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# Climate change scenarios for Great Lakes Basin ecosystem studies

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*Abstract*

Significant change in global climate could occur due to human-induced changes in the chemistry of the atmosphere. We provide a basis for the continuing assessment of potential impacts of climate change on aquatic ecosystems. A series of climate change scenarios have been developed for the Great Lakes Basin using general circulation models (GCMs), climate spatial transpositions, and historical climate analogs. The direct impacts of climate change on the Great Lakes ecosystem would occur through higher air and water temperatures. Indirect climate change impacts include both positive and negative changes in precipitation, decreases riverine runoff, less snowfall and snowpack accumulation, higher evapotranspiration, and a reduction in lake levels and connecting channel flows. These climate and hydrologic changes affect the quantity and quality of wetland and aquatic habitats, alter the frequency and timing of lake turnover, and change dissolved oxygen, and alter fish community composition and dynamics. We provide an integration of Great Lakes climate scenarios. We also illustrate, for the first time, the spatial variability of the climate change scenarios on a tributary river-basin scale.

There is growing concern that human activities such as burning of fossil fuel and various land-use practices are altering the composition of the atmosphere. Concentrations of radiatively active gases such as carbon dioxide, methane, ozone, nitrous oxide, and chlorofluorocarbons are increasing in the atmosphere. Enhancing the "greenhouse effect" could lead to significant warming with global mean temperatures attaining levels higher than experienced in recorded history. The warming as well as indirect effects on precipitation, soil moisture and runoff, for example, would have important implications for human and ecological systems. Generally, past climate has been considered a reliable guide for planning in the future through the use of 30-yr climate normals; however, this perspective needs to be reassessed in relation to climate change. Climate change scenarios are a technique that may be used to simulate plausable climate "futures" for assessing potential impacts on the Great Lakes and other aquatic ecosystems within the basin.

Climate scenarios, defined as descriptions of possible climate conditions at some unspecified future time that are physically consistent (Lamb 1987), are used to develop an understanding of the sensitivity of a region, activity, or ecosystem to climate variability and change. These scenarios are not single predictions or forecasts. They represent a range of possible futures—"what if" situations for exploring the implications of a changed climate system or future climate variability not represented in the instrumental record. The scenarios represent climatic conditions that could occur. At present, there is no way of determining which scenario is best nor can probabilities of occurrence be assigned due to the many uncertainties that remain. However, a range of climate scenarios can provide an indication of the nature and extent of sensitivities to climate variability and change.

## GCM climate change scenarios

The most advanced, physically based tool for developing climate change scenarios are General circulation models (GCMs). Atmospheric GCMs represent the complex interaction of physical processes that link the radiation budget of the atmosphere and surface to global circulation and the hydrological cycle. Although these models are complex, they are still a crude representation of the real climate system and are limited by our knowledge of climate processes and feedback mechanisms. GCMs can capture the important large-scale features of the global climate system but their poor regional resolution leads to an inadequate representation of regional climate. For example, large inland water bodies such as the Laurentian Great Lakes are not represented in the GCM models discussed in this paper. However, double carbon dioxide ($2 \times CO_2$) equilibrium response GCM experiments are an internally consistent representation of the sensitivity of the climate system to increased greenhouse gas concentrations and provide an assessment of the future state of the climate.

GCM experiments of doubling of atmospheric carbon dioxide ($2 \times CO_2$) are the most effective method of testing how changes in the greenhouse effect will modify climate processes and hence the climate of the earth and weather patterns around the world. However, other methods for climate scenario development such as spatial climate transpositions and historical climate analogus are also useful in sensitivity studies and impact assessments. We describe a series of climate scenarios developed to study the impacts of climate variability and change in the Great Lakes–St. Lawrence Basin. The U.S. Environmental Protection Agency (Smith and Tirpakels 1989) and the International Joint Commission (IJC) Water Levels Ref-

Table 1. Comparison of GCM-simulated temperature increases for the Great Lakes-St. Lawrence Basin: Range of temperature change from $2 \times CO_2$ to $1 \times CO_2$.

| GCM* | General comments | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| CCC GCM2 | Greater temp. increase than OSU, GFDL or GISS<br>Sharpest rise in winter (of all GCMs) | Greatest increase of all seasons; N and W parts show greatest rise<br>(4.0–9.1°C) | SW part shows sharp increase<br>(3.3–8.3°C) | SW part shows sharp increase<br>(3.9–6.2°C) | Smallest increase of all seasons; increase in temp. as move S<br>(2.7–4.7°C) |
| GISS | Warmest in winter and autumn | Warmest in N part<br>(4.5–6.6°C) | Warmest in S part<br>(3.8–4.8°C) | Steady increase in temp. as move N–S<br>(2.7–3.8°C) | Increase in temp. as move NE–SW<br>(3.0–6.0°C) |
| GFDL | Greatest temp. increase of all GCMs (in all seasons); very steady and sharp increase in summer | Sharp increase as move N<br>(5.0–8.7°C) | Similar rise as in winter<br>(4.4–8.0°C) | Very sharp rise as move E–W<br>(5.6–8.6°C) | Season with smallest rise as move E–W<br>(5.6–7.0°C) |
| OSU | Smallest temp. increase of all GCMs (in all seasons); temp. rises equally in all seasons | Greatest increase of all seasons; temp. increases as move NE–SW<br>(3.4–4.2°C) | Warming gradually as move E–W<br>(2.9–3.5°C) | Temp. increase as move E–W<br>(3.0–4.0°C) | Very gradual increase as move S<br>(2.6–3.3°C) |

* CCC—Canadian Climate Center GCM; GISS—Goddard Institute for Space Studies; GFDL—Geophysical Fluid Dynamics Lab; OSU—Oregon State University. Source: Mortsch and Burton 1992.

erence Study (Louie 1991, unpubl. rep.; Mortsch 1991) used GCM scenarios. This methodology is compared with historical analog scenarios (Quinn and Changnon unpubl.; Quinn 1991) and to climate transposition scenarios (Croley et al. 1995). The binational Great Lakes–St. Lawrence Basin Project on "Adapting to the impacts of climate change and variability," which includes an ecosystem component, will use $2 \times CO_2$ GCM and climate transposition scenarios described here to undertake its climate impact assessments (Mortsch et al. 1993; Ryan et al. 1994). The climatic and meteorological outputs from the climate change scenarios are linked with hydrologic and ecosystem models to assess some of the potential impacts on the Great Lakes–St. Lawrence Basin ecosystem.

For these experiments, the GCM is run in two modes: current conditions ($1 \times CO_2$) and $2 \times CO_2$ conditions. In the $1 \times CO_2$ simulation, the average global $CO_2$ concentration is set at the present level. The model is run until a stable climate is attained; this represents current climatic conditions. The $CO_2$ gas component of the GCM is doubled from its present level and the model is run again until it reaches a new equilibrium. The difference between the $1 \times CO_2$ and $2 \times CO_2$ simulation is an estimate of the sensitivity of the climate system to a doubling of carbon dioxide (Boer et al. 1992). We developed monthly ratios or differences in climatic elements from the $1 \times CO_2$ and $2 \times CO_2$ GCM model runs and used them to modify the historical time series of climatological variables (Atmos. Environ. Serv. 1994; Cohen 1991; Croley 1990, unpubl. rep.). Historical spatial and temporal variation of the climate data are maintained in the scenarios generated by this method because only the means are altered and the variability inherent in the times series is maintained. The modified historical climate time-series data are then used as input to impact models. This is one method climate impact assessment researchers have used to overcome the poor regional resolution of the GCM outputs.

GCM modeling experiments seem to agree on an average global temperature rise of 1.5–4.5°C based on a doubling of $CO_2$ or its equivalent (Houghton et al. 1990; Atmos. Environ. Serv. 1994). Changes in the amount and seasonal distribution of precipitation are likely. Studies also suggest a larger percentage of rain may fall as heavy downpours (Whetton et al. 1993). At the regional level of the Great Lakes–St. Lawrence Basin, the seasonal temperature and precipitation grid point changes are compared in Tables 1 and 2. The $1 \times CO_2$ and $2 \times CO_2$ simulations for the second generation Canadian Climate Centre GCM (CCC GCM2) (McFarlane et al. 1992; Boer et al. 1992) and the first generation Goddard Institute for Space Studies (GISS) (Hansen et al. 1983), Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald 1987), and Oregon State University (OSU) (Ghan et al. 1982) GCMs are used in the analysis.

The most significant temperature increases occur in winter for all the GCM experiments. Mean winter temperature increases of 3.4–9.1°C imply effects on freeze-thaw frequencies, ice formation, and the heat balance of lakes. Summer temperature increases range from 2.7 to 8.6°C and the frequency of heat waves and droughts may increase. The autumn period in three models experiences the least warming. Within the Great Lakes Basin, the GCM scenarios do not suggest climatic conditions that are cooler than the existing climate. The spatial distribution of the annual $2 \times CO_2 - 1 \times CO_2$ precipitation and

Table 2. Comparison of GCM precipitation for the Great Lakes-St. Lawrence Basin. Range of precipitation ratios ($2 \times CO_2$ : $1 \times CO_2$).

| GCM* | General comments | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| CCC | Wetter in spring and winter in N–NW part; drier in S part in summer and autumn | Wetter in N and NW parts; drier in SW parts | Sharp rise in precip. as move N | Generally drier than normal except for NE part | Sharp drop in precip. as move S; increase in N part |
| | | (0.9–1.2) | (0.9–1.4) | (0.8–1.1) | (0.7–1.3) |
| GISS | Wettest of all GCMs; wetter as move N (all seasons, esp. winter and summer) Sharp drop in autumn precip. | Progressively wetter as move N | Wetter as move NE | Increase in precip. as move N | Sharp decrease in precip. as move NW–SE |
| | | (1.0–1.2) | (1.0–1.1) | (1.0–1.3) | (0.7–1.2) |
| GFDL | Very wet winter; drier in spring, summer, and autumn (esp. NW parts) | Sharp rise in precip. throughout basin | Precip. increases as move NW–SE | Sharp decrease in precip. throughout basin | Precip. declines in NW from L. Superior; increase in precip. in SE part |
| | | (1.1–1.3) | (0.95–1.2) | (0.7–0.9) | (0.8–1.1) |
| OSU | Precip. increases as move SE–NW in winter and autumn | Precip. increases as move SE–NW | Precip. decreases as move NE–SW | Decrease in N part; increase in S portion | Sharp increase as move SE–NW |
| | | (1.0–1.2) | (0.9–1.1) | (0.9–1.1) | (1.0–1.3) |

* CCC—Canadian Climate Center; GISS—Goddard Institute for Space Studies; GFDL—Geophysical Fluid Dynamics Lab; OSU—Oregon State University. Source: Mortsch and Burton 1992.

temperature grid-point changes for the CCC2 GCM are illustrated in Fig. 1. The $1 \times CO_2$ and $2 \times CO_2$ GCM climate elements were interpolated onto a 1° by 1° grid to estimate subgrid values to improve the interface for hydrological and ecological impact modeling. The maps illustrate that annual precipitation increases in the northern portion of the basin and decreases in the south. Temperature changes are largest in the south and southwestern portions of the basin.

## Hydrological and ecological impacts of GCM climate change scenarios

Croley (1990, unpubl. rep.) developed the methodology to link climate change scenarios of air temperature, precipitation, wind speed, cloud cover, and humidity with hydrologic models of the Great Lakes. Hydrologic model outputs include basin runoff, evapotranspiration, lake-water surface temperatures, lake evaporation, and lake levels. The outputs are produced through a series of linked models on rainfall-runoff relationships for 121 subbasins for moisture storage and runoff estimation, overlake precipitation, lake thermodynamics for heat storage and evaporation, hydrological response for determining connecting channel flows and levels and lake levels, and regulation plans for Lakes Superior and Ontario.

The current hydrology was simulated using time series of current or base-case climate data from observing stations in the basin for the period 1951–1980 (OSU, GFDL, GISS) and 1951–1988 (CCC GCM2). For example, area-averaged daily precipitation, maximum and minimum temperature were produced for 121 subbasins and daily air temperature, cloud cover, humidity and wind speed were produced for the five Great Lakes and Lake St. Clair. Areal averages of the monthly $1 \times CO_2$ and $2 \times CO_2$ GCM grid-point differences for wind speed and the ratios for air temperature, humidity, precipitation, and cloud cover were applied to the base-case climate to derive the $2 \times CO_2$ climate scenario which was input to the hydrologic models.

The simulated changes in Great Lakes hydrology are presented as a result of the application of the four GCM scenarios (CCC GCM2, GFDL, GISS, and OSU) to historical climate time-series data as per Croley (1990, unpubl. rep.). The outputs of particular interest for ecosystem studies are the annual runoff changes, mean annual outflow changes, mean annual water level changes, and surface-water temperature changes. These values are presented in Table 3 on an individual lake basis. In the four GCM climate change scenarios, water resources decline in the Great Lakes- St. Lawrence Basin.

Significant annual runoff declines to all Great Lakes Basins except Superior have been modeled for the GCM climate change scenarios. Mean annual outflows also decline. From an ecological perspective, these hydrologic changes have serious implications. For example, a 40% decrease in the outflow of the St. Lawrence River would alter the freshwater–salt-water balance in the river and Gulf of St. Lawrence. The seasonal change in the distribution of runoff is not apparent in these mean annual summaries; however, an earlier spring runoff has been modeled, while winter flows may increase as more precipitation may fall as rain instead of snow. Summer flows are low.

Great Lakes levels decline for all $2 \times CO_2$ scenarios and remain at or below historic lows for long periods. Lake Michigan-Huron experiences the most severe decreases

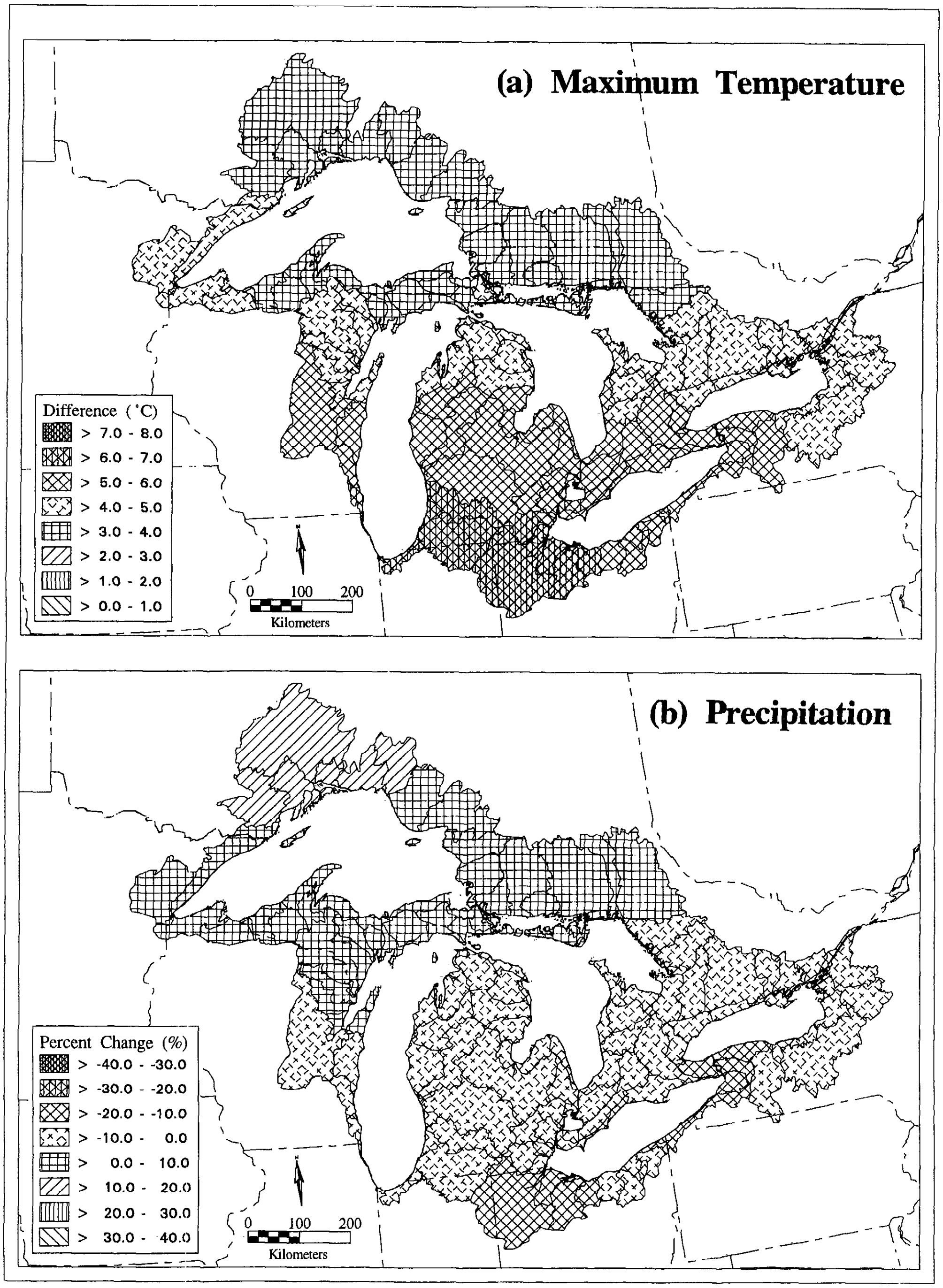

Fig. 1. [a.] Maximum air temperature differences, $2\times CO_2 - 1\times CO_2$ (°C). [b.] Precipitation differences, $2\times CO_2 - 1\times CO_2$ (mm).

of 100–250 cm. Modeling these scenarios on the water levels in smaller, inland lakes has not been undertaken; however, their water supplies are also expected to decrease. The distribution and areal extent of shoreline wetlands along the Great Lakes will be affected by changes in lake level. Particularly vulnerable are wetlands in Lake St. Clair, shallow bays in the other Great Lakes, and enclosed wetlands that are prevented from migrating lakeward and hence dry out. These lake-level declines suggest significant implications for littoral ecosystems, but quantitative assessments have not been undertaken.

Higher air temperatures and warmer water temperatures affect the energy balance of the lakes. For example, winter ice cover may be reduced. Also, the buoyancy-driven mixing of the water column may be affected along with the frequency of seasonal turnover. Many of the lakes

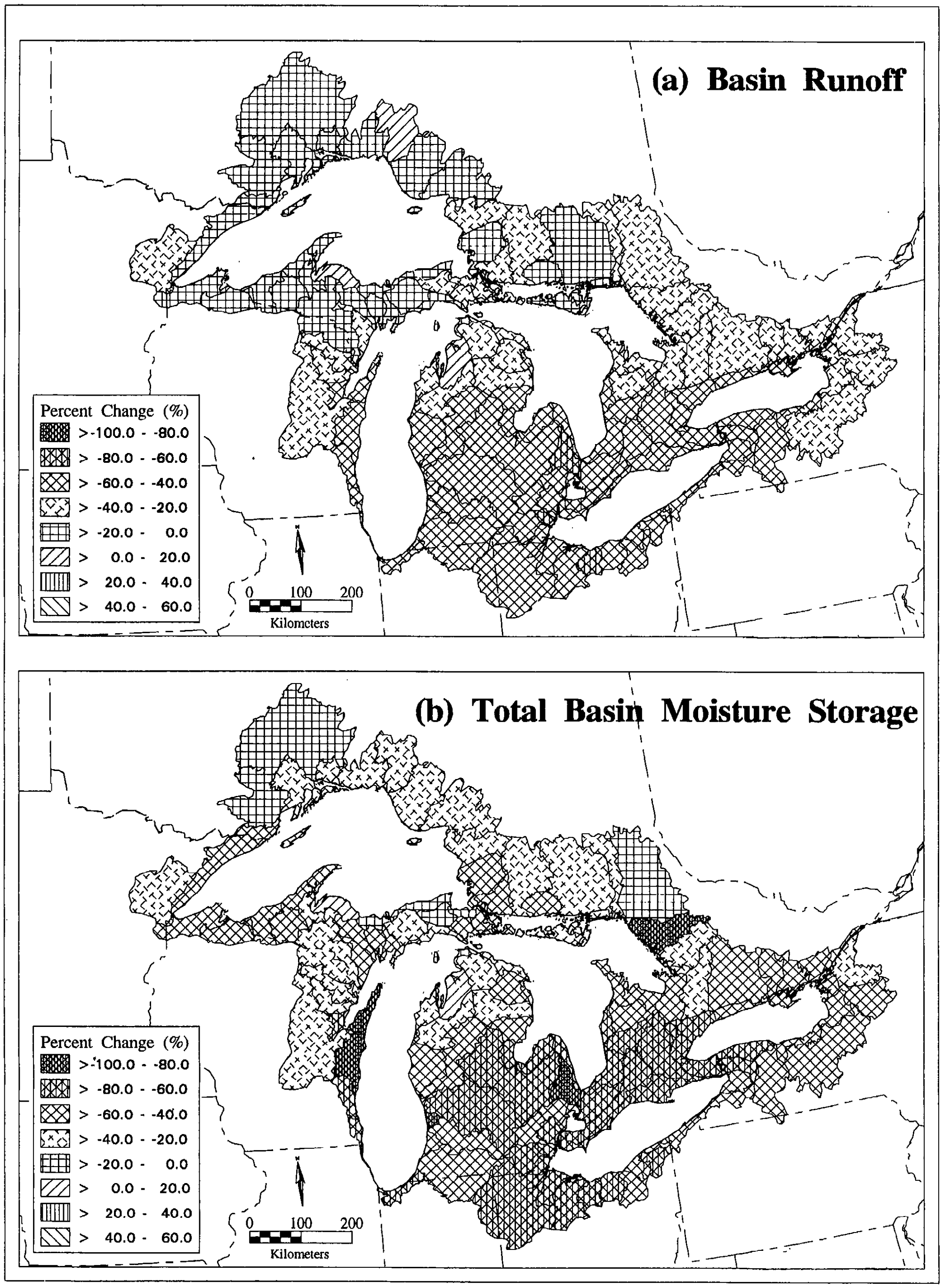

Fig. 2. [a.] Runoff differences, $2\times CO_2 - 1\times CO_2$ (%). [b.] Soil moisture differences, $2\times CO_2 - 1\times CO_2$ (%).

could become monomictic rather than dimictic. The likelihood of anoxia in several basins then increases as well as the associated changes in chemistry and biota that follow. Lake Erie is the most vulnerable, although its surface temperatures increase the least in $2\times CO_2$ scenarios. Changes in thermal conditions would also affect the health, survival, and productivity of phytoplankton, zooplankton, and cold-, cool-, and warm-water fish species. Conditions suitable for new invasions of exotics may occur.

In Fig. 2, the changes in the annual runoff and total basin moisture storage for 121 subbasins in the Great Lakes Basin are illustrated using the CCC GCM2 climate scenario. Moisture storage in the subbasins is predicted to decline substantially due in large part to higher air temperatures and associated higher evapotranspiration

Table 3. Simulated changes in Great Lakes hydrology using the four GCM scenarios.

| Lake/river | GCM scenarios CCC | GFDL | GISS | OSU |
|---|---|---|---|---|
| Change in annual runoff* (%) | | | | |
| Superior | −12 | −2 | −2 | −8 |
| Michigan | −38 | −24 | −24 | −14 |
| Huron | −36 | −29 | −29 | −9 |
| Erie | −54 | −41 | −41 | −19 |
| Ontario | −34 | −33 | −33 | −7 |
| Mean annual outflow changes (%) from base case† | | | | |
| Superior | −13 | — | −2 | −19 |
| Michigan-Huron | −33 | — | −25 | −20 |
| Erie | −40 | — | −32 | −23 |
| Ontario | −39 | — | — | — |
| St. Lawrence River at Montreal | −40 | — | — | — |
| Mean annual water level changes (m) from base case‡ | | | | |
| Superior | −0.23 | | −0.46 | −0.47 |
| Michigan-Huron | −1.62 | −2.48 | −1.31 | −0.99 |
| Erie | −1.36 | −1.91 | −1.16 | −0.87 |
| Ontario | −1.30 | — | — | — |
| St. Lawrence River at Montreal | −1.30 | — | — | — |
| Change in mean annual surface water temperature* (°C) | | | | |
| Superior | +5.1 | +7.4 | +5.6 | +4.8 |
| Michigan | +5.6 | +5.5 | +4.7 | +3.4 |
| Huron | +5.0 | +6.0 | +4.7 | +3.6 |
| Erie | +4.9 | +5.0 | +4.4 | +3.0 |
| Ontario | +5.4 | +5.9 | +4.9 | +3.6 |

* Croley 1990, unpubl. rep.

† Hartmann 1990; Croley unpubl. rep.

‡ Hartmann 1990;; Croley 1990, unpubl. rep.; Int. Jt. Comm. unpubl. rep.

rates, although precipitation increases in northern portions of the basin. Reductions in basin runoff are most severe where air temperature increases and precipitation decreases are largest. Reduced tributary flows and less storage of moisture in the subbasins are expected to affect inland wetland hydrology, geochemistry, ecological functioning, and instream and lake-water quality as well as reduce groundwater recharge.

## Climate transposition scenarios

Climate change scenarios developed from GCMs produce changes in the mean values of climatic elements by applying $1 \times CO_2$ and $2 \times CO_2$ differences or ratios to historic climate time series or the base case. Thus, these climate change scenarios maintain the same variability as the base-case climate. Potential changes in variability are not considered. Transposition climate scenarios were developed specifically to introduce changes in the mean and variability of climate elements (Croley et al. 1995) and to examine the sensitivity of systems to both of these changes. Four separate climatic regimes from areas to the south and west of the Great Lakes were chosen using GCM temperature and precipitation changes as guides. The Great Lakes Basin was transposed to these regions. For example, scenario 1 was selected to represent warm and dry conditions and the basin is transposed 6°S by 10°W, scenario 2 (6°S by 0°W) is warm and wet, scenario 3 (10°S by 11°W) is very warm and dry, and scenario 4 is very warm and wet and the basin is moved 10°S by 5°W.

Areal averages of the transposed climatic elements for 121 watersheds and overlake surfaces were derived by Thiessen-weighting of daily data for the four scenarios for the period 1948–1990. The areally averaged transposed data were input to the hydrological models by the same method used by Croley (1990, unpubl. rep.) for GCMs. The transposition scenario results were compared to Great Lakes hydrology derived from the base case or current climate time series for the period 1951–1990. In these transposition scenarios, air temperature increased 4–10°C and precipitation ranged from −20 to +70% of the base case (Table 4), which is a much larger range in climate conditions than obtained from the GCM scenarios. These scenarios still contain a bias toward warmer future climates, although precipitation scenarios are wetter and drier than current conditions.

Annual net basin supply changes range from +74 to

Table 4. Changes in overland air temperature and precipitation from base case. (Data from Croley et al. 1995.)

| Lake | Scenario 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Temperature (°C) | | | | |
| Superior | 6.9 | 6.8 | 0.4 | 4 |
| Michigan-Huron | 5.8–6.3 | 5.6–4.6 | 9.8 | 10.1–10.3 |
| Erie | 6.1 | 4.4 | 9.4 | 8.2 |
| Ontario | 6.2 | 6.5 | 9.3 | 9.7 |
| Precipitation (%) | | | | |
| Superior | −23 | +6 | −20 | −21 |
| Michigan-Huron | +3 to +26 | +39 to +40 | +1 to +48 | +59 to +70 |
| Erie | +31 | +44 | +37 | +55 |
| Ontario | +26 | +18 | +49 | +33 |

Table 5. Changes in mean annual lake outflows, lake level, and surface-water temperature from base case. (Data from Croley et al. 1995.)

| Lake | Scenario 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Mean annual lake outflow (%) | | | | |
| Superior | −96 | −48 | −100 | −58 |
| Michigan-Huron | −66 | −9 | −68 | −7 |
| Erie | −56 | +1 | −59 | −1 |
| Ontario | −48 | −1 | −48 | −4 |
| Mean annual lake level (m) | | | | |
| Superior | −2.12 | −0.75 | −11.3 | −0.97 |
| Michigan-Huron | −3.33 | −0.23 | −3.49 | −0.23 |
| Erie | −2.14 | +0.01 | −2.28 | +0.04 |
| Ontario | −1.5 | −0.03 | −1.52 | +0.03 |
| Mean annual surface-water temperature (°C) | | | | |
| Superior | +5.1 | +5.9 | +7.5 | +9.2 |
| Michigan | +4.1 | +4.6 | +7.4 | +9.0 |
| Huron | +5.0 | +5.4 | +9.7 | +9.5 |
| Erie | +6.2 | +4.8 | +8.9 | +7.8 |
| Ontario | +6.1 | +5.6 | +10.2 | +9.2 |

−103%. The supplies to the Great Lakes drop significantly in the westernmost scenarios (1 and 3) due to increased evapotranspiration and evaporation. Precipitation increases for the easternmost scenarios (2 and 4) offset the evaporation and evapotranspiration losses. Table 5 summarizes the predicted changes in annual outflow, lake levels, and water-surface temperature.

## Historical climate analog scenarios

The final method we discuss develops climate scenarios from existing, observed climate data within the basin to examine the impact of climate extremes that could plausibly occur in current climatic conditions. In this example, a climate block procedure was used to develop climate analog scenarios. Because the frequency of abnormal annual precipitation events has been shown to be the most critical factor in Great Lakes net basin supply (Quinn unpubl.) and lake levels (Changnon 1987), four climate scenarios were developed to focus on extreme precipitation conditions in the Great Lakes. The climate scenarios depict two wet periods and two dry periods (Quinn and Changnon unpubl.). The scenarios were constructed from extremes in annual lake-year (August–July) precipitation data from 1854 to 1987. Extreme years were identified by their deviation from the long-term average (1900–1987). Other meteorological information, such as temperature data, was incorporated in the scenario development because the hydrologic impact assessment methodology is also based on the work of Croley (1990, unpubl. rep.) and requires additional climate data input.

The four scenarios encompass a 12-yr period of time or a composite climatic block (Wigley et al. 1986). The selection of the 12-yr period is based largely on response times of Great Lakes water levels to climatic variability (Hartmann 1988). The physical plausibility of choosing this period is supported by harmonic-spectral analyses of historical precipitation data for the midwestern U.S. that indicates, at varying levels of statistical significance, significant spectral peaks between 10 and 13 yr long (Neill and Hsu 1981).

The scenarios were selected by screening 12-yr moving sums of annual lake-year precipitation for each Great Lake basin and then selecting the sums which were the most extreme (wet or dry) across the entire Great Lakes Basin. All candidate 12-yr periods had 8 yr or more with annual precipitation above (wet) or below (dry) the 1900–1987 average annual precipitation. The period 1914–1925 was selected as the driest 12-yr period in the Great Lakes Basin, and the years 1975–1986 were rated the wettest in the 1854–1987 period. Two final modified climate scenarios (one wet, one dry) were developed from the 1914–1925 dry and 1975–1986 wet scenario.

The sequential pattern of wet and dry years across the entire Great Lakes Basin was retained for each scenario. However, the magnitude of the annual precipitation value was changed if it was above average in the wet periods or below average in the dry periods. These changes were based on the basin-wide annual values—not on the annual values for each individual lake basin. In the 1975–1986 wet period, the wet years were magnified by substituting historical data from the wettest years in the period 1900–1987. The wettest years of 1900–1987 replaced the wettest years of 1976–1986 based on their ranked magnitudes. In the 1914–1925 dry period, the dry years were magnified by substituting historical data from the years in 1900–1987. The driest years of 1900–1987 replaced the driest years of 1914–1925 based on their ranked magnitudes. The nondry years in the 12-yr dry period (1914–1925) were not altered nor were the nonwet years in the 12-yr wet period (1975–1986). By this process, the 1900–1987 record annual extremes were used to increase the departures that were experienced during the wettest and

Table 6. Cumulative precipitation (CP) and net basin supplies (NBS) for dry and wet scenarios (in cm on the lake surfaces).

| Scenario | | Superior CP | Superior NBS | Mich-Huron CP | Mich-Huron NBS | Erie CP | Erie NBS | Ontario CP | Ontario NBS |
|---|---|---|---|---|---|---|---|---|---|
| Dry | Historical | 808 | 752 | 907 | 917 | 1,003 | 594 | 1,016 | 2,045 |
| | Modified | 813 | 770 | 848 | 798 | 935 | 465 | 975 | 1,951 |
| Wet | Historical | 1,001 | 1,090 | 1,062 | 1,191 | 1,156 | 899 | 1,179 | 2,527 |
| | Modified | 1,013 | 1,120 | 1,077 | 1,209 | 1,217 | 1,006 | 1,252 | 2,789 |

driest 12-yr period in the Great Lakes. The modified wet scenario resulted in 4% more precipitation over the entire basin than the historical wet scenario (1975–1986) and the modified dry scenario resulted in 5% less precipitation over the basin than the historical dry scenario (1914–1925) as illustrated in Table 6.

## Conclusions

We have summarized the application of various techniques to estimate climatic scenarios and illustrate the potential hydrologic impacts of climate variability and change in the Great Lakes Basin. The GCM climate change scenarios are physically based modeling results that should be used in climate impact assessments. They develop climate conditions outside the past climate that has helped to shape the Great Lakes ecosystem. The weaknesses of the scenarios are poor regional resolution, poor treatment of regional climate processes, and maintaining existing variability of climate elements and changing only the means. However, scenarios based on GCM experiments reflect the best current attempts of atmospheric science to address the climate change issue. Anticipated improvements will include finer regional resolution and regional climate models nested within GCMs.

Climate transposition scenarios provide a new scenario development technique. The method introduces a change in the mean of climate variables but more importantly introduces a change in the variability both spatially and temporally. Decision-makers and planners can better relate to a discussion of the impacts of the climate for any region, for example, than they can to the more esoteric GCM modeled scenarios. Climate transposition does have weaknesses—most significantly that the spatial variability of the transposed regional climate may contain topographic effects, such as mountains, that are not appropriate for a particular region.

The potential impacts of climate change are significant. The scenarios indicate, in general, a warmer climate with either positive or negative changes in precipitation. The modeling results indicate that there is a potential for major changes in the hydrologic water balance in the Great Lakes. In the four $2\times CO_2$ scenarios, the supply of water to the Great Lakes decreases, although precipitation increases throughout large portions of the basin. The warmer air temperatures and higher rate of evaporation and evapotranspiration increases moisture loss, decreases runoff, and leads to a decline in lake levels. The warmer climate would lead to increased water-surface temperatures and changes in the thermal structure in all of the lakes, leading to potential changes in ice cover and habitat temperatures. In addition, the potential for decreased turnover could increase anoxia in several of the lake bottom waters. In some $2\times CO_2$ scenarios the decreases in lake level are quite significant; for example, Lake Michigan-Huron and Lake Erie levels drop >1 m in the CCC, GFDL, and GISS scenarios. Water-level declines of this magnitude have important impacts on wetlands, fisheries, and human use of the shoreline. Decreased flows in the St. Lawrence River may allow salt water to penetrate farther upstream. The next challenges are to quantitatively identify the current climate-ecosystem links and undertake rigorous impact assessments that identify the direct and indirect impacts of climate change on Great Lakes ecosystems.

## *References*

ATMOSPHERIC ENVIRONMENT SERVICE. 1994. Modelling the global climate system. Minister of Supply and Services, Canada.

BOER, G. J., N. A. MCFARLANE, AND M. LAZARE. 1992. Greenhouse gas-induced climate change simulated with the CCC second-generation general circulation model. J. Clim. **5:** 1045–1077.

CHANGNON, S. A. 1987. Climate fluctuations and record-high levels of Lake Michigan. Bull. Am. Meteorol. Soc. **68:** 1394–1402.

COHEN, S. J. 1991. Caveats in applying GCM output to regional impact assessments, p. 16–32. *In* Proc. Symp. on Climate Scenarios. Univ. Waterloo.

CROLEY, T. E. 1990. Laurentian Great Lakes double-$CO_2$ climate change hydrological impacts. Clim. Change **17:** 27–48.

———, F. H. QUINN, K. KUNKEL, AND S. J. CHANGNON. 1995. Potential Great Lakes hydrology and lake level impacts resulting from global warming, p. 67–72. Proc. 6th Symp. Global Change Studies. Dallas.

GHAN, S. J., AND OTHERS. 1982. A documentation of the OSU two-level atmospheric GCM. CRI Rep. 35, Oregon State Univ.

HANSEN, J., AND OTHERS. 1983. Efficient three-dimensional global models for climate studies: Models I and II. Mon. Weather Rev. **3:** 609–662.

HARTMANN, H. C. 1988. Potential variation of Great Lakes Levels: A hydrologic response analysis. NOAA TM ERL GLERL-68, Environ. Res. Lab., Boulder.

———. 1990. Climate change impacts on Laurentian Great Lakes levels. Clim. Change **17:** 49–68.

HOUGHTON, J. T., G. J. JENKINS, AND J. S. EPHRAMUS [eds.], 1990. Climate change: The IPCC scientific assessment. Cambridge.

LAMB, P. J. 1987. On the development of regional climatic scenarios for policy-oriented climatic-impact assessment. Bull. Am. Meteorol. Soc. **68:** 1116–1123.

LOUIE, P. Y. T. 1991. Proposed GCM scenarios for the phase 2 study, p. 67–74. *In* Proc. Symp. on Climate Scenarios. Univ. Waterloo.

MCFARLANE, N. A., G. J. BOER, J.-P. BLANCHET, AND M. LAZARE. 1992. The Canadian Climate Centre second-generation general circulation model and its equilibrium climate. J. Clim. **5:** 1013–1044.

MANABE, S., AND R. T. WETHERALD. 1987. Large-scale changes in soil wetness induced by an increase in carbon dioxide. J. Atmos. Sci. **44:** 1211–1235.

MORTSCH, L. D. 1991. A summary: Presentations, discussion and consensus, p. 75–78. *In* Proc. Symp. on Climate Scenarios. Univ. Waterloo.

———, AND I. BURTON. 1992. Climate change in the Great Lakes Basin: impacts research priorities and policy issues, p. 17–30. *In* Climate change in the Great Lakes Basin. Ill. Global Climate Change Program Office.

———, G. KOSHIDA, AND D. TAVARES. 1993. Adapting to the impacts of climate change and variability, p. 69–71. *In* Proc. Great Lakes–St. Lawrence Basin Proj., Quebec City.

NEILL, J. C., AND C. F. HSU. 1981. Using non-integer spectral analysis in discerning spatially coherent rainfall periodicities. Time Ser. Anal. **5**: 375–384.

QUINN, F. H. 1991. Proposed climate analog scenarios for the IJC Phase 2 levels study reference, p. 59–66. *In* Proc. Symp. on Climate Scenarios. Univ. Waterloo.

RYAN, C. M., F. H. QUINN, AND M. J. DONAHUE. 1994. Great Lakes climate change—research priorities for assessing the impacts of climate change in the Great Lakes Basin, p. 1–53. *In* Proc. Great Lakes Climate Change Workshop. Ypsilanti.

SMITH, J. B., AND D. TIRPAKELS [eds.]. 1989. The potential effects of global climate change on the United States. Report to Congress. U.S. EPA Office of Policy, Planning and Evaluation.

WHETTON, P. H., A. M. FOWLER, M. R. HAYLOCK, AND A. B. PITTOCK. 1993. Implications of climate change due to the enhanced greenhouse effect on floods and droughts in Australia. Clim. Change **25**: 289–317.

WIGLEY, T. M. L., P. D. JONES, AND P. KELLY. 1986. Empirical climate studies: Warm world scenarios and the detection of a $CO_2$ induced climate change induced by radiatively active gases, p. 271–322. *In* The greenhouse effect, climatic change and ecosystems. Wiley.