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Laurentian Great Lakes Hydrology and Lake Levels under the Transposed 1993 Mississippi River Flood Climate

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ABSTRACT. *The Laurentian Great Lakes are North America's largest water resource, and include six large water bodies (Lakes Superior, Michigan, Huron, Erie, Ontario, and Georgian Bay), Lake St. Clair, and their connecting channels. Because of the relatively small historical variability in system lake levels, there is a need for realistic climate scenarios to develop and test sensitivity and resilience of the system to extreme high lake levels. This is particularly important during the present high lake level regime that has been in place since the late 1960s. In this analysis, we use the unique climate conditions which resulted in the 1993 Mississippi River flooding as an analog to test the sensitivity of Great Lakes hydrology and water levels to a rare but actual climate event. The climate over the Upper Mississippi River basin was computationally shifted, corresponding to a conceptual shift of the Great Lakes basin 10° west and 2° south. We applied a system of hydrological models to the daily meteorological time series and determined daily runoff, lake evaporation, and net basin water supplies. The accumulated net basin supplies from May through October 1993 for the 1993 Mississippi River flooding scenario ranged from a 1% decrease for Lake Superior to a large increase for Lake Erie. Water levels for each lake were determined from a hydrologic routing model of the system. Lakes Michigan, Huron, and Erie were most affected. The simulated rise in Lakes Michigan and Huron water levels far exceeded the historically recorded rise with both lakes either approaching or setting record high levels. This scenario demonstrates that an independent anomalous event, beginning with normal lake levels, could result in record high water levels within a 6- to 9-month period. This has not been demonstrated in the historical record or by other simulation studies.*

INDEX WORDS: *Great Lakes, water levels, hydrology, climate impacts.*

INTRODUCTION

The Great Lakes are North America's largest water resource system with a basin area of about 770,000 km^2, of which about one third is lake surface. It is one of the most intensively used freshwater systems in the world, serving multiple interests including navigation, hydropower, recreation, water supply, food supply, and riparian. The system includes the six large water bodies (Lakes Superior, Michigan, Huron, Erie, Ontario, and Georgian Bay), Lake St. Clair, and their connecting channels. The outflows from Lakes Superior and Ontario are regulated by regulatory works in the St. Marys and St. Lawrence rivers respectively. The remainder of the system is naturally regulated. Water levels change slowly due to the large lake surface areas and constricted outlet channels which integrate short-term climate fluctuations. The Great Lakes water levels have been continuously gauged since 1860, with some individual records going back to the early 1800's. Because of the small historical interannual variability in annual lake levels, about 1.8 m, and seasonal variability, about 20–40 cm, significant uses have become dependent upon water levels changing little, resulting in interests being sensitive to even small changes in lake levels. In any analysis of the system, it is desirable to account for climatic variability not reflected in the relatively short instru-

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mental record to insure robustness in water resource development and policy analysis and development. This is particularly important because of the unprecedented high lake level climate regime that has been in place since the late 1960s.

Climate scenarios, defined as descriptions of possible climate conditions at some specified future time which are physically consistent, have been developed based upon climate blocks (Quinn and Changnon 1989, IJC 1993), stochastic analysis, (Lee *et al.* 1994), general circulation models (Croley 1990, Hartmann 1990), and climate transposition (Croley *et al.* 1996). Climate scenarios based upon human experience have political and social credibility that computer generated scenarios, such as GCMs, lack (Glantz 1988). In this analysis, we used the unique climate conditions resulting in the 1993 Mississippi River flooding (Changnon 1996), and transposed them to the Great Lakes basin to test the sensitivity of Great Lakes hydrology and water levels to a rare but actual climate event. The 1993 Mississippi River flooding scenario allows us to test the hypothesis that an independent anomalous event, beginning with near average lake levels, could result in record high water levels within a 6- to 9-month period. This is a valuable scenario for water resource and policy development because (1) it actually occurred, (2) it occurred close to the Great Lakes basin, and (3) it could plausibly happen in the Great Lakes basin.

METHODOLOGY

The first step of the study was to transpose the climate of the upper Mississippi basin to the Great Lakes basin. Detailed records of daily weather were available at over 1,100 sites in the Upper Mississippi River basin during the 1993 flooding event. By computationally "moving" these stations over the Great Lakes basin, we can construct a physically plausible and coherent scenario of an alternative climate for the area. The resulting data set ensures representation of realistic meteorological temporal and spatial variability because we are using actual station data from a dense observational network.

As shown in Figure 1, the climate (described by records at all of the meteorological stations) of the Upper Mississippi River basin was computationally shifted, corresponding to a shift of the Great Lakes basin 10° west and 2° south for the period July 1992 through December 1993. This shift was intended to maximize the potential impacts for Lakes

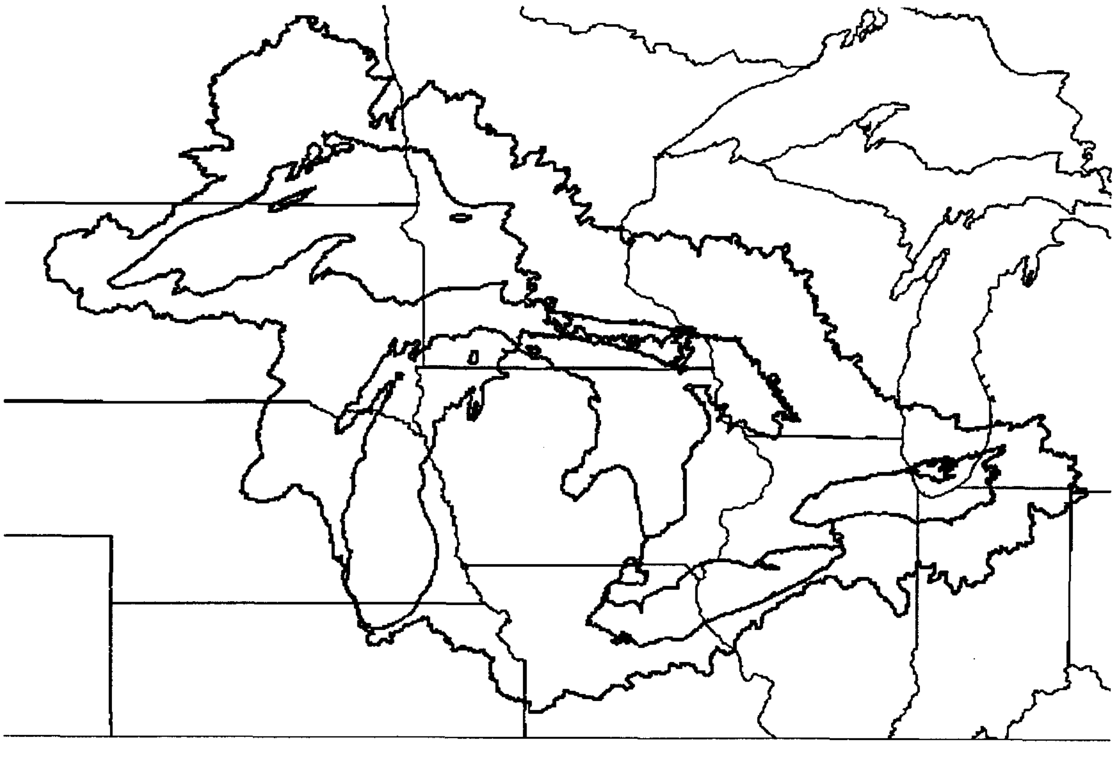

FIG. 1. Transposed Great Lakes basin.

Michigan-Huron, Erie, and Ontario, where the largest socio-economic problems would occur. All meteorological station data were relocated and Thiessen-weighted to obtain areal averages on a daily basis over the 121 watersheds within the Great Lakes basin. For comparability with current procedures, the precipitation over the lake surfaces was estimated from the overland stations. The transposed meteorology included daily precipitation, air temperature, cloud cover, humidity, and wind speed. Lake effects were not included as they were considered unlikely to influence the results on an annual basis (Croley *et al.* 1996).

Establishing when unique climate conditions begin is important when using climate anomalies. For this study we examined four transposed scenarios with different beginning dates, the earliest of which was July 1992. Future Great Lakes water levels are dependent upon both present levels and future water supplies. Two scenarios, "MS1," 6 months beginning May 1993, and "MS2," 10 months beginning January 1993, were selected for detailed analysis as they provided the most critical combinations of initial lake levels and future water supplies for developing extreme lake levels.

The second step in the methodology was to convert the climate scenarios into hydrologic scenarios. This was accomplished with a suite of hydrological models. Scientists at the Great Lakes Environmental Research Laboratory (GLERL) have developed, calibrated, and verified conceptual model-based techniques for simulating hydrological process in the Laurentian Great Lakes and their tributary basins (including Georgian Bay and Lake St. Clair as separate entities). These models have been integrated into a system to estimate net basin water supplies (NBS) equal to the overlake precipitation plus runoff to the lakes minus lake evaporation, lake levels, whole lake heat storage, and water and energy balances for making forecasts and for assessing impacts associated with climate change and variability (Croley 1990,1993,1995; Croley and Hartmann 1987,1989; Croley and Lee 1993; Hartmann 1990). These include daily rainfall-runoff models for the 121 Great Lakes tributary basins (Croley 1983a,b), over-lake precipitation, and one-dimensional (depth) lake thermodynamic models for each of the Great Lakes, Lake St. Clair, and Georgian Bay (Croley 1989,1992; Croley and Assel 1994). Lake evaporation fluxes are the primary outputs from the thermodynamic models that are used in this study. Model assessments are summarized elsewhere (Croley *et al.* 1995, Croley *et al.* 1996).

We first developed a "base case" by applying the system of hydrological models to the (untransposed) historical daily meteorological time series of air temperature, precipitation, wind speed, humidity, and cloud cover for the 121 subbasins and seven lake surfaces within the Great Lakes basin. We then simulated the 43 years between 1951 and 1993 with arbitrary initial conditions (for soil moisture, snow pack, groundwater storage, lake heat storage, and water surface temperature). We repeated the simulation with end conditions used as initial conditions until there was no change (to arrive at a "steady-state" condition). We took values of soil moisture, snow pack, groundwater storage, lake heat storage, and water surface temperatures from this "base case" hydrology for 1 May 1993 and 1 January 1993, to use as initial conditions in estimating the Great Lakes hydrology for scenarios MS1 and MS2 (respectively). The system of hydrological models was then applied to the transposed daily meteorological time series for MS1 and MS2 by using the initial conditions from the "base case" hydrology. The impacts were estimated by comparing the outputs for MS1 and MS2 with the corresponding outputs from the "base case." The simulated daily runoff and lake evaporation values for each transposed scenario were integrated into monthly values for each lake and Georgian Bay and were combined with monthly over-lake precipitation to estimate monthly net basin water supplies (NBS) to each lake.

The final step in the methodology is the simulation of the Great Lakes water levels and flows in the connecting channels. Great Lakes levels and flows have been simulated for a variety of studies, including changed climates, (Quinn 1988, International Joint Commission 1976, Hartmann 1990, Lee *et al.* 1994) to examine levels and flows that would be obtained from other than historical conditions. The basic procedure is to determine lake levels and connecting channel flows by routing the simulated water supplies through the Great Lakes system with a hydrological response model provided by Environment Canada, similar to Quinn (1978). In addition to net basin supplies, monthly diversions and consumptive use data are also input to the model. The monthly net basin supplies for scenarios MS1 and MS2, along with the appropriate diversions and ice and weed retardation values, were used to drive the routing model. The outputs of the model are beginning-of-month and monthly mean water levels (quarter monthly for Lakes Erie and Ontario) for each lake in the system, including Lake St. Clair, and monthly flows in the connecting channels. The model routing consists of regulation plans, channel routing dynamics, and water balances, combined to estimate lake levels and connecting channel flows from water supplies to the lakes. Lake Superior is regulated by Plan 1977-A (International Lake Superior Board of Control 1981, 1982) and Lake Ontario by Plan 1958-D (International St. Lawrence River Board of Control 1963). The regulation plans are Plan92HQ for Superior through Erie and Plan58HQ for Ontario, modified from the existing operational regulation plans by Lee *et al.* (1994) to operate under climatic extremes. The modifications provide robustness for the plans, to handle the wide range of outflows expected during climate change and stochastic hydrologic studies of the Great Lakes basin, than were used in the derivation of the plans. In addition, several minor modifications were made to allow the models to function under the extreme high and low lake levels and flows expected under transposed climates. Middle lake outflows are represented with stage-fall-discharge equations as functions of lake levels or of lake level differences between lakes. Flow retardation from ice and weeds are given by monthly median retardation values. Constant diversions are used for the Ogoki, Long Lac, and Chicago diversions, and monthly means are used for Welland Canal diversions. Each lake storage, with all inflows and outflows, is described by mass continuity equations. The system of equations is solved numerically. It should be noted that in the routing model, Lakes Michigan and Huron, including Georgian Bay, are considered as one lake hydraulically as they are joined at the Straits of Mackinac.

RESULTS

Monthly air temperature, precipitation, runoff, lake evaporation, and NBS from May to October 1993 for the base case and scenario MS1 are shown in Tables 1–6 for each of the lakes. An inspection of the hydrologic variables for MS1, the most criti-

TABLE 1. Selected Lake Superior hydrologic variables for transposed Mississippi scenario 1.

	Temperature[a]		Precipitation[b]		Runoff[b]		Evaporation[b]		Evapotranspiration[b]	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	8.8	13.0	92.4	96.0	77.9	66.9	2.0	−1.6	47.8	106.5
June	12.7	16.3	76.5	147.4	61.0	55.9	−3.1	−4.7	72.6	139.2
July	16.3	18.9	126.8	181.6	47.4	55.2	−6.3	−5.9	128.2	175.1
Aug.	17.5	19.7	75.9	78.3	34.2	33.1	−1.1	6.3	78.0	67.4
Sept.	9.2	12.2	69.7	28.6	36.8	27.3	57.4	69.1	30.0	20.3
Oct.	3.4	6.6	47.0	13.6	42.0	23.4	85.4	98.4	10.9	9.1
Total	11.3[c]	14.5[c]	488.3	545.5	299.3	261.8	134.3	161.6	367.5	517.6
Diff.		3.1°C		11.7%		−12.6%		20.2%		40.8%

[a]Measured over land in °C.
[b]Expressed as equivalent depths in mm over the lake surface.
[c]Average instead of Total.

TABLE 2. Selected Lake Michigan hydrologic variables for transposed Mississippi scenario 1.

	Temperature[a]		Precipitation[b]		Runoff[b]		Evaporation[b]		Evapotranspiration[b]	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	12.8	15.0	85.6	139.8	85.0	110.6	−1.1	−4.7	74.8	115.3
June	16.8	19.3	153.5	167.6	83.4	75.1	−3.2	−5.7	135.5	151.2
July	20.8	22.3	97.0	274.3	50.3	100.8	3.4	−1.6	106.6	231.6
Aug.	20.6	22.4	98.1	99.8	33.9	49.5	26.3	38.1	89.0	92.5
Sept.	12.6	14.5	111.0	96.0	49.5	54.1	105.1	115.1	63.3	58.5
Oct.	7.5	9.7	64.9	35.6	59.5	49.5	95.6	104.8	32.0	24.4
Total	15.2[c]	17.2[c]	610.1	812.5	361.6	439.6	226.4	246.0	501.2	673.5
Diff.		2.0°C		33.2%		21.6%		8.7%		34.4%

[a]Measured over land in °C.
[b]Expressed as equivalent depths in mm over the lake surface.
[c]Average instead of Total.

TABLE 3. Selected Lake Huron hydrologic variables for transposed Mississippi scenario 1.

	Temperature[a]		Precipitation[b]		Runoff[b]		Evaporation[b]		Evapotranspiration[b]	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	8.8	13.0	92.4	96.0	77.9	66.9	2.0	–1.6	47.8	106.5
May	12.3	15.3	63.5	154.2	36.3	54.5	3.4	–3.1	66.7	135.2
June	16.6	19.6	104.8	207.3	29.1	38.6	2.8	–2.2	100.4	179.0
July	21.2	22.4	53.3	272.8	13.9	59.1	12.7	–0.1	61.3	248.7
Aug.	20.6	22.2	108.0	226.6	11.9	27.7	24.1	19.3	95.4	197.2
Sept.	13.0	14.3	96.6	98.2	19.4	38.4	89.6	98.1	70.4	66.5
Oct.	7.6	9.8	71.1	29.4	34.8	23.6	96.3	102.2	37.5	26.0
Total	15.2[c]	17.3[c]	497.3	988.5	145.4	241.9	228.9	214.2	431.7	852.6
Diff.		2.1°C		98.8%		66.4%		–6.4%		97.4%

[a] Measured over land in°C.

[b] Expressed as equivalent depths in mm over the lake surface.

[c] Average instead of Total.

TABLE 4. Selected Georgian Bay hydrologic variables for transposed Mississippi scenario 1.

	Temperature[a]		Precipitation[b]		Runoff[b]		Evaporation[b]		Evapotranspiration[b]	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	10.1	14.0	115.5	128.2	210.8	181.0	0.5	–2.6	72.6	118.6
June	15.3	17.7	50.8	207.2	162.5	184.9	1.9	–0.2	107.0	214.2
July	19.3	21.0	59.5	143.1	71.6	109.1	14.8	6.8	95.4	160.1
Aug.	19.2	21.0	81.9	140.8	45.3	63.8	33.1	35.7	61.4	124.4
Sept.	10.9	12.5	95.2	86.4	102.6	86.2	113.3	126.4	45.1	39.8
Oct.	5.0	8.1	101.8	33.1	168.1	81.5	141.7	134.8	20.0	23.1
Total	13.3[c]	15.7[c]	504.7	738.8	760.9	706.5	305.3	300.9	401.5	680.2
Diff.		2.4°C		46.4%		–7.1%		–1.4%		69.4%

[a] Measured over land in °C.

[b] Expressed as equivalent depths in mm over the lake surface.

[c] Average instead of Total.

TABLE 5. Selected Lake Erie hydrologic variables for transposed Mississippi scenario 1.

	Temperature[a]		Precipitation[b]		Runoff[b]		Evaporation[b]		Evapotranspiration[b]	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	15.0	17.3	40.4	123.3	23.3	69.3	14.5	6.5	34.6	97.8
June	19.3	21.7	120.0	161.7	48.8	61.1	22.8	18.2	106.0	135.6
July	22.9	24.5	80.9	299.6	14.4	142.9	70.3	64.9	77.8	239.2
Aug.	22.0	24.5	44.4	128.0	4.5	39.4	105.3	115.0	44.0	113.5
Sept.	15.3	16.2	121.9	256.8	47.6	257.7	244.6	227.1	87.0	134.6
Oct.	9.5	11.3	62.8	45.5	48.3	68.6	204.6	200.6	47.9	31.0
Total	17.3[c]	19.3[c]	470.4	1014.9	186.9	639.0	662.1	632.3	397.3	751.7
Diff.		1.9°C		115.8%		241.9%		–4.5%		89.2%

[a] Measured over land in °C.

[b] Expressed as equivalent depths in mm over the lake surface.

[c] Average instead of Total.

TABLE 6. Selected Lake Ontario hydrologic variables for transposed Mississippi scenario 1.

	Temperature[a]		Precipitation[b]		Runoff[b]		Evaporation[b]		Evapotranspiration[b]	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	12.9	15.7	50.5	70.6	186.5	185.4	–0.1	–2.6	51.5	66.8
June	17.3	19.3	104.2	201.4	112.6	148.1	–3.9	–4.9	93.8	166.7
July	21.4	23.0	58.4	108.6	38.8	66.5	–1.5	1.8	55.8	114.6
Aug.	20.6	22.5	56.4	115.4	22.9	30.7	16.2	28.1	54.0	105.7
Sept.	14.2	15.0	120.5	147.1	70.5	111.5	91.6	109.5	74.9	91.2
Oct.	7.9	9.9	80.3	76.0	143.3	158.4	89.3	109.9	39.1	44.0
Total	15.7[c]	16.6[c]	470.3	719.1	574.6	700.6	191.6	241.8	369.1	589.0
Diff.		1.9°C		52.9%		21.9%		26.2%		

[a] Measured over land in °C.

[b] Expressed as equivalent depths in mm over the lake surface.

[c] Average instead of Total.

cal scenario as will be discussed later, reveals that precipitation over the Great Lakes under this transposed scenario generally is greater than the base case for May–August, but declines to less than the base for September on some lakes and for October on all lakes. The total precipitation over the 6-month period for scenario MS1 exceeds the base case on all lakes; this is plotted in Figure 2. However, runoff into each of the lakes was not proportionally higher for scenario MS1; only Lake Erie showed increased runoff for all 6 months of the scenario. On Lake Superior, runoff was less for 5 of the 6 months, resulting in decreased total runoff; the runoff was also less on Georgian Bay. However, the other lakes showed increased runoff throughout most of the 6-month period with 6-month totals exceeding the base case; this is also plotted in Figure 2. As shown in Tables 1–6 the less-than-proportional increase in runoff resulted from increased evapotranspiration driven by higher air temperatures. Air temperatures were greater under scenario MS1 than for the base case on all lakes for all months of the study. The differences were greater for the northern-most basins (Superior and Georgian Bay), which correspond to the only drops in basin runoff (see Fig. 2). For the other lakes, the air temperature averaged only about 2°C higher under scenario MS1.

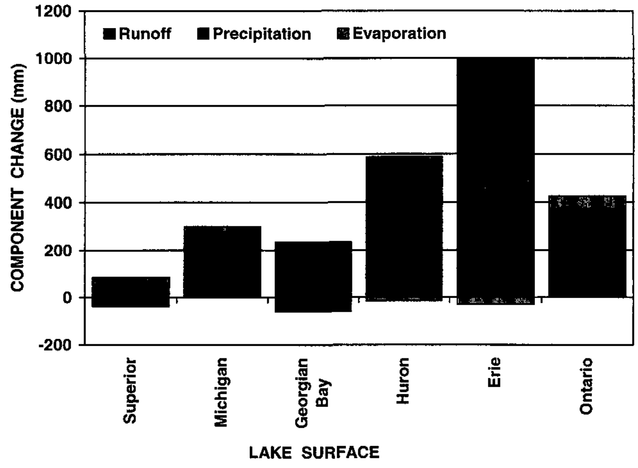

FIG. 2. Changes in 6-month total NBS components for transposed Mississippi scenario 1 over June–October 1993.

The higher average air temperatures for scenario MS1 generally resulted in very little lake evaporation change, as can be seen in Tables 1–6 and summarized in Figure 2. This is interesting since air temperatures greatly increased evapotranspiration (as just discussed); however, this is explained by noting the large heat storage capacity of the lakes versus land. Over land, there is almost no capacity to store heat, and evapotranspiration tracks air temperature quite well. However, the lakes have extremely large thermal storage capacities, and the initial heat storages for both the base case and scenario MS1 are the same. Heat additions to the lake, while greater for scenario MS1, do not change the heat content appreciably until the last two months of the scenario, reflecting the effect of the stable conditions. This is true on all lakes but Erie, which is a shallow lake with less heat storage capacity.

The accumulated NBS from May through October 1993, for scenario MS1, ranged from a 1% decrease for Lake Superior to a large increase for Lake Erie; see Table 7. The core of the anomalous net basin supplies appears to be centered over Lakes Huron and Erie due to the centering of the

TABLE 7. Monthly net basin supplies.[a]

	Superior		Michigan		Huron		Georgian Bay		Erie		Ontario	
	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1	Base	MS1
May	168.3	164.6	171.6	254.5	96.4	211.8	325.8	311.9	49.2	186.1	237.1	258.6
June	140.6	207.9	240.0	248.4	131.0	248.1	211.4	392.3	146.1	204.6	220.7	354.4
July	180.6	242.6	143.9	376.7	54.4	332.0	116.2	245.4	25.0	377.7	98.7	173.3
Aug.	111.1	105.1	105.6	111.3	95.7	235.0	94.0	168.9	–56.4	52.3	63.1	117.9
Sept.	49.1	–13.2	55.3	35.0	26.3	38.5	84.5	46.2	–75.1	287.4	99.4	149.1
Oct.	3.6	–61.4	28.5	–19.7	9.5	–49.2	128.2	–20.2	–93.5	–86.5	134.3	124.5
Total	653.3	645.6	744.9	1006.2	413.3	1016.2	960.1	1144.5	–4.7	1021.6	853.3	1177.8
Diff.		–1.2%		35.1%		145.9%		19.2%				38.0%

[a]Expressed as equivalent depths in mm over the lake surface.

transposed climate. Figure 2 shows that the primary increase in NBS was due to greatly increased precipitation coupled with small increases in lake evaporation and runoff for most basins (and a large increase in runoff for Lake Erie). Lakes Huron, Erie, and Ontario, on the southeast segment of the basin, showed the greatest impacts.

Since the 10 months of MS2 contain the time period of MS1, a 6-month comparison of both is possible in Table 8. While both MS1 and MS2 result in increased net basin supply totals, scenario MS1 is more extreme. As the precipitation is the same for both scenarios, the differences in NBS between the two scenarios are due to changes in runoff and lake evaporation and are summarized in Table 9. These changes, in turn, result from differences in the initial basin and lake thermal conditions at the end of April 1993 (initial to the MS1 simulation) as compared with the end of April conditions given by MS2. NBS differences between MS1 and MS2 over the May through October time period are generally slight, the only exceptions being Lakes Superior and Ontario with a maximum difference of about 10%. With the exception of Lake Huron, the total NBS for MS1 were greater than for the corresponding MS2 values. Generally the base case had wetter and warmer conditions for the January–April period than did scenario MS2 (Figs. 3 and 4) and therefore had higher NBS. This made for a more saturated basin and warmer water surface temperatures for the beginning of May in the base case. In Figure 3, the NBS values for Lake Michigan-Huron are the areally weighted over-lake values for Lake Michigan (.49), Lake Huron (.35), and Georgian Bay

TABLE 8. Six-month net basin water supplies comparison[a].

	6 Months			9 Months	
Lake	Base	MS1	MS2	Base	MS2
Superior	653	646	581	679	613
Michigan	745	1,006	975	1,108	1,280
Huron	413	1,016	1,022	564	1,184
Georgian Bay	960	1,144	1,131	1,691	1,806
Erie	–5	1,022	969	711	1,642
Ontario	853	1,178	1,074	1,898	2,123

[a]Expressed as equivalent depths in mm over the lake surface.

TABLE 9. Net basin water supply and components differences[a].

	NBS			Runoff			Evaporation		
Lake	MS1	MS2	Diff.	MS1	MS2	Diff.	MS1	MS2	Diff.
Superior	645.6	580.6	–10.1%	261.8	232.5	–11.2%	161.6	197.2	22.0%
Michigan	1,006.2	975.0	–3.1%	439.6	410.8	–6.6%	246.0	248.2	0.9%
Huron	1,016.2	1,021.9	0.6%	241.9	233.6	–3.4%	214.2	200.0	–6.6%
Georgian Bay	1,144.5	1,130.8	–1.2%	706.5	719.0	1.8%	301.0	327.0	8.6%
Erie	1,021.6	968.7	–5.2%	639.0	648.0	1.4%	632.3	694.0	9.8%
Ontario	1,177.8	1,073.7	–8.8%	700.6	643.8	–8.1%	241.8	289.1	19.6%

[a]Expressed as equivalent depths in mm over the lake surface.

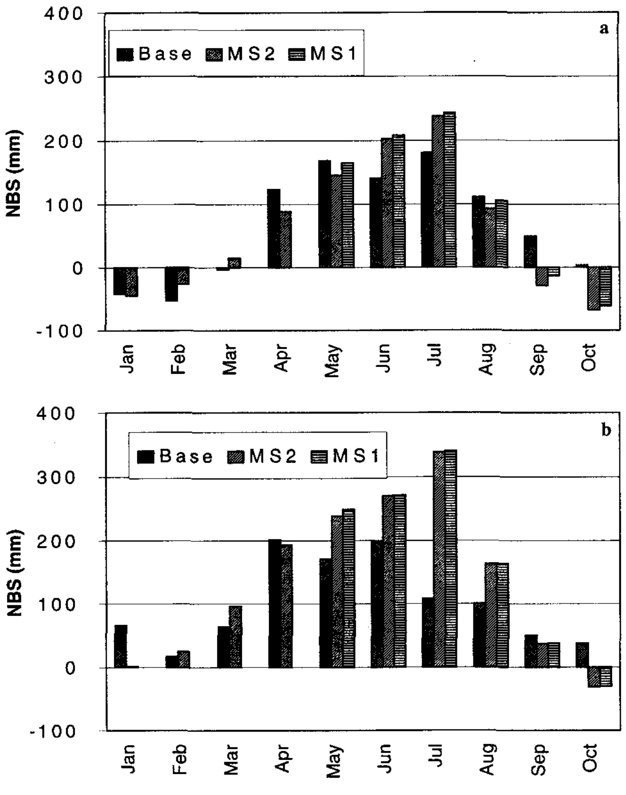

FIG. 3. Transposed 1993 Mississippi scenarios 1 and 2 monthly NBS for a) Lake Superior, and b) Lake Michigan-Huron.

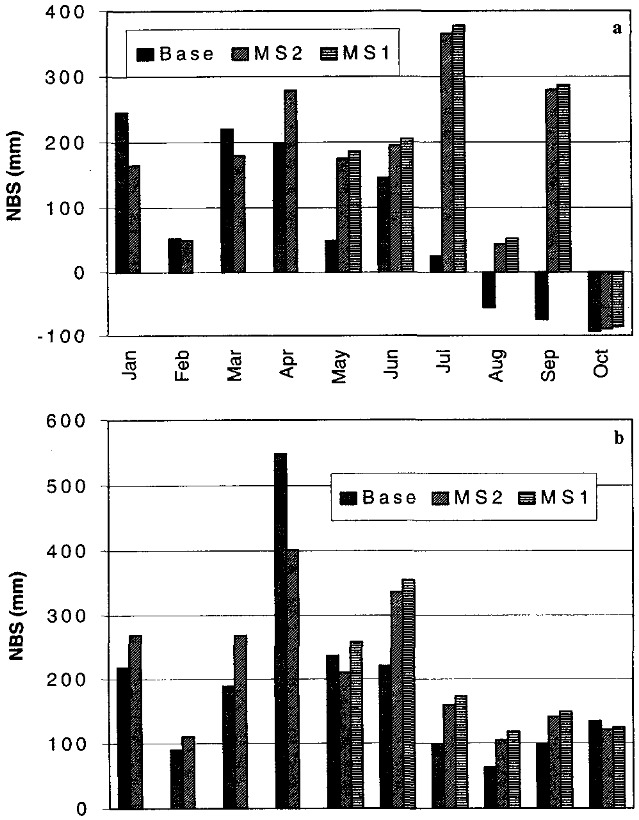

FIG. 4. Transposed 1993 Mississippi scenarios 1 and 2 monthly NBS for a) Lake Erie, and b) Lake Ontario.

(.16), based on water surface areas. Of particular note are the extremely high NBS for the MS1 and MS2 scenarios on Lake Michigan-Huron in July, Lake Erie in July and September, and for the base case on Lake Ontario in April. Also the differences between the base case and scenario MS2 for January–October are much less pronounced than for scenario MS1, showing why MS1 is the critical scenario for lake level analysis.

The relative rankings, in decreasing order, of the May–October NBS for the base case and MS1 scenario relative to historical values from 1900–1989 are respectively: 37 and 39 for Lake Superior, 4 and 1 for Lake Michigan-Huron, 59 and 27 for Lake Erie, and 11 and 2 for Lake Ontario. While extreme supplies were experienced on Lakes Michigan-Huron and Ontario, all values of NBS, with the exception of Lake Michigan-Huron, have occurred in past historical records. The MS1 scenario NBS for Lake Michigan-Huron was 40% greater than the maximum NBS of record (1912) and 46 percent greater than the NBS leading to record high lake levels in 1986.

The Great Lakes water levels in the winter and spring of 1993 were in the normal range, about 20 cm above their long-term means. The routing model was run with beginning-of-month starting water levels for January 1993 (MS2) and June 1993 (MS1). The monthly average lake level outputs from the routing model are illustrated in Figures 5–7 along with the base case levels and record high levels. Table 10 summarizes the comparisons with the record high level for each lake. For Lake Superior, the climate anomaly had a relatively small impact, which could also be inferred from the changes in the net basin supplies. This was due primarily to the centering of the transposed climate. However, Lake Michigan-Huron showed an extreme rise in lake levels. The small differences in scenarios MS1 and MS2 are due primarily to the relatively higher starting level in May as compared with January and secondarily to the different antecedent basin condi-

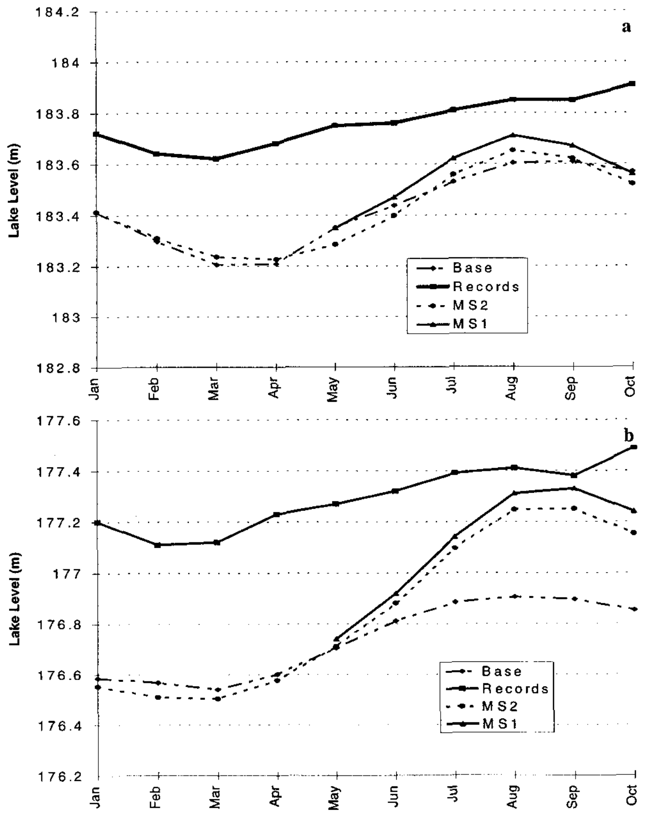

FIG. 5. Transposed 1993 Mississippi scenarios 1 and 2 monthly mean lake level for a) Lake Superior, and b) Lake Michigan-Huron.

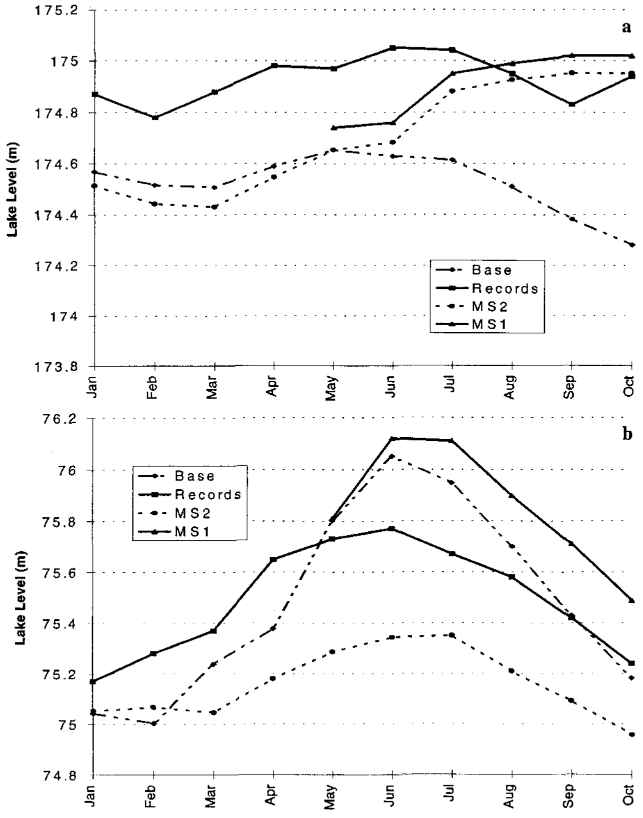

FIG. 6. Transposed 1993 Mississippi scenarios 1 and 2 monthly mean lake level for a) Lake Erie, and b) Lake Ontario.

tions. The lake rose sharply between May and August, peaking and nearly breaking the monthly mean record in September. The rise in level between May and September, 59 cm, would have been the largest rise recorded since the gauging measurements began in 1860. The prior record rise for this period was 38 cm in 1943. Thus, at higher starting elevations, record lake levels would have been set.

For Lake Erie, the monthly water levels rose sharply from May through August, setting record highs in August, September, and October. Differences between the two scenarios are due to the relative differences in starting elevations and antecedent basin conditions. Lake Erie also had a record rise in levels of 28 cm from May to October. This compares with the record May to October rise of 32 cm set in 1990. Thus, while Lake Erie set record high lake levels under the scenarios, the summer rise was not nearly as extreme as on Lake Michigan-Huron.

The extreme base case levels on Lake Ontario, much higher than would be indicated by the net basin supplies, are the result of ice conditions in the St. Lawrence River during the 1992–1993 winter. The lack of a stable ice cover caused unseasonably low discharges from Lake Ontario down the St.

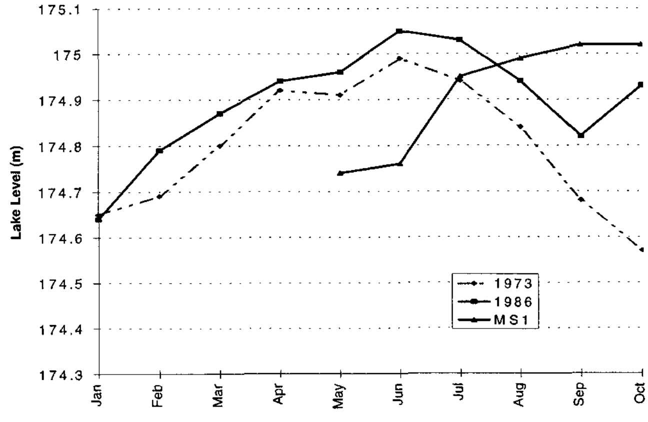

FIG. 7. Comparison of recent record high events of 1973 and 1986 with scenario MS1 for Lake Erie.

TABLE 10. Great Lakes record high water levels comparison[a].

Lake	Record Level[b]	Transposed Level	
		MS1	MS2
Superior	183.85	183.7	183.6
Michigan-Huron	177.59	177.3	176.9
Erie	175.05	175.0	174.6
Ontario	75.77	76.1	75.4

[a]Levels are expressed in meters with respect to the International Great Lakes Datum of 1985.
[b]Based on period 1860–1994.

Lawrence River that resulted in additional water being stored on the lake during the winter. This led to high beginning-of-month levels at the start of the anomaly and subsequently contributed to the record water levels. The recorded 1993 spring rise in Lake Ontario levels, 31 cm, was much smaller than the record rise of 54 cm occurring in 1972. The comparison with the base case levels in Figure 6 indicates extremely high modeled water levels as well, which did not occur in nature. Deviations were undertaken in the late spring to discharge more water than called for under the standard operation of the regulation plan. This resulted in the lake peaking in May with a monthly mean of about 75.6 m and then falling throughout the remainder of the summer and fall. Thus, similar actions may have been taken during the climate anomaly that would lead to lower than simulated levels, very high but no records.

CONCLUSIONS

Because of its location, the Great Lakes basin has not been subjected to the hydrologic extremes experienced in most of the country. This has limited our ability to plan for and assess potential impacts of extreme climatic events on water supplies and water levels. This study shows that an anomalous event, like the 1993 Mississippi flood climatology, could cause record high water levels on the Great Lakes. With this particular transposition, Lakes Michigan-Huron and Erie were most affected. The rise in Lake Michigan-Huron water levels for MS1 and MS2 scenarios far exceeded the recorded rise. Both lakes either approached or set record levels. The regulation plans for Lakes Superior and Ontario appear to be sufficiently robust, as modified, to cope with water supplies of this magnitude without failing. While the simulated levels for Lake Ontario showed record highs, under both base case and climate scenarios, this would probably not occur during actual operations. In 1993, additional water was released from Lake Ontario that resulted in much lower water levels than would have occurred under strict operation of the regulation plan. This would also likely be the case under the climate anomaly. This climate scenario is also appropriate for use as a management scenario for Great Lakes water level studies. Because the climate anomaly is an anomalous climatic event, it can be superimposed on any recorded or simulated level scenario. Thus, it can be used to assess further modifications to the existing regulation plans, to test new regulation plans or other non-structural policies, which might be warranted to mitigate or to adapt to potential extreme high lake levels. This scenario demonstrates that there is the potential for a series of extreme NBS which, beginning with normal lake levels, could result in record high water levels within a 6- to 9-month period. This is in contrast to past experience; the record high water level events of 1973 and 1986 were due to relatively small rises of 5–15 cm superimposed on existing high water levels as shown on Figure 7. This quick record rise from normal lake levels has not been demonstrated anywhere in the historical record or by other simulation studies.

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