CLIMATE CHANGE IMPACTS ON GREAT LAKES WATER SUPPLIES

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ABSTRACT: The Great Lakes Environmental Research Laboratory (GLERL) and the Canadian Climate Centre (CCC) combined models to estimate net basin supplies for each of the Great Lakes under a changed climate. GLERL used their hydrological models of the 121 watersheds draining into the Great Lakes, over-lake precipitation into each lake, and the heat storage in, and evaporation from, each lake. The CCC provided a "present-climate" simulation ($1xCO_2$) and a changed-climate scenario ($2xCO_2$) developed from their atmospheric global circulation model. GLERL used the CCC outputs of air temperature, precipitation, humidity, wind speed, and cloud cover, to consider steady-state doubling of atmospheric CO_2. They abstracted differences between the $1xCO_2$ and $2xCO_2$ atmospheres, made these changes to historical data, and observed the impact of the changed data in the hydrological model outputs. The higher air temperatures lead to higher overland evapotranspiration, lower runoff, earlier runoff peaks, reduced snow pack, shortened snow season, and reduction in soil moisture. Water temperatures increase and peak earlier; heat resident in the deep lakes increases throughout the year. Mixing of the water column diminishes and lake evaporation increases. Net basin supplies to each of the Great Lakes drop 20-100 percent.
KEY TERMS: Great Lakes; Climate Change; Hydrology.

INTRODUCTION

Preliminary estimates of the impact of climatic warming on the Great Lakes water resources have been undertaken and are summarized elsewhere (Croley and Hartmann, 1989; Croley, 1990a,b). The Great Lakes Environmental Research Laboratory (GLERL) assessed steady-state and transient changes in Great Lakes hydrology consequent with simulated atmospheric scenarios from three atmospheric general circulation models (GCMs). Those studies, in part, and the high water levels of the late 1980s prompted the International Joint Commission (IJC) to reassess climate change impacts on the Great Lakes. The methodology established in those studies was adopted with slight modifications for use in the IJC studies with a Canadian GCM.

GLERL developed conceptual model-based techniques for simulating 1) moisture storages and runoff from the 121 subbasins draining into the Great Lakes, 2) over-lake precipitation into each of the Great Lakes and Lake St. Clair (hereafter included as a Great Lake), and 3) the heat storages and evaporation from each of the lakes. These models are described briefly elsewhere (Croley, 1990a,b). GLERL models each of these components separately and combines them to estimate lake water supplies in response to possible meteorology. Integration of these models allows the consideration of a climate change scenario, supplied by the Canadian Climate Centre (CCC) from its global circulation model (GCM). Cohen (1991) discusses the problems with this approach.

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This paper outlines the linkage methodology between the hydrology models and the GCM and summarizes and interprets the results.

METHODOLOGY

GLERL's general procedure for the investigation of steady-state behavior under a changed climate is similar to that used for the EPA, as detailed elsewhere (Croley, 1990a,b, 1991; Louie, 1991). It requires that GLERL first simulate 38 years of "present" hydrology, with their runoff and lake evaporation models, by using historical daily maximum and minimum air temperatures, precipitation, wind speed, humidity, and cloud cover data for the 1951-88 period. This is called the "base case" or "1xCO_2" scenario. The initial conditions were arbitrarily set but an initialization simulation period of 1 January 1948 through 31 December 1950 was used. This allowed the models to converge to conditions (basin moisture storages, water surface temperatures, and lake heat storages) initial to the 1 January 1951 through 31 December 1988 period. GLERL then attempted to estimate "steady-state" conditions, but there were problems.

The procedure to estimate "steady-state" conditions is to repeat the 41-yr simulation, with initial conditions set equal to their values at the end of the simulation period, until they are unchanging. These initial conditions were for basin moisture storages, lake heat storages, and surface temperatures. This procedure requires many iterations for a few subbasins with very slow groundwater storages and suggests very different initial groundwater storages than were used in calibrations. Actually, the original calibrations of the models used arbitrary (but fixed) initial conditions. GLERL should have determined initial conditions also in the calibrations, but that was unfeasible; there is little confidence in calibrated parameter sets that suggest very slow groundwater storages since only 10 to 20 years were used in the calibrations. Some of the groundwater storage half-lives were on the order of several hundred years in some cases. Therefore, the best estimate of "present" hydrology is to use calibrated parameters with initial conditions on "the same order" as those assumed in the calibrations. GLERL did the latter and then conducted simulations with adjusted data sets.

Average monthly absolute air temperatures, specific humidities, cloud cover, precipitation, and wind speed were supplied for each month of the year by the CCC as resulting from their second-generation general circulation model; see McFarlane (1991). These were available at grid points spaced 3.75 degrees latitude by 3.75 degrees longitude. Louie (1991) interpolated monthly averaged data to a grid of 1 degree latitude by 1 degree longitude for both the "present" and "future" atmospheres. "Future" has two times the CO_2 content of the "present" atmosphere. He weighted values at surrounding grid points inversely to the square of the distance to each point. GLERL computed ratios of "future" (2xCO_2) to "present" (1xCO_2) monthly average absolute air temperatures, specific humidities, cloud cover, and precipitation and monthly average differences of 2xCO_2 to 1xCO_2 wind speeds at each of these gridpoints. They then used these ratios and differences with the historical data to estimate the 41-year sequences (1948-88) of atmospheric conditions associated with a changed climate, referred to as the "2xCO_2" scenario.

GLERL inspected each of the 770,000 square kilometers within the Great Lakes Basin to see which gridpoint it was closest to and applied the monthly adjustment at that gridpoint to data representing that square kilometer. By combining all square kilometers representing a watershed or the lake surface, GLERL derived an areally-averaged adjustment to apply to their areally-averaged data sets for the watershed or lake surface, respectively. They then used the 2xCO_2 scenario in simulations similar to the base case scenario. They repeated the 41-yr simulation with initial conditions set equal to their values at the end of the simulation period, until they were unchanging, to estimate "steady-state" future conditions. They then interpreted differences between the 2xCO_2 scenario and the base case scenario, for the 1951-88 period, as resulting from the changed climate.

BASIN HYDROLOGY

The annual cycle of all hydrological variables were averaged over the 1951-88 period and inspected. The average steady-state $2xCO_2$ climate air temperatures are 4.4-6.1°C higher throughout the annual cycle than the $1xCO_2$ climate (base case). The $2xCO_2$ precipitation is generally 8% higher over the Superior basin to 10% lower over the Erie basin with a fairly smooth change with longitude. The $2xCO_2$ scenario yields a general increase in both air and water temperature that follows the $1xCO_2$ climate patterns. The air temperature difference varies from 5.3°C on Lakes Superior and Huron to 5.9°C on Lake Michigan. Relative humidity over the lakes is increased, probably due to the increased lake evaporation, and cloud cover generally has decreased slightly for the $2xCO_2$ climate. Over-water wind speed is not greatly affected.

On the Superior basin, the average steady-state snowpack storage is reduced by more than half; see Figure 1. On the other basins, more to the south, the snowpack is almost entirely absent under the $2xCO_2$ climate; see Table 1. This reduction in snowpack accumulation results from the higher air temperatures, especially during the winter, that accompany the changed climate. The snow season also is shortened more than one month. The effects on the snowpack are felt throughout the basin in terms of the derived moisture storages. The total moisture storage maximum occurs earlier in the $2xCO_2$ climate than in the $1xCO_2$ climate scenario; see Figure 1. This general lowering of moisture storage in each of the basins is summarized in Figure 1 and Table 1 and in some cases represents greater than a 50% reduction in available total basin storage.

The resulting average annual steady-state evapotranspiration from the land portion of the basins is higher for the $2xCO_2$ climate in all lake basins, with a fairly smooth change with longitude from 26% higher over the Superior basin to 17% higher over the Erie basin; see Figure 1 and Table 1. However, over the seasonal cycle, $2xCO_2$ evapotranspiration exceeds the base case the most in the late spring to early summer (late on Lake Superior basin) and is actually smaller in July; see Figure 1.

LAKE HEAT BALANCE

The heat budget gives rise to increased water surface temperatures as summarized in Figure 1 and in Table 1. The average steady-state increase in water surface temperatures for the $2xCO_2$ scenario ranges from 4.8°C on Lake St. Clair to 5.6°C on Lake Michigan. Water surface temperatures peak earlier on deep lakes under the $2xCO_2$ climate than under the $1xCO_2$ climate; see Figure 1. Large amounts of heat now reside in the deep lakes throughout the year. Some of the deep lakes (Michigan, Huron, and Ontario) show water surface temperatures that stay above 3.98°C throughout the average annual cycle. Figure 2 illustrates this for 1961 on Lake Superior. This means that bouyancy-driven turnovers of the water column do not occur in the same way as they do at present.

In some years, the large lakes are changed from dimictic lakes (turnovers occur twice a year as water temperatures pass through the point of maximum density, 3.98°C) to monomictic lakes (maximum turnover occurs at the temperature "reversal" where temperatures stop declining and start rising again, and the minimum temperature is greater than 3.98°C). Figure 2 shows that the $1xCO_2$ temperature profile for Lake Superior passed through 3.98°C in June 1961 and approached in December the January 1962 transition. Under the $2xCO_2$ scenario, temperatures remain above 3.98°C but approach a vertical profile most in March. This represents the change from dimictic to monomictic. Table 2 shows that the large lakes remain dimictic under the $2xCO_2$ climate only between 2% to 76% of the time. The largest change is associated with Lake Ontario which is the furthest south of the deep lakes. Least affected are Lakes Erie and St.Clair which are very shallow and have relatively little heat storage. As the lakes move to one reversal per year in some years, instead of two turnovers per year, the interarrival times of the

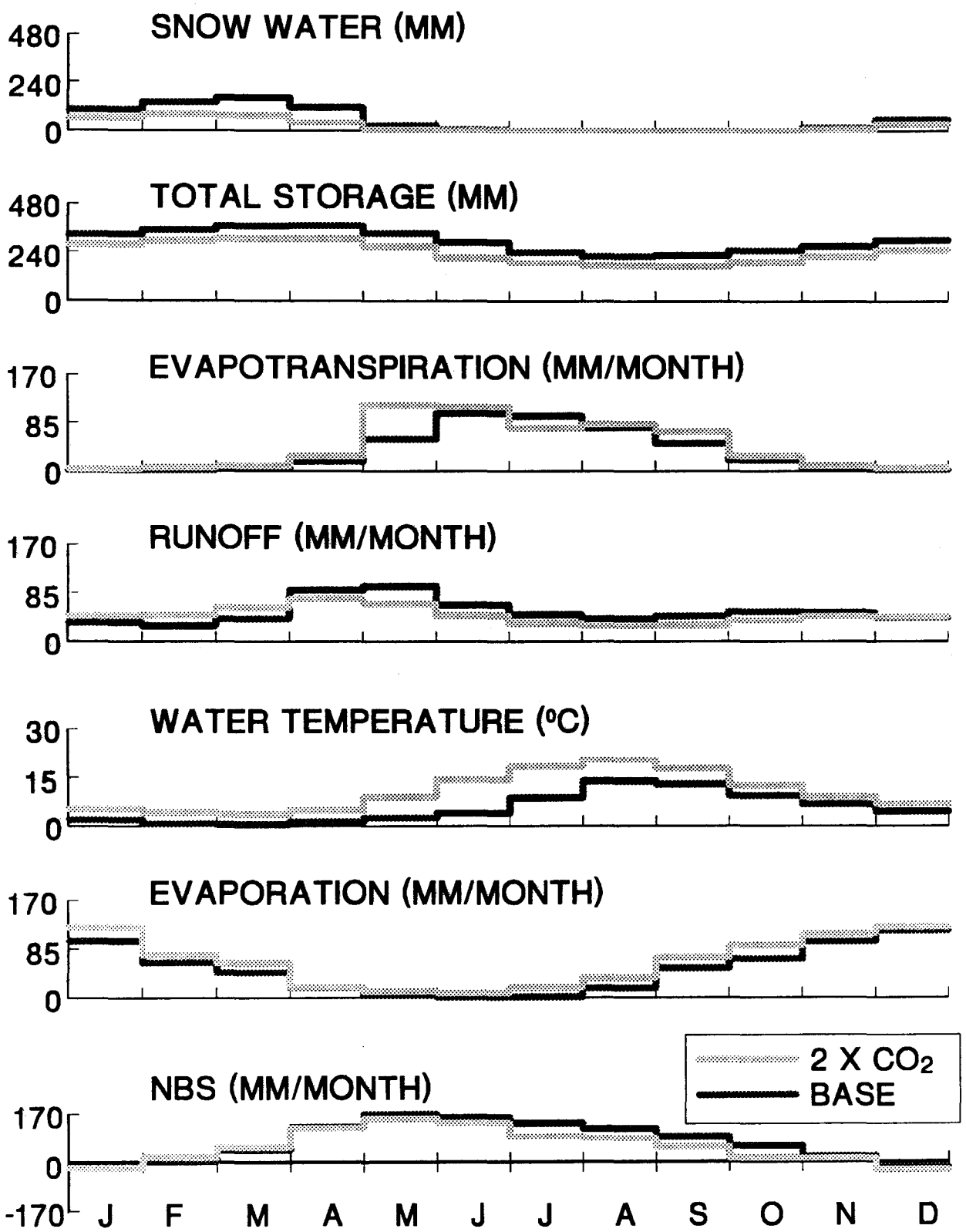

Figure 1. Selected CCC-GCM Lake Superior Annual Hydrological Cycles

Table 1. Selected Average Annual Steady-State Hydrology Differences.

Basin	Snow Water Equivalent[a] and Relative Changes			Total Basin Storage[a] and Relative Changes		
	$1xCO_2$	$2xCO_2$	Diff.	$1xCO_2$	$2xCO_2$	Diff.
Superior	50 mm	24 mm	-51 %	295 mm	237 mm	-20 %
Michigan	12 mm	2 mm	-87 %	114 mm	68 mm	-40 %
Huron	28 mm	6 mm	-79 %	99 mm	57 mm	-43 %
St. Clair	9 mm	1 mm	-91 %	28 mm	9 mm	-67 %
Erie	6 mm	1 mm	-90 %	24 mm	8 mm	-65 %
Ontario	16 mm	2 mm	-85 %	61 mm	33 mm	-46 %

Basin	Evapotranspiration[a] and Relative Changes			Water Temperature and Absolute Differences		
	$1xCO_2$	$2xCO_2$	Diff.	$1xCO_2$	$2xCO_2$	Diff.
Superior	423 mm	534 mm	26 %	5.4°	10.5°	5.1°
Michigan	507 mm	600 mm	18 %	8.5°	14.1°	5.6°
Huron	493 mm	608 mm	24 %	8.0°	13.0°	5.0°
St. Clair	535 mm	632 mm	18 %	1.0°	15.8°	4.8°
Erie	565 mm	659 mm	17 %	0.9°	15.8°	4.9°
Ontario	472 mm	575 mm	22 %	9.0°	14.4°	5.4°

[a]Expressed as a depth over the land portion of the basin.

maximum mixing extent increase. Table 2 illustrates that the average interarrival time grows to nearly a full year on Lake Ontario since only 2% of the years have dimictic behavior. Table 2 also illustrates the monomictic reversal temperature is, of course, well above the point of maximum water density.

The timing of maximum turnovers or temperature reversals shifts. Table 3 shows the time between the spring turnover and the fall turnover (for dimictic behavior) increases. The spring turnover occurs earlier and the fall turnover occurs later in the annual cycle. For monomictic behavior, the single maximum turnover occurs even earlier in the year then the dimictic turnovers. These are consequences of greater heat storage in, and heat inputs to, the lakes. Table 3 also summarizes the maximum depths at turnover in the lakes. Dimicitic spring turnovers exhibit shallower average depths under $2xCO_2$ conditions, and fall turnovers are deeper where not limited by the depth of the lake. Monomictic turnovers are generally even deeper.

The increased heat in storage also means that ice formation will be greatly reduced over winter on these deep Great Lakes. The higher heat content of the lake earlier in the year allows the $2xCO_2$ climate water surface temperatures to peak earlier than the $1xCO_2$ climate; see Figure 1. As over-lake air temperatures are affected by the water temperatures, they also peak ahead of the base case for deep lakes.

NET SUPPLY COMPONENTS

Runoff from the land portion of the basin is reduced by the $2xCO_2$ climate in all basins, changing from only 12% lower over the Superior basin to 56% lower over the St. Clair basin in a fairly smooth variation with latitude; see Table 4. The average annual cycle of

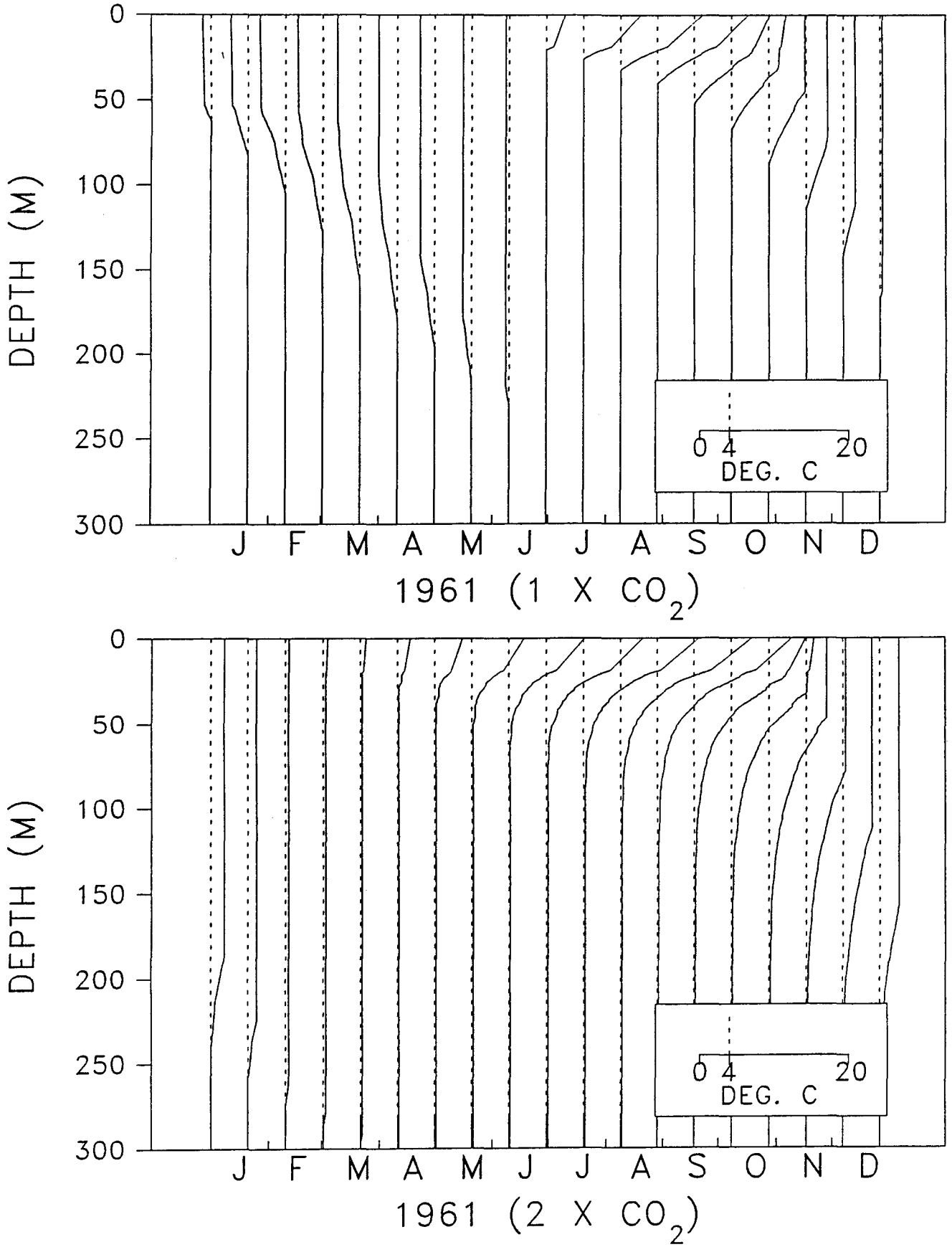

Figure 2. 1961 Lake Superior 20-Day Temperature-Depth Profiles Climatic Shift

Table 2. Average Characteristics of Turnovers/Reversals

	Fraction Dimictic		Interarrival Times		$2xCO_2$ Monomictic Reversal Water Temperature
	$1xCO_2$	$2xCO_2$	$1xCO_2$	$2xCO_2$	
Superior	100 %	67 %	182 d	211 d	4.5 °C
Michigan	100 %	15 %	182 d	318 d	4.9 °C
Huron	100 %	24 %	182 d	292 d	4.9 °C
St. Clair	100 %	100 %	183 d	185 d	
Erie	100 %	76 %	183 d	206 d	4.9 °C
Ontario	100 %	2 %	182 d	356 d	5.9 °C

Table 3. Average Dates and Depths of Maximum Turnover.

Basin	$1xCO_2$		$2xCO_2$		
	Dimictic		Dimictic		Monomictic
	Spring	Fall	Spring	Fall	
			DATES		
Superior	02 Jul	23 Dec	24 Apr	11 Feb	24 Mar
Michigan	27 May	01 Jan	27 Mar	28 Jan	22 Feb
Huron	26 May	10 Jan	26 Mar	11 Feb	10 Mar
St. Clair	30 Apr	20 Nov	04 Mar	28 Nov	
Erie	30 Apr	24 Dec	03 Mar	06 Jan	01 Feb
Ontario	20 May	18 Jan	10 Mar	29 Jan	03 Mar
			DEPTHS		
Superior	234 m	162 m	127 m	257 m	297 m
Michigan	132 m	111 m	52 m	199 m	231 m
Huron	229 m[a]	229 m[a]	140 m	229 m[a]	229 m[a]
St. Clair	6 m[a]	6 m[a]	6 m[a]	6 m[a]	
Erie	64 m[a]	64 m[a]	48 m	64 m[a]	53 m
Ontario	232 m	242 m	70 m	244 m[a]	244 m[a]

[a]Maximum average depth of the lake.

runoff has changed as well; peak runoff occurs slightly earlier and with smaller magnitude under the $2xCO_2$ climate than under the $1xCO_2$ climate; see Figure 1. This is largely the result of the very big changes observed in the snowpack accumulation and ablation as well as in other basin moisture storages. The higher water surface temperatures under the $2xCO_2$ climate result in increased annual lake evaporation of about 31-33%; see Figure 1 and Table 4.

Over-lake precipitation, runoff (not including the inflow from the upper lakes), and lake evaporation sum algebraically as the net basin supply, presented in Figure 1 and Table 4. Net basin supply is less under the $2xCO_2$ climate than under the $1xCO_2$ climate on all lakes. This is true throughout the year for Lake Erie and for most months on the other lakes. Net basin supplies are lower throughout the annual cycle except for February and March on Lake Superior, February on Lakes Michigan and Huron, January on Lake St. Clair, and January and February on Lake Ontario.

Table 4. Average Annual Steady-State Net Supply Components Differences.

Basin	Over-Lake Precipitation[a] and Relative Changes			Basin Runoff[a] and Relative Changes		
	$1xCO_2$	$2xCO_2$	Diff.	$1xCO_2$	$2xCO_2$	Diff.
Superior	817 mm	880 mm	8 %	615 mm	539 mm	-12 %
Michigan	825 mm	797 mm	-3 %	635 mm	393 mm	-38 %
Huron	869 mm	852 mm	-2 %	836 mm	539 mm	-36 %
St. Clair	849 mm	772 mm	-9 %	4453 mm	1980 mm	-56 %
Erie	905 mm	817 mm	-10 %	803 mm	372 mm	-54 %
Ontario	930 mm	879 mm	-5 %	1694 mm	1123 mm	-34 %

Basin	Over-Lake Evaporation[a] and Relative Changes			Net Basin Supply[a] and Relative Changes		
	$1xCO_2$	$2xCO_2$	Diff.	$1xCO_2$	$2xCO_2$	Diff.
Superior	561 mm	736 mm	31 %	871 mm	684 mm	-21 %
Michigan	647 mm	854 mm	32 %	813 mm	336 mm	-59 %
Huron	627 mm	829 mm	32 %	1079 mm	562 mm	-48 %
St. Clair	936 mm	1234 mm	32 %	4367 mm	1517 mm	-65 %
Erie	898 mm	1197 mm	33 %	810 mm	-8 mm	-101 %
Ontario	665 mm	874 mm	31 %	1959 mm	1127 mm	-42 %

[a]Expressed as depths over the lake.

Table 5. Average Annual Steady-State Great Lakes Basin Hydrology and Net Basin Supply Components.

Scenario	Over Land Precipitation (cms)	Evapotranspiration (cms)	Basin Runoff (cms)	Over Lake Precipitation (cms)	Over Lake Evaporation (cms)	Net Basin Supply (cms)
$1xCO_2$	13815	7825	5987	6604	4992	7783
$2xCO_2$[a]	13598	9518	4077	6578	6587	4180
CCC[a]	-2%	22%	-32%	0%	32%	-46%
GISS[b]	2%	21%	-24%	4%	27%	-37%
GFDL[c]	1%	19%	-23%	0%	44%	-51%
OSU[d]	6%	19%	-11%	6%	26%	-23%

[a]Canadian Climate Centre, prepared by Louie (1991).
[b]Goddard Institute for Space Studies GCM, used by Croley (1990a).
[c]Geophysical Fluid Dynamics Laboratory GCM, used by Croley (1990a).
[d]Oregon State University GCM, used by Croley (1990a).

Table 5 summarizes the changes in the hydrologic and net basin supply components for the entire Great Lakes basin. They were computed by converting the equivalent depths in Table 4 to annual flow rates on each lake and adding them over all the lakes. The changes

from the base case are also expressed relatively in Table 5. Also expressed are the relative changes from other studies that used other general circulation models (Croley, 1990a,b); they are provided for comparison. Net basin supplies to all Great Lakes are seen to drop to about one half under the CCC GCM; this corresponds to the GCM from the Geophysical Fluid Dynamics Laboratory (GFDL) in the earlier studies. This drop in net basin supply seems to result from the increases in lake evaporation and overland evapotranspiration (reducing subsequent runoff to the lakes) observed in the $2xCO_2$ scenario from the GCM.

CONCLUSIONS

The study results should be received with caution as they are of course dependent on the GCM outputs, which have large uncertainties. Furthermore, changes in variabilities that would take place under a changed climate are not addressed. Seasonal timing differences in the GCM for the changed climate are not reproduced with the method of coupling used herein. Seasonal meteorology patterns are preserved as they exist in the historical data. Seasonal changes induced by the changed meteorology because of a time-lag storage effect are observable however. Shifts in snowpack or water surface temperature growth and decay are examples. Changes in annual variability are less clear, again as a result of using the same historical time structure for both the base case and the changed climate scenarios.

The higher air temperatures under the $2xCO_2$ scenarios lead to higher over-land evapotranspiration and lower runoff to the lakes. Peak runoff occurs earlier since snowpack is reduced up to 100% and the snow season is shortened more than one month. This also results in a reduction in available soil moisture. Water surface temperatures peak earlier and are higher with larger amounts of heat resident in the deep lakes throughout the year. Also, bouyancy-driven turnovers of the water column do not occur as often on all lakes except St. Clair. Currently, they occur twice a year on all lakes. Without biannual turnovers, hypolimnion chemistry may be altered; oxygen may be depleted, releasing nutrients and metals from lake sediments. The lakes may experience more than a single winter turnover if temperature gradients are small and winds are strong enough to induce turbulent mixing (not considered here). Ice formation will be greatly reduced over winter on the deep Great Lakes and lake evaporation will increase. The average steady-state net supplies to all lakes are seen to drop. This implies that lake levels will drop. The magnitude of the drop can be assessed by considering the hydraulics of the connecting channels and outlet works operation on each of the lakes (Lee and Quinn, 1992).

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