J. Great Lakes Res. 28(4):537–554
Internat. Assoc. Great Lakes Res., 2002

Evaluation of Potential Impacts on Great Lakes Water Resources Based on Climate Scenarios of Two GCMs

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ABSTRACT. *The results of general circulation model predictions of the effects of climate change from the Canadian Centre for Climate Modeling and Analysis (model CGCM1) and the United Kingdom Meteorological Office's Hadley Centre (model HadCM2) have been used to derive potential impacts on the water resources of the Great Lakes basin. These impacts can influence the levels of the Great Lakes and the volumes of channel flow among them, thus affecting their value for interests such as riparians, shippers, recreational boaters, and natural ecosystems. On one hand, a hydrological modeling suite using input data from the CGCM1 predicts large drops in lake levels, up to a maximum of 1.38 m on Lakes Michigan and Huron by 2090. This is due to a combination of a decrease in precipitation and an increase in air temperature that leads to an increase in evaporation. On the other hand, using input from HadCM2, rises in lake levels are predicted, up to a maximum of 0.35 m on Lakes Michigan and Huron by 2090, due to increased precipitation and a reduced increase in air temperature. An interest satisfaction model shows sharp decreases in the satisfaction of the interests of commercial navigation, recreational boating, riparians, and hydropower due to lake level decreases. Most interest satisfaction scores are also reduced by lake level increases. Drastic reductions in ice cover also result from the temperature increases such that under the CGCM1 predictions, most of Lake Erie has 96% of its winters ice-free by 2090. Assessment is also made of impacts on the groundwater-dependent region of Lansing, Michigan.*

INDEX WORDS: *Climate change, water resources, lake levels, ice cover, model.*

INTRODUCTION

The Great Lakes have historically enjoyed a relatively small range in lake levels (Fig. 1), approximately 2 m from the recorded maximum monthly mean to the recorded minimum monthly mean. (All lake levels given in this paper are referenced to the International Great Lakes Datum 1985.) Superimposed upon the average levels are seasonal cycles of 0.40 to 0.45 m amplitude. The lake levels for the past 30 years have been in a high water level regime, the highest in recorded history, due to increased summer and fall precipitation. Record highs were set in 1973 and again in 1986. In 1997, Lake Erie rose again to near-record highs. However, during 1999 and 2000, the lake levels have experienced a decline, second in this century only to the Dust Bowl drought of 1931, although this decline leveled out during 2001. The lake levels in 2000 were between their longer term (1900 to 1969) mean and record lows. Impacts of the recent drop are being experienced by the shipping industry, the hydropower industry, recreational boaters, and some individual water supplies.

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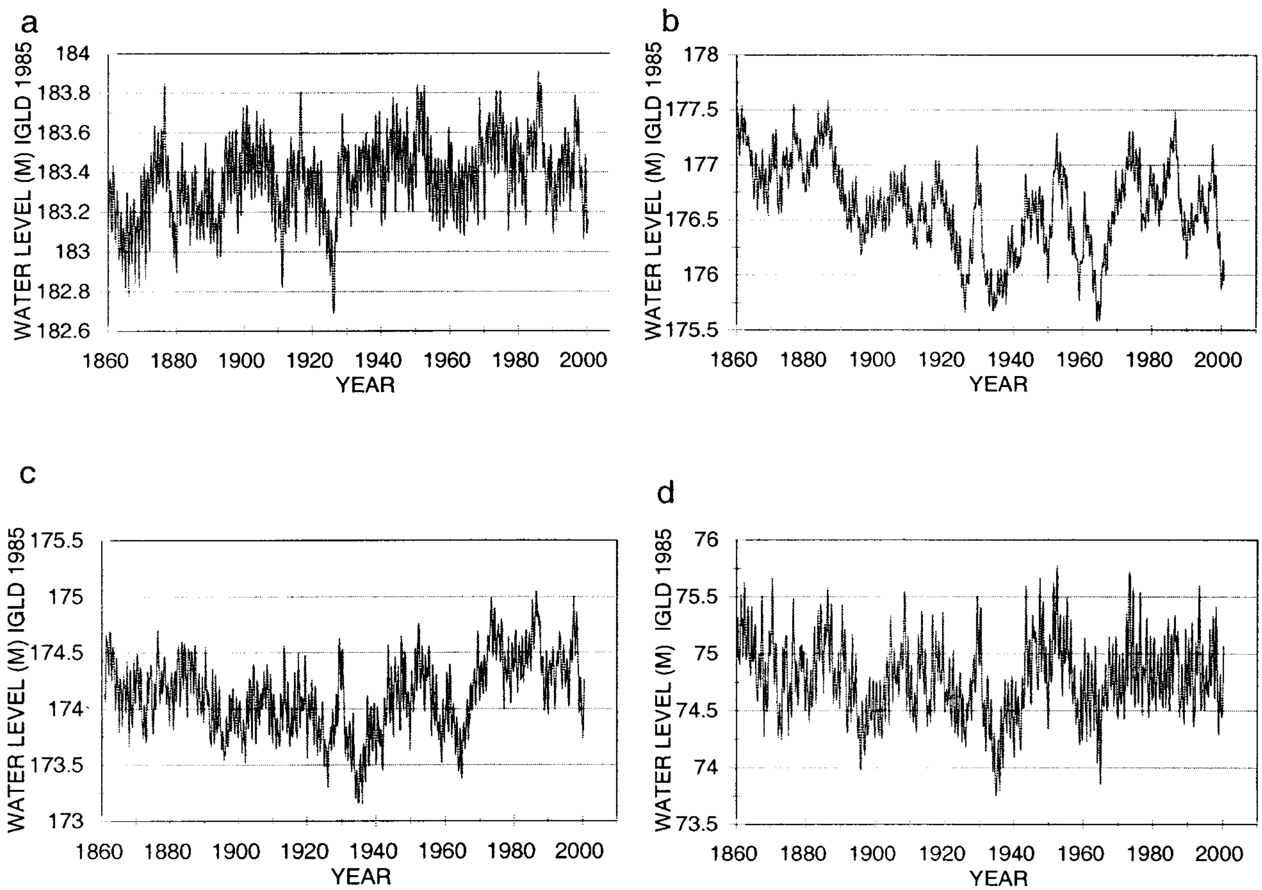

FIG. 1. Historical water levels of (a) Lake Superior, (b) Lakes Michigan and Huron, (c) Lake Erie, and (d) Lake Ontario. All water levels are referenced to the International Great Lakes Datum 1985.

The Great Lakes basin is shown in Figure 2. The basin has a total land area of 534,000 km^2 and a water surface area of 247,000 km^2. Two of the lakes, Superior and Ontario, are regulated by controlling their outflows according to approved regulation plans under the auspices of the International Joint Commission. In addition to this regulation, the hydraulics of the system result in a major backwater effect, in which the water level of downstream lakes can affect the amount of flow through connecting channels and hence the level of upstream lakes.

A number of $2 \times CO_2$ equilibrium climate scenarios have been developed (Mortsch and Quinn 1996, Croley 1990), showing that increases in atmospheric greenhouse gas concentration produce a warming effect that enhances evaporation in the Great Lakes drainage basin and over the lakes themselves. Although general circulation models (GCMs) simulating climate produced varying results in terms of change in precipitation (both wetter and drier futures), they agreed in showing a decrease in basin runoff, an increase in lake surface temperature, and a consequent increase in lake evaporation. This resulted in reduced interlake channel flow and water levels on all of the Great Lakes. Time-averaged water level reductions ranged from 0.23 m to 2.48 m, depending on the lake and the GCM used as input. A review of the results of GCMs in terms of temperature, precipitation, and evaporation in the Great Lakes basin, along with extremes in the historical record, is included in Mortsch *et al.* (2000). Examples of consequences of an anticipated decrease in water levels of the Great Lakes, ranging from decrease in the efficiency of shipping in lake vessels to changes in biotic primary production within the lakes, are discussed in Sousounis and Bisanz (2000), Magnuson *et al.* (1990, 1997), Meisner *et al.* (1987) Changnon

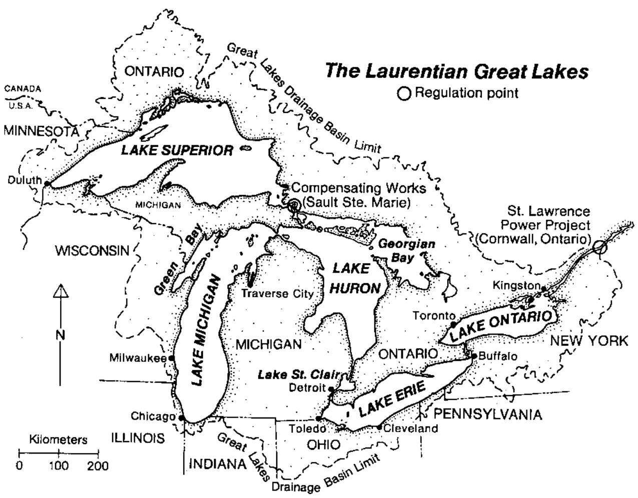

FIG. 2. Map of the Great Lakes region. The dashed contour indicates the boundaries of the Great Lakes drainage basin. The open circles indicate the points at which Lakes Superior and Ontario are regulated.

and Glantz (1996), Mortsch *et al.* (1998), and other papers within this special section.

This paper aims to assign quantitative predictions of changes in aspects of the Great Lakes that may result from future changes in mean atmospheric conditions. These aspects include lake levels, lake ice concentration, combinations of interest satisfaction for various groups of users of the St. Lawrence River, and the available groundwater in a special area of interest near Lansing, Michigan. This study expands on previous studies (Croley 1990) by using the results of transient GCM simulations that include ocean-atmosphere coupling and the direct effects of aerosol pollutants, rather than the older equilibrium doubled-CO_2 experiments. The newer transient model methodology allows examination of possible scenarios at both earlier and later time horizons Some of the information presented here may be valuable in additional studies for special interests in the Great Lakes basin.

TREATMENT OF DATA FROM GENERAL CIRCULATION MODELS AND OBSERVATIONS

To develop input data for climate scenarios for this study, monthly mean data from GCM runs with transient CO_2 content and sulfate aerosol concentrations were acquired from the Canadian Centre for Climate Modelling and Analysis (CCCma, their Coupled General Circulation Model, CGCM1, Boer *et al.* 2000a,b) and from the United Kingdom Meteorological Office's Hadley Centre for Climate Prediction and Research (their model HadCM2, Johns *et al.* 1997). Although the model formulations are different, the external forcings were identical, including the rate of increase in greenhouse gases and the concentration of sulfate aerosols (Reader and Boer 1998).

GCM Simulation of Recent Past

Figures 3 and 4 show for the land in the basins of Lake Superior and Lake Erie, respectively, the monthly means of the maximum and minimum screen-height air temperatures from the GCM runs during the 1961 to 1990 base period, each compared to observed mean air temperatures interpolated from stations to the entire drainage basins. The CGCM1 in the Lake Superior Basin (Fig. 3) has a cold bias during the winter and spring and a warm bias during the summer and fall. Each of these biases is especially strong in the daily minimum temperature, reaching values greater than 5°C

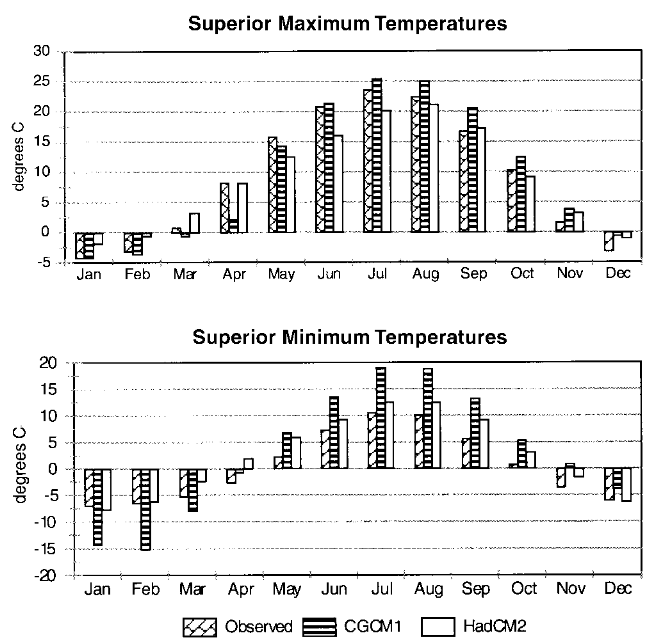

FIG. 3. Monthly means of the (a) daily maximum screen temperature and (b) daily minimum screen temperature for the land within the Lake Superior basin. All quantities are averaged over the base periods used for the observations, 1954 to 1995.

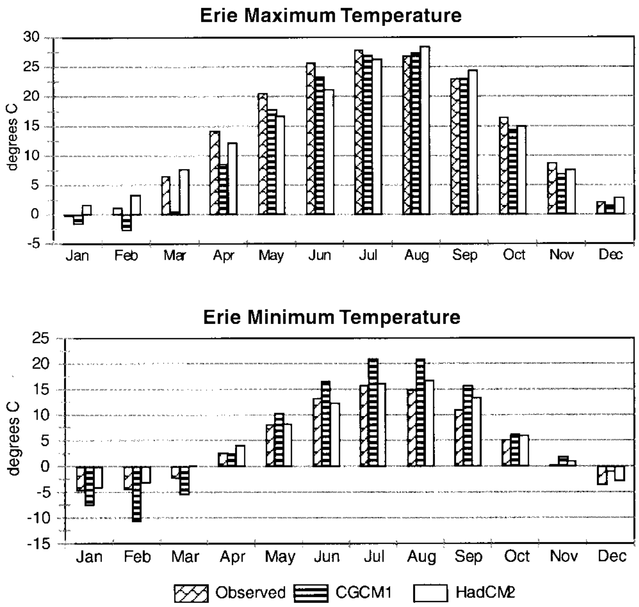

FIG. 4. As in Figure 3 but for the land within the Lake Erie basin.

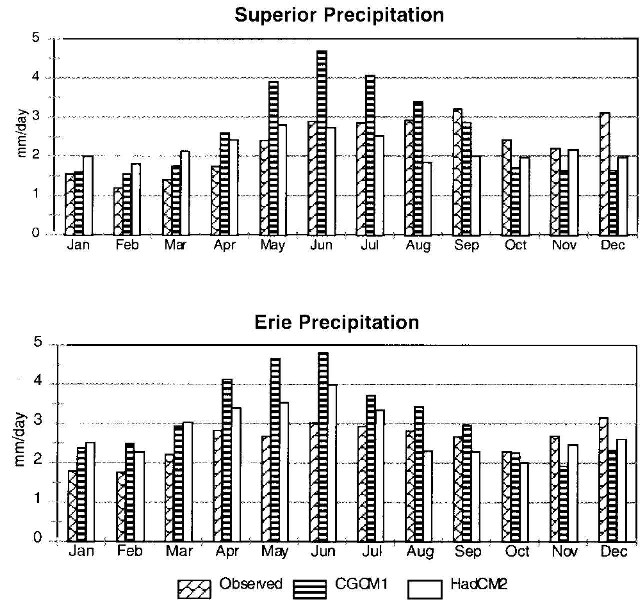

FIG. 5. Monthly mean precipitation for the period 1954 to 1995 for the land within the (a) Lake Superior and (b) Lake Erie basins from observations and two GCMs.

compared to observations. The HadCM2 has a warm bias during the winter and early spring that is greater in the maximum temperature than minimum. During the summer, it has a cold bias in the daily maximum temperature, and a warm bias in the daily minimum temperature. Nearly all of the HadCM2's biases are less than about 3°C.

Most results for the Lake Erie basin (Fig. 4) are qualitatively similar to those described for the Lake Superior basin. In terms of maximum temperature, though, the CGCM1 maintains a cold bias into the summer, although the minimum temperature has a warm bias during the summer. The magnitude of the biases over the Lake Erie basin for CGCM1 are generally less than those over the Lake Superior basin. The HadCM2's shift from a cold bias to a warm bias occurs around August in the Lake Erie basin, whereas this shift is delayed until October or November in the Lake Superior basin.

The mixture of sign and magnitude in maximum and minimum temperature biases indicates that neither model has a systematic and seasonally consistent bias in the diurnal temperature range. Although firm attribution of model biases is beyond the scope of this paper, one possible reason for the CGCM1 having a cold bias during winter and a warm bias during summer, in contrast to the HadCM2, is that it lacks any representation of the Great Lakes, whereas the HadCM2 does include the presence of the Great Lakes, albeit in a very crude spatial representation (Johns *et al.* 1997).

Figure 5 shows the monthly means of precipitation over the Lake Superior and Lake Erie basins from the observations and the GCMs. In both basins, the CGCM1 produces a large overestimate of summertime precipitation and some underestimate during the fall and early winter. As with the air temperature, it is possible that the explanation lies in the absence of the Great Lakes and substitution of a land surface in the CGCM1 model, which could lead to enhanced atmospheric instability and convective activity during the summer and an absence of lake effect precipitation during the fall and early winter. The HadCM2 does better than the CGCM1 at replicating the observed precipitation during the early summer and late fall. In the Lake Superior basin, however, HadCM2 produces overestimates of precipitation during the late winter and spring, and underestimates in August, September, and December. In the Lake Erie basin, the HadCM2 has overestimates comparable to those of CGCM1 during January through March, but performs better than CGCM1 throughout the rest of the year.

Because of the assortment of biases in key meteorological variables, and the way in which these biases could result in error by propagating into impacts models that are driven by these variables, the raw output of the GCMs is not used in this study. Instead, changes within the GCMs of key meteorological variables between a base period and future periods of interest were calculated and used to perturb observed meteorological data for use as input to hydrologic models.

Future Scenarios

The period 1961 to 1990 was used as the base (reference) model period. The model-simulated variables from this period were compared to predictions for future periods of 20 years' duration centered around 2030, 2050, and 2090. Although the 2050 period most closely approximates a doubled CO_2 atmosphere relative to the base period, drawing parallels to previous doubled-CO_2 experiments should be done with caution, as the new experiments contain coupled oceans, which cause a time lag in global warming in these transient simulations.

Different elements of the hydrologic simulation system, described in the following section, use the following variables derived from the GCM runs: daily maximum and minimum temperatures, precipitation, relative humidity (used directly from the GCM or derived from other measures of humidity), cloud fraction, and wind speed. The changes in these variables from the period centered about 1975 to those centered about 2030, 2050, or 2090 are expressed as ratios and differences. Because the range of legitimate choices of temperature scale (Celsius, Kelvin, or Fahrenheit) makes ratios problematic, changes in temperature are expressed as differences. For other variables, because of the hard limits to their range (never less than zero, and for some variables never greater than one), future departures are expressed as ratios.

These differences and ratios were calculated at each GCM gridpoint for each variable and each month of the year, based on the GCM mean values of the variables for each month. These means were calculated over all of the years in the base period and the future periods, and using all available runs from each model. (The CGCM1 was run three times and the HadCM2 four times for the entire length of the model run—1900 to 2100—using different initial conditions. Because of the chaotic nature of atmospheric circulation as depicted in the models, these different runs diverge and yield independent realizations of possible climate change, consistent with the same greenhouse gas and aerosol forcing and the model's formulation. Unfortunately, not all of the data from each run of the models were available, and data were averaged among the different runs as available. Non-linearities in response to the GCM output are thus not fully accounted for.) Monthly mean data were interpolated from the GCM gridpoints using an inverse-distance weighting method to give values representative of the 121 drainage sub-basins of the Great Lakes basin, each corresponding to a tributary river, plus values for each of the lakes, including Lake St. Clair, and with Georgian Bay treated separately from the rest of Lake Huron. Daily observations of the input variables over the 42-year period 1954 to 1995 were also spatially interpolated to each lake and the 121 sub-basins.

The remainder of this paper concentrates on analysis of the results of water resources-related models using observed input variables adjusted by the differences and ratios derived from the GCM results (perturbed cases) compared to the results with unadjusted input variables (base case). Note that, in all simulations, the *observed data* from 1954 to 1995 were used (the time period for which we have an adequate database for both the USA and Canada portions of the study area), but the adjustments for the future scenarios were based on the difference in *GCM* results between the GCM's base period of 1961 to 1990 to the time periods of the future scenarios (2021 to 2040, 2041 to 2060, and 2081 to 2100). The air temperature, humidity, and wind speed variables over the lakes were each adjusted according to an empirical formula as in Croley (1989), incorporating the lake surface temperature as a contributing factor to their expected values over the lake. This helps to account for the difference between conditions over the lakes and those observed over land.

A drawback of this method is that it does not reflect changes in variability of any variable at any time scale other than the mean annual cycle and the daily cycle insofar as daily high and low temperatures are used. In the perturbed case, the variation follows the same sequence as in the base case, adjusted only by a ratio or difference. There may be little point to representing changes in short-term variability explicitly, as water resources parameters such as soil moisture, groundwater storage, and lake levels have a strong time-integrating effect and GCM results may be unreliable at these time scales, especially for water-related quantities such as rainfall intensity. However, variability of precipitation and other variables at interannual and longer time scales can affect groundwater storage and Great Lakes levels much more than short-term variability.

MODEL FORMULATION

Hydrologic Modeling System

The hydrologic modeling suite is a combination of the lake evaporation model of Croley (1989) and the runoff model of Croley (1983). The lake evaporation model calculates a heat budget for each of the Great Lakes, based on the net surface flux of shortwave (solar) radiation, longwave (thermal) radiation, latent heat flux (proportional to evaporation), and sensible heat flux. This budget uses as input daily means of top-of-atmosphere shortwave radiation, air temperature, relative humidity, cloud cover, and wind speed. From this energy budget and mixing due to wind, it calculates accumulated heat storage and a temperature profile for each lake. In subsequent timesteps, the newly predicted surface temperature feeds back as a factor in the heat budget. The output of interest in this study is the lake evaporation, as it affects the moisture balance of the Great Lakes system.

The runoff model (Croley 1983) calculates runoff, evaporation, and percolation within each of the Great Lakes' 121 sub-basins based on a cascade among five reservoirs: the snowpack, upper soil zone, lower soil zone, groundwater, and surface storage. Precipitation is one input; it is considered rainfall when the air temperature is above 0°C, and otherwise is considered snowfall and enters the snowpack to await melting. The partitioning of rainfall or snowmelt among its possible fates of runoff, evaporation, or percolation is calculated using the daily maximum and minimum temperatures and nine parameters, which are empirically calibrated separately for each of the 121 sub-basins.

The amount of water that runs into the lakes from the land (R) is added to the precipitation that occurs over the lakes (P), and the evaporation over the lakes (E) is subtracted, to arrive at a net basin supply (NBS):

$$NBS = R + P - E \quad (1)$$

This net basin supply must be balanced by a combination of the net outflow from the lake and change in the lake level. The flow through interlake channels is simulated by a channel routing model, which includes the effects of lake regulation (Quinn 1978, Clites and Lee 1998). This model predicts the outflow that would result from a given lake level and recalculates the lake level at each time step based on this outflow and the lake's net basin supply. Neither of the computer models currently used to guide regulation decisions was robust enough to handle the extremely low supplies predicted using CGCM1. The lake level and outflows reported in this study were obtained using the upper lakes regulation and routing model, altered (Lee *et al.* 1994) to permit extreme high or low supplies. The Lake Ontario operational regulation model also needed alteration to successfully run under these low supply conditions. A modified version of the model that prescribed "pre-project" flows below a specified level (74 m, IGLD 85) was used and performed satisfactorily (Lee *et al.* 1994).

The Interest Satisfaction Model

An Interest Satisfaction (IS) Model (Eberhardt 1992, 1994) was also run to simulate the water levels of Lake Ontario and the degree of satisfaction of various stakeholders given those levels. The model specifies quarter-monthly outflows based on the degree to which various interests are satisfied with a particular level or outflow; i.e., interest satisfaction relationships are used as constraints. All interest satisfaction criteria are referenced to places along the St. Lawrence River, which are shown in Figure 6.

The data used in the calibration of the model are based on coordinated quarter-monthly data from two files (net basin supply and Lake Erie outflows) which are standard basis-of-comparison files used in most Great Lakes regulation model studies (IJC 1993, 1997). Together they represent the net total supply (NTS) to Lake Ontario. The period of record in the calibration was 1900 to 1993. Historic quarter-monthly flows (1900 to 1993) into Lake St. Louis from the Ottawa River were taken from previous update studies and evaluations. The original calibration considered the criteria specified by the existing plan for Lake Ontario regulation, Plan 1958-D (IJC 1963). However, the model used in the evaluation of extreme climates was not constrained by the existing plan criteria, thus allowing the extreme hydrologic conditions resulting from the GCMs to be identified.

The model uses ten IS relationships to determine the quarter-monthly outflow. The outflow specified provides the maximum satisfaction based on the addition of ten IS values. The relationships consider (1) riparian, (2) recreational boating, and (3) com-

FIG. 6. Lake Ontario and the St. Lawrence River. All criteria of the Interest Satisfaction model refer to locations within these regions.

mercial navigation interests on Lake Ontario; (4) commercial navigation on Lake St. Lawrence; (5) hydropower in the international reach of the St. Lawrence River; (6) hydropower in the Canadian reach of the St. Lawrence River; (7) riparian; (8) recreational boating; and (9) commercial navigation interests on Lake St. Louis; and (10) Montreal Harbour interests. All of the IS relationships are functions of water elevation, except for hydropower which is a function of head differential as a result of outflow. The impact on environmental factors (wetlands) are assessed in terms of the 10-year moving average of the range of levels compared to the preproject (pre-St. Lawrence and Power Project) range.

In order to cope with the extreme conditions resulting from the GCMs, modifications were made within the original IS Model. The outflow range was modified to include values from 3,110 to 9,910 m^3/s. The former outflow is below the minimum flows required for hydropower, and the latter is above the optimal flow for hydropower and commercial navigation. In the original calibration and formulation, weighting factors were assigned to achieve the best results within the existing criteria framework of Plan 1958-D (IJC 1963). The modification to assess the GCMs has all weights equal to unity for all interests except for commercial navigation through Lake St. Lawrence at Long Sault. By maintaining optimal levels at this location just upstream of the outflow control at the Moses-Saunders powerhouse, analyses of upstream and downstream levels can proceed; however, existing criteria are violated. The base case also reflects the violation of criteria as compared to critical values.

Ice Cover Models

Accumulated freezing degree-days (FDD) are used in empirical models of initial ice formation, ice growth, ice decay, and ice extent (Richards 1963, Snider 1971, Rogers 1976, Shen and Yapa 1983). Assel (1991) developed a FDD model to simulate the daily spatial average ice cover, i.e., the percent of surface covered by ice, for west, center, and east basins of Lake Erie and west, east, and Whitefish Bay basins of Lake Superior. Assel's ice cover models were applied for a 1950 to 1995 base period for Lake Erie, a 1950 to 1993 base period for Lake Superior, and for the three increased CO_2 scenarios (2030, 2050, and 2090) for CGCM1 and HadCM2.

A detailed description of Assel's ice cover model, summarized here for the sake of brevity, is available in Assel (1991). The date of initial ice formation in this model is determined by an empirically derived threshold FDD accumulation for each lake basin. Ice extent is a function of FDD (and frequently increases) between the dates of initial ice formation and seasonal maximum FDD accumulations. This date separates a period of ice growth from a period of ice loss. Ice extent between the date of maximum FDDs and loss of all ice cover is a function of the date and magnitude of the seasonal maximum FDDs and an empirically derived average daily ice melt rate.

Accumulated freezing degree-days (Assel 1986) are calculated from daily maximum and minimum temperatures at meteorological stations at Duluth, Minnesota; Sault Ste. Marie, Houghton, and Detroit, Michigan; Fort William, Ontario; Cleveland and Toledo, Ohio; and Buffalo, New York. Overlake temperature adjustment factors, described in Croley (1989), were applied to observed daily maximum and minimum air temperatures for the 1950 to 1995 base period to generate CGCM1 and HadCM2 scenario temperatures (for the 2030, 2050, 2090 periods) at the meteorological stations. Station temperature adjustment factors were calculated as the inverse distance weighted average temperature difference of the four GCM grid points nearest each meteorological station.

The closing of the Port Dover, Ontario, meteorological station used by Assel (1991) in his ice models of Lake Erie necessitated re-calibration of the ice cover models for the center and eastern basins of Lake Erie using air temperatures from the Buffalo, New York, meteorological station. In addition, questionable meteorological data for 1995 at Fort William, Ontario, used in the ice models for Lake Superior made it expedient to reduce the base period to the winters of 1950 to 1993 for Lake Superior modeled ice cover.

Lansing Regional Groundwater

To assist with the evaluation of the regional water-supply system, a groundwater flow model was developed in a previous study to simulate the regional, steady-state response of the Saginaw aquifer to major groundwater withdrawals in the Tri-County region (Fig. 7; Holtschlag *et al.* 1996; Luukkonen *et al.* 1997). Glacial deposits underlie the entire Tri-County region and form the uppermost aquifer. The Saginaw aquifer underlies the glacial deposits and consists of the water-bearing sandstones in the Grand River and Saginaw Formations. In the model, the Tri-County region is divided into a variably spaced grid with the upper layer representing flow in the glacial deposits and the lower layer representing flow in the Saginaw aquifer. The spatial variation of average groundwater recharge rates was determined from an analysis relating base flow characteristics of streams to land use and basin characteristics in the Lower Peninsula of Michigan (Holtschlag 1994).

The streamflows estimated by the hydrologic modeling suite described above were used to modify input to the groundwater flow model. However, the streamflow estimates generated for the base case at the mouth of the Grand River were compared to actual flows measured at the U.S. Geological Survey (USGS) gaging station for the Grand River at Grand Rapids, Michigan (04119000). Flows at Grand Rapids are assumed to be similar to those at the mouth of the Grand River. Simulated flows above 30% flow duration agree with actual streamflow measurements (Fig. 8). Below 30% flow duration, simulated flows are less than actual streamflow measurements. Because this comparison indicates that simulated low flows are lower than actual flows, estimates of base flow will likely be too low in some cases.

Programs developed by Rutledge (1998) were used to determine the base flow portion of total streamflow for the reference and changed climate conditions. Recharge rates in the Tri-County regional groundwater flow model were adjusted on the basis of the predicted change in base flow to streams from the reference condition to each of the

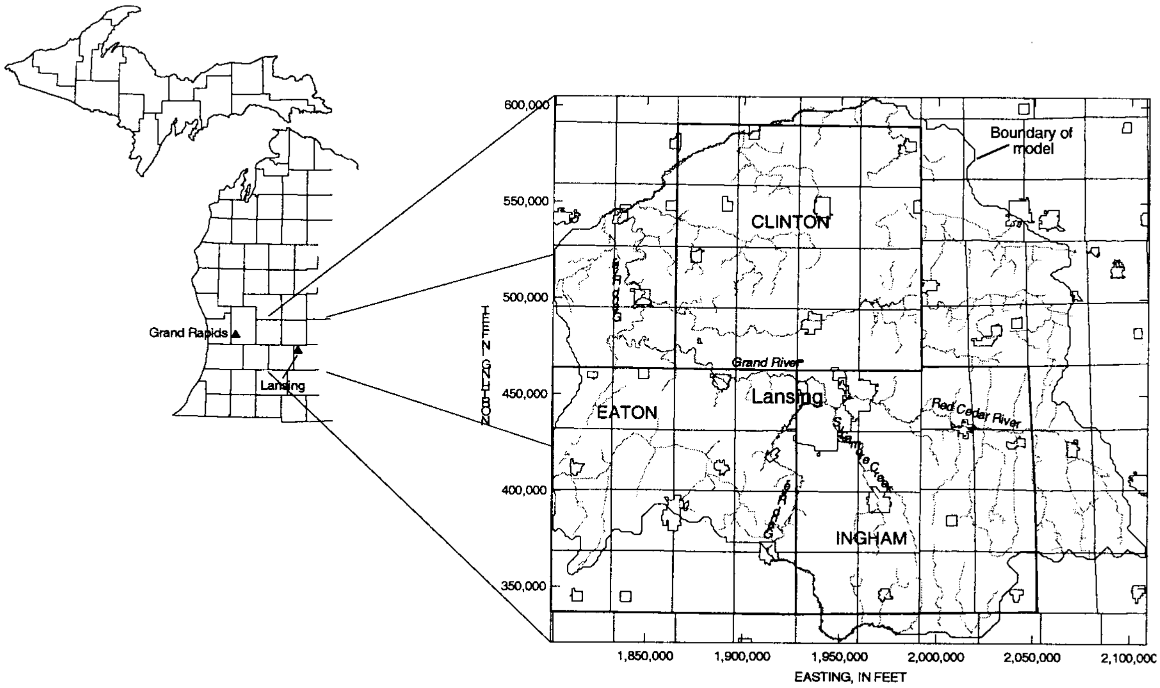

FIG. 7. Active model area in the Tri-County region in the Lower Peninsula of Michigan.

CGCM1 and HadCM2 changed climate predictions. The adjusted groundwater recharge estimates were used as input for the USGS MODFLOW (McDonald and Harbaugh 1988) Tri-County regional groundwater flow model under 1995 and 2030 pumping scenarios.

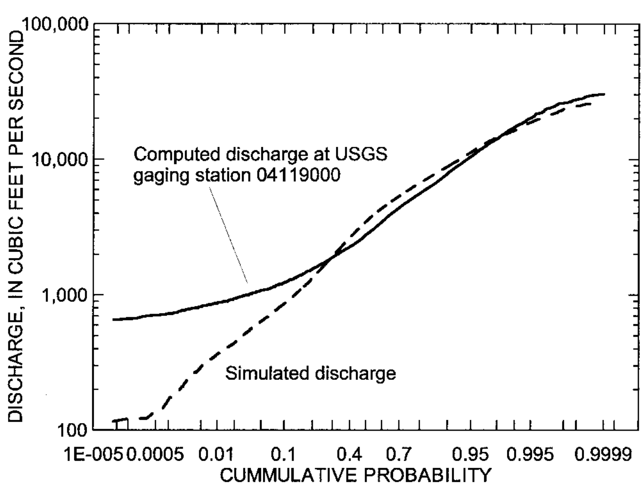

FIG. 8. Comparison of actual and simulated discharge for the Grand River.

RESULTS

GCM Climate Changes and Hydrologic Changes

The CGCM1 and HadCM2 display distinct responses to increased greenhouse gases in terms of precipitation and air temperature for the various lake basins. CGCM1 has air temperature increases over the Great Lakes in the range of 3°C by 2050 (Table 1), and small changes in precipitation with varying sign among the individual lake basins (Table 2). The HadCM2, on the other hand, has a smaller air temperature increase by 2050 (between 1 and 2°C) than CGCM1 or any of the models used by Croley (1990), Mortsch and Quinn (1996), or Chao (1999). It also has annual mean precipitation increased by factors greater than 1.05 in each lake basin (Table 2). This makes it less prone to water deficits relative to the base case than CGCM1.

The future mean annual runoff (Table 3) is reduced considerably when using the CGCM1 output. Combined with increased lake surface evaporation (Table 4) due to a strong increase in lake surface temperature, this yields a reduction in net basin supply (see equation 1) that increases in magnitude with time. In contrast, annual mean runoff is little changed or slightly increased when using HadCM2.

TABLE 1. Air temperature differences. Model minus Base Scenario (°C).

	CGCM1			HadCM2		
Lake	2030	2050	2090	2030	2050	2090
Superior	1.9	2.9	5.4	1.2	1.6	2.9
Michigan-Huron	2.2	3.2	5.6	1.0	1.4	2.7
Erie	2.5	3.4	5.9	0.9	1.3	2.6
Ontario	2.1	3.0	5.4	1.0	1.4	2.7

TABLE 2. Precipitation ratios. Model/ Base Scenario.

	CGCM1			HadCM2		
Lake	2030	2050	2090	2030	2050	2090
Superior	1.04	1.05	1.14	1.04	1.05	1.16
Michigan-Huron	1.02	1.04	1.14	1.08	1.08	1.20
Erie	0.97	0.98	1.05	1.08	1.11	1.21
Ontario	1.01	1.00	1.07	1.08	1.09	1.17

Combined with modest changes in lake surface temperature, the result is little change or a small increase in net basin supply during each of the time periods investigated.

Lake Levels

Lake levels and outflows were calculated from the hydrologic inputs using the channel routing model. Figure 9 shows examples of the resulting time series for Lake Erie. Using the perturbations given by the CGCM1 for 2090 (Fig. 9a), there is a drop in lake level of just over 1 m, while for HadCM2 (Fig. 9b), there is an increase of roughly 0.3 m. It should be noted that the historical meteorological data were used as inputs in both cases, but they were perturbed in the 2090 cases. Because the perturbations are based on the average changes in a meteorological variable in a given month, but do not vary from year to year, the resultant timeline has very nearly the same series of variations as the base case, offset by a near-constant number. Although there is some change in the shape of the annual cycle, the remainder of this paper will highlight the time-averaged changes in lake levels.

To illustrate the relative impacts of various combinations of precipitation and air temperature changes, changes in air temperatures and precipitation for various model simulations are plotted in Figures 10 and 11 along with a relative indication of lake level changes. Tables 5 and 6 contain the same information in table form. Lakes Superior and Michigan-Huron were chosen as they are the least affected by changes in upstream conditions.

Among all of the Great Lakes in 2030, CGCM1 input results in lake level reductions ranging from 0.22 m to 0.72 m, with greater reductions in 2090, up to a maximum of 1.38 m on Lakes Michigan and Huron (Table 7). The magnitude of these changes in lake level are large enough to distinguish them from normal variability, except on Lake Ontario.

A very different picture emerges from using the HadCM2 (Table 8). The wetter climate results in water level rises of up to 0.35 m, but mostly less

TABLE 3. Change in mean annual runoff (%).

	CGCM1			HadCM2		
Lake	2030	2050	2090	2030	2050	2090
Superior	–5	–8	–13	–4	0	+4
Michigan	–12	–15	–20	+3	+4	+10
Huron	–7	–10	–16	+1	+3	+5
Erie	–23	–28	–37	+3	+4	+11
Ontario	–10	–15	–24	+5	+4	+8

TABLE 4. Change in mean annual lake evaporation (%).

	CGCM1			HadCM2		
Lake	2030	2050	2090	2030	2050	2090
Superior	+17	+24	+39	+7	+13	+19
Michigan	+15	+21	+34	+6	+10	+16
Huron	+13	+22	+33	+6	+10	+17
Erie	+12	+20	+29	+6	+9	+17
Ontario	+12	+20	+31	+6	+9	+16

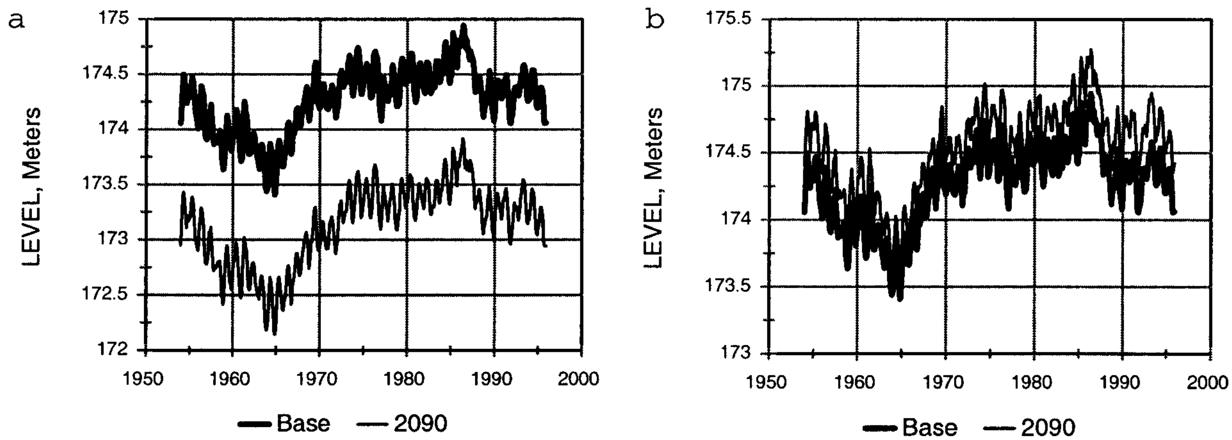

FIG. 9. Time series of Lake Erie levels under base case (observed) meteorological conditions compared to those using the perturbations derived from the 2090 simulation of the (a) CGCM1 and (b) HadCM2.

than 0.10 m. The increases in water level do not rise above the level of natural variability on any of the lakes. Outflows from each of the lakes (not shown) are increased in each of the time periods. Table 8 indicates lower water levels in 2050 than in 2030 on Lakes Michigan-Huron and Erie. This may indicate some inadequacy in using 20-year averaging periods for the GCM data in indicating century-long trends, as the random variability between 20-year periods appears to exceed the secular trend.

In accounting for the discrepancy between the results of the HadCM2 and the GCMs used in previous studies (Figs. 10 and 11), it should be noted that many of the models used in previous assessments used equilibrium doubled CO_2. That is, simplified ocean models were allowed to come into equilibrium with an atmosphere with doubled greenhouse gas content, in contrast to the transient models, in which full dynamical ocean models were run coupled with an atmosphere with greenhouse gas content changing in time. The newer, transient approach effects a delay in warming by bringing the thermal capacity of the oceans into play in the model. The earlier equilibrium doubled CO_2 model runs also did not include the effect of increased sulfate aerosol concentration in the atmosphere.

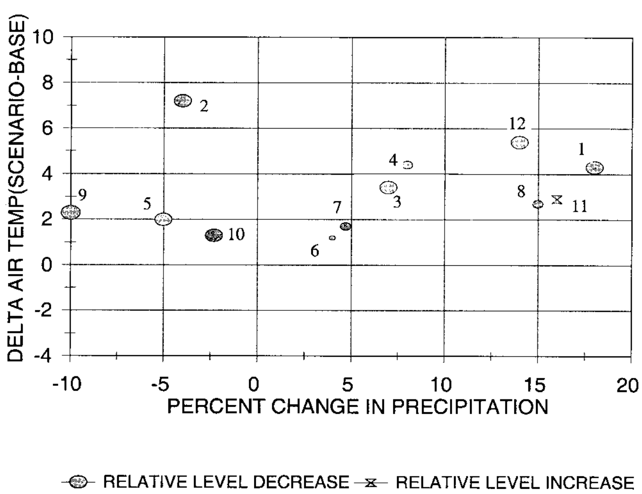

FIG. 10. Lake Superior comparison. The size of the markers is keyed to the magnitude of the change in lake level. The squares indicate the model from Table 5.

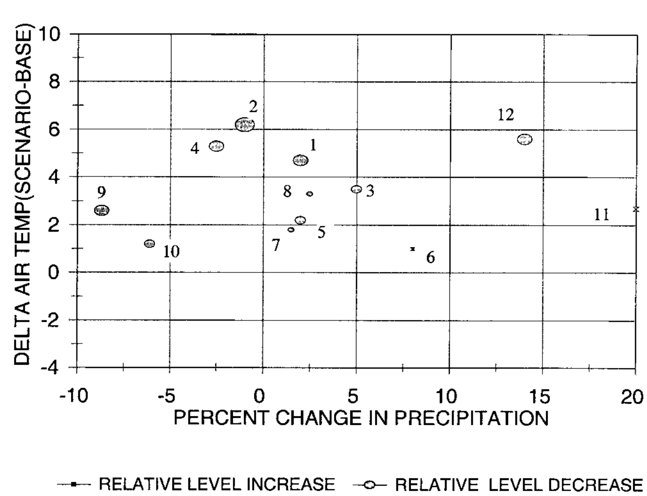

FIG. 11. Lake Michigan-Huron comparison. Same as Figure 10, but for Lake Michigan-Huron.

TABLE 5. Model statistics and numbers for Lake Superior. Current results are combined with previous results.

Model	Model	Period	Type	Δ air temp (°C)	Δ Precip. (Percent)	Δ Level (Meters)
1	GISS	2xCO_2	Equilib.	4.3	18	–.47
2	GFDL	2xCO_2	Equilib.	7.2	–4	(failed)
3	OSU	2xCO_2	Equilib.	3.4	7	–.46
4	CCC1	2xCO_2	Equilib.	4.4	8	–.23
5	CGCM1	2030	Transient	2.0	–5	–0.22
6	HadCM2	2030	Transient	1.2	4	–0.01
7	GFTR2	2020	Transient	1.7	5	–.2
8	HCTR2	2020	Transient	2.7	15	–.1
9	MOTR2	2020	Transient	2.3	–10	–.8
10	CCTR2	2020	Transient	1.3	–2	–.5
11	HadCM2	2090	Transient	2.9	16	0.11
12	CGCM1	2090	Transient	5.4	14	–0.42

Clear and straightforward reasons for the coolness and moistness of the future time periods in HadCM2 relative to CGCM1 are unknown. Nonetheless, HadCM2's disagreement with other models widens the range of potential outcomes in hydrologic response to greenhouse warming. One difference of HadCM2 from CGCM1 and previously studied models (Croley 1990) is that it includes the presence of the Great Lakes as a water surface with significant thermal inertia. It is doubtful that this is a full explanation of the increased precipitation and lesser increase in temperature, as differences of similar magnitude have been noted in portions of North America remote from the Great Lakes (Frederick and Schwarz 1999).

Interest Satisfaction Model

Plan 1958-D (IJC 1963) contains a limit which specifies outflows from Lake Ontario varying between 5,320 and 5,950 m^3/s (depending on the time of year) as minimum flows to guarantee dependable power generation. The maximum outflow from Lake Ontario specified by Plan 1958-D is 8780 m^3/s, after which commercial navigation may have problems with cross-currents in certain reaches of the St. Lawrence River. Under the climate scenarios used here, the interest-based model gave outflows varying from 3,110 to 9,910 m^3/s. The minimum outflow value is lower than the period of record's (1860 to 1998) minimum monthly value of 4,360 m^3/s which occurred in February 1936. The model

TABLE 6. Model statistics and numbers for Lake Michigan-Huron. Current results are combined with previous results.

Model	Model	Period	Type	Δ air temp (°C)	Δ Precip. (Percent)	Δ Level (Meters)
1	GISS	2xCO2	Equilib.	4.7	2	–1.31
2	GFDL	2xCO2	Equilib.	6.2	–1	–2.48
3	OSU	2xCO2	Equilib.	3.5	5	–0.99
4	CCC1	2xCO2	Equilib.	5.3	–3	–1.62
5	CGCM1	2030	Transient	2.2	2	–0.72
6	HadCM2	2030	Transient	1.0	8	0.05
7	GFTR2	2020	Transient	1.8	2	–0.4
8	HCTR2	2020	Transient	3.3	3	–0.5
9	MOTR2	2020	Transient	2.6	–9	–1.4
10	CCTR2	2020	Transient	1.2	–6	–0.9
11	HadCM2	2090	Transient	2.7	20	0.35
12	CGCM1	2090	Transient	5.6	14	–1.38

TABLE 7. CGCM1 Scenarios–Annual Mean Levels (difference from Base, m).

Levels	Base	2030	2050	2090
Superior	183.42	–0.22	–0.31	–0.42
Michigan-Huron	176.54	–0.72	–1.01	–1.38
Erie	174.27	–0.60	–0.83	–1.13
Ontario	74.81	–0.35	–0.53	–0.99

TABLE 8. HadCM2 Scenarios–Annual Mean Levels (difference from Base, m).

Levels	Base	2030	2050	2090
Superior	183.42	–0.01	–0.01	+0.11
Michigan-Huron	176.54	+0.05	+0.03	+0.35
Erie	174.27	+0.05	+0.04	+0.27
Ontario	74.81	+0.02	+0.04	+0.01

was able to evaluate both the dry (CGCM1) and wet (HadCM2) forecast conditions. Optimal levels are maintained on Lake St. Lawrence in all dry and wet cases (97.9 to 100% satisfaction) so that evaluations upstream and downstream of this location can proceed as mentioned in the Model Formulation section.

In CGCM1, extremely low levels were experienced throughout the system, becoming most extreme in the 2090 scenario. In the 2030 scenario, all interests are generally satisfied less than a third of the time. The greatest satisfaction values are for downstream interests around Lake St. Louis including riparians, commercial navigation, and hydropower (Table 9), although values are no more than 41.2%. Levels on Lake Ontario are low (Table 10) with 31 of the 42 years evaluated experiencing levels below the critical value of 74.15 m (chart datum). The low levels impact Lake Ontario riparians and recreational boaters in terms of exposure of less desirable shorelines, inaccessible docks, and inadequate water at shore wells. The incidence of low outflows results in hydropower not meeting its minimum requirements. In the 2050 scenario, all of the above concerns are intensified. In the 2090 scenario, each year experiences levels below critical values at all locations in the Lake Ontario-St. Lawrence River system. Satisfaction drops to near zero for all interests, except commercial navigation on Lake St. Lawrence, which is forced to optimal levels. However, since there is still a 0.95 meter range, on average, environmental factors still post a 41.9% satisfaction value, although specific environmental benefits are not identified.

In HadCM2, the discomfort felt by riparians was offset by the high satisfaction scores of the hydropower and commercial shipping sectors in the 2030 and 2050 scenarios. However, the incidence of higher outflows results in spillage of water at hydroplants and also in higher river velocities, impacting navigation. In each of the HadCM2 scenarios, the lowest satisfaction values are for Lake Ontario riparians and recreational boaters on both Lakes Ontario and St. Louis (Table 9). High water throughout the Lake Ontario-St. Lawrence River system would result in extensive flooding. Recreational boaters would also experience difficulties with submerged docks. The highest levels, which result with the 2090 scenario, cause an overall reduction in satisfaction for all interests with the exception of commercial navigation in Lake St. Louis and Montreal Harbour. However, a new record high level would be set at Montreal (Table

TABLE 9. Satisfaction (%) values by interest for various GCM scenarios.

Interest	Base Case	CGCM1			HadCM2		
		2030	2050	2090	2030	2050	2090
Lake Ontario Riparians	27.5	11.3	0.6	0	26.3	25.5	15.5
Lake Ontario Rec. Boaters	15.2	0.6	0	0	16.8	17	8.2
Comm. Nav. on Lake Ontario	57.7	20.5	3.4	0.1	61.3	60.4	53.6
Hydropower at Moses-Saunders	66.9	15.7	1.4	0	75.1	74.1	59.6
Lake St. Louis Riparians	79	41.2	24.7	6.5	78.3	77.2	74.2
Lake St. Louis Rec. Boaters	37.6	16.6	8.1	1.3	36.7	35.8	34.5
Hydropower for Hydro Quebec	60.2	31.7	11.3	0.7	63	63.1	54.1
Montreal Harbour	70	9.5	1.5	0.1	63.8	63.1	74.4
Comm. Nav.—Lake St. Louis	83.5	23.9	4.3	0	85.4	83.9	89.7
Env. Factors based on levels range	64.7	47.6	42.9	41.9	62.8	62.3	68.1
Comm. Nav.—Lake St. Lawrence	99.6	100	100	99.2	99.9	99.9	97.9

TABLE 10. Comparison of hydrologic factors (elevations in m, IGLD85; outflows in m³/s). Values in parentheses indicate the number of years in which critical values in the maximum or minimum water levels are reached or violated.

Factors	Critical Value	Base Case	CGCM1 2030	CGCM1 2050	CGCM1 2090	HadCM2 2030	HadCM2 2050	HadCM2 2090
Lake Ontario Elevations								
Maximum	75.37	76.02 (17)	75.02	74.72	74.53	75.97 (22)	75.99 (18)	76.27 (30)
Minimum	74.15	73.8 (9)	73.43 (31)	73.33 (41)	73.09 (42)	73.9(4)	73.85 (4)	73.97 (3)
Avg. 10-year Range (m)		1.46	1.08	0.97	0.95	1.42	1.41	1.54
Lake St. Lawrence								
Maximum	74.25	74.75 (3)	73.79	73.43	73.58	74.67 (2)	74.71 (2)	74.74 (17)
Minimum	72.5	72.41 (1)	72.71	72.69	72.51	72.77	72.77	72.77
Lake St. Louis								
Maximum	22.33	22.88 (9)	22.03	22.03	21.82	22.94 (10)	23.02 (9)	23.1 (14)
Minimum	20.6	20.25 (9)	19.44 (41)	19.4 (42)	19.39 (42)	20.33 (8)	20.29 (9)	20.45 (3)
Montreal Harbour								
Maximum	9.1	9.54 (2)	8.56	8.54	7.91	9.39 (3)	9.38 (1)	9.37 (6)
Minimum	5.55	4.6 (21)	3.78 (42)	3.65 (42)	3.64 (42)	4.51 (24)	4.53 (22)	4.72 (15)
Lake Ontario Outflow								
Maximum	9,910	9,910 (1)	8,260	7,771	7,130	9,910 (1)	9,910 (1)	9,910 (14)
Minimum	5,320	4,430 (9)	3,140 (27)	3,120 (40)	3,110 (42)	4,690 (5)	4,620 (5)	4,980 (2)

10), which would impact riparians. The 2090 scenario also has the highest incident of years with flows up to 9,910 m³/s, which requires spillage at hydropower facilities and difficult velocities for navigation. In terms of environmental factors, satisfaction is fairly high since the average range for these scenarios is between 1.42 and 1.54 m, although as is the case with the CGCM1 scenarios, no specific benefits are identified.

Great Lakes Ice Cover

Ice duration for the 1950 to 1995 base period ranged from 11 to 16 weeks (Table 11), similar to the base period of 1951 to 1980 used in Assel (1991). Under the increasing CO_2 scenarios using CGCM1, ice duration is reduced by approximately 12 to 47 days (2030 scenarios), 16 to 52 days (2050 scenarios), and 37 to 81days (2090 scenarios). The range of reduction in ice season duration in Assel (1991) for steady state $2xCO_2$ conditions for three GCM scenarios was 35 to 91 days (5 to 13 weeks), similar to the 2090 scenarios of this analysis. The calculation of average ice season duration includes winters with no ice cover. It should thus be viewed with caution as the mean of a quantity with a hard lower limit of zero.

Annual maximum monthly ice cover frequently occurred in February during the base period (Assel *et al.* 1983). Average February ice cover can be used as a proxy for changes in ice cover extent between the base period and the scenarios. February is ice-free for a majority of the CGCM1 scenarios on Lake Erie, for about 40% of the CGCM1 2090 scenarios on Lake Superior, and for a majority of years in the HadCM2 2090 scenario for the eastern and central basins of Lake Erie (Table 12). Whitefish Bay, at the eastern end of Lake Superior, is a special case because it is much shallower than the east and west basins of that lake, and is representative of the shallow shore regions of Lake Superior. It forms an ice cover most winters (Table 12) and its average ice coverage is greater relative to the other lake basins.

Average February ice cover for the base period (not shown) exceeds 50% for all but the eastern Lake Superior basin (42%). Average February ice cover (excluding Whitefish Bay) is:

1. ≤ 31% of its base period averages for the 2030 CGCM1 scenarios,
2. ≤ 75% of its base period averages for the 2030 HadCM2 scenarios,

TABLE 11. Average ice duration (days).

Scenario Years	Base 1951–95	CGCM1 2030	CGCM1 2050	CGCM1 2090	HadCM2 2030	HadCM2 2050	HadCM2 2090
			Lake Superior Basins				
West Basin	111	83	69	32	97	91	66
East Basin	108	80	65	28	95	90	68
Whitefish Bay	115	91	77	40	103	99	77
			Lake Erie Basins				
West Basin	91	44	40	27	76	71	51
Center Basin	77	41	35	11	57	52	39
East Basin	92	51	39	11	69	63	50

TABLE 12. Percent of ice-free winters.

Scenario Years	Base 1951–95	CGCM1 2030	CGCM1 2050	CGCM1 2090	HadCM2 2030	HadCM2 2050	HadCM2 2090
			Lake Superior Basins				
West Basin	0	2	7	43	0	0	7
East Basin	0	4	9	45	0	0	4
Whitefish Bay	0	0	4	36	0	0	4
			Lake Erie Basins				
West Basin	2	33	52	74	6	6	17
Center Basin	2	63	78	96	17	22	61
East Basin	2	63	76	96	15	22	61

3. ≤ 21% of its base period averages for the 2050 CGCM1 scenarios, and
4. ≤ 67% of its base period averages for the 2050 HadCM2 scenarios.

By 2090, average February ice cover is only 2 to 11% for the east and west Lake Superior basins and 1 to 29% for the three Lake Erie basins. However, substantial ice covers may still form in extreme winters. Discrepancies in ice cover between the two GCMs are consistent, in a qualitative sense, with the warmer winter temperatures for the CGCM1 relative to the HadCM2 scenarios. However, there are discrepancies in the sensitivity between Lake Superior and Lake Erie.

Under the 2030 and 2050 CGCM1 scenarios, there is a large difference between the maximum February ice cover for Lake Erie relative to Lake Superior. In Lake Erie the maximum ice cover is not that different than the base period maximum, but for Lake Superior the maximum ice cover in the east and west basins is greatly reduced. By 2090, this is also the case for Lake Erie. Thus, if the CGCM1 scenarios are believed, there will be a large difference in maximum ice cover between Lakes Erie and Superior. The reason for this may be the following: Each lake requires a certain cooling threshold before it experiences near-total ice cover; beyond this threshold, ice cover extent is not strongly sensitive to greater cooling. This threshold seems to be more frequently and decisively exceeded under present-day conditions over the shallow Lake Erie, while it is only marginally achieved over Lake Superior. The reduced cooling under CO_2-enhanced conditions will thus more easily place Lake Superior substantially below this cooling threshold, giving it substantially less than total ice cover, while Lake Erie remains near or above it, giving it near-total ice cover.

Lansing Regional Groundwater

The 19.7% decrease in base flow to streams predicted in the CGCM1 2030 case resulted in declines in groundwater levels in both the glacial deposits (layer 1) and the Saginaw aquifer (layer 2) in the Tri-County region (Table 13). The 4.1% increase predicted for 2030 by the HadCM2 resulted in a rise in groundwater levels in both the glacial de-

TABLE 13. Changes in ground-water levels in the glacial and Saginaw aquifers. Positive changes indicate decreases in ground-water levels; negative changes indicate increases in ground-water levels; average values in parentheses.

	Changes in ground–water levels (m)	
Climate scenarios	1995 Pumping rates	2030 pumping rates
CGCM1 2030 predictions—layer 1	0–2.7 (0.6)	0–3.5 (0.6)
CGCM1 2030 predictions—layer 2	0–2.6 (0.6)	0–2.6 (0.6)
HadCM2 2030 predictions—layer 1	–0.5–0 (–0.1)	–0.8–0 (–0.1)
HadCM2 2030 predictions—layer 2	–0.5–0 (–0.1)	–0.5–0 (–0.1)

posits and the Saginaw aquifer. These changes in groundwater levels were greater when projected 2030 pumping rates were simulated.

Within the Lansing area, groundwater levels in the Saginaw aquifer declined by as much as 2.7 m under the CGCM1 predictions and increased about 0.1 m under the HadCM2 predictions when 1995 pumping rates were simulated. When pumping rates were increased, groundwater levels in the Saginaw aquifer declined by as much as 3.5 m under the CGCM1 predictions and increased about 0.1 m in the Lansing area under the HadCM2 predictions.

Changes in recharge rates, combined with increased pumping rates projected for 2030, led to dewatering of some areas within the glacial deposits. For the base condition, areas of about 1.0 km^2 south and west of Lansing were dewatered during model simulations. An area of about 0.5 km^2 was dewatered in the same area as in the simulation of the HadCM2 predictions, despite an increase in recharge. For the simulation using the CGCM1 predictions, areas of about 4.4 km^2 to the south, west, and southeast of Lansing were dewatered during model simulations.

Streamflow in the portions of the Grand River, Red Cedar River, and Sycamore Creek within the Lansing area were compared. At 1995 pumping rates, overall groundwater contribution to streamflow declined by 32% from the base condition according to the CGCM1 predictions and increased about 6% from the base condition according to the HadCM2 predictions. Changes were greater under 2030 pumping rates.

CONCLUSIONS

The climate scenarios presented here depict a wide range in levels and flows for the Great Lakes in the 21st century. CGCM1's drier, warmer climate has Lakes Michigan-Huron dropping 0.72 and 1.38 m by the years 2030 and 2090, respectively. Lake Superior experiences the smallest impact on its lake levels, dropping by 0.22 and 0.42 m at the same dates. Flows in the connecting channels are reduced by 11% to 33% of base case flow. In contrast, HadCM2's wetter, warmer climate has Lake Michigan-Huron rising by 0.05 and 0.35 m in the years 2030 and 2090, respectively, with Lake Superior lowering 0.01 m by 2030 and rising 0.11 m by 2090. The connecting channel flows have changes ranging from a 4% decrease to a 10% increase.

Four significant findings are unique to this study. The first is that the transient model CGCM1 for the year 2030 indicates that significant changes to the Great Lakes water resources could come sooner rather than later. Second, the use of the HadCM2 has also demonstrated for the first time that there is a potential for slightly higher water levels under climate change. Nine prior model runs for the Great Lakes water resource studies using various GCMs as input, including the current CGCM1, have all indicated a major lowering of lake levels and a reduction of water supplies. Third, through the use of the interest satisfaction regulation model for Lake Ontario, impacts on specific interests using a variety of regulation scenarios can be assessed. Finally, groundwater predictions based on the CGCM1 simulations show some decreases in groundwater levels for the vicinity of Lansing, Michigan, and some expansion of the area in which the aquifer becomes entirely dewatered.

In addition to these results that are new with this study, the duration and extent of ice cover are reduced under enhanced greenhouse gas conditions. This is true when using both the CGCM1 and HadCM2 models, with varying magnitude of change. Also, the maximum ice cover extent appears to be less sensitive to warming on Lake Erie than on Lake Superior, perhaps because of the difference in their thermal capacity.

Some concern is warranted for the water supplies derived from aquifers in the Great Lakes basin. The predictions based on the CGCM1 simulations show some decreases in groundwater levels for the vicinity of Lansing, Michigan, and some expansion of the area in which the aquifer becomes entirely dewatered.

This study has reaffirmed that no one method of impact assessment is completely adequate. Many of the shortcomings of our method have been noted in the Treatment of Data section. It would be useful to sustain and expand this line of study, allowing attention to be paid to depicting changes in interannual climate variability, effects of land use change, and more complete treatment of interaction between the surface and the atmosphere.

ACKNOWLEDGMENTS

Thanks to T. Hunter for carrying out much of the data preprocessing and executing the hydrologic models. Useful discussions were held with T. Croley, D. Cuthbert, K. Kunkel, L. Mortsch, R. Moulton, and P. Sousounis. Earlier variants of this material were constructively reviewed by L. Carter, S. Cohen, B. Hobbs, M. MacCracken, R. Rohli, and D. Schwab. This work was partially funded by the National Assessment of the Potential Consequences of Climate Variability and Change of the United States Global Change Research Program. This is GLERL Contribution Number 1190.

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Submitted: 19 October 2000
Accepted: 26 February 2002