In the future, many of the climatic trends already observed in Chicago and the Great Lakes region are projected to continue, with much greater changes expected under higher, as compared to lower, emission scenarios. Depending on future emissions and the response of the climate system to those emissions, temperatures across the Great Lakes could increase by 2–6 °C (3.5–11 °F) before the end of the century.

Initially, temperatures are projected to increase more rapidly during the winter season, possibly as a result of feedbacks related to melting snow. During the second half of the century, however, greater temperature changes are projected for summer months, exacerbating concerns regarding water availability. Larger temperature increases are also projected for the more southerly Great Lake states as compared to the northern part of the region.

Warmer temperatures imply a range of both positive and negative impacts for the region. Decreased energy use in winter and risk of cold-related illness and death must be balanced against a higher demand for electricity in summer months, accompanied by more frequent extreme heat events and heat waves and associated increases in heat-related mortality (Hayhoe et al., 2010). Shifting seasons affect native species and entire ecosystems, lengthening the growing season and altering fundamental characteristics such as plant hardiness zone (Hellmann et al., 2010).

Climate change is also likely to alter the timing and distribution of precipitation across the region. Specifically, winter and spring precipitation is projected to rise by as much as 20–30% before the end of the century, with little change to a decrease in summer precipitation to balance the warmer temperatures expected during those months. Slightly larger increases in precipitation are projected for states south of the Great Lakes, with little decrease in winter snow at least for the first half of the century.

The projected shift in the timing of precipitation has important implications for water resources, agriculture, and infrastructure in the region. Warmer temperatures and similar or reduced precipitation in summer, during the growing season, means that farmers may have to increase their reliance on groundwater sources to water their crops (UCS, 2009). More precipitation in winter and spring could mean greater chances of both heavy snowfall and rainfall events. Most rivers reach their peak levels in spring, swelled by melting snow. Combining increases in precipitation with already high river levels could increase flood risk for many areas (Cherkauer and Sinha, 2010).

Finally, we also examined the implications of projected changes in temperature and precipitation on Great Lakes water levels. Although these are a complex function of both regulatory action and climatic variables, by altering only the climate controls we found the differential effects of changing temperature and precipitation were likely to balance each other out over much of the coming century, leading to little net change in Great Lakes levels in coming decades. Only towards the end of the century, and under higher emissions, did a significant drop in lake levels begin to become apparent. It is important to note, however, that lake levels require decades, sometimes even centuries, to reach equilibrium under new climate conditions. As evidenced by the work of Croley and Lewis (2006), transient decreases in lake levels represent only a small fraction of the long-term equilibrium change that would result from sustaining these levels of change over time scales of decades to centuries.

Long-term reductions in lake levels can have significant economic impacts on Great Lakes shipping and recreational boating, as well as operations at ports such as Chicago. Lower lake levels require more dredging and channel maintenance, which incur economic costs and disturb ecosystems. A case study using the 1964–65 low water period as a proxy for future change (Chamnon, 1993) revealed more dredging than usual was required for both commercial and recreational users. Lake carrier loads were reduced by 5–10%, requiring more trips and
increased costs. Total cost was estimated at around $100 million (1988 dollars), with economic impacts for a 1.5-m drop ranging from $3.5 to $35 billion (1988 dollars). A more recent study by Schwartz et al. (2004) estimated that for a 3-ft decline in lake levels, the cost for an individual lakeside town, in terms of marina and harbor dredging, and loss of freighter capacity, could be close to $7 million.

All of these changes are likely to have a considerable impact on the region’s character, its cities, and climate-sensitive sectors of its economy. For this reason, the companion studies in this issue explore the implications of projected climate changes on Great Lakes hydrology, ecosystems, society, and infrastructure.

Because climate change is already affecting the Great Lakes region, and some additional warming is inevitable, it is essential to prepare to adapt to the changes that cannot be avoided. However, timely actions to significantly reduce emissions do have the potential to prevent temperatures from rising to levels consistent with, or even below, those presented for the lower emissions scenario used in this study. The greater the extent of the emissions reductions achieved, the greater the ability of ecosystems, human communities, and economic sectors to adapt to the coming climate. Projections such as these have already prompted the City of Chicago to set the goal of reducing its emissions 80% by 2050 (more information available online at: http://www.chicagoclimateaction.org/); a reduction that, if adopted by all industrialized nations, would have a good chance of limiting climate change to even less than the amount of change projected under the lower emission scenario used here (Meinshausen et al. 2006).

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