TRANSPOSED CLIMATES FOR STUDY OF WATER SUPPLY VARIABILITY ON THE LAURENTIAN GREAT LAKES

KENNETH E. KUNKEL and STANLEY A. CHANGNON
Midwestern Climate Center, Illinois State Water Survey, Champaign, Illinois 61820-7495, U.S.A.

THOMAS E. CROLEY II and FRANK H. QUINN
Great Lakes Environmental Research Laboratory, National Oceanic and Atmospheric Administration, Ann Arbor, Michigan 48105, U.S.A.

Abstract. Hydrological models of the Great Lakes basin were used to study the sensitivity of Great Lakes water supplies to climate warming by driving them with meteorological data from four U.S. climate zones that were transposed to the basin. Widely different existing climates were selected for transposition in order to identify thresholds of change where major impacts on water supplies begin to occur and whether there are non-linear responses in the system. The climate zones each consist of 43 years of daily temperature and precipitation data for 1,000 or more stations and daily evaporation-related variables (temperature, wind speed, humidity, cloud cover) for approximately 20–35 stations. A key characteristic of these selected climates was much larger variability in inter-annual precipitation than currently experienced over the Great Lakes. Climate data were adjusted to simulate lake effects; however, a comparison of hydrologic results with and without lake effects showed that there was only minor effects on water supplies.

1. Introduction

The importance of the Laurentian Great Lakes to the economy of the United States and Canada has prompted a number of studies on the impacts of potential climate change. The Great Lakes Environmental Research Laboratory (GLERL) constructed system-wide hydrological models of the Great Lakes (Croley, 1994) for studying the effects of varying climates on basin water supplies. These models are state-of-the-art, consisting of detailed mathematical descriptions of the underlying physical processes and implemented with a high degree of spatial and temporal resolution. They have been used over the last several years with general circulation model (GCM) outputs to assess changes associated with various $2 \times CO_2$ climate change scenarios (USEPA, 1989; Croley, 1990, 1995; Hartmann, 1990). In these studies, GLERL conducted the hydrological simulations with historical climate data sets that were adjusted based on GCM climate simulations from the Goddard Institute of Space Studies (GISS), the Geophysical Fluid Dynamics Laboratory (GFDL), the Oregon State University (OSU), and the Canadian Climate Centre (CCC). Climate change effects were expressed as differences in mean hydrological variables.

There were several important limitations in these studies that restrict the application of the results. Spatial and temporal (inter-annual, seasonal, and daily) variabilities are the same (temperature) or proportional (precipitation) in the adjusted

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data sets ($2 \times CO_2$ scenarios) as in the historical period (base case). This is a result of applying simple differences or ratios to calculate $2 \times CO_2$ scenarios from base case scenarios. Furthermore, the use of GCM outputs to drive GLERL's hydrological process models forced the use of inappropriately large spatial and temporal scales for studying Great Lakes impacts of climate change. While the hydrological process models were defined over daily intervals and subbasin areas averaging 4,300 km^2, the GCM adjustments were made over monthly time intervals and grids of 7.83° latitude by 10° longitude (GISS), 4.44° by 7.5° (GFDL), 4° by 5° (OSU), and 3.75° by 3.75° interpolated to 1° by 1° (CCC).

Two issues are addressed in this study that were not addressed in the previous studies because of the aforementioned limitations. One is to assess the sensitivity of water supply variability to variability in the climate. This water supply variability is the singular key problem for shipping, power production, and resource managers. In the recent past, major impacts have been experienced during periods of high (e.g., mid-1980s) and low (e.g., early 1960s) water supplies. An increase in variability would cause substantial water management problems, even if mean values did not change. A second issue to be addressed is to quantify the response of the system to different climate conditions with a wide range of possible outcomes. It is of particular interest to identify the thresholds of climate conditions where effects on water supplies become severe or where the response of the system becomes non-linear.

In order to gain this more complete understanding of the Great Lakes system and to fully capitalize on the physically-based hydrologic models, it is desirable to have climate data at the finer spatial and temporal resolutions usable in the model. Since this is primarily a sensitivity study designed to gain a more fundamental understanding of the response of the Great Lakes system, it is not essential to drive the hydrological models with climate data that are precisely tied to GCM predictions of future climate change. In fact, it was desirable to construct some climates well beyond the likely range of future climate change in order to elucidate possible non-linear responses. The method chosen was to transpose data for climates which exist to the south and west of the Great Lakes. Lengthy (at least 40 years) and detailed records of daily weather conditions at many sites are available across all parts of the U.S. Such data sets for widely varying climates incorporate adequate ranges and frequencies of extreme events, ensuring that the desired widely different temporal and spatial variabilities are represented and transposed over the Great Lakes. Since heat storage dynamics of the Great Lakes water bodies are best represented with separate lake thermodynamics models, the Great Lakes were considered as seven separate water bodies with Lake Huron and Georgian Bay treated separately.

The data volume and processing for this study were substantial and resources were available to examine only a few scenarios. It was thus necessary to choose these scenarios judiciously. These choices were based on the following considerations:

- The range of temperature and precipitation changes should be large to minimize ambiguity in elucidating the functional response of the lakes to climate change.
- Some scenarios should represent temperature changes within the range of GCM predictions for doubled-CO_2 changes. However, it was not considered necessary to investigate climate changes on the lower end of the range because previous studies (e.g., International Joint Commission, 1993) had examined scenarios within the envelope of current climatic variability.
- The topography of the Great Lakes basin is generally characterized by modest to moderate hilliness. In extreme eastern sections (New York, Vermont), there is low mountain terrain. While it was not possible to identify climate zones with similar topography for transposition, we did not choose zones from the mountainous western U.S. because those climates have very sharp spatial gradients created by the highly complex topography. This is a feature that is not characteristic of the current Great Lakes climate and unlikely to be in any future climate. Although climate zones 2 and 4 include the Appalachian Mountains in their eastern sections, this is not unlike the eastern sections of the Great Lakes Basin.

This study is discussed in two papers. In addition to the above statement of the study's rationale, this paper describes those features of the climates that are likely to be pertinent to the hydrological results and outlines a methodology used to estimate lake effects. A companion paper presents the results of hydrological model runs with the transposed climates, specifically the effects of the large climate differences on hydrological variables (Croley et al., 1998). Net basin supplies and lake level effects are presented elsewhere (Croley et al., 1996) and will be discussed in an upcoming paper.

2. Climate Data Requirements for Hydrologic Modeling

The Great Lakes basin is shown in Figure 1, repeated from Croley (1990) for convenience. It contains an area of approximately 770,000 km^2, about one-third of which is water surface. Cursory descriptions are given by Freeman and Haras (1978), the U.S. Army Corps of Engineers (1985), and the Coordinating Committee on Great Lakes Basin Hydraulic and Hydrologic Data (1977). The basin extends some 3,200 km from the western edge of Lake Superior to the Moses-Saunders Power Dam on the St. Lawrence River. The water surface drops in a cascade over this distance from 180 m to sea level.

The Great Lakes hydrological models to be used in this study require daily values of precipitation, air temperature, wind speed, humidity, and cloud cover or insolation at many surface locations. Daily temperature and precipitation are available directly from climate records. Wind speed, humidity, and cloud cover are available as hourly observations and daily averages must be calculated for input to the models. In past determinations of water supply effects from climate change sce-

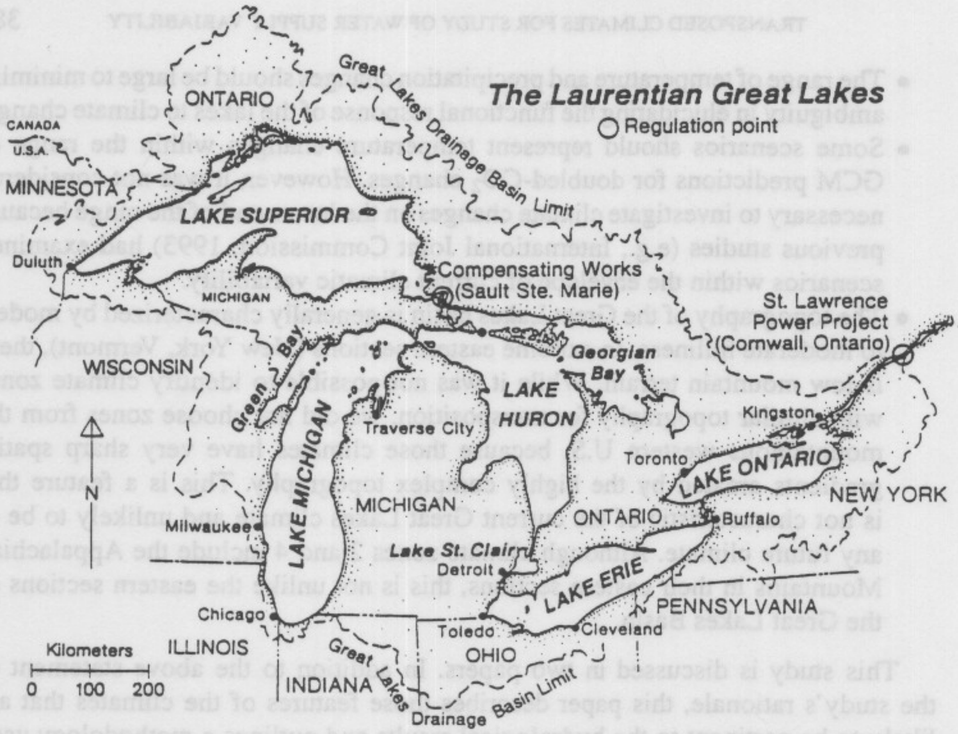

Figure 1. Great Lakes basin.

narios (Croley, 1990, 1994, 1995; Croley and Hartmann, 1989; Hartmann, 1990), GLERL used about 1,800 meteorological stations for daily overland precipitation and air temperature and about 40 meteorological stations for hourly over-lake air temperature, humidity, wind speed, and cloud cover (for determining insolation). Other experience suggests that 200–300 stations per lake basin for overland precipitation (Croley and Hartmann, 1987) and about 5–8 stations per lake for the calculation of over-lake meteorology (primarily evaporation) (Croley and Hartmann, 1989, 1990) would be sufficient for operation of the large-area runoff and evaporation models at daily time intervals for studies of the type considered here. Thus, the climate data should ideally possess the following characteristics:

- Daily precipitation and daily maximum and minimum air temperature at a high spatial density of approximately 1 station per 10^3 km^2.
- Daily averages of hourly observations of wind, humidity, cloud cover, and air temperature at a spatial density of approximately 1 station per 2–3 $\times 10^4$ km^2.
- At least 30 years in length, ideally 40 years or more, in order to study variability.
- Spatial and temporal data coherence that is realistic and consistent with the physical laws governing atmospheric behavior.

3. Climate Scenarios

Four widely different climate zones were selected. The spatial transposition method (Changnon, 1991) takes advantage of the dense network of observing sites in the United States and Canada and allows selection of a wide range of climate conditions that achieve the above requirements. At the available station density (Figure 2), the chosen climate zones each include approximately 1,000–1,700 climate (temperature and precipitation) stations within a Great Lakes Basin-sized area. For a 40-year period of daily measurements, this corresponds to about 15–25 million values for each climate variable.

In the assessment performed for the Intergovernmental Panel on Climate Change (IPCC), general circulation model (GCM) estimates of global warming from an equivalent doubling of CO_2 are in the range of 1.5 °C–4.5 °C (Mitchell et al., 1990). Warming in the Great Lakes region is greater than the global mean. Mitchell et al. (1990) present regional maps of warming for three GCMs. In the region of the Great Lakes, these models show a range of warming from 5 to greater than 8 °C in the winter and 4 to 6 °C in the summer. These temperature changes guided the selection of climates 1 and 2.

Daily maximum and minimum air temperatures, precipitation, and snowfall were obtained for the 43-year period of 1948–1990 from the dense array of stations in the National Weather Service's cooperative observer network (Figure 2a). Data from 1951–1990 were used here, to match the period used in the companion paper (Croley et al., 1998). A subset of stations also measures hourly air temperature, wind speed, humidity, and cloud cover, located generally at National Weather Service offices and airport observing stations (Figure 2b). Figure 3 depicts the shift for each climate zone. Climate zone 1 (warm and mixed, shifted 6° S and 10° W of the Great Lakes) has warmer temperatures and mixed precipitation changes. Climate 2 (warm and wet, 6° S × 0° W) corresponds to warmer temperatures but with increased precipitation. The next two climate zones selected represent conditions well outside the current climate of the basin and allow study of how the Great Lakes might respond to major climatic differences. Climate 3 (very warm and mixed, 10° S × 11° W) corresponds to much higher temperatures than current basin values and mixed precipitation changes compared to the current Great Lakes climate. While generally wetter over much of the basin than the existing climate, climate 3 is drier in the western part of the basin. Climate 4 (very warm and wet, 10° S × 5° W) corresponds to much higher temperatures and much greater precipitation than in the current basin climate.

By taking the stations depicted in Figure 2 and translating their locations in accordance with Figure 3, station networks were created for each of these climate zones. These are depicted in Figure 4a for stations reporting daily air temperature and precipitation and in Figure 4b for stations reporting hourly air temperature, humidity, wind speed, and cloud cover. The relocated meteorological station data

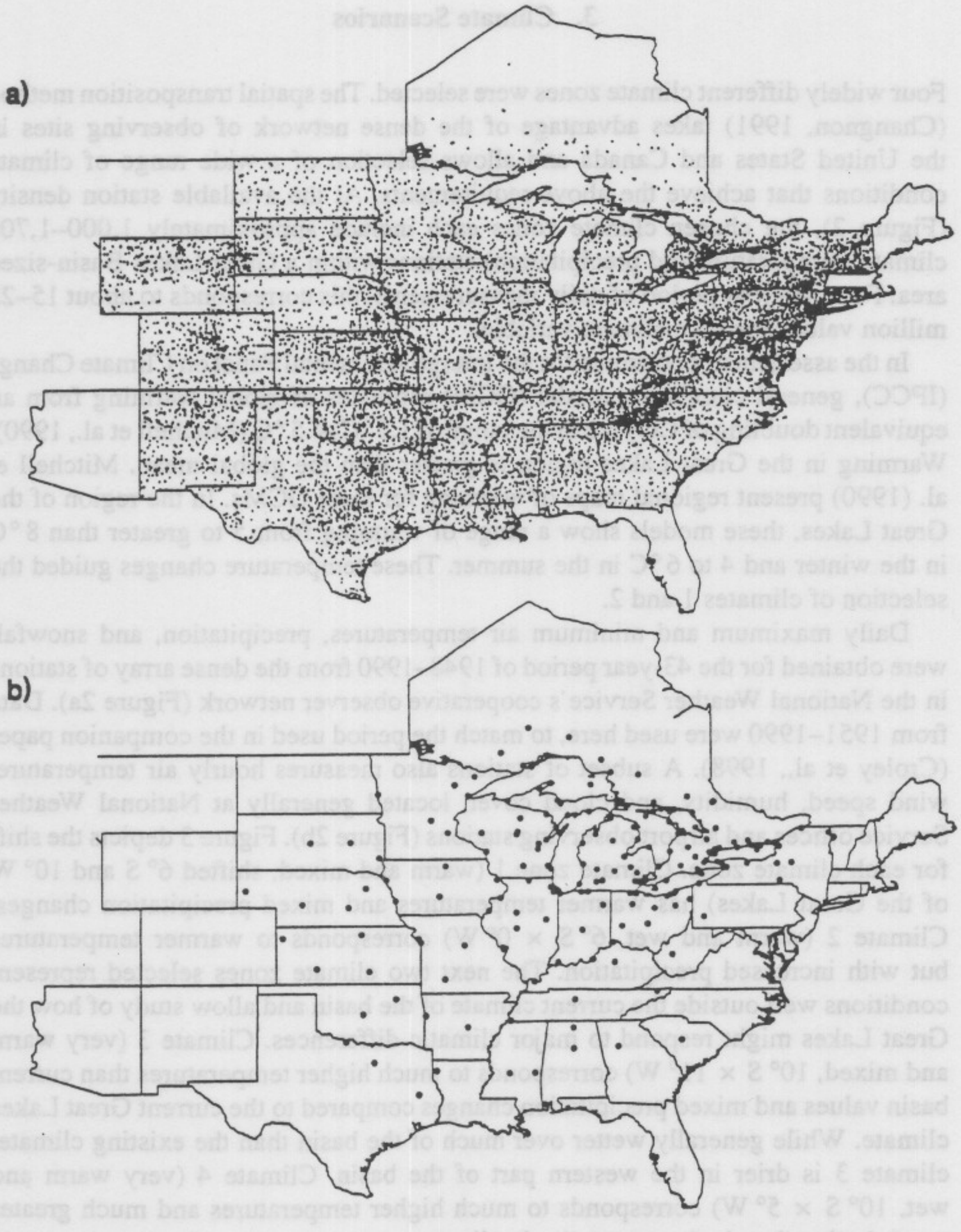

Figure 2. Climatological surface stations available for use in this study: (a) daily observing stations in the U.S. National Weather Service cooperative observer network, and (b) hourly observing stations, either NWS offices or airport stations. The daily observing stations were compiled as state files. Thus, the map includes all stations in a state even if only a portion of that state was within a climate zone.

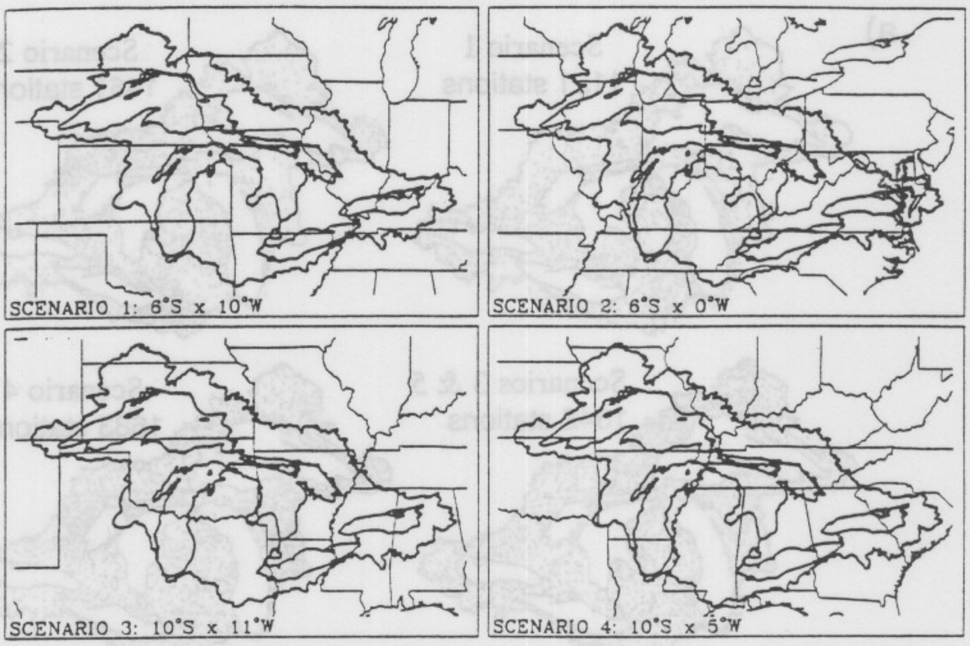

Figure 3. Shift in the location of the Great Lakes for the four climate zones.

were Thiessen-weighted (Croley and Hartmann, 1985) to obtain areal averages over the 121 watersheds and 7 lake surfaces for all days of record (1951–1990).

4. Climatology

The use of actual meteorological data from regions with different climate conditions puts certain constraints on the climatological patterns. A brief description of the spatial variations of climate conditions across the four regions is offered in order to more fully understand the hydrological findings in the companion paper (Croley et al., 1998).

The spatial pattern of U.S. temperature everywhere east of the Rocky Mountains is characterized by a predominantly north-south gradient. Temperature changes produced by transposition of the selected zones to the Great Lakes obviously maintain this north-south gradient. The summertime temperature gradients are somewhat weaker than the gradients during the rest of the year. Therefore, the temperature changes of the four selected zones are somewhat smaller in the summer than in the other seasons with respect to the current climate. Basically all four climate zones yield north-south gradients similar to that now existing in the Great Lakes basin. Climates 1 and 2 are warmer than current conditions by roughly 4 to 7 °C, approximately in the range of predicted warming shown by Mitchell et al. (1990). Climates 3 and 4 are warmer than current conditions by 9 to 10 °C (Table I).

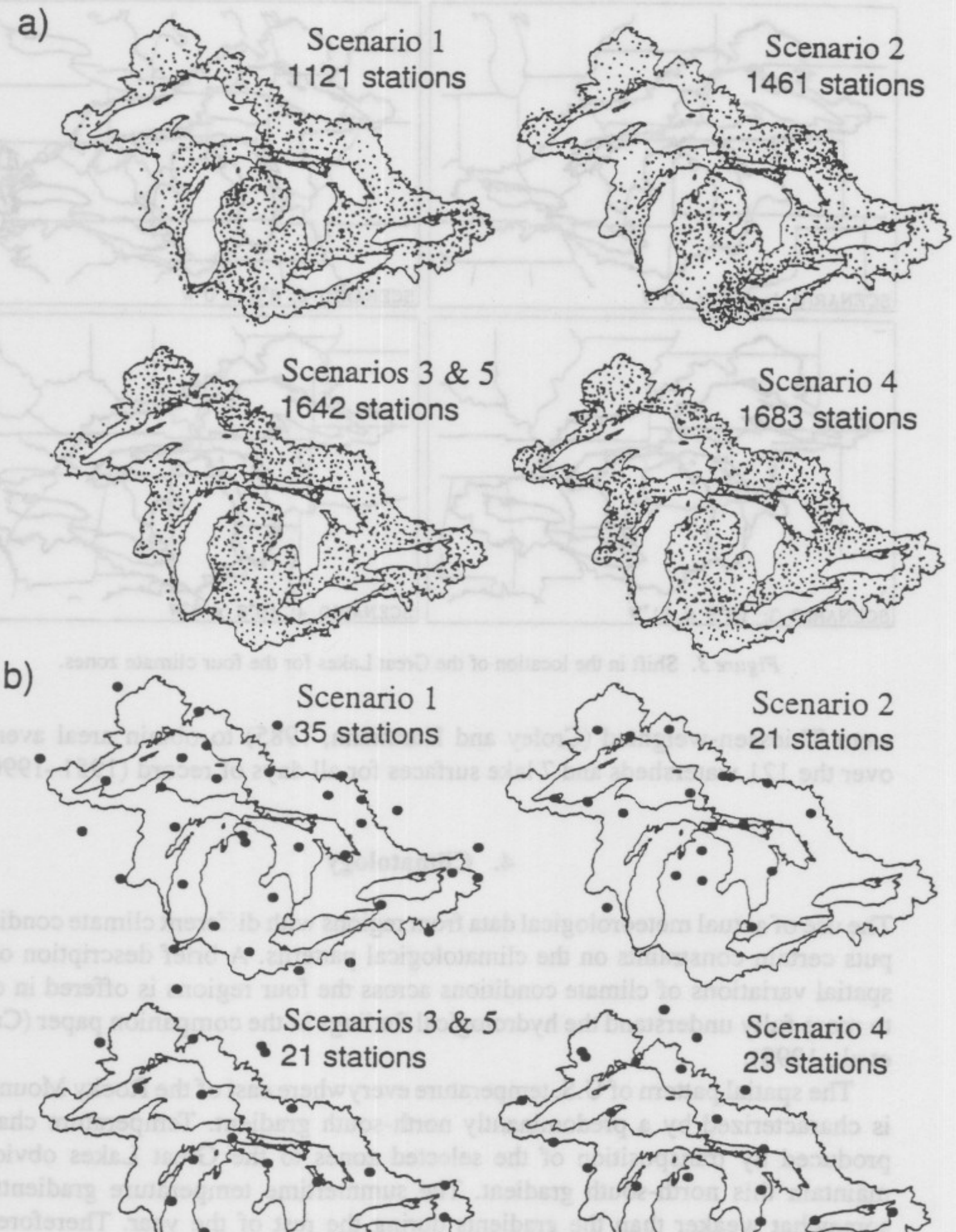

Figure 4. Locations and number of stations in the four climate zones for (a) daily temperature and precipitation, and (b) hourly air temperature, wind speed, humidity, and cloud cover.

Table I

Average annual overland air temperature (°C) for the base case and changes (°C) for the four climate zones[a]

Basin	BASE	#1	#2	#3	#4	#5
Superior	2.3	6.9	6.8	10.4	10.9	10.4
Michigan	7.2	6.3	5.6	9.8	9.4	10.1
Huron	7.1	5.8	4.6	9.8	9.1	10.3
Georgian	4.3	7.0	5.7	10.4	9.8	10.6
St. Clair	8.3	5.2	3.9	9.3	8.9	9.4
Erie	9.1	6.1	4.4	9.4	8.2	9.4
Ontario	7.2	6.2	6.5	9.3	9.7	9.3

[a] Climate #1 is 6° S × 10° W; #2 is 6° S × 0° W; #3 is 10° S × 11° W; #4 is 10° S × 5° W; #5 is #3 with lake effects.

Precipitation patterns for the four climate zones are more complex. Annual total precipitation exhibits a north-south gradient in the eastern part of the U.S., similar to the gradient in temperature. However, the direction of the gradient gradually rotates westward, becoming nearly east-west in the High Plains. There are also pronounced seasonal differences in the gradients. The gradients are large during the colder half-year (November–April). During the warmer half-year, the gradients are smaller; in fact, there is little spatial variation during mid-summer. As a result of these patterns, the amount of precipitation over most lakes in most transposed climates is greater than current values (Table II), with the largest changes occurring in the cold season. Climate 4 has the largest precipitation increase of around 50% over the entire basin. However, in climates 1 and 3, the western part of the basin is positioned in the east-west precipitation gradient. Thus, these two climates produce slight decreases in precipitation over the western lakes relative to the existing climate over the basin. Climates 1 and 3 for Lake Superior show roughly a 20% decrease in annual precipitation. Because the movement of these four climate zones generally results in greater precipitation, none of them are warmer and drier than current conditions over the whole basin.

Total annual snowfall exhibits a predominantly north-south gradient except for the snowbelt areas on the lee sides of the Great Lakes. Thus, the transposition of climates from the south and west result in a significant decrease in snowfall for all climates because of the warmer temperatures to the south.

The spatial pattern of dewpoint temperature is similar to that of precipitation. When combined with the temperature gradient, the pattern of relative humidity exhibits only weak gradients over the eastern U.S. However, a westward decrease in relative humidity occurs throughout the Great Plains. Thus, for climates 2 and 4, each with little or no east-west shift, there is little change in relative humidity for the Great Lakes. For climates 1 and 3, there are decreases in relative humidity over the western part of the basin. However, even in climates 2 and 4, the average

Table II
Average annual overland precipitation (mm) for the base case and changes (%) for the four climate zones[a]

Basin	BASE	#1	#2	#3	#4	#5
Superior	817	−23%	6%	−20%	21%	−20%
Michigan	828	3%	39%	1%	59%	4%
Huron	813	26%	40%	48%	70%	51%
Georgian	908	2%	10%	30%	47%	31%
St. Clair	854	28%	33%	51%	61%	53%
Erie	913	31%	44%	37%	55%	39%
Ontario	934	26%	18%	49%	33%	49%

[a] Climate #1 is 6° S × 10° W; #2 is 6° S × 0° W; #3 is 10° S × 11° W; #4 is 10° S × 5° W; #5 is #3 with lake effects.

water vapor pressure deficit increases everywhere in all basins, even where relative humidity does not increase, due to the non-linear relationship between temperature and saturation water vapor pressure.

The Great Lakes are located in a region of relatively high cloud cover and low solar radiation. Cloud cover generally decreases to the south and west of the Great Lakes. Thus, there is decreased cloud cover in all climate zones. Wind speed gradients are weak in much of the eastern U.S. but wind speeds increase somewhat toward the west within the Great Plains. Thus, in most climate zones, wind speed does not change significantly from the existing values. The exception is the western part of the basin in climates 1 and 3 where slight increases in wind speed are experienced.

When the patterns for each of the evaporation-related variables are combined, the spatial pattern of potential evaporation is characterized by a gradient with increasing values from north-east to southwest. This can be seen in the analysis of Farnsworth et al. (1982), who produced a map of estimated free water surface evaporation. In their analysis, particularly high values are seen in the southern Great Plains. For the current climate of the Great Lakes, annual free water surface evaporation ranges from around 700 mm in the north to near 900 mm in the south. All four climatic zones have significantly higher values of potential evaporation: 850–1400 mm (the spatial range for climate 1), 75–1000 mm (climate 2), 900–1700 mm (climate 3), and 900–1400 mm (climate 4).

The inter-annual variability of temperature is not significantly different from current Great Lakes conditions (Table III). However, there are very large increases in inter-annual precipitation variability in all climate zones for all lakes (Table IV). This partly reflects increases in mean precipitation. However, the coefficient of variability (standard deviation/mean) of annual precipitation is also much larger than in the current climate (Table V). In scenarios 1 and 3, the coefficient of variability is 35% to 90% larger. The increases in climates 2 and 4 are smaller, but

Table III

Annual standard deviation of overland air temperature (°C) for the base case and changes (%) for the four climate zones[a]

Basin	BASE	#1	#2	#3	#4	#5
Superior	0.80	−13%	−13%	−13%	−13%	−13%
Michigan	0.60	17%	0%	0%	0%	0%
Huron	0.60	17%	17%	0%	0%	−17%
Georgian	0.70	0%	−14%	−14%	−14%	−14%
St. Clair	0.60	17%	17%	0%	0%	0%
Erie	0.60	0%	0%	−17%	0%	−17%
Ontario	0.60	0%	−17%	0%	0%	0%

[a] Climate #1 is 6° S × 10° W; #2 is 6° S × 0° W; #3 is 10° S × 11° W; #4 is 10° S × 5° W; #5 is #3 with lake effects.

Table IV

Annual standard deviation of overland precipitation (mm) for the base case and changes (%) for the four climate zones[a]

Basin	BASE	#1	#2	#3	#4	#5
Superior	83.8	27%	41%	52%	110%	52%
Michigan	93.8	84%	64%	64%	124%	64%
Huron	89.1	127%	52%	153%	154%	153%
Georgian	93.8	76%	17%	114%	101%	114%
St. Clair	121.9	80%	22%	106%	90%	106%
Erie	109.7	99%	51%	105%	103%	105%
Ontario	89.6	99%	71%	149%	96%	149%

[a] Climate #1 is 6° S × 10° W; #2 is 6° S × 0° W; #3 is 10° S × 11° W; #4 is 10° S × 5° W; #5 is #3 with lake effects.

still significant. Only in climate 2 for the central part of the basin are the increases less than 10%. Thus, these climate zones provide the required increase in temporal variability to analyze the potential effects on lake water supply variability.

Changes in the temporal variability of the evaporation-related variables (temperature, wind speed, humidity, and cloud cover) are also generally positive but the magnitude is generally smaller than the precipitation changes. For most of the lakes, the increases are in the range of 0–15%. Thus, precipitation variability is the predominant factor influencing the lake hydrological variability results presented in the companion paper.

5. Consideration of Lake Effect

Large-scale geographic influences may place constraints on physically plausible outcomes for the Great Lakes climate. Thus, since the climate data in these four

Table V

Annual coefficient of variability for overland precipitation for the base case and changes (%) for the four climate zones[a]

Basin	BASE	#1	#2	#3	#4
Superior	0.10	65%	33%	90%	74%
Michigan	0.11	79%	18%	62%	41%
Huron	0.11	80%	9%	71%	49%
Georgian	0.10	73%	6%	65%	37%
St. Clair	0.14	41%	–8%	36%	18%
Erie	0.12	52%	5%	50%	31%
Ontario	0.10	58%	45%	67%	47%

[a] Climate #1 is 6° S × 10° W; #2 is 6° S × 0° W; #3 is 10° S × 11° W; #4 is 10° S × 5° W.

climate zones are affected to some extent by differing geographic influences, certain characteristics of some zones may not have a high likelihood of occurrence in any future climate of the Great Lakes Basin (e.g., occasional very heavy rain events in climate zone 4 due to tropical storms and hurricanes). Nevertheless, they are useful in revealing the response of the system to a wide range of conditions.

One geographic factor of potential importance is the regional effect of the lakes themselves on basin climate. The data for the four climate zones of course do not reflect such well-known phenomena as lake effect snows in the late autumn and winter, inhibited near-shore and overlake convection in the late spring and summer, and moderation of near-shore temperatures in the winter and summer. To estimate whether these lake effects had a significant influence on basin-wide hydrology, it was necessary to derive quantitative estimates of the lake effect under current climate conditions. A sensitivity test was conducted in which data for climate 3 were modified to produce a simulated lake effect using the existing magnitude and location of lake effects. The hydrologic models were driven by data for climate 3 with and without simulated lake effects to determine the sensitivity of basin hydrologic components to the lake effects. If the estimated lake effects were found to create major changes in the hydrologic components of the lakes, the lake effects would be applied to data for the three other zones.

Numerous past studies have investigated the effects of the lakes on climatic conditions in the Great Lakes Basin. For example, Day (1926) investigated precipitation in the drainage area of the Great lakes, and Horton and Grunsky (1927) studied the hydrology of the basin including estimated effects on precipitation and temperature. Petterssen and Calabrese (1959) evaluated weather influences related to the warming of air by the Great Lakes. Blust and DeCooke (1960) made comparisons of precipitation on islands in Lake Michigan with precipitation on the perimeter of the lake. Changnon (1968) made an intensive study of the precipitation climatology of Lake Michigan, and Lyons (1966) assessed lake effects on storms and convective activity. Braham and Dungey (1995) studied lake effects on winter precipitation over Lake Michigan. The use of atmospheric models to simulate and calculate the effects of the Great Lakes on regional climate conditions has begun (e.g., Bates et al., 1995), but as yet is limited to examining short periods of time; hence, modeling of lake effects for this study was infeasible. One of these past studies of the Lake Michigan basin used an empirical three-step climatological technique for defining the extent of the lake effect on monthly, seasonal, and annual precipitation, temperature, and other weather conditions (Changnon, 1968). A similar technique is used in this study to derive estimates of lake effects around each lake for the four seasons, and for the seven variables of precipitation, maximum air temperature, minimum air temperature, mean air temperature, cloud cover, wind speed, and water vapor pressure. A complete description of the findings of this analysis is found in Scott and Huff (1996).

5.1. METHOD OF ANALYSIS

It was assumed that any hydrologically significant lake effect would occur within 80 kilometers of the lake shore. This was based on the results of a previous study (Changnon, 1968). In that study, maps of 35 individual years were drawn for seasonal temperature, precipitation, humidity, and wind. For each year, a climatological assessment of the extent of lake effect was made by a visual analysis of the contours on the maps. The 80-km band criteria was derived as an envelope of lake effect derived from the greatest areal extents found in the individual years. As applied here, a smoothed boundary (rather than a precise 80-km line) was used. For each meteorological element evaluated, three maps were manually generated for each season of the year based on data for the period 1951–1980. The first map was based on all observations and established the overall spatial distribution pattern over the Great Lakes Basin and surrounding areas, incorporating both lake-induced changes and those produced by the broad-scale climatology of the region.

A relatively large region surrounding the basin was used to produce a second map that was an estimate of the pattern that would exist if the lakes had no effect on the climate. This second map was based on a subset of the data from which all stations in the 80-km lake effect band were eliminated. The pattern existing in the no-effect region surrounding the basin was used as the primary guide in establishing the climatological pattern assumed to exist if no lake effects were present.

The 'no-effect' and 'all-data' maps were compared and the magnitude of the lake effect was derived by calculating the differences between the two sets of values at selected points. These differences were used to manually generate a third map of lake effects based on the computed differences. The analyzed difference data were digitized for grid points and used to adjusted the data for climate zone 3.

5.2. LAKE EFFECT PATTERNS

Figure 5 shows the three maps generated for winter precipitation across the Great Lakes basin and surrounding region. As noted, a large area surrounding the Great Lakes basin was included since it was essential for estimating the no-lake effect patterns over and beyond the basin.

Figure 5a shows the precipitation pattern using all data. Precipitation maxima are indicated over the eastern part of Lake Superior, eastern Lake Huron, south of Lake Erie, and east of Lake Ontario. A less-pronounced maximum is located over eastern Lake Michigan.

Figure 5b shows the spatial pattern estimated to exist without the presence of the lakes. The maxima (Figure 5a) over and downwind of the lakes are generally no longer discernible, except for a small area just east of Lake Ontario where topographic effects are important.

Figure 5c is the pattern of differences between the maps of Figures 5a and 5b. A major increase in precipitation induced by the lake effect is centered over the Lake Superior basin and extends east of the lake. The lake-induced increase, which exceeds 100 mm over the eastern part of the lake, corresponds to an increase of over 50%. The maximum of greater than 50 mm in the Lake Huron area corresponds to an increase of approximately 35%, similar to those found at the eastern ends of Erie and Ontario. The 50-mm maxima along the eastern shore of Lake Michigan correspond to increases of over 35%.

Except for Lake Superior, the lake-induced increases in winter precipitation are generally in the 20% to 35% range, similar to those obtained in the Lake Michigan basin by Gatz and Changnon (1976). The greater increases in the Lake Superior basin are probably caused in part by its larger surface area, resulting in a longer fetch of air flow over the lakes, and its greater depth, minimizing ice cover.

Significant lake-effect increases in autumn precipitation were also observed. By contrast, decreases in summer precipitation of 10–20% were found. With respect to temperature, increases in minimum temperatures were observed during all seasons with the largest effects (4° to 8 °C near Lakes Superior, Huron, and Michigan) observed in the winter. Decreases in maximum temperature (more than 3 °C near Superior, Huron, and Michigan) were observed in spring and summer. Lake effects on cloud cover were found to be similar in sign as for precipitation, with increases of up to 25% in winter and decreases of about 10% in summer. Water vapor pressure effects were also found to be similar as for precipitation with a magnitude of up to +15% in winter and −10% in summer.

Seasonally-dependent lake effect values were used to modify the meteorological data within 80 km of the lakes for climate 3. This climate was chosen for the test because the precipitation range across the basin is the greatest of the four climates. Thus, the results should reveal whether the importance of the lake effect is significantly dependent on precipitation magnitude. Tables I–IV indicate that the inclusion of the lake effect results in small annual temperature (0.5 °C or

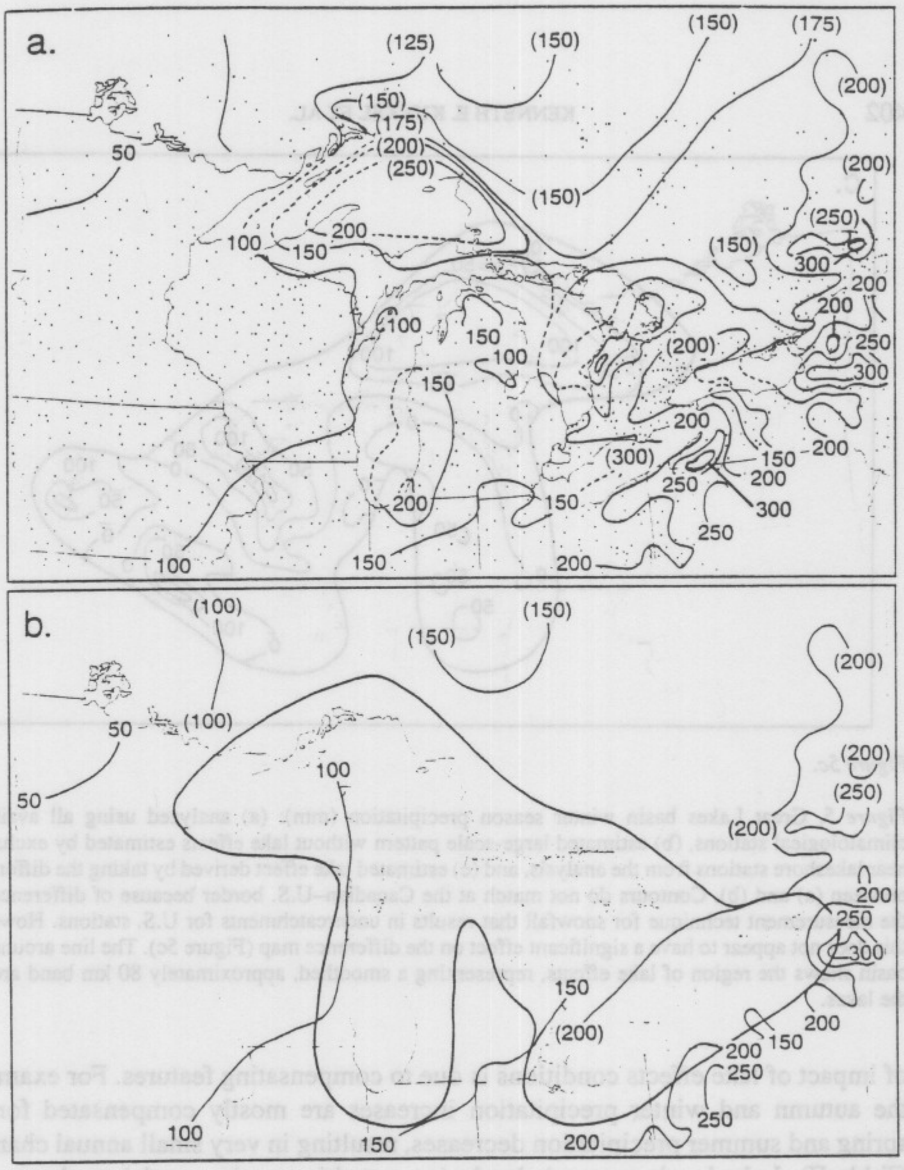

Figure 5a,b.

less) and annual precipitation (3% or less) changes compared to climate 3 without lake effects. Results from the hydrologic model runs (Croley et al., 1997) with climate 3 conditions (both with and without the calculated lake effects) showed little significant differences in basin hydrologic conditions with lake effects. Changes in both the mean and variability of runoff, overland evapotranspiration, and overlake evaporation were within 5% of the results without lake effects included. The lack

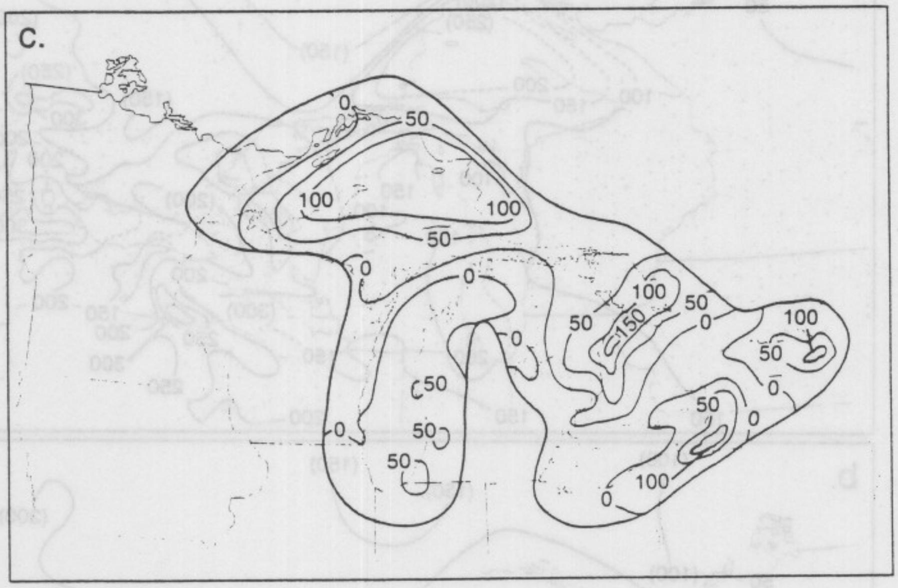

Figure 5c.

Figure 5. Great Lakes basin winter season precipitation (mm): (a) analyzed using all available climatological stations, (b) estimated large-scale pattern without lake effects estimated by excluding near lakeshore stations from the analysis, and (c) estimated lake effect derived by taking the difference between (a) and (b). Contours do not match at the Canadian–U.S. border because of differences in the measurement technique for snowfall that results in undercatchments for U.S. stations. However, this does not appear to have a significant effect on the difference map (Figure 5c). The line around the basin shows the region of lake effects, representing a smoothed, approximately 80 km band around the lakes.

of impact of lake effects conditions is due to compensating features. For example, the autumn and winter precipitation increases are mostly compensated for by spring and summer precipitation decreases, resulting in very small annual changes (Table II). Lake levels respond slowly (on a multi-year time scale) to changes in water supplies and, from an impacts standpoint, the low frequency contribution to variability is dominant. Thus, the details of this intra-annual compensation do not affect the major findings of this study which focus on the interannual changes. Since the precipitation changes in climate 3 (–20% to +51%) span nearly the entire range of all four climates (–20% to +70%) and negligible effects were found, there is no reason to expect significant effects for the other three climates. Hence lake effects were not applied to the climates of the three other zones (1, 2, and 4).

6. Summary

This study has two major objectives: to investigate the sensitivity of the mean and the variability in Great Lakes water supplies to changes in climate means and variability, and to quantify the response of the Great Lakes system to changes in climate over a wide range of outcomes. Of particular interest are possible thresholds of climate change where impacts become severe or where the response of the system becomes non-linear. A climate transposition approach was used to select four climates, each consisting of 45 years of daily temperature and precipitation data at 1000 or more stations and evaporation-related variables (hourly air temperature, wind speed, humidity, cloud cover) for 20–36 stations. A key characteristic of these climates is the large inter-annual precipitation variability which is much greater than currently experienced over the Great Lakes, a necessity for studying water supply variability behavior. It was also necessary to investigate whether the effects of the Great Lakes on near-shore climate had significant hydrologic consequences. To accomplish this, an analysis of the lake effects was conducted. This produced quantitative estimates of the lake effect on a seasonal basis for the different climatic elements that affect the hydrology. Adjustments were made to one of the transposed climates to represent the lake effects. The results showed that lake effects were not important in modifying long-term Great Lakes water supplies.

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