



CLIMATE CHANGE AND CHICAGO

PROJECTIONS AND POTENTIAL IMPACTS

CHAPTER THREE - WATER

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WATER

Chicago's development as one of the largest cities of the world is inextricably connected with its location on the sub-continental divide separating the Great Lakes and Mississippi River basins. The city's proximity to an apparently inexhaustible supply of fresh water and to this key transportation nexus led to its rapid growth in the middle of the 19th century and to the establishment of the economic base that continues to drive the prosperity of the entire region. In addition to providing a source of drinking water, Lake Michigan and its connected waterways support a wide variety of commercial and recreational uses. Visitors to Chicago marvel at the beauty and accessibility of the lakefront and, often hidden from casual view, the city's waterways provide habitat and sustain a large number of important plant and animal species. Understanding how climate change might affect these waters is critical to the overall evaluation of the impacts of climate change on the Chicago region.

This chapter summarizes both the changes in climate and the anticipated responses of the aquatic systems these changes will affect. We begin with a discussion of the how expected changes in precipitation and temperature will affect the region's hydrological balance, including local rivers and streams and Lake Michigan. Possible effects of changes in stream flow and precipitation on the area's beaches are covered next. Finally, we explore the possible effects of climate change on the Lake Michigan aquatic ecosystem.

Precipitation and other key hydrological variables

Model description

In order to estimate the potential impacts of climate change on the hydrological cycle in the greater Chicago area, monthly temperature and precipitation fields from the six climate model simulations (GFDL, HadCM3 and PCM models for the A1fi higher and B1 lower scenarios) were first statistically downscaled to daily values for the Midwest with a resolution of $1/8^\circ$ or about 8.5 by 6.5 miles, at the latitude of Chicago. 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 climate model output for long-range streamflow forecasting¹, later adapted for use in studies examining the hydrologic impacts of climate change², and compares favorably to different statistical and dynamic downscaling techniques³.

Downscaled temperature and precipitation were then used as input to the Variable Infiltration Capacity (VIC) model version 4.1.0 r3^{4,5,6,7}. This hydrological model simulates the full water and energy balance at the earth's surface by modeling processes such as canopy interception, evapotranspiration, runoff generation, infiltration, soil water drainage, soil freeze and thaw, and snow pack accumulation and melt. A single set of model forcings (precipitation, temperature, radiation, etc.) and soil properties (porosity, saturated hydraulic conductivity, etc.) are specified at each $1/8^\circ$ grid cell, while any number of vegetation types can have their parameters (leaf area index, stomatal and architectural resistances, etc.) defined.

Outputs from the VIC model include gridded fields of evapotranspiration, runoff, snow water equivalent, soil moisture profiles, and freeze and thaw depths. The runoff fields (surface and baseflow) from these simulations may then be routed through stream networks using a lumped routing model⁸ (for small basins) that can be compared with observed streamflow measurements for the historical period of the record. The VIC model has been applied extensively at scales ranging from river basin⁹, regional and continental¹⁰, up to global scales^{11, 12}. For the analysis presented here, values used in the text are for the Chicago area only (latitude 41 to 42.5°N and longitude 88.5 to 87°W), while spatial figures show a wider domain with Chicago near the center.

These simulations make two assumptions that should be considered when interpreting the results. First, this version of the model does not represent the effects of impermeable area within the watershed. The extent of impermeable surface is likely to increase in the future for Chicago area leading to greater increases in direct runoff and decreases infiltration and baseflow. Second, summer convective storms tend to be more limited in their spatial coverage than frontal storms, thus increasing the intensity of precipitation. This was not explicitly represented in these model simulations but it is likely to lead to higher summer peak flows that obtained from this analysis.

Annual and seasonal average precipitation

According to the full range of IPCC climate models, annual average precipitation in the Chicago metropolitan area is expected to increase by up to 20% by the end of the century (Table 2.1). Precipitation tends to vary significantly from year to year, however. During the historical reference period (1961-1990), Chicago's annual precipitation averaged 36 inches per year. Some years, however, it was less than 25 inches while other years saw more than 45 inches (Figure 3.1). Similarly, in the future, precipitation is expected to continue to vary from year to year. So, even though an overall increase in precipitation is projected by most climate models, there are still likely to be dry and wet years – although by the end of the century, every two out of three years is likely to be a “wet” year (i.e.,

with more than 40 inches of precipitation over the year).

As shown in Table 2.1 and Figure 3.2, most of the increase in annual precipitation is projected to occur in winter and spring. By the end of the century, in fact, the majority of Chicago's precipitation is expected to fall in the spring. In summer, precipitation is likely to decrease. Little change is expected in the autumn. Similar patterns of change are shown by both the higher and lower emissions scenarios, although the higher scenario suggests slightly larger winter/spring increases as well as greater decreases (up to 20%) in summer.

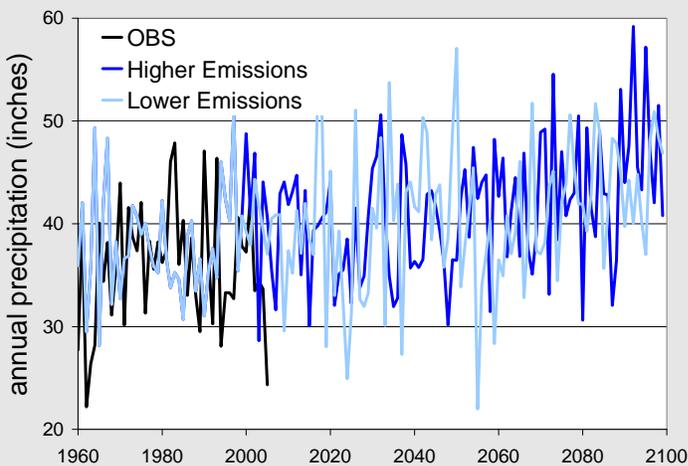


Figure 3.1. Observed historical and projected future annual precipitation (in inches) under the lower and higher emissions scenarios.

The projected shift in the timing of precipitation has important implications for water resources, agriculture, and infrastructure in the region. Less precipitation in summer, during the growing season, means that farmers may have to increase

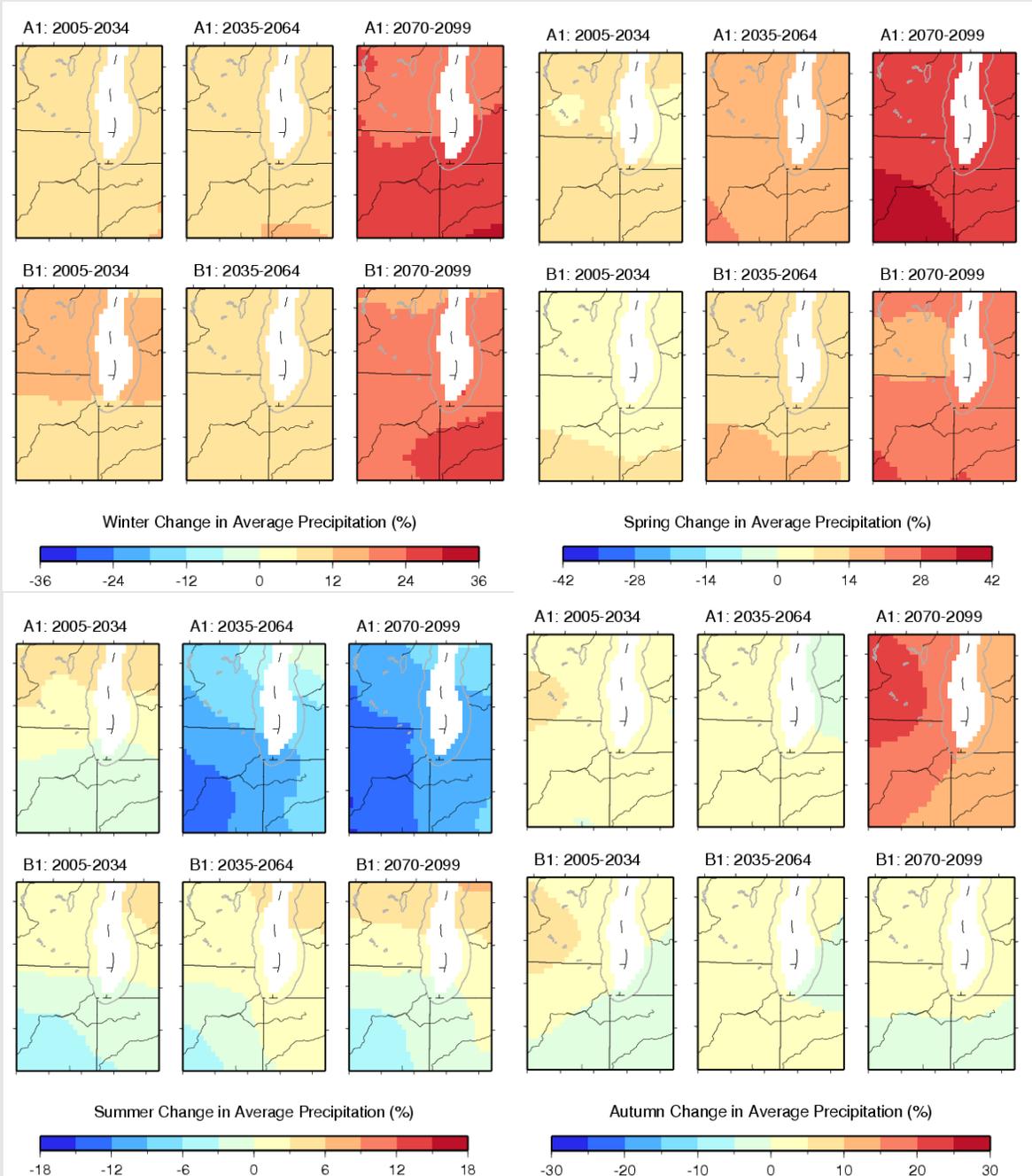


Figure 3.2. Projected changes in annual average seasonal precipitation (in units of percentage change relative to 1961-1990 averages) as simulated by the VIC hydrological model under the higher (A1fi) and lower (B1) emissions scenarios. Results shown are the average of VIC simulations driven by output from the GFDL, HadCM3 and PCM climate models.

their reliance on groundwater sources to water their crops. More precipitation in winter and spring could mean greater chances of 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 mean an increase in flood risk for many areas, and the potential for damage to homes, buildings, roads and bridges.

Snow and rain

As winter temperatures have warmed across the region, more precipitation has been falling as rain and less as snow. Since 1980, almost 3 out of 4 winters have seen below-average snowfall. As temperatures continue to warm over the rest of the century, it would be expected that there would be less snow and more rain. Climate projections show, however, that the total amount of snowfall in each winter is not projected to change dramatically, remaining around 40 inches per year despite much warmer winter temperatures (Figure 3.3a). This is due to the fact that winter precipitation is projected to increase (by 20-30% by the end of the century), increasing the number of wet days (defined as having precipitation greater than 0.5mm) that occur each winter (Figure 3.3b). With a larger number of wet days during the winter months, there is a greater chance that on the days

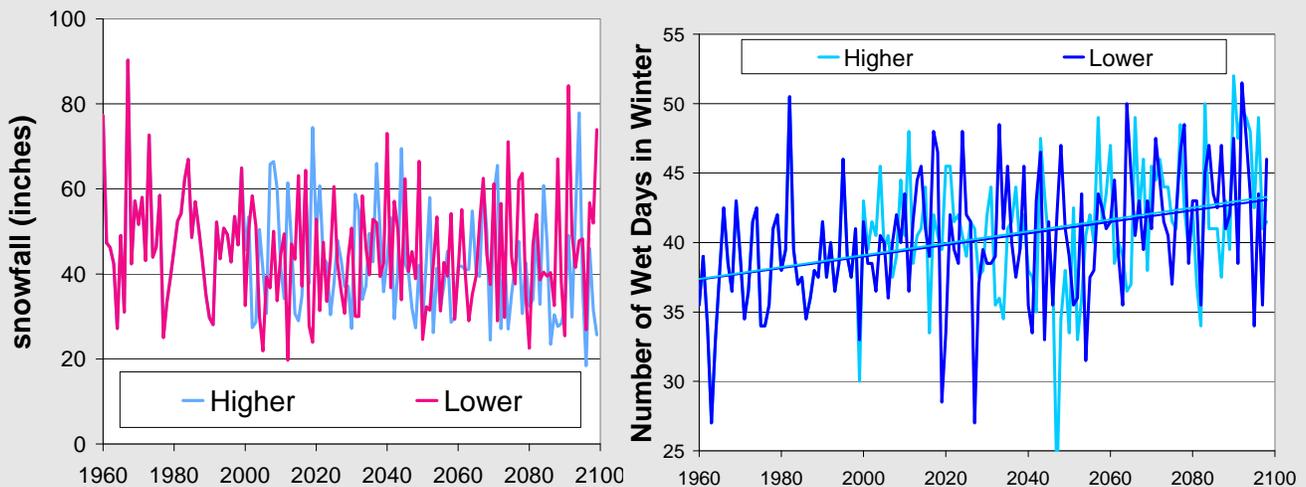


Figure 3.3. Historical and projected future (a) annual snowfall (in inches) and (b) number of wet days each winter (with a “wet day” being defined as > 0.5 mm of precipitation) for Chicago under the lower and higher emissions scenarios. Shown are the average of the GFDL and PCM climate model output (daily precipitation data for HadCM3 A1fi scenario not available), downscaled to the Chicago O’Hare, Midway, and University locations, with snowfall being estimated as occurring when daily maximum temperatures were less than 5°C.

when it is cold enough to snow, that there will be sufficient precipitation to do so. Thus, over the coming century it appears that the effects of increasing precipitation at least partially offset the effects of warming temperatures on Chicago's total winter snowfall amounts, with the net result being little change in the *amount* of winter snowfall.

In contrast to the lack of trend in the amount of snowfall per year, however, increasing air temperatures in the Chicago area are projected to reduce the duration of the cold season, limiting the formation of snow and soil frost. Thus, even though the actual amount of snow that falls during any given winter may not change much, the winter snow season is likely to become much shorter than it is today.

The number of days with snow on the ground is projected to decrease from an annual average of 40 days (during the historical reference period 1961-1990) to between 13 and 23 days per year (Figure 3.4a). Most of the change will be due to the last date of snow cover in the spring coming earlier and earlier in the year – about a week earlier by mid-century under either scenario, and up to 2 weeks under the lower and 3 weeks under the higher emissions scenario by the end of the century (Figure 3.4b). The number of days with soil frost is likely to decrease by nearly half, from an annual average of a little over 4 months to just over 2 months (Figure 3.4c). Soil frost will start two weeks later in the year, thaw nearly a month earlier, and penetrate to only about half its current average annual depth of 44 cm (Figure 3.4d).

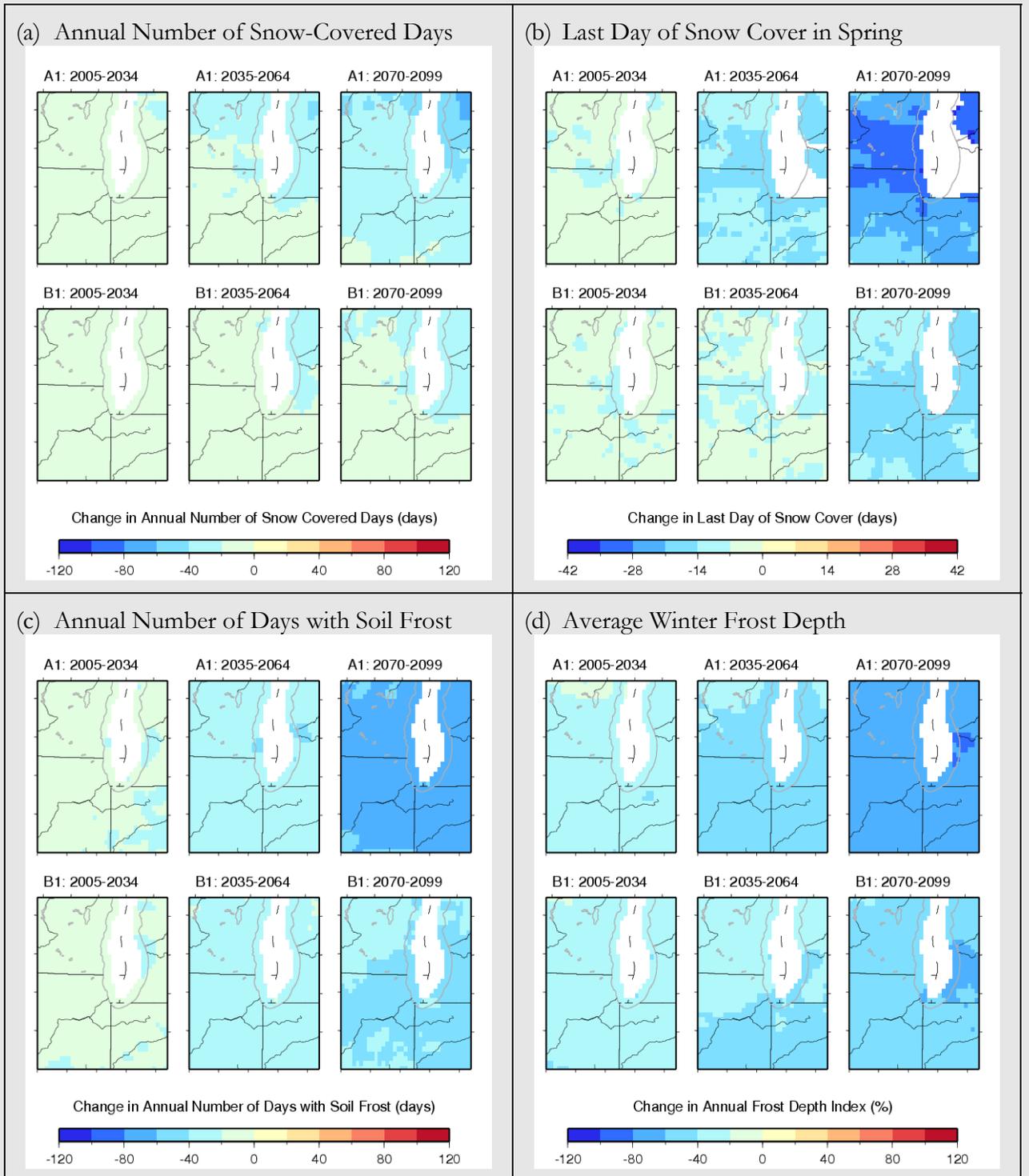


Figure 3.4. Projected future change in (a) the number of snow-covered days per year, (b) the last date of snow cover in the spring, (c) the length of the soil frost season, and (d) average winter frost depth, relative to the 1961-1990 average for the higher (A1fi) and lower (B1) scenarios as simulated by the VIC hydrological model driven by downscaled projections from the GFDL, HadCM3 and PCM models.

Extreme precipitation

The frequencies of heavy rain events (defined as occurring on average once per year during the past century) have doubled since the early 1900s. Increases in the number of individual rainy days, short-duration (one to seven days) heavy rain events, and week-long heavy rain events have also been observed^{13,14,15,16}.

Extremes in precipitation often result in negative societal impacts. Heavy precipitation that leads to flooding can damage crops and cause soil erosion, contaminate the water supply, promote infectious disease, disrupt transportation, and lead to property damage or loss. Drought conditions can likewise cause serious problems, resulting in reduced crop yields, increased livestock deaths, greater risk of wildfires, reduced hydropower generation, and enhanced risk of water-borne diseases¹⁷. In the Chicago region, extremely heavy precipitation events can lead to storm water discharge of contaminants into water bodies¹⁸. Empirical evidence from Chicago indicates that approximately 2.5 inches of rainfall in a day is a threshold for combined sewer overflow into Lake Michigan¹⁹.

The intensity of heavy precipitation events in Chicago is expected to continue to increase over the coming century, with the largest increases corresponding to the

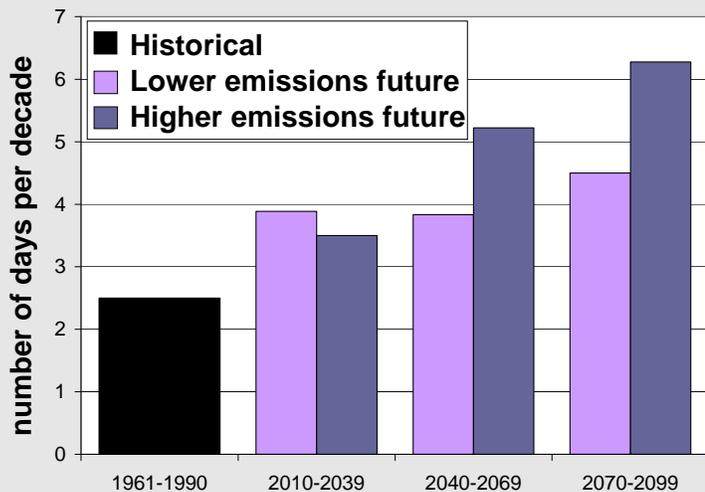


Figure 3.4. Projected changes in the frequency of heavy precipitation events (more than 2.5" per day), as simulated by the GFDL and PCM models downscaled to the Chicago University, Midway, and O'Hare weather stations (daily HadCM3 precipitation not available).

heavier events. Both of the climate models used in this assessment show this response, although they differ on the magnitude of the increase. For example, the frequency of precipitation events exceeding 2.5 inches per day is expected to increase by nearly 50% as early as the 2010-2039 period and to rise by 80 to 160% by the end of this century (Figure 3.5). This change means that the occurrence of such heavy precipitation events would rise from about once every four years to once every other year by the late 21st century. Adaptation may thus be required to counteract the

enhancement in flooding and storm water contamination implied by the models. Despite the more frequent intense precipitation, the total amount of rainfall during the summer is expected to either change little (+1% in the low emissions scenario) or to decrease substantially (-15% in the high emissions scenario). These timescale-dependent precipitation changes suggest an increased probability of drought, a supposition supported by an increase in the average number of days between rainfall (11 to 31%) and the maximum number of days per year between rainfall events, i.e., consecutive dry days (increase from 6 to 53%).

The differing downscaled projections for total versus heavy precipitation is consistent with other global climate models and meteorological theory. While the sign of the change in seasonal or annual precipitation is dependent on uncertain variations in global circulation patterns, the precipitation intensity of a single event is regulated primarily by the local amount of moisture in the atmosphere at the time of a storm²⁰. Because the moisture-holding capacity of the atmosphere increases exponentially with temperature, a warmer future climate will be able to support much heavier precipitation occurrences. This expectation is borne out by a number of other climate modeling studies that strongly suggest that a combination of more intense precipitation and longer dry spells will accompany global warming^{21,22,23}.

Evapotranspiration and runoff

Simulations indicate that evapotranspiration (ET) has historically used 71% of the annual average precipitation, or in other words 29% of precipitation leaves the area as runoff and groundwater recharge. Future climate projections indicate that annual average evapotranspiration will increase by only about 1% resulting in a decrease in the ET fraction to about 64%, suggesting a proportional increase in surface runoff and groundwater recharge. A minor decrease in winter ET is seen under higher emissions in the short term, possibly due to a decrease in snow cover resulting in a slight increase in soil frost – especially of the exposure of frozen soil to the atmosphere (snow sublimation is included in ET, but there is no mechanism to sublimate soil frost).

These simulations did not account for changes in vegetation water consumption due to warmer air temperatures, especially in the spring, or increases in atmospheric carbon. Analysis of historic river runoff records²⁴ indicate that observed increases in river discharge cannot be completely attributed to changes in climate. Instead, observed trends are consistent with the suppression of

evapotranspiration related to the increase in atmospheric Carbon. Numerous studies^{25,26,27} of the effect that excess carbon will have on plant transpiration have yielded mixed results, with some plant types more sensitive to temperature (higher ET) than carbon (lower ET) and others being more balanced in their response (minimal change in ET). These simulations do account for the effects of temperature to the existing vegetation, but does not account for possible changes in the physiology of the plants and the effect of such changes on evapotranspiration are difficult to determine. Earlier greening of vegetation and longer growing seasons are likely to increase the amount of evapotranspiration, though probably not enough to return the evapotranspiration ratio to its current levels.

Total runoff, the sum of direct surface flow and baseflow (groundwater return flows), is the amount of water available for streamflow. On an annual average basis, total runoff is projected to increase by between 29 and 43% to reflect the increase in annual precipitation and the associated small changes in evapotranspiration. The largest percent increases (49-88%) in total runoff occur in the winter where warmer air temperatures reduce the amount of snow cover even as precipitation increases (Figure 3.6). Spring total runoff values increase between 37-49%. This is an increase in total runoff volume of nearly twice that of winter, as spring flows are also more than twice those in the winter. Despite decreases in summer precipitation, total runoff in the summer increases by 15-22%, but this is due to increases in baseflow (26-30%) resulting from a wetter spring. Summer surface runoff actually decreases by up to 15%. Autumn total runoff will remain largely unchanged or increase slightly as increased precipitation during this time will continue to be used to recharge soil moisture lost to spring and summer evapotranspiration.

Storage of water in the soil column is projected to increase by only 1-2% annually by the end of the century. Winter and spring soil moisture storage will increase the most, between 2% and 4% as precipitation will fall as snow less often and the snow will melt more frequently, rather than building up on the ground, allowing more water to infiltrate the soil. Spring soil moisture storage is projected to increase by up to 3%, while in the summer it will decrease by up to 1%. Although these amounts are too small in of themselves to significantly impact the region, they would tend to exacerbate the effects of severe dry and wet events.

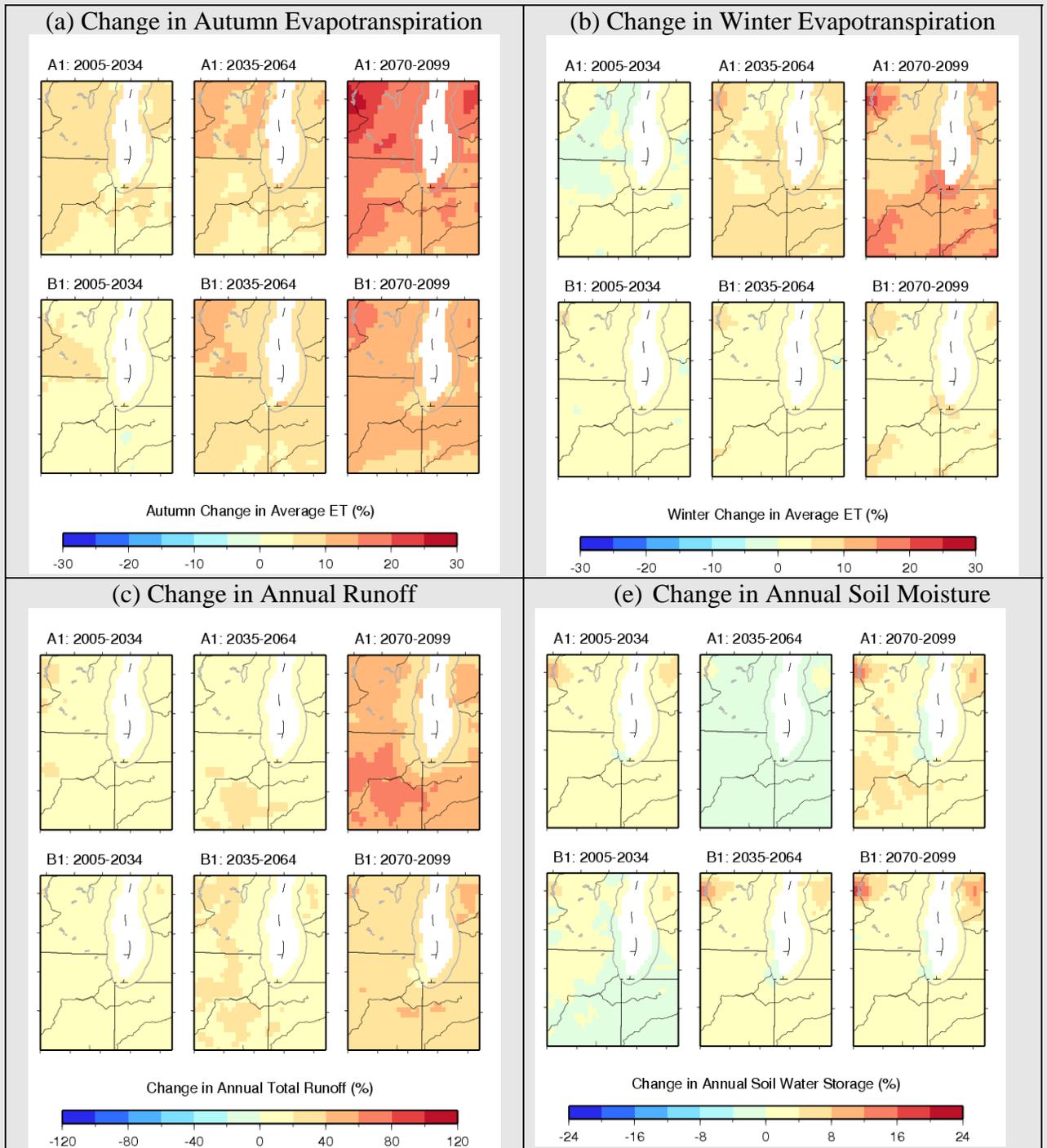


Figure 3.5. Projected future change in evapotranspiration in (a) fall and (b) winter, and in annual (c) runoff and (d) soil moisture. Changes in spring and summer ET (not shown) are on the order of 5% or less. Projected changes shown relative to the 1961-1990 average for the higher (A1fi) and lower (B1) scenarios as simulated by the VIC hydrological model driven by downscaled projections from the GFDL, HadCM3 and PCM climate models.

River and stream flow

Climate change is also expected to alter the amount and timing of river and stream flow, with increased precipitation (and more of it falling as rain, less as snow) in winter and spring bringing heavier and earlier peak flows during that time, while warmer, drier summers mean lower flows. Heavy precipitation events, however, could also contribute to flooding so we will also discuss potential changes in “extreme” streamflow with implications for flooding events.

Projections of total runoff and its components runoff and baseflow provide the most direct analysis of how climate change may affect regional river flows. As discussed in the previous section, average annual total runoff is projected to increase by the end of the century with most of that increase reflected in increases in baseflow rather than direct runoff. This translates into an increase in minimum annual flows of between 22% and 26% annually. Largest increases are in the winter and spring with minimum annual flows increasing between 69% and 186%. Summer and fall minimum flows are not projected to change significantly. These increases are largely due to higher seasonal precipitation and reduced snow accumulation.

Maximum annual total runoff is actually projected to decrease by up to 5% despite higher precipitation in all but the summer months (Figure 3.7). Seasonal changes help identify the reason for this conflicting result - winter flows increase by 3-18% and spring flows decrease by 2-5%. On average, current spring maximum total runoff is twice that of any other season. This is due largely to snow melt. As discussed in the previous section, by the end of the century snow is projected to melt up to a month earlier; this will shift some of the melt water into winter rather than spring runoff. Also with warmer air temperatures and fewer days of snow cover, a smaller fraction of winter precipitation will fall as snow so when the snow does melt it will contribute less water to regional streams. Meanwhile, summer maximum total runoff increases by 7-13% in part because of the wetter spring increasing summer baseflow, but also due to increased storm activities. Currently, summer total runoff maximums are half that of the spring totals, by the end of the century that difference will be cut by 25%.

Another way to look at changes in high flows is to analyze changes to the highest 5% of annual flows by looking at magnitude of the 0.05 exceedence probability (Figure 3.8). There is only a 5% probability that daily total runoff will exceed this value on any given day within a year. On an annual average basis this value

increases between 21% and 33%. So while annual maximum total runoff may decrease because of reduced snow melt, high total runoff values are increasing significantly. Seasonally, winter flows experience the greatest percent increase (33-47%) while spring total runoff volumes increase the most but with a percentage increase of only 17-27%. Summer values increase by 22%, while fall values range between a decrease of 4% and an increase of 17%.

Annual peak flows can also be analyzed by routing VIC simulated runoff and baseflow through major river systems. Peak flow analysis for the Illinois and Wabash Rivers (Figure 3.9) indicates that for most of the coming century changes in annual maximum flow will be minimal, but by the later part of the century flood peaks with a return period of 10 years or more are likely to increase.

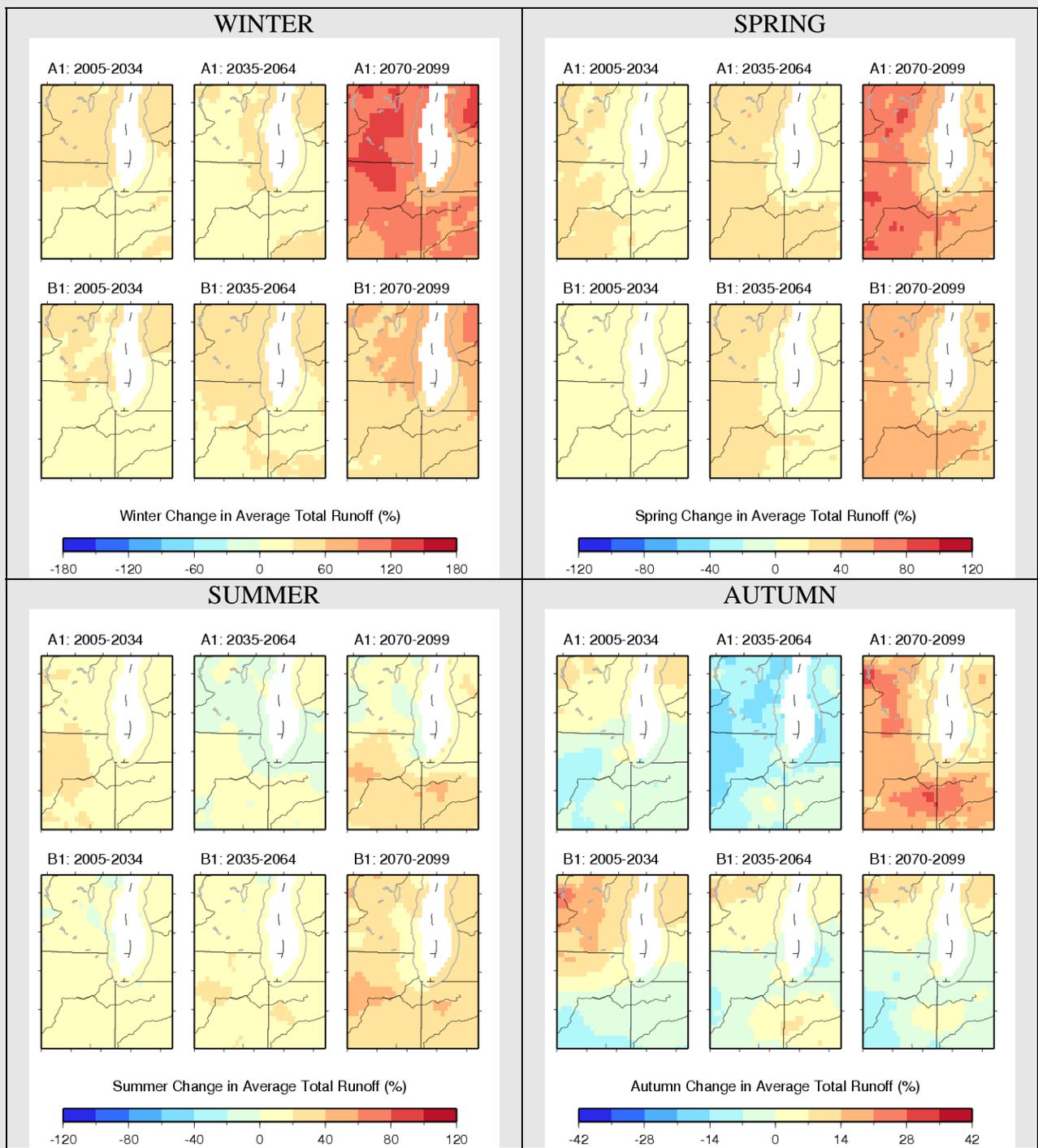


Figure 3.6. Projected future change in runoff in (a) winter, (b) spring, (c) summer and (d) fall. Annual runoff changes are shown in Figure 3.6(e). Projected changes shown in units of percentage change relative to the 1961-1990 average for the higher (A1fi) and lower (B1) scenarios as simulated by the VIC hydrological model driven by downscaled projections from the GFDL, HadCM3 and PCM climate models.

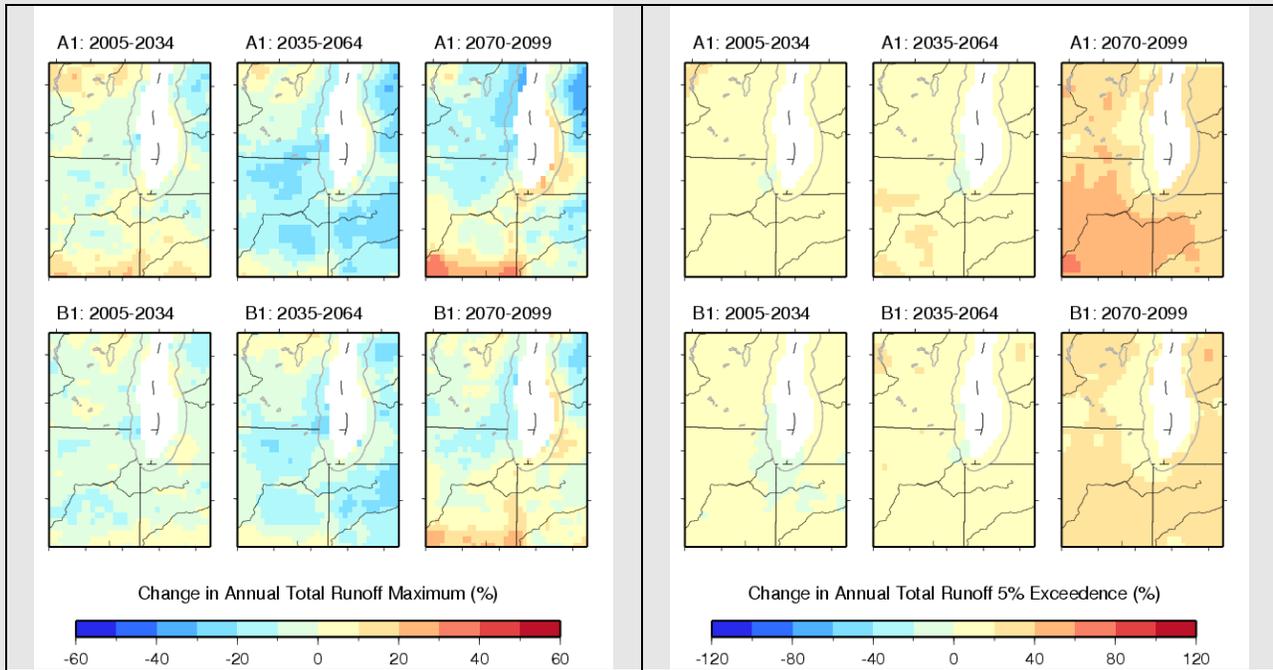


Figure 3.7. Projected changes in the magnitude of (a) annual maximum runoff and (b) the highest 5% of annual flows. Projected changes shown in units of percentage change relative to the 1961-1990 average for the higher (A1fi) and lower (B1) scenarios.

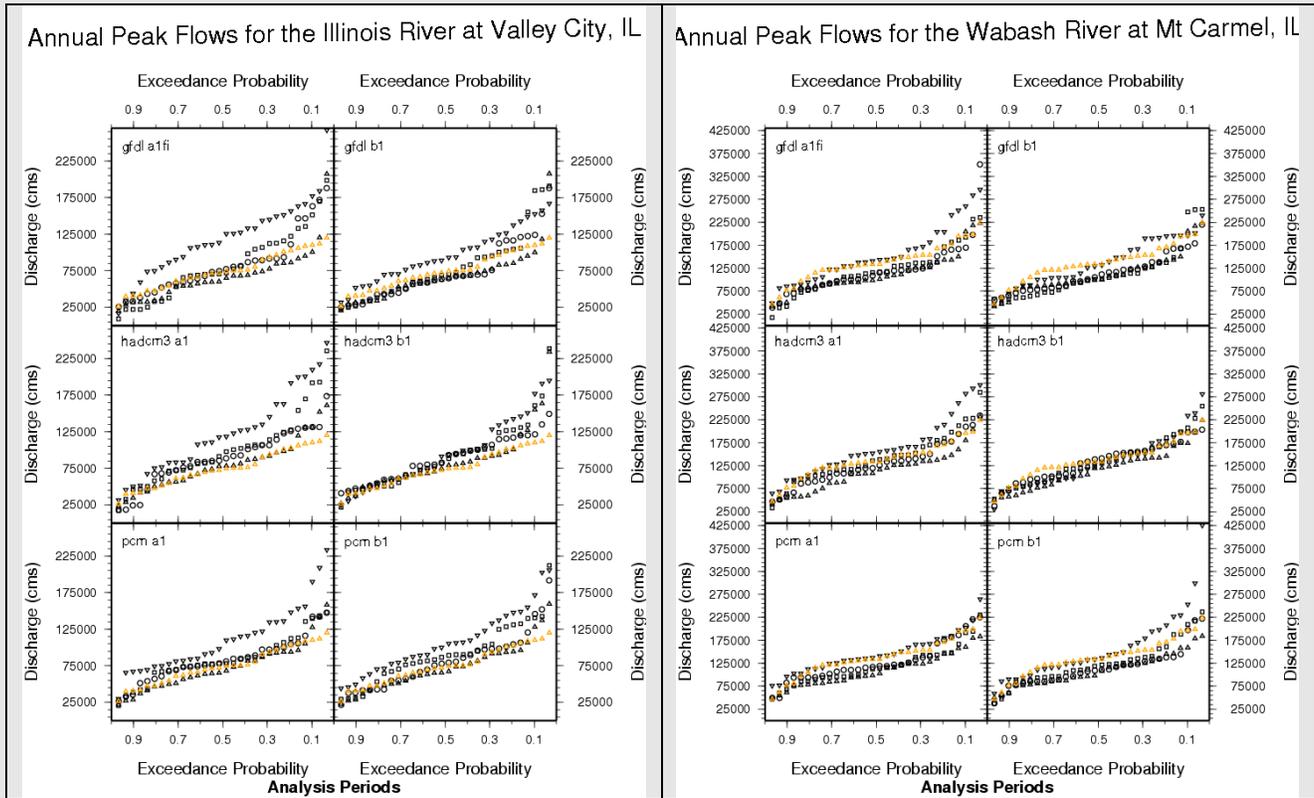


Figure 3.8. Projected changes in annual peak flows for (a) the Illinois River at Valley City, IL, and (b) the Wabash River at Mount Carmel, IL, as simulated by the VIC hydrological model.

Changes in Lake Michigan ice cover and lake levels

The Great Lakes cover over 100,000 mi², of which Lake Michigan accounts for about one-quarter, or 22,000 mi² (Figure 3.9). With a volume of nearly 1200 cubic miles, an average depth of 280 feet, and a length of over 300 miles, Lake Michigan is second only to Lake Superior in the amount of water it contains.

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.

Climate change is expected to impact the Great Lakes, and Lake Michigan in particular, in several ways. As discussed next, warming air temperatures will lead to warmer lake temperatures, altering water circulation patterns, particularly the timing and duration of summer stratification. Warmer air temperatures are expected to reduce the duration and extent of ice cover on the lake. Finally, changes in temperature, precipitation, humidity, and other climate variables are also expected to affect lake levels, with some changes acting to increase lake levels while others cause decreases. 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.

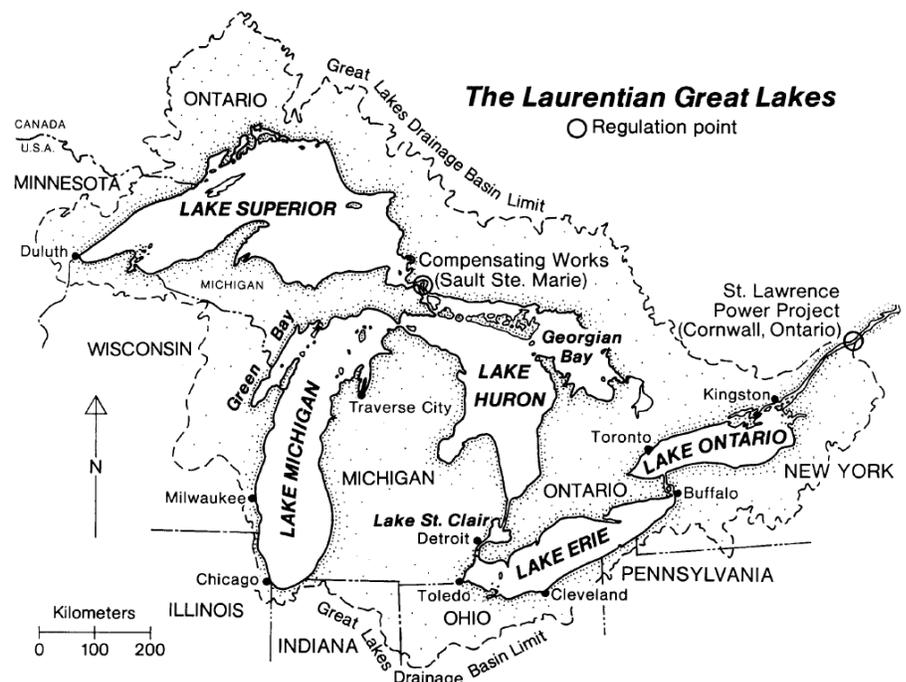


Figure 3.9. The Great Lakes basin. (Source: Croley, 2006)

Modeling approach

Here, we use a model for estimating future lake levels and changes in ice cover, developed by the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory (GLERL), called the Advanced Hydrologic Prediction System (AHPS). Future changes are based on climate projections of changes over the entire Great Lakes region, not just the Chicago area.

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 LBRM consists of moisture storage arranged as a serial and parallel cascade of "tanks" coinciding with the upper and lower soil zones, a groundwater zone, and the surface channel system. Water enters the snow pack, which supplies the basin surface. Infiltration is proportional to this supply and to saturation of the upper soil zone. Water percolates from the upper to the lower soil zone and from the lower to the groundwater zone. Water also flows from the upper, lower, and groundwater zones into the surface channel system, as surface runoff, interflow and groundwater flow respectively.

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 observations²⁸. The parameters represent present-day hydrology and are not changed in the simulations.

Evaporation is handled by GLERL's Lake Thermodynamic Model, which adjusts over-land climate data from the 40 over-land stations that are used to estimate over-water meteorology for over-water or over-ice conditions based on empirical relationships between the two. Surface processes include 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.

The full AHPS model uses meteorological data from 1948-1999 to provide daily time series of temperature and precipitation over each of the 121 watersheds that drain into the Great Lakes. This historical meteorological data is used with the AHPS to compute year-to-year base case “historical reference” lake levels

Model evaluation

To test the model, we first compare model-simulated “historical” net basin supply and lake levels calculated using observed temperature and precipitation records with observed basin supply and lake levels. When comparing model-simulated with observed lake levels, it is important to note that the International Joint Commission mandates that Lake Superior outflows and levels be regulated to balance Lakes Superior, Michigan, and Huron water levels. Lakes Michigan and Huron are then considered to be one lake, hydraulically speaking, because of their connection through the Straits of Mackinac. A relatively small flow of Lake Michigan water is diverted into the Mississippi River basin at Chicago, but most of the water flows from Lake Huron through the St. Clair River, Lake St. Clair, and Detroit River system into Lake Erie. The drop in water surface between Lakes Michigan-Huron and Lake Erie is only about 8 feet, causing a large backwater effect between Lakes Erie, St. Clair, and Michigan-Huron, where changes in Lakes St. Clair/Erie are transmitted upstream to Lake Michigan-Huron.

The AHPS model is relatively successful at reproducing observed basin supply values for Lakes Michigan-Huron over the past 50 years. However, historical observed water levels are generally lower than the simulated by the model (Figure 3.11). This bias in the direction of over-estimation probably results from the historical changes in Lake Superior operations and in the St. Clair River channel that has been dredged over time. It also may be related to variation in crustal rebound occurring after retreat of the last ice sheet; crustal rebound results in relative tilting of Lake Michigan-Huron towards its outlet, suggesting higher outflows and lower levels in the historical record than simulated by this model²⁹.

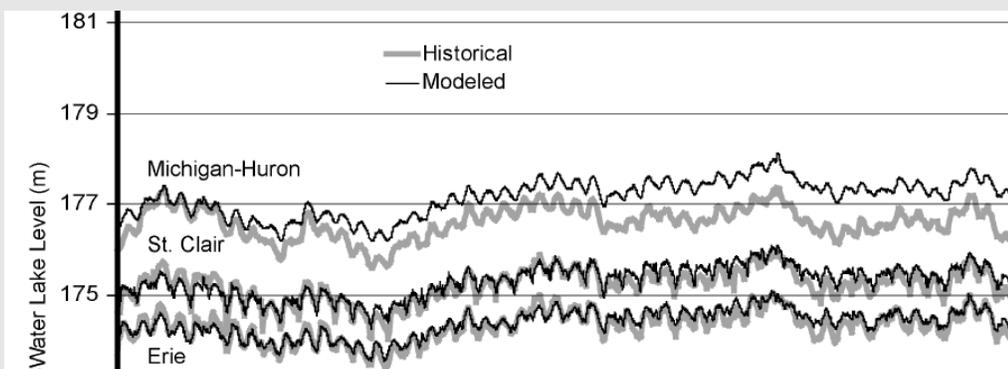


Figure 3.10. Comparison of historical observed and model-simulated (a) net basin supply (in units of millimeters over the lake surface area), and (b) lake levels (in units of metres above sea level).

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 in 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.

Changes in winter ice cover

It is rare for Lake Michigan to freeze over completely. In the past, on average about 45% of the lake is ice-covered during the winter, with open water generally occurring over the southern part of the lake due to its deeper waters and warmer temperatures. Despite the area's reputation for harsh winters, the only years in the recent past when Lake Michigan came close to being completely frozen over were 1977 and 1979, when extended periods of low temperatures resulted in an extensive ice buildup in the southern half of the lake and over 90% ice coverage³⁰ (Figure 3.12). Recently, warmer temperatures have kept the ice cover far below average levels. In 1998, only about 15% of Lake Michigan was ice-covered, even in late February when the icepack is usually at its greatest. Even less was covered in 2002, the last year for which satellite records are available. Ice records from Grand Traverse Bay in northern Lake Michigan show that the bay has not frozen over in the past five winters, marking the first time in at least 150 years that the bay had five consecutive winters without freeze-up³¹.

This regional trend agrees with long-term lake and river ice records over the Great Lakes region³² and the Northern Hemisphere as a whole³³ that show a trend for later freeze-up and earlier break-up dates over the past 150 years.

In the future, warming temperatures due to climate change are expected to continue the downward trend in both winter average ice cover as well as the extent of peak ice coverage. AHPS 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 mid-century, consistent with observed trends.

The impacts of decreased ice cover can be both positive and negative. Less ice cover in the winter means increased evaporation, which could lower lake levels, as discussed next. In terms of its impacts on aquatic ecosystems, although reduced ice cover would extend the \$4B sport-fishing season, near-surface ice fishing activities would be limited. Furthermore, ice formation over shallow areas of the lake protects wetlands and aquatic ecosystems (particularly fish hatching grounds) from wind and waves. An indirect effect of reduced ice cover is the potential for increased shoreline erosion during winter storms.

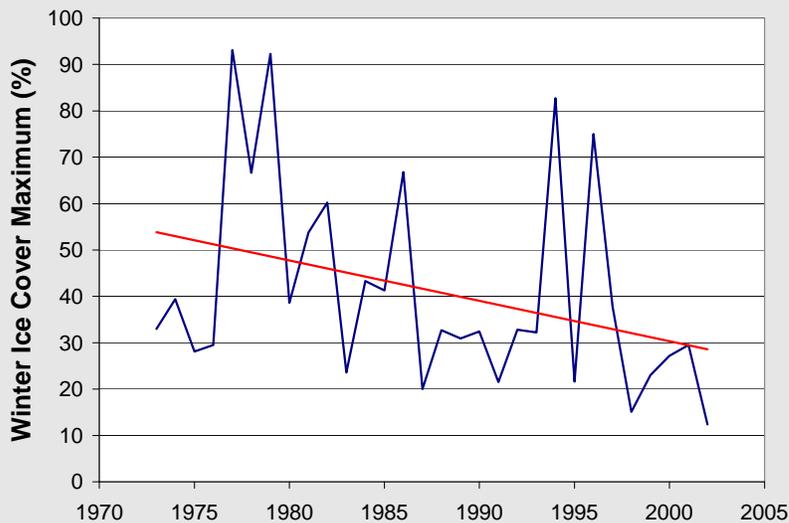


Figure 3.11. Maximum winter ice coverage (in units of percentage coverage relative to Lake Michigan surface area) based on satellite records from 1973 to 2002. (Source: Assel, 2003).

Reduced ice cover could have beneficial effects as well. Winter ice jams in the rivers connecting the Great Lakes can cause flooding upstream of the jam and reduced water availability for hydropower generation downstream. When the jams break, the surge of ice and water down the river can damage infrastructure and endanger inhabitants along the river's banks. Less ice cover in the winter would significantly reduce the likelihood of ice jams. Shorter ice-covered seasons will also open more of the Great Lakes to shipping and recreational boating.

Climate influences on lake levels

The Great Lakes have tremendous capacity for water and heat storage. This means that the lakes respond slowly to changes in climate. Precipitation causes major long-term variations in lake levels^{34, 35}. From 1900 through 1939, 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. There are three periods of particular interest to estimating the influence of climate on lake levels – the high precipitation in the early 1950s, the low precipitation in the early 1960s that led to the record low lake levels, and the consistently high precipitation from the late 1960s through the late 1980s.

Variations in air temperature also influence lake levels. 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. Coupled with the higher lake evaporation due to both reduced winter ice cover and the enhanced ability of warmer air to hold water vapor, lake levels tend to drop with increasing air temperature.

A long-term perspective on Lake Michigan levels has been reconstructed through geologic and archaeologic evidence³⁶. Conditions several thousand years ago were not necessarily the same as today due to isostatic rebound and uplift from the last ice age. In general, though, this analysis provides additional perspective on possible conditions we may experience in the future. In particular, the record over the last 2,500 years, during which time the Great Lakes were in their current state, shows major lake level fluctuations. During most of this time the levels were much higher and more variable than they have been during the last 120 years of record. If the past is any indication, lake levels in the future could go through a considerably larger range than we have experienced lately. Indeed, the period of “long-term” record from the early 1900’s through the 1960’s, which makes up what many consider to be normal, may actually represent “abnormal” conditions in the context of the last several thousand years.

Over the last century or so, historical water levels have still been highly variable in the Great Lakes, with no clear trend for lower water levels from 1860 to the present³⁷. Since 1860, the Lake Michigan-Huron system has exhibited the greatest range of level fluctuations of all the Great Lakes³⁸. Despite the lack of

overall trends in water level, however, there *are* trends in the seasonal timing of water level changes from the 1960s to at least 1998 if not beyond³⁹. For example, the seasonal rises and falls of water level for Lakes Erie and Ontario are occurring one month earlier than before, while the maximum water level of Lake Superior is occurring slightly earlier in the year. Also, in the past 100 years Lake Michigan's winter minimum has shifted from January to March⁴⁰. These trends apparently result from earlier snowmelt and earlier declines in summer runoff. Earlier seasonal runoff has also been observed from 1920 to 1995 for southern Lake Michigan⁴¹. All these trends are consistent with the likely impacts of climate change in the Great Lakes region, and as such are projected to continue over the coming century.

Determining the potential impact of future climate change on the region requires using a model that can relate changes in climate, as simulated by climate models, to the hydrology of the region and 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. For example, one study found both increases and decrease in annual mean net basin supply, negative (-11%) in the mid-21st century and positive (+15%) in the late 21st century⁴². In contrast, a second study⁴³ 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 different GCMs (general circulation models) to estimate future levels for Lake Michigan⁴⁴. Both models produced widely varying results, as by the late 21st century 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 for the same time frame, both relative to the base period of 1961-1990. Not surprisingly, simulations that predicted a rise in lake level were based on GCM simulations showing a larger increase in precipitation and smaller increase in temperatures than the GCM simulations that resulted in a decrease in lake levels. Taking these estimates to the extreme, a fourth study⁴⁵ 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.

Based on the steady-state relationships between lake levels, temperature, and precipitation calculated by the “terminal lakes” from the AHPS steady-state model, Kunkel et al.⁴⁶ estimated that, based on steady-state “end-of-century” conditions, Lake Michigan levels could drop by about 0 to 3 ft under a lower emissions scenario and 3 to 10 feet under a higher emissions scenario, relative to the 1971-2000 average lake levels. Although reflecting the full range of uncertainty in projections of regional temperature and precipitation as simulated by the IPCC AR4 climate models, the estimates by Kunkel et al. 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. Hence, while the projections of Kunkel et al. emphasize the importance of mitigating climate change to prevent major long-term drops in lake levels, they do not provide information regarding the magnitude of changes that should be expected over the coming century, while climate is continuously changing. For that reason, 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), mid-century (2040-2069) and end-of-century (2070-2099). These estimates of lake level changes are much smaller than the steady-state estimates of Kunkel et al., as in these more realistic transient or time-dependent simulations, in any given year the lakes have not yet had time to fully respond to the given change, just as they would in the real

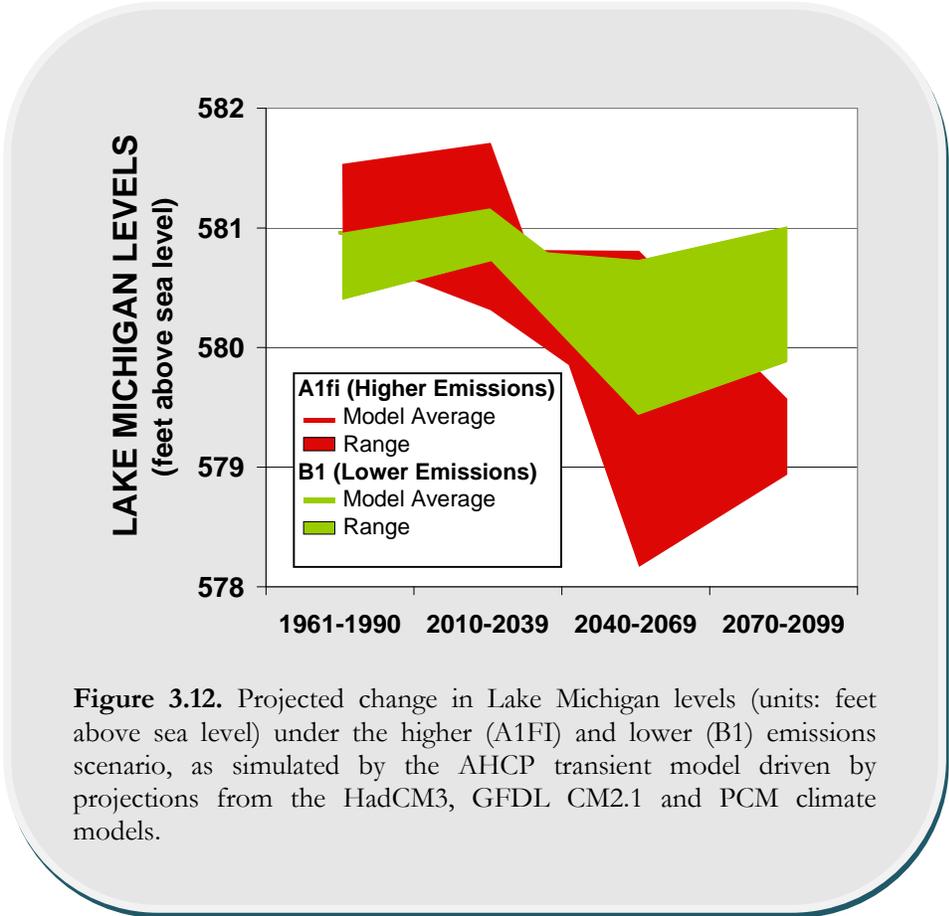


Figure 3.12. Projected change in Lake Michigan levels (units: feet above sea level) under the higher (A1FI) and lower (B1) emissions scenario, as simulated by the AHCP transient model driven by projections from the HadCM3, GFDL CM2.1 and PCM climate models.

world. Looking at the drivers of lake level changes, we see that 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 (Figure 2.6). This increase in precipitation largely counters 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 begin to cause a net drop in lake levels by end-of-century on the order of 1.5 feet (Figure 3.13).

Running a sensitivity experiment for one simulation, we found that the main drivers of change were temperature and precipitation, with smaller contributions from wind and humidity. Temperature caused the lake levels to drop but these effects were 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 we have determined lake level changes of almost zero under a lower emissions scenario and about 1.5 feet under the higher scenario by end-of-century according to the transient runs. Note, however, that these are average changes in lake levels – there would still be natural year-to-year variability, like we have seen in the past, relative to these changes in the average, that could be on the order of several feet.

Impacts of lowered lake levels

Lowered lake levels can have a wide variety of impacts along the shoreline. On the positive side, lower lake levels would lead to beach expansion. On the clearly negative side, however, reduced lake levels imply significant economic impacts on Great Lakes shipping and recreational boating, and operations at the Port of Chicago. Lower lake levels would require more dredging and channel maintenance, which in addition to incurring economic costs are also ecosystem-disturbing activities. Ships would have to carry reduced loads, increasing their costs. On the shoreline, there may be damage to wooden shoreline protection structures exposed to the air.

In terms of ecological impacts, because almost all of Chicago's lakefront is either beach or protected by revetment, lower lake levels would have relatively minor effects on shoreline habitat. Wetland areas in connecting waters such as Lake Calumet or Wolf Lake, however, would be affected, though given the highly

managed nature of these systems (Wolf Lake currently is undergoing a major restoration project) what these effects may be is far from clear.

As a case study, Changnon⁴⁷ actually studied the shoreline effects of the record-low levels of Lake Michigan during 1964-65 as a proxy of the impacts that future lake level decreases could have. Although beach expansion was initially viewed as a positive impact, he found that new buildings built along the beach expansion were damaged during subsequent higher lake levels that occurred in the 1970s due to long-term (decadal) oscillations of lake levels. During this record-low level period, more dredging than usual was required to keep waterways flowing for both commercial and recreational users. Furthermore, lake carrier loads were reduced by between 5 and 10%, which required more trips (10-15% more frequent) and higher costs (iron ore and coal increased by 10%). Extensive damage was done to wooden shoreline protection structures, as they developed dry rot once exposed to the air from the lowered lake levels. As with the damage to the new buildings along the beach expansion areas, it was the rise in lake levels in future years that then caused the damage to the weakened structures. Changnon estimated that if future lake levels were to fall by less than 1.0 m in the next 50 years, the impacts would be similar to what was experienced during the 1964-65 period, namely increased harbor dredging, moderately expanded beaches and alterations in slips and piers. The total cost of these impacts was estimated to be around \$100 million (1988 dollars); however, many of the adjustment costs could be offset by normal maintenance and replacement costs. The more severe case was estimated when lake levels were to fall by at least 1.5m. At those levels he estimated a very sizeable economic impact would occur, costing between \$3.5 and \$35 billion (1988 dollars).

In terms of future impacts, Schwartz et al. (2004) estimate 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.

Impacts on water quality at monitoring stations and beaches

The Great Lakes region has experienced dramatic morbidity effects from heavy rainfall and runoff, and the 1993 Milwaukee cryptosporidiosis outbreak, which involved 405,000 cases and 54 fatalities, was preceded by the heaviest rainfall in fifty years in the related watersheds⁴⁸. Beach closings from contaminated runoff can serve as a direct indicator of climate related risks to surface waters and human exposure to pathogens⁴⁹. Chicago has extensive exposure to Lake

Michigan, with frequent closings of public beaches (31 days per year on average) and subsequent risk of waterborne illness linked to recreational exposures (Chicago Park District data).

The projected summertime climate changes may affect beach contamination through thermal and hydrological modifications. Prior research suggests that Chicago beach closures are correlated with the magnitude of recent precipitation, lake temperature and lake stage⁵⁰. Climate models project more frequent and intense heavy rainfall events, warmer lake waters, and lower water levels^{51,52}, all of which would favor enhanced contamination.

A study conducted by the USGS of contamination events at the Chicago's 63rd Street beach found that rainfall in the previous 24 hours, water temperature, and wind direction were meteorological factors that best explained beach closures⁵³.

Climate change, and associated severe weather events, can affect water quality in complex ways. One example is provided by cryptosporidiosis, one of the most prevalent diarrheal diseases in the world. Cryptosporidium is a protozoan associated with domestic livestock, which can contaminate drinking water (where the oocyst is resistant to chlorine treatment) during periods of heavy precipitation. The 1993 cryptosporidiosis outbreak in Milwaukee, which resulted in 403,000 reported cases, coincided with unusually heavy spring rains and runoff from melting snow⁵⁴. In fact, a review of waterborne disease outbreaks from all causes in the United States over nearly 50 years demonstrated a distinct seasonality, a spatial clustering in key watersheds, and an association with heavy precipitation⁵⁵. Certain watersheds, by virtue of the land use patterns and the presence of human and animal fecal contaminants, are at higher risk of surface water contamination after heavy rains, and this has serious implications for drinking water purity.

Aquatic ecosystems

In assessing the potential impacts on Chicago of climate-related changes in the Lake Michigan ecosystem, we must begin by considering the relationships between the city and the aquatic ecosystem. Because Chicago is a coastal city, it is dependent on Lake Michigan. Indeed in his September 2002 testimony before Congress, Mayor Daley described Lake Michigan as “an integral part” of the city and referred to the lake as “Chicago’s most valuable natural resource.” Not only does the city depend on the lake for drinking water and recreation, Chicago is unique among Great Lakes cities in the aesthetic quality of its lakefront. The

value of each of these natural assets, drinking water, recreational opportunities, and aesthetic quality, is either directly or indirectly linked to the Lake Michigan ecosystem. In this section we explore how climate change might be expected to affect these linkages and what impacts changes may have on the future development of Chicago.

As described in Chapter 2, we anticipate that Chicago could see substantial increases in annual and seasonal temperatures, particularly under the higher emissions scenario. We also expect to see changes in precipitation patterns, notably increases in winter and spring precipitation and, under the higher emission scenario, decreases in summer precipitation. Because increases in summer evaporation would be approximately offset by increased winter and spring precipitation, lake levels are expected to change little under the lower emissions scenario. Lake levels are predicted to fall as much as 1.5 feet by the end of the century under the higher emissions scenario.

The influences of air temperature, precipitation patterns, and water levels on the lake ecosystem are interrelated and complex. Several studies^{56,57} have shown that the effects of many interacting factors must be integrated to understand how ecosystems might respond to climatic changes. As temperatures warm in the future and the warm season lengthens, seasonal mixing that replenishes critical oxygen to biologically productive lake zones could decrease, reducing lake biomass productivity by 20%. This would lead to losses of zooplankton and phytoplankton that are essential for aquatic food chains and critical for the survival of many species of fish that live in the Great Lakes. Cold-water stream habitats in the area could also be altered by a warming climate, which would threaten cold-water species such as walleye and trout. As a large percentage (almost 90%) of the fish in the Great Lakes are dependant on coastal wetlands for successful reproduction, declines in water levels would reduce access to breeding habitat, shelter for young fish and an abundance of food from the vegetation and invertebrates in the wetlands. Stocking strategies may be required to rebuild stocks of native species if declines in production hold true.

Simulations based on climate simulations^{58,59} suggest that, relative to present conditions, peak lake temperatures will be higher and thermal stratification of the lake will begin earlier, will be stronger, and will end later in the year. To appreciate the effects of these changes, we note that biological processes in Lake Michigan are, in large part, regulated by the annual temperature cycle of the lake. Warming lake waters, along with increased sunlight, stimulate the

growth of phytoplankton, the plants that form the base of the lake food chain. This growth is referred to as primary production. Phytoplankton growth continues until the surface water of the lake warms sufficiently to isolate it from the colder and nutrient-rich deeper water, a process known as stratification. Several studies^{60,61,62} have examined the possible consequences of this change in thermal cycle on the lake biota. Although the effects are complicated and the important processes are not completely understood, these researchers tend to agree on the broad implications of the anticipated changes in climate.

Earlier warming in the spring, coupled with increase nutrient loading associated with higher levels of winter and spring precipitation may lead to earlier onset of phytoplankton growth. Because the surface waters would be expected to warm more rapidly under most scenarios, mixing between the surface and deep waters would be inhibited earlier in the year and the net effect on total primary production would be negative. Such a reduction in the size of the phytoplankton crop would have negative effects on the higher trophic levels (zooplankton and fish) that depend on the phytoplankton for their energy. Stronger stratification also would tend to reduce the mixing of oxygen-rich surface waters to the lake bottom. Because bottom dwelling biota (bacteria, as well as plants and animals) require oxygen, isolated bottom waters may become oxygen depleted with strong negative effects on the important benthic components of the aquatic food web. Earlier warming of lake surface waters would extend the period of time when inshore waters are accessible to most species of fish, thus increasing thermal habitat. Because the surface waters also would warm to temperatures above that preferred by cold and cool water species sooner, these fish would tend to move to the colder deeper waters earlier in the year.^{63,64}

Climate-associated changes in the structure of the Lake Michigan ecosystem may be especially significant in the nearshore, the area that is most visible and important to coastal cities like Chicago. Warmer temperatures and changes in nutrient cycling may stimulate the growth of filamentous algae such as *Cladophora*, which is both an aesthetic problem and a possible promoter of pathogens⁶⁵. Growth of *Cladophora* illustrates the complexity of the problem of trying to understand how climate change may affect the Lake Michigan ecosystem. If offshore primary production is reduced as described above, Lake Michigan waters may be relatively enriched in nutrient phosphorus. More available phosphorus may stimulate the growth of the attached algae such as *Cladophora*. Furthermore, reduced phytoplankton production would result in clearer waters and deeper light penetration. If lake levels are lower as a result of

climate change then more of the lake bottom will be exposed to sunlight and more habitat would be available for the nuisance algae. Complicating the situation even more is the largely unexplored issue of how the susceptibility of the lake ecosystem to invasive species such as the zebra and quagga mussels depends on changes in climate. In general, a changing climate (regardless of the nature of the change) will favor invasive species that can exploit the changed environment over already established species that may have more specialized needs. Under the warming scenarios, invasive species that have been limited to the warmer regions of the lake may migrate northward.

One consequence of lake warming is a reduction in the amount of winter ice cover. Ice cover tends to shield the lake bottom and shoreline from the disturbing effects of storms. Changes in the frequency of winter storms, coupled with projected increases in winter and spring precipitation and runoff may result in increased rates of shoreline erosion and higher levels of early season water turbidity. Higher spring turbidity would both increase water treatment costs and change the light regime, reducing the light available for algal production. Thus, the potential early onset of primary production associated with higher water temperatures might be negatively affected by reduced light, further limiting the amount of phytoplankton available to higher trophic levels.

Although considerable uncertainty must be assigned to the climate change scenarios and the lake's ecosystem response described above, the consensus of research suggests that some changes will have negative impacts on Chicago. Warmer waters may reduce algal productivity and limit the forage base for sport fish affecting recreational opportunities. Changes in the lake water temperature cycle are likely to perturb the behavior of indigenous fish species as fish seek to maintain their preferred temperature ranges. Changes in phytoplankton species composition may lead to noxious algae blooms affecting the aesthetics of the drinking water and increasing water treatment costs. Warmer weather may increase the demand for use of the cities beaches, but increased *Cladophora* growth may result in diminished beach aesthetics and increased occurrence of beach closure because of pathogenic bacteria.

When considering the question of how climate-related changes in the Lake Michigan ecosystem may impact Chicago, we must appreciate that the Great Lakes already are a highly disturbed and managed system. Years of industrialization and population growth coupled with invasions of alien species dating back to the opening of the Welland Canal and St. Lawrence Seaway have

taken their toll on this magnificent body of water. Programs of pollution control, stocking of game fish, and management of water flows all have been implemented to restore the benefits of the Great Lakes to those who live and visit their shores. Changing climate adds another stress to those that will continue as Chicago's population grows and places additional demands on Lake Michigan waters.

In conclusion, we expect that warming will both strengthen and extend the duration of lake stratification. The stronger the stratification, the weaker the mixing between the upper (warmer) layers and the deeper (colder) layers. Because oxygen is consumed by bottom-dwelling biota reducing the exchange between the oxygen-rich surface waters and the oxygen-depleted deep waters can cause the bottom waters to go anoxic, killing the bottom dwellers, some of which may be major food sources for fish like perch. This occurs frequently in Lake Erie now. The reduced mixing also inhibits the flux of nutrients from the bottom waters (which are relatively enriched) to the surface waters where the light needed for photosynthesis is. The lack of nutrients limits the phytoplankton growth even if there is sufficient light.

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