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Warmer and Drier Climates that Make Terminal Great Lakes

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ABSTRACT. *A recent empirical model of glacial-isostatic uplift showed that the Huron and Michigan lake level fell tens of meters below the lowest possible outlet about 7,900 ^{14}C years BP when the upper Great Lakes became dependent for water supply on precipitation alone, as at present. The upper Great Lakes thus appear to have been impacted by severe dry climate that may have also affected the lower Great Lakes. While continuing paleoclimate studies are corroborating and quantifying this impacting climate and other evidence of terminal lakes, the Great Lakes Environmental Research Laboratory applied their Advanced Hydrologic Prediction System, modified to use dynamic lake areas, to explore the deviations from present temperatures and precipitation that would force the Great Lakes to become terminal (closed), i.e., for water levels to fall below outlet sills. We modeled the present lakes with pre-development natural outlet and water flow conditions, but considered the upper and lower Great Lakes separately with no river connection, as in the early Holocene basin configuration. By using systematic shifts in precipitation, temperature, and humidity relative to the present base climate, we identified candidate climates that result in terminal lakes. The lakes would close in the order: Erie, Superior, Michigan-Huron, and Ontario for increasingly drier and warmer climates. For a temperature rise of* T*°C and a precipitation drop of* P% *relative to the present base climate, conditions for complete lake closure range from* $4.7T + P > 51$ *for Erie to* $3.5T + P > 71$ *for Ontario.*

INDEX WORDS: *Climate change, Great Lakes, hydrology, water levels, terminal lakes.*

INTRODUCTION

Background and Purpose

About 9,500 radiocarbon (^{14}C) years before present (BP) the large upstream glacial Lake Agassiz in northwestern Ontario and Manitoba supplied melt water from the last glaciation to the upper Great Lakes through outlets to the Lake Nipigon basin and thence to the Superior and Huron-Michigan basins (Teller 1985, 1987). About 8,000 ^{14}C years BP, Lake Agassiz merged with glacial Lake Ojibway in northern Ontario and northeastern Quebec, and drained into the Ottawa River valley and thence to the North Atlantic Ocean via the St. Lawrence River valley (Teller and Leverington 2004), thereby bypassing the Great Lakes basin; see Figure 1.

Recent construction of an empirical exponential model of isostatic uplift for the Great Lakes region following the last glaciation allowed comparison of the elevations of rebounding lake outlets with reconstructed lake levels based on ^{14}C-dated water level indicators such as abandoned shorelines, isolation basins, submerged tree stumps, and unconformities (Lewis *et al.* in press a, b). The early

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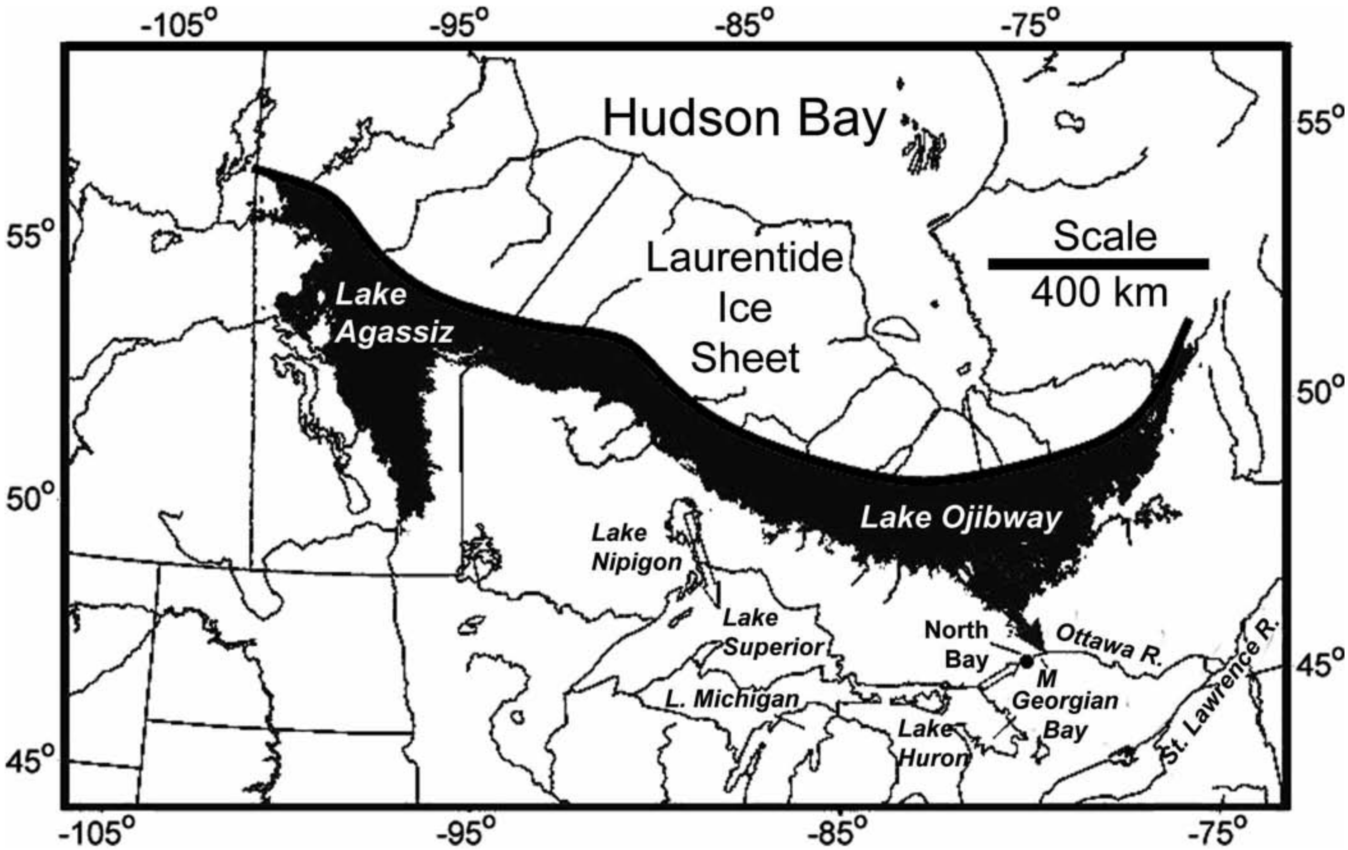

FIG. 1. Paleogeography of the region north of the upper Great Lakes at 7,900 ^{14}C BP when the combined outflow of Lakes Agassiz and Ojibway was routed to the Ottawa and St. Lawrence river valleys (solid arrow). At this stage the water supply of the Great Lakes was no longer supplemented by inflow from upstream sources, but was supplied by precipitation alone, as at present. Prior to 8,000 ^{14}C BP, overflow from Lake Agassiz passed into the Lake Nipigon and Lake Superior basins (open arrow). The upper Great Lakes then overflowed the North Bay outlet (open arrow) into the Mattawa River (M) and thence to the Ottawa and St Lawrence river valleys. Adapted from Figure 4p in Teller and Leverington (2004).

Holocene results for the Huron, Georgian Bay, and Michigan basins reveal several periods of low lake levels (lower than present) due to overflow drainage through the isostatically depressed outlet area near North Bay, Ontario, to the Ottawa and St. Lawrence valleys; see Figure 1. These results were anticipated on the basis of previous syntheses (Eschman and Karrow 1985; Hansel *et al*. 1985; Lewis and Anderson 1989; Barnett 1992; Clark *et al*. 1994; Colman *et al*. 1994a, b; Lewis *et al*. 1994; Rea *et al*. 1994; Moore *et al*. 1994, 2000; and Larson and Schaetzl 2001). Surprisingly, however, the results showed that lake levels fell below the Huron-Michigan basin outlet after 8,000 ^{14}C years BP, possibly for a few centuries during which lowest water levels were up to 30 m below the overflow sill at North Bay; see Figure 2.

The inferred 7,900 ^{14}C years BP low stand of the Michigan and Huron basins occurred after melt water drainage from upstream glacial Lake Agassiz began to bypass the Great Lakes basin, leaving it susceptible to the early dry Holocene climate (Edwards *et al.* 1996). As the Great Lakes basin had then entered its present hydrological regime of water supply by precipitation only, and as differential glacial-isostatic crustal uplift was accounted for, the only known process that could explain the sub-outlet low levels is climatic reduction in water supply, either by enhanced evaporation or reduced precipitation or both. [This result for the Huron and Michigan basins is similar to the conclusions of Holcombe *et al.* (2003) who recognized low-level shore features beneath Lake Erie, and noting the

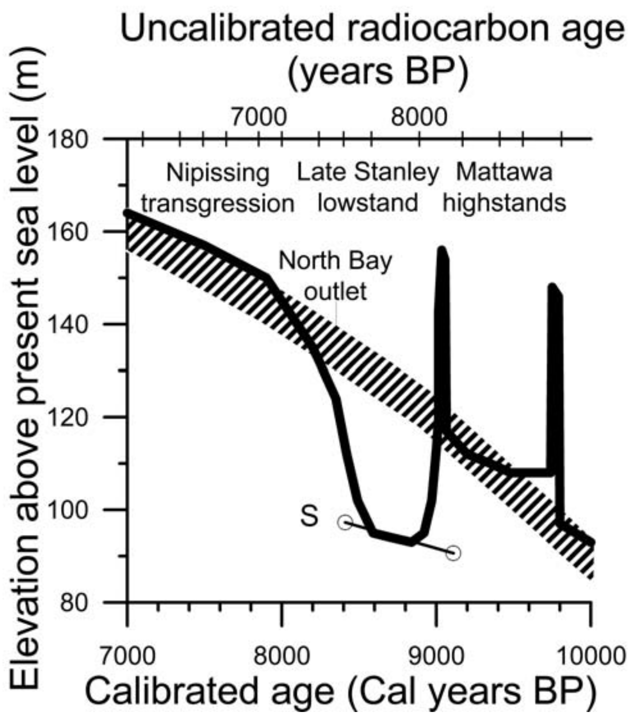

FIG. 2. Huron basin lake level (black line) between 10,000 and 7,000 cal BP based on the original elevations of lake-level indicators computed by an empirical exponential model of glacial rebound for the Great Lakes basin that removes the effects of glacial-isostatic uplift. For clarity, data are removed from the plot except for the Stanley unconformity constraint (S). At about 7,900 ^{14}C BP (about 8,800 cal BP) the lake level, indicated by the Stanley unconformity (S–line indicates original elevation and circles bracket its age of 7,900 ± 300 ^{14}C BP), descended tens of meters below the North Bay outlet (gray band), the lowest possible point of overflow for the Huron basin at the time. The thickness of the grey band indicates the depth of water over the outlet sill at full discharge. Adapted from Lewis et al. (in press a, b).

high level of evaporative losses in the present Lake Erie water balance, suggested that the Erie lake level may have fallen below the level of its outlet sill because of enhanced evaporation sometime in the early to middle Holocene.] This episode of lowest levels appears as an extraordinarily severe impact of a dry climate, possibly of short duration, on the upper Great Lakes hydrological system and may have extended to the lower lakes.

Preliminary study of thecamoebians and pollen in the sediment sequence of Georgian Bay suggests increased lake water salinity and reduced precipitation at the time of the closed low stands (Sarvis 2000, Blasco 2001), conditions that are consistent with reduced water supply. In Hamilton Harbour, western Lake Ontario, studies of ostracodes (Delorme 1996), diatoms, pollen, and isotopes (Duthie *et al*. 1996) all reveal a low water phase and suggest a drier climate about 7,500 ^{14}C years BP. Similarly, in Mud Lake on the Keweenaw Peninsula beside Lake Superior, pollen and plant macrofossil analyses indicate an onset of a drying episode at 7,900 ^{14}C years BP with notably reduced water levels extending to after 7,000 ^{14}C years BP (Booth *et al*. 2002). As these widely-separated sites both indicate a lowering of lake levels and onset of a drier climatic episode, it is reasonable to envision that the inferred dry climate conditions that impacted the Huron and Michigan basins also affected other basins of the Great Lakes system. The low stand period correlates also to a relatively rapid transition in vegetative cover in the Great Lakes region from boreal to the mixed Great Lakes-St. Lawrence Forest as recorded in pollen diagrams (McAndrews 1994, Dyke *et al.* 2004). Complementary review and assessment of the available paleoclimate information for the Great Lakes watershed, coupled with new studies of proxy climatic and limnological indicators (pollen, isotopes, diatoms, ostracodes, and thecamoebians) focused on the period spanning the closed low stand are in progress, and will be reported in future publications.

For this re-assessment, it would be helpful to obtain approximate information about the amplitude of climatic change that might be expected to have caused the upper Great Lakes low stands. Accordingly, we have used a hydrological model to explore the excursion from the present climate that would force the Great Lakes into hydrologic closure in terms of increased temperature and reduction in precipitation. In this study, the hydrology of the Erie and Ontario basins is considered separately from that of the upper Great Lakes, as the isostatically-depressed North Bay outlet for the upper lakes remained at a lower elevation than the St. Clair River connection to Lake St. Clair and Lake Erie until much later, about 5,500 ^{14}C years BP (Eschman and Karrow 1985). Other attributes of the region such as land cover, geography, and bathymetry were modeled as they are at present.

This low stand episode offers an opportunity, once paleoclimate is better quantified, to acquire information about the hydrological sensitivity of the Great Lakes system to high-amplitude climate change. Such information would be beneficial for model studies and projections of future levels of the Great Lakes under global warming in which some climate modeling scenarios project levels below instrumentally-observed “natural variability” (Mortsch and Quinn 1996, Mortsch *et al.* 2000, Lofgren *et al.* 2002). It should be noted that the 7,900 ^{14}C years BP low stand episode occurred while the residual Laurentide ice sheet, then in the latitudes of Hudson Bay, was rapidly retreating and wasting away (Dyke *et al.* 2003). This was a period of rapid change in the proportions of land, ice, and water areas, with parallel changes in albedo and reorganization of atmospheric circulation (Dean *et al.* 2002). As a result, the inferred occurrence of closed low stand conditions in the Great Lakes basin is seen as a product of extremely unusual conditions. It is not regarded as an analog for future conditions, but rather, as a natural experiment from which important information about lake-climate sensitivity might be derived.

The purpose of this paper is to demonstrate that if a climate is extreme enough, levels on some Great Lakes would drop sufficiently to cut off outflow, thereby making those lakes terminal. We look at excursions in temperature and precipitation from the present climate to disclose those values that would drive the Great Lakes hydrology to produce terminal lakes. This is not an attempt to simulate past hydrology exactly, but to explore the possible magnitude of changed climates that might have produced terminal lakes about 7,900 ^{14}C years ago in accordance with recently acquired glacial-isostatic rebound evidence that Huron and Michigan basin lake levels had descended below their overflow outlets.

Study Area

The Great Lakes basin area is 770,000 km^2 (300,000 mi^2), about one-third of which is water surface; see Figure 3. The basin extends 3,200 km (2,000 mi) from the western edge of Lake Superior to the St. Lawrence Power Project, Cornwall, Ontario on the St. Lawrence River. The water surface drops in a cascade over this distance some 180 m (600 ft). Lake Superior is largest and deepest and has two diversions into it: the Long Lac and Ogoki. Lake Superior flows through the lock and compensating works at Sault Ste. Marie and down the St. Marys River into Lake Huron where it is joined by water flowing from Lake Michigan. Lake Superior outflows and levels are regulated to balance Lakes

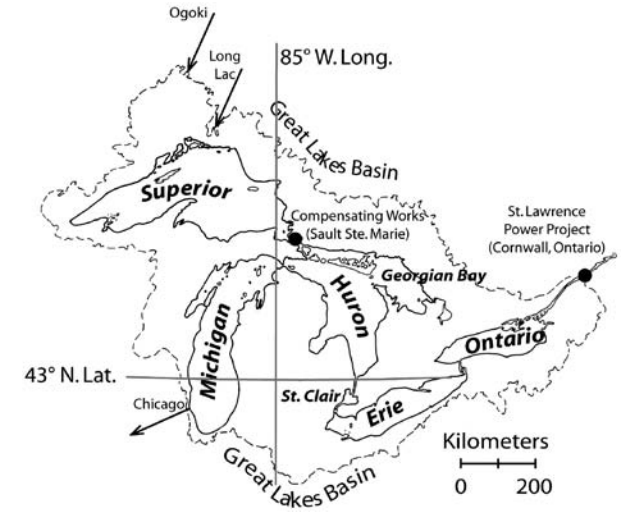

FIG. 3. Laurentian Great Lakes location map.

Superior, Michigan, and Huron water levels, according to Regulation Plan 1977, under the auspices of the International Joint Commission.

Lakes Michigan and Huron are considered to be one lake hydraulically because of their connection through the deep Straits of Mackinac. A relatively small flow of Lake Michigan water is diverted into the Mississippi River basin at Chicago. The water flows from Lake Huron through the St. Clair River, Lake St. Clair, and Detroit River system into Lake Erie. The drop in water surface between Lakes Michigan-Huron and Lake Erie is only about 2 m (8 ft). This results in a large backwater effect between Lakes Erie, St. Clair, and Michigan-Huron; changes in Lakes St. Clair and Erie levels are transmitted upstream to Lake Michigan-Huron.

From Lake Erie, the flow is through the Niagara River and Welland Diversion (used for navigation and hydropower) into Lake Ontario. There is also a small diversion into the New York State Barge Canal System which is ultimately discharged into Lake Ontario. Lake Ontario outflows and levels are regulated in accordance with Regulation Plan 1958D to balance interests upstream on Lake Ontario with those downstream on the St. Lawrence Seaway. The outflows are controlled by the Moses-Saunders Power Dam between Massena, New York and Cornwall, Ontario. From Lake Ontario, the water flows through the St. Lawrence River to the Gulf of St. Lawrence and to the Atlantic Ocean. Lakes Superior, Michigan, Huron, and Ontario are very deep (229–405 m) while Lakes Erie and St. Clair are very shallow (6–64 m).

Approach

We use the Great Lakes Environmental Research Laboratory's (GLERL's) Advanced Hydrologic Prediction System (AHPS), a system of hydrology, thermodynamic, and hydraulic models for the Great Lakes (Croley 2005). GLERL uses these models to make probabilistic outlooks of Great Lakes hydrology and water levels (see http://www.glerl.noaa.gov/wr/ahps/curfcst /curfcst.html), and to assess climate change impacts in the Great Lakes (Croley and Luukkonen 2003, Croley 2003, Lofgren *et al.* 2002, Quinn and Croley 1999, Croley *et al.* 1998). For the purpose of this study, we adjusted the present models to simulate the Great Lakes in their pre-European-settlement natural state by removing the influences of channel control works and regulation plans. Also, we kept watersheds of the upper and lower lakes separate, as they were during the early Holocene, i.e., no outflow from the Huron basin to the St. Clair-Erie basin. Accordingly, we use the models here with water balances on all lakes, and with lake outflow rating curves, selected to represent "natural" or "pre-development" conditions. We account for lake area variations with changes in water level, but do not remove present-day diversions and consumptions as they are relatively insignificant for our purpose.

First we consider all lakes as interdependent (as they are now, but with "natural" outlet and connecting channel flows) to see if simulations with historical meteorology (1948–1999) produce hydrology and lake levels comparable with the historical records. This allows us to assess the reasonableness of the modified models. Then, we model two systems of Great Lakes independently: 1) Lakes Superior, Michigan, and Huron (the upper Great Lakes), and 2) Lakes St. Clair, Erie, and Ontario (the lower Great Lakes) with no inflow from the upper Great Lakes since they drained via the North Bay outlet to the Mattawa and Ottawa rivers when overflow occurred prior to and after the low stand 7,900 ^{14}C years ago. Next, we consider steady state hydrology by modeling over an extended period constructed by repeating the adjusted meteorological record until consecutive 52-year segments are identical. We finally consider each lake as part of its parent system (upper or lower system) with a water balance on all lakes.

CHANGED-CLIMATE METHODOLOGY

The hydrology models here use daily meteorological data from 1948–1999, compiled from about 1,800 stations for over-land meteorology (precipitation and air temperature) and about 40 stations for over-lake meteorology (air temperature, humidity, wind speed, and cloud cover); see Figure 4. These data, compiled for previous studies (Croley 1990, Hartmann 1990, Croley 1992b, Croley *et al*. 1998, Lofgren *et al*. 2002, Croley 2003), provide daily meteorological time series over each of the 121 riverine watersheds that drain into the Great Lakes and the seven Great Lake water surfaces. Annual average precipitation and air temperature are, respectively, 80.9 cm and 2.93°C (Superior basin), 84.5 cm and 6.49°C (Michigan-Huron), 91.9 cm and 9.19°C (Erie), and 92.3 cm and 7.41°C (Ontario). We used these historical meteorological data with our hydrology models (discussed subsequently) to compute the "present" or "base case" scenario. We then apply selected precipitation ratios and air temperature differences to the historical me-

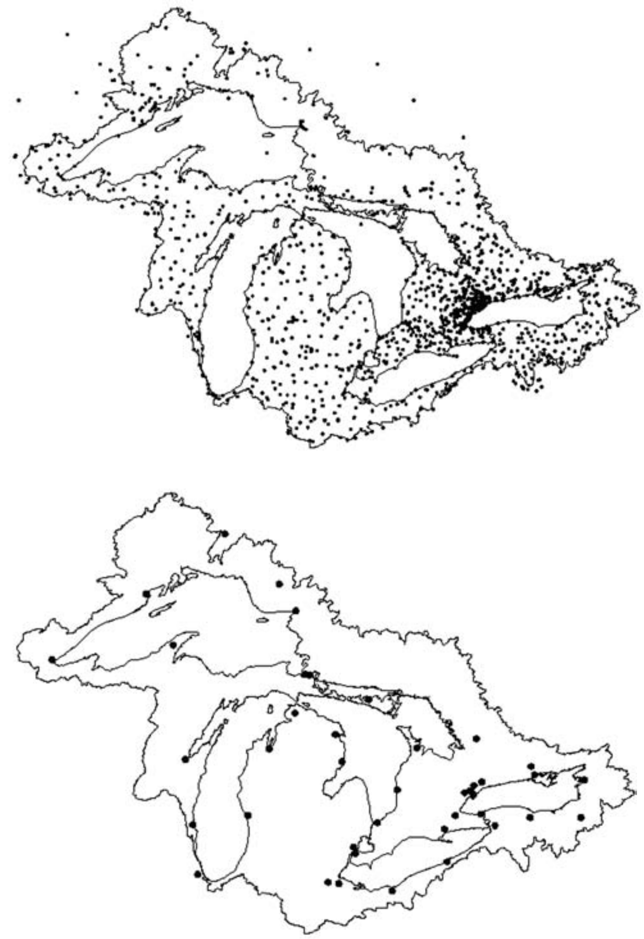

FIG. 4. Great Lakes Meteorological Station Network—overland (top) and overlake (bottom).

teorological data and use these modified meteorological time series with our hydrology models to construct changed climate scenarios.

All precipitation is adjusted by multiplying the actual precipitation by a single precipitation ratio and all air temperatures are adjusted by adding a single temperature difference to the actual temperatures. In addition, humidity is adjusted; for precipitation ratios below unity, which are all that are considered here, the absolute humidity is multiplied by the ratio. Thus, if precipitation is halved, then so is humidity.

HYDROLOGY MODELS

GLERL's AHPS consists of daily runoff models for each of the 121 watersheds, lake thermodynamic models for each of the seven water bodies, hydraulic models for the four connecting channels and five water body outflow points with operating plans encoded for Lakes Superior and Ontario, and simultaneous water balances on all the lakes. It is described in detailed overviews elsewhere (Croley 2003, 2005).

Runoff

GLERL's Large Basin Runoff Model (LBRM) consists of moisture storages arranged as a serial and parallel cascade of "tanks" coinciding with the upper and lower soil zones, a groundwater zone, and the surface channel system (Croley 2002). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Water percolates from the upper to the lower soil zone and from the lower to the groundwater zone (deep percolation). Water also flows from the upper, lower, and groundwater zones into the surface channel system, as surface runoff, interflow, and groundwater flow respectively. "Groundwater" refers to intra-, not inter-, watershed storage. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Evapotranspiration is proportional to available water and to sensible heat (a complementary concept in that evapotranspiration reduces available sensible heat). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration. Complete analytical solutions exist. The model has been calibrated to each of the 121 watersheds contributing to the Great Lakes by minimizing root mean square error between daily model outflows and adjusted outflow observations. Each calibration determined parameters for infiltration, snow melt, surface runoff, percolation, interflow, deep percolation, groundwater flow, surface storage, and evapotranspiration from all moisture storages by systematically searching the parameter space (with a gradient-search technique). The model agrees quite well with weekly and monthly outflow observations (Croley 2002, 2003). These parameters represent present-day hydrology and are not changed in the simulations. All 121 model applications are used in the simulations.

Evaporation

GLERL's Lake Thermodynamic Model adjusts over-land data (original or adjusted as a changed-climate scenario) from the 40 over-land stations that are used to estimate over-water meteorology for over-water or over-ice conditions based on empirical relationships between the two (Croley 1989, 1992a; Croley and Assel 1994). Surface flux processes are represented for reflection and short-wave radiation, net long-wave radiation, and advection. Aerodynamic equation bulk transfer coefficients for sensible and latent heat are formulated with atmospheric stability effects. Energy conservation accounts for heat storage; superposition of heat additions or losses determines temperature-depth profiles. Each addition is parameterized by age and mixes throughout the volume. Mass and energy conservation account for ice formation and decay. The model has been calibrated to each of the seven lake surfaces by minimizing root mean square error between daily model surface temperatures and observations. The model enables one-dimensional modeling throughout of spatially averaged water temperatures over the lake depth and can be used to follow thermal development and turnovers in the lake.

Lake Area Adjustment

For each lake, precipitation p is provided as a scenario-dependent boundary condition and runoff r and evaporation e are estimated with the runoff and evaporation models. They are expressed as depths over the lake surface, in m, for a given time interval (day), and are based on the lake area C as coordinated between the US and Canada (CCGLBHHD 1977). That is, no variation of lake area is actually considered in their determination in the runoff and evaporation models. However, we adjust to actual lake area A by converting these depth rates into volumetric flow rates,

$$P = \frac{pA}{\Delta} \tag{1}$$

$$R = r\frac{C}{B-C}\frac{B-A}{\Delta} \tag{2}$$

$$E = \frac{eA}{\Delta} \tag{3}$$

where P = volumetric precipitation rate in m^3s^{-1}, R = volumetric runoff rate in m^3s^{-1}, E = volumetric evaporation rate in m^3s^{-1}, B = basin area (including the lake), and Δ = number of seconds in the time interval. Note, B and C are constants for a lake while p, r, e, and A vary with time. Precipitation and evaporation are directly converted by simply multiplying the overlake rates by actual lake area. Runoff is first multiplied by the coordinated lake area (over which it was expressed) to calculate the modeled runoff volume, then divided by the coordinated land area (to express it as the equivalent yield per unit of land area), and then multiplied by the actual land area to calculate the adjusted runoff volume. Thus "R" gets bigger as "A" gets smaller. Of course, there is some error involved with this procedure since p, r, and e actually depend on actual lake area too and should have been computed from models considering actual lake area and volume changes. Also, exposed land areas would not have the same properties as the original basin. Consideration of the uncertainty associated with these errors is beyond the scope of this exploratory study.

Outflow Relations

Unmanaged lake outflow depends on lake level and outflow sill elevation for lakes not affected by backwater (such as Superior, Erie, and Ontario) or on these variables as well as downstream lake level for lakes affected by backwater (such as Michigan-Huron and St. Clair). (We consider the present Great Lakes here to facilitate later validation of the model.) Southam (1989) described a quantitative empirical relationship between water elevation and outflow for each lake that represents "natural" conditions, prior to the introduction of societal developments. For the Laurentian Great Lakes watershed, these developments include regulation of outflows of Lakes Superior and Ontario, modification of connecting channels through dredging or shoreline changes, use of ice control measures, and diversion of water into and out of the lakes. Any impacts caused by land use modification, consumptive uses, and regulation of tributary rivers are viewed as reflected by changes in water supplies to the lakes and not by changes in elevation—outflow relationships, and were not considered in that study. We converted Southam's relationships from their original English units and IGLD'55 water level datum (CCGLBHHD 1979) to metric units and IGLD'85 water level datum (CCGLBHHD 1995), respectively (Croley 2006). We also transformed his Lake Erie adjustment for channel project removals to one compatible with basic weir formulae and expressed Ontario outflows in terms of the 1985 sill elevation (Croley 2006). The resultant equations are

$$Q_S = 824.721(Z_S - 181.425)^{1.5} - H_S, \qquad Z_S \geq 181.425 \tag{4}$$

$$\begin{aligned} Q_T &= 46.440\left(\frac{1}{2}Z_T + \frac{1}{2}Z_C - 166.549\right)^2 (Z_T - Z_C)^{\frac{1}{2}} - H_T, && Z_T \geq Z_C \geq 166.549 \\ &= 46.440\left(\frac{1}{2}Z_T - \frac{1}{2}166.549\right)^2 (Z_T - 166.549)^{\frac{1}{2}} - H_T, && Z_T \geq 166.549 > Z_C \end{aligned} \tag{5}$$

$$\begin{aligned} Q_C &= 70.714(Z_C - 165.953)^2 (Z_C - Z_E)^{\frac{1}{2}} - H_C, && Z_C \geq Z_E \geq 165.953 \\ &= 70.714(Z_C - 165.953)^2 (Z_C - 165.953)^{\frac{1}{2}} - H_C && Z_C \geq 165.953 > Z_E \end{aligned} \tag{6}$$

$$Q_E = 701.504(Z_E - 169.938)^{1.5} - H_E, \qquad Z_E \geq 169.938 \tag{7}$$

$$Q_O = 577.187(Z_O - 69.622)^{1.5} - H_O, \qquad Z_O \geq 69.622 \tag{8}$$

where Q_S, Q_T, Q_C, Q_E, and Q_O = outflows from Lakes Superior, Michigan-Huron, St. Clair, Erie, and Ontario, respectively in m^3s^{-1}, Z_S, Z_T, Z_C, Z_E, and Z_O = respective water elevations with respect to the IGLD'85 water level datum in m, and H_S, H_T, H_C, H_E, and H_O = respective ice retardations in m^3s^{-1} as shown in Table 1. Note, outflows are zero

TABLE 1. Great Lake outflow ice and weed retardation[a] (Southam 1989).

Month (1)	Superior m^3s^{-1} (2)	Mich.-Huron m^3s^{-1} (3)	St. Clair m^3s^{-1} (4)	Erie m^3s^{-1} (5)
January	113	1,020	425	113
February	113	136	425	142
March	113	651	227	85
April	113	170	57	142
May				
June				57
July				142
August				113
September				85
October				57
November				
December		113	142	

[a]No values for Ontario are given in the reference.

when elevation is below the "sill" elevation of the lake; the sill is the lowest elevation for which flow from the lake is still possible (e.g., Lake Superior's sill level is 181.425 m). We ignore the small elevation differences, introduced by the datum change, between Michigan-Huron and St. Clair levels and between St. Clair and Erie levels to keep the equations physically meaningful; i.e., when Lakes Michigan-Huron and St. Clair are at the same level ($Z_T = Z_C$) or Lakes St. Clair and Erie are at the same level ($Z_C = Z_E$), there should be no flow between the respective pair of lakes ($Q_T = 0$ or $Q_C = 0$). However, backflow is possible from Lake Erie to Lake St. Clair and from Lake St. Clair to Lake Michigan-Huron. This backflow is not described by these equations (but is addressed subsequently).

Note that when St. Clair water level is below the Michigan-Huron sill, the sill elevation is controlling in (5); likewise when Erie water level is below the St. Clair sill, the sill elevation is controlling in (6). These are reasonable extensions, made here to allow flow computations as lake levels drop below those historically experienced. Note that $Q_S = 0$ when the Superior water level is below the sill of 181.425m, $Q_T = 0$ when Michigan-Huron is below the sill of 166.549 m, $Q_C = 0$ when St. Clair is below the sill of 165.953 m, $Q_E = 0$ when Erie is below the sill of 169.938 m, and $Q_O = 0$ when Ontario is below the sill of 69.622 m.

Since (4)–(8) were derived from semi-empirical stage-fall-discharge or rating curves that were fit to a range of flows and elevations not necessarily close to the sill, the sill elevations estimated here are in error. Sill heights on all lakes but St. Clair are well above the bottom of the lake. On Lake St. Clair, the bottom of the lake is 168.4 m (subtract maximum coordinated depth from chart datum in column 6 of Table 2); this is above the Michigan-Huron and St. Clair sills. This corresponds to a channel running along the bottom of Lake St. Clair; i.e., the lake bottom is at the top of this channel and we can have flow from the Lake St. Clair basin without lake storage. Since the lake bottom is below the Erie sill of 169.938 m, we see that St. Clair will never be empty as long as Lake Erie is not terminal (water line above its sill). Lake outflows in (4) and (5)–(8) are set to zero when negative values would be computed (ice retardation would drop to equal flow rate).

Hypsometric Relations

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD 1977) provided graphical relations, for each lake, between depth and volume; inspection reveals that simple power relations are a very good fit,

$$V = a(M - D)^b$$
$$A = -\frac{d}{dD}V = ab(M - D)^{b-1} \qquad (9)$$

where A = area of horizontal surface at depth D below a reference elevation, M = maximum depth, V = lake volume beneath horizontal surface at depth D, and a and b are empirical parameters. By requiring that the coordinated values of area, C, and vol-

TABLE 2. Coordinated values of Great Lake parameters (CCGLBHHD 1977).

Parameter (1)	SUP (2)	MIC (3)	HUR (4)	GEO (5)	STC (6)	ERI (7)	ONT (8)
chart datum, m	183.2	176.0	176.0	176.0	174.4	173.5	74.2
maximum depth, m	405	281	229	164	6	64	244
coordinated area, km^2	82,100	57,800	40,640	18,960	1,114	25,700	18,960
coordinated volume, km^3	12,100	4,920	2,761	779	3.4	484	1,640

ume, S, (CCGLBHHD 1977) exist at the reference elevation (chart datum), where $D = 0$, for each lake, as in Table 2, the parameters are

$$a = M\frac{C}{S} \qquad b = \frac{S}{M^a} \tag{10}$$

Writing (9) in terms of elevation instead of depth,

$$V = a(Z - Z_B)^b \qquad A = ab(Z - Z_B)^{b-1} \tag{11}$$

where Z = elevation at depth D, in m, and Z_B = elevation of lake bottom, in m, given from Table 2 by subtracting maximum depth from chart datum.

Water Balance

The adjusted over-lake precipitation, runoff to the lake, and lake evaporation are used in a water balance,

$$\frac{dV}{dt} = I - Q + P + R - E \tag{12}$$

where t = time, I = volumetric water body inflow rate (outflow from the upstream lake) , and Q = volumetric water body outflow rate. Note that V, A, and Q are *not* simple functions of Z. Determination of the proper equation to use in (4)–(8) depends on downstream water level, which in turn depends on which equation is used. Likewise, backwater adjustments (described subsequently) are not reflected in (4)–(8). For these reasons, it is not possible to solve (1)–(12) analytically. Equations (1)–(3) and (12) are applied over time interval Δ to each water body based on the lakes and connecting channels arrangement,

$$\Delta V_S \cong (I_S - Q_S)\Delta + p_S A_S + R_S \frac{C_S}{B_S - C_S}(B_S - A_S) - e_S A_S \tag{13}$$

$$\begin{aligned}\Delta(V_M + V_H + V_G) \cong\ & (I_T - Q_T)\Delta \\ & + p_M A_M + R_M \frac{C_M}{B_M - C_M}(B_M - A_M) - e_M A_M \\ & + p_H A_H + R_H \frac{C_H}{B_H - C_H}(B_H - A_H) - e_H A_H \\ & + p_G A_G + R_G \frac{C_G}{B_G - C_G}(B_G - A_G) - e_G A_G\end{aligned} \tag{14}$$

$$\Delta V_C \cong (I_C - Q_C)\Delta + p_C A_C + R_C \frac{C_C}{B_C - C_C}(B_C - A_C) - e_C A_C \tag{15}$$

$$\Delta V_E \cong (I_E - Q_E)\Delta + p_E A_E + R_E \frac{C_E}{B_E - C_E}(B_E - A_E) - e_E A_E \tag{16}$$

$$\Delta V_O \cong (I_O - Q_O)\Delta + p_O A_O + R_O \frac{C_O}{B_O - C_O}(B_O - A_O) - e_O A_O \tag{17}$$

where ΔV = change in volume and the subscripts refer to individual Great Lakes or extended water bodies: Superior (S), Michigan (M), Huron (H), Georgian Bay (G), Michigan-Huron (T), St. Clair (C), Erie (E), and Ontario (O). Equation (14) considers Lakes Michigan and Huron, including Georgian Bay, as one water body. Boundary conditions are

$$I_S = 0 \tag{18}$$

$$I_T = Q_S \tag{19}$$

$$\begin{aligned} I_C &= Q_T, && \text{for upper Great Lakes flowing into lower} \\ &= 0, && \text{for upper Great Lakes flowing into the Mattawa and Ottawa basins}\end{aligned} \tag{20}$$

$$I_E = Q_C \tag{21}$$

$$I_O = Q_E \tag{22}$$

For each water body, it is necessary to compute the inflow as outflow from the upstream lake, the lake(s) area, and the adjusted net basin supplies as part of the solution. This requires calculating lake levels as part of the water balance. We solve (4), (5)–(8), (11) for each lake, (13)–(17), and (18)–(22) simultaneously at each time step. Our numerical procedure at each time step is: ***i***) given p, r, e, and Z_0 (water elevation at beginning of time step) for all lakes, ***ii***) calculate A_0 (lake area at beginning of time step) and V_0 (lake volume at beginning of time step) for all lakes from (11) and Q_0 (outflow rate at beginning of time step) for all water bodies from (4) and (5)–(8), ***iii***) approximate Z_1 (end-of-time-step water elevation) as Z_0 for all lakes, ***iv***) calculate A_1 (end-of-time-step lake area) for all lakes from (11) and Q_1 (end-of-time-step water body outflow rate) for all water bodies from (4) and (5)–(8), ***v***) approximate outflow rates and lake areas over the time increment as linear, $Q = (Q_0 + Q_1)/2$ and $A = (A_0 + A_1)/2$, ***vi***) calculate the changes in storage for all water bodies over the time interval by using these approximate outflow rates and lake areas in (13)–(17) and (18)–(22), and ***vii***) calculate $V_1 = V_0 + \Delta V$ for each lake and then find Z_1 by using V_1 with (11) for each water body (for Lake Michigan-Huron, interpolate for Z_1 by using V_1 with (11) applied to Lakes Michigan, Huron, and Georgian Bay and summed). Repeat steps ***iv–vii*** until successive values of Z_1 for all lakes change negligibly. Repeat steps ***i–vii*** for the next time step, and so forth.

When solving (4), (5)–(8), (11), (13)–(17), and (18)–(22), we check and correct for backflow between lakes. This could occur if water levels on Lake Erie are above those on St. Clair (and above the St. Clair sill) or those on St. Clair are above those on Lake Michigan-Huron (and above the Michigan-Huron sill). For those times when backflow would occur between two lakes, we simply balance the lakes involved so that water levels on both are equal and the flow between them is zero. Furthermore, we consider sill heights in this adjustment and do not let backflow reduce a lake's level below the upstream sill. Note that backflow does not occur when simulating the existing system with the existing climate. It also does not occur when simulating the upper lake system (Superior, Michigan, and Huron) with any climate since (5) is replaced with a relation that is a function of Michigan-Huron levels only (discussed subsequently). Backflow corrections are only required when simulating the existing system or the lower lake system (St. Clair, Erie, and Ontario) with warmer or dryer climates. The equations solution converges to an insignificant difference within 2–15 iterations (the difference between water elevations in successive iterations, summed over all lakes, is less than one thousandth of a millimeter).

VALIDATION

To check the models and water balance approximations, we simulated the entire interconnected Great Lakes for the historical meteorological record. First, we compared simulated net basin supplies (precipitation + runoff – lake evaporation) resulting from the model, applied to the historical meteorological record with actual initial conditions, directly to historical net basin supplies (computed as a water balance residual from historical lake levels and flows). Figure 5 compares our estimates with historical NBS and shows good agreement, as expected since historical meteorology data are used in the simulation. Differences can be ascribed to water balance errors in the computation of residual NBS and to modeling errors in the computation of the NBS components. The biggest differences occur on Lake Ontario, suggesting they arise from water balance errors in computing the historical residual NBS.

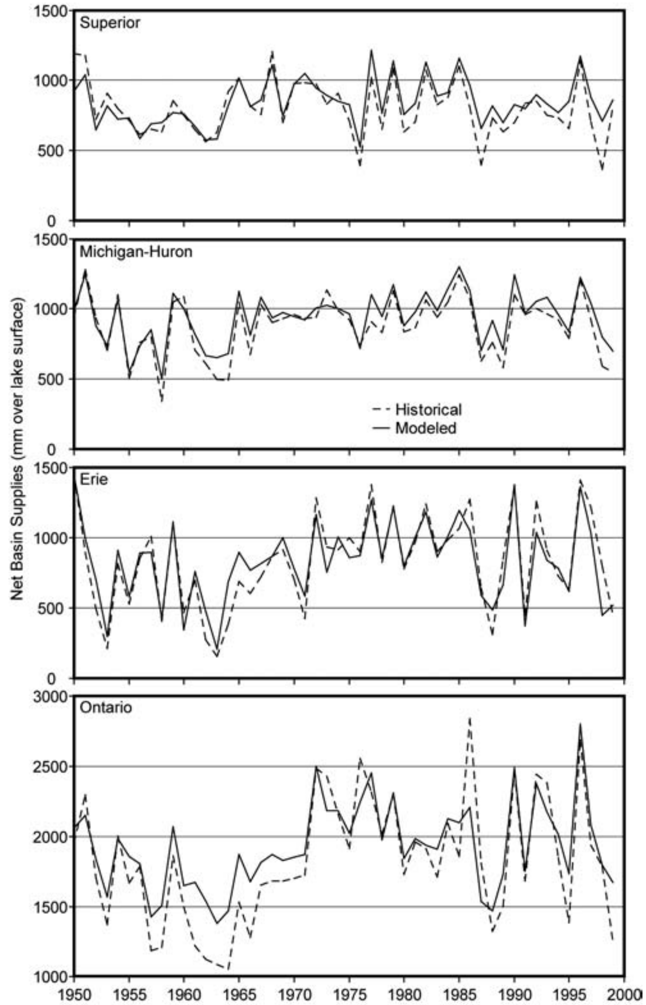

FIG. 5. Net basin supply comparison for 1948-1999 showing reasonable agreement between water supplies based on computation of observed lake levels and flows (historical) and supplies simulated from observed meteorology (modeled).

Next, we compared simulated lake levels resulting from the model, applied to the historical meteorological record with actual initial conditions, directly to historical levels. For this comparison, we

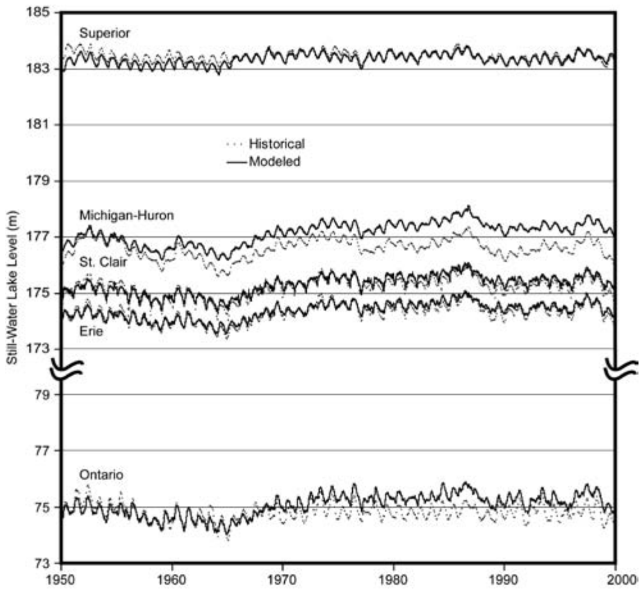

FIG. 6. Great Lake levels as observed 1948-1999 (historical) compared with simulated levels (modeled) showing reasonable agreement.

included all diversions but used the natural outflow and channel relationships. Figure 6 is a plot of daily simulated levels and monthly historical levels; it shows fair agreement, but has expected deviations. On Superior, levels match well with historical data after about 1965 but differ before; this could be due to sparse water level station networks prior to 1965 (hard to evaluate), poorer meteorological estimates prior to 1965 (when station densities are lowest on Superior and areal estimates are often underestimated), and differences in the outflow and channel relationships (water was released on Superior in 1965 to alleviate low water levels downstream; there were also changes in the Superior regulation plan between 1970–77; the model simulation uses an unchanging outflow and channel relationship). On Michigan-Huron, it appears that the historical water levels are lower than the simulated; this lowering probably results from the historical changes in Lake Superior operations and in the St. Clair River channel which has been dredged over time. It also may be related to variation in crustal rebound occurring after retreat of the last ice sheet; crustal rebound results in relative tilting of Lake Michigan-Huron toward its outlet suggesting higher outflows and lower levels in the historical record than simulated (Quinn and Sellinger 1990). Lakes St. Clair and Erie are very similar to the simulation but Ontario shows lower water levels historically, probably as a result of the difference between regulated Niagara flows and the natural outflow and channel conditions. The model appears to simulate the system reasonably well when all sources of differences between the simulations and historical flows are considered. Connecting channel flow differences (not shown here) also match well.

CHANGED CLIMATES

Before applying the simulations to changed climates (i.e., changed temperature and precipitation), we ascertained that the present-day diversions in the hydrology models were on the order of a few centimeters; see Table 3 (IGLDCUSB 1985). [Note that these diversions affect lakes upstream as well as downstream. The Chicago diversion affects Superior because resultant lower Michigan-Huron levels are used in regulation of Superior. The Welland diversion lowers Lake Erie and, because of connecting channel hydraulics (upstream and downstream lake levels determine channel flow), lower Erie levels lower Michigan-Huron and lower Michigan-Huron levels lower Superior as just discussed.] Thus, they are negligible compared to the changes in net basin supplies or drops in water levels to be simulated with changed climates. Therefore, we ignore them; no effort was made to remove these diversions from the existing models.

TABLE 3. Summary of average annual Great Lakes diversion impacts (IGLDCUSB 1985).

Diversions (1)	Amount (m^3s^{-1}) (2)	Superior (cm) (3)	Mich.-Huron (cm) (4)	Erie (cm) (5)	Ontario (cm) (6)
Ogoki-Long Lac	160	+6	+11	+8	+7
Chicago	90	–2	–6	–4	–3
Welland	270	–2	–5	–13	0
COMBINED	—	+2	–1	–10	+2

Steady-State Simulation

We use both the historical and modified meteorological time series with our models to simulate base case and climate change hydrology scenarios, respectively. We estimate steady state hydrology by modeling with arbitrary initial conditions (snow pack, water storages in the basins, thermal structure of the lakes, lake levels, and so forth) over an extended period constructed by repeating the adjusted meteorological record until consecutive 52-year segments are identical. (The models always converge no matter where started). The number of iterations required to reach this state depends largely on the arbitrary lake level assumed at the beginning and the final lake levels; it sometimes represents a longer time than might be expected for the climate change itself. (The effect of the initial conditions other than lake levels is much shorter, usually on the order of a couple of years.) However, since lake levels are unknown prior to the changing climate and since we want to avoid representing climate change as abrupt, we use this "steady-state" behavior to assess the effects of climate change.

Upper Great Lakes

Separating upper lakes (Superior, Michigan, Huron) from lower lakes (St. Clair, Erie, Ontario), for purposes of simulating the system about 7,900 ^{14}C years BP, is accomplished by changing Lake Michigan-Huron outflow to a function only of the water level in Lake Michigan-Huron (and not of St. Clair) and then by modeling only these upper lakes. The outflow function ideally should represent conditions of 7,900 ^{14}C years ago but those are as yet unknown. As a proxy, the spillway equation of (4), (7), or (8) was arbitrarily used along with the present-day sill elevation taken from (5). We determined the leading coefficient by trial and error to match a long-term water balance with historical levels,

$$Q_T = 185(Z_T - 166.549)^{1.5} - H_T, \quad Z_T \geq 166.549 \qquad (23)$$

Note again, outflow in (23) is set to zero for negative values or for elevations below 166.549 m.

When lake levels are always below the sill elevation, then the lake is terminal. We looked at 36 climate scenarios, each defined in terms of the precipitation drop from the base case (0–50% in steps of 10%) and the temperature rise above the base case (0–5°C in steps of 1°C). We calculated the steady-state average water level resulting from each and plotted it with precipitation drop and temperature rise as shown in Figure 7 for Lakes Superior and Michigan-Huron. Note three regions in each graph of Figure 7: the region where all water levels are above the sill elevation in the lower left of the graphs, the region where all water levels are below the sill elevation in the upper right of the graphs, and the intermediate region where water levels are both above and below the sill elevation. We determined the boundaries of these regions by looking at maximum and minimum water levels in each simulation and comparing them to the sill elevations. Since behavior of steady-state average water levels is fundamentally different in each of these regions, we restricted linear interpolation in each region to only values therein.

By using linear approximations, note that the climate isolines for a terminal Lake Superior in Figure 7 drop about 1°C for every 4.7% change in precipitation. Figure 7 suggests that Lake Superior should be a terminal lake for climates with a temperature rise T (°C) and a precipitation drop P (%) such that $4.7T + P > 60$. Likewise, the isolines in Figure 7 for a terminal Lake Michigan-Huron drop about 1°C for every 4.5% change in precipitation; Lake Michigan-Huron should be terminal for climates with a temperature rise T (°C) and a precipitation drop P (%) such that $4.5T + P > 63$.

Lower Great Lakes

For the lower Great Lakes, we looked at Lakes St. Clair, Erie, and Ontario, with no inflow to Lake St. Clair as was the case prior to and after the low stand 7,900 years ago when Michigan-Huron flowed into the Mattawa and Ottawa watersheds; see (20). Since the St. Clair lake bottom is above its sill elevation, there can be flow into Erie even when Lake St. Clair is empty. Thus, St. Clair can never be terminal (with water still in it); it can only dry up. We have to consider Lakes St. Clair and Erie as one water body to investigate Lake Erie becoming terminal. We looked again at the 36 climate scenarios, previously defined, and calculated the steady-state water levels resulting from each. We found that Lake Erie became terminal in this range of climate variations but Lake Ontario did not. Therefore, we considered a larger range of climate variations by taking nine precipitation ratios (0–80% in steps of 10%) and eleven temperature rises (0–10°C in steps of 1°C) and plotted the average steady-state water

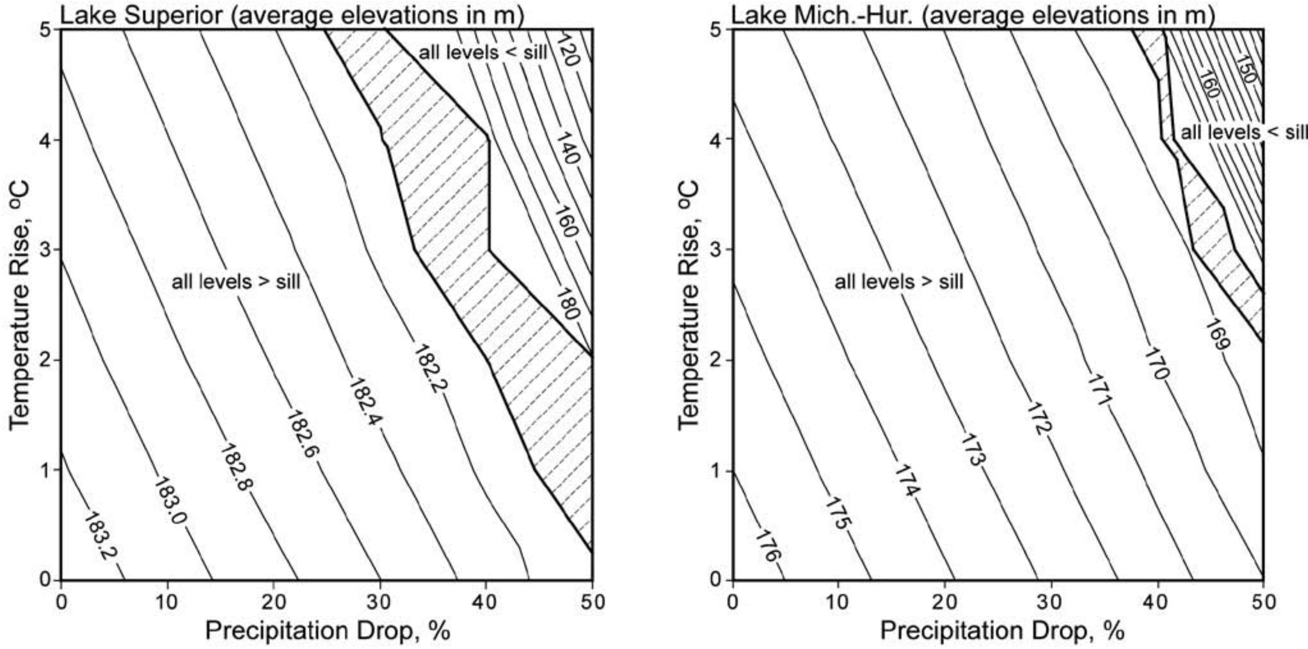

FIG. 7. Steady-state upper Great Lakes average water levels as a function of temperature rise and precipitation drop relative to the present base climate.

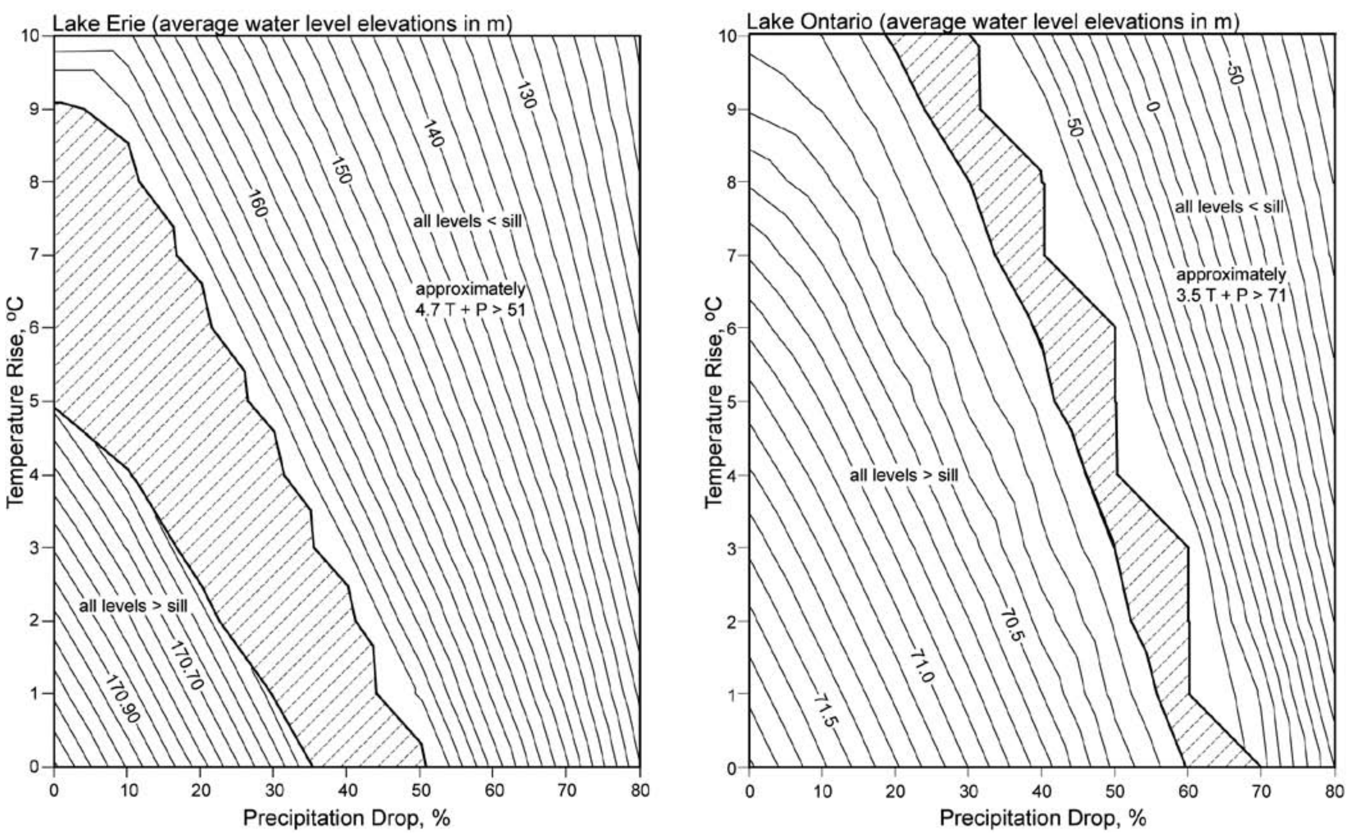

FIG. 8. Steady state lower Great Lakes average water levels as a function of temperature rise and precipitation drop relative to the present base climate.

level resulting from each in Figure 8 for Lakes Erie and Ontario.

Note that we again define three regions in each graph of Figure 8 for water levels above the sill, below the sill, and both above and below the sill, by looking at maximum and minimum water levels and sill elevations. We again restrict linear interpolation in each region to only values in that region. Note that the isolines for a terminal Lake Erie in Figure 8 drop about 1°C for every 4.7% change in precipitation. Figure 8 suggests that Lake Erie should be a terminal lake for climates with a temperature rise T (°C) and a precipitation drop P (%) such that $4.7T + P > 51$. Likewise, the isolines in Figure 8 for a terminal Lake Ontario drop about 1°C for every 3.5% change in precipitation; Lake Ontario should be terminal for climates with a temperature rise T (°C) and a precipitation drop P (%) such that $3.5T + P > 71$.

SENSITIVITIES

Each climate considered herein is specified over the entire upper Great Lakes basin or over the entire lower Great Lakes basin in their respective analyses. That is, the same changes made to historical data, to construct a hypothetical climate, were used across all water bodies and their basins in each analysis. For example, the 1°C increase applied to Lake Ontario meteorological data was applied at the same time to the Lake Erie meteorological data in the analyses. Thus, no consideration is made of more complex changed climates (such as a 1°C change in Lake Erie air temperatures with a 2°C change in Lake Ontario air temperatures). Given this limitation, the order of the lakes going terminal as climate gets warmer and drier is approximately: Erie, Superior, Michigan-Huron, and Ontario. (The order varies a little depending on the path of the changes from the present climate taken in Figures 7 and 8.) For both Great Lake subsystems (upper and lower), the uppermost lake goes terminal before the lowermost lake; this is not strictly necessary. There may be climates (where meteorological conditions are different over the uppermost lake and the lowermost lake) that would yield the lowermost lake terminal while the uppermost lake was not terminal. However, those changed climates were not investigated herein. As more is learned about past climates from paleoclimatic considerations, we can fine tune the observations made herein.

Likewise, the climate changes considered herein were simplified. We multiplied all historical daily precipitation amounts, without regard to season of the year, by a constant ratio and we added to all historical daily air temperatures, again without regard to season of the year, a constant value. Undoubtedly, we could consider more reasonable changes by considering the season of the year, and even location. Again, as more is learned about past climates from paleoclimatic considerations, we can make these additional considerations. However, we think these results are generally indicative of how climate effects would influence Great Lakes terminal lake status. Indeed, Lofgren *et al.* (2002) summarized many of the past Great Lake climate studies that used general circulation model experiments for $2\times CO_2$ studies; those climates that were warmer and drier showed good agreement with Figure 7.

Since we used only the available 52 years of daily meteorological data, continuously repeated, to represent steady-state, we biased our results somewhat; only the storm events on record are represented. The "transitional zone" in both Figures 7 and 8 might be wider if a longer period were used since more marginal storm events would be included that allowed some small outflow at water levels close to sill elevations.

There are also many errors of approximation in this study; our calculations used over-lake precipitation, over-lake evaporation, and runoff to the lake from models that assumed fixed values (coordinated between the U.S. and Canada) for lake areas and volumes, and then adjusted them for the actual lake and basin areas obtained in a comprehensive water balance. Better consideration would modify the runoff and lake evaporation models directly to consider the actual lake areas and volumes in an integrated water balance that employs these models directly. Likewise, the hypsometric relations and outflow relations (both rating coefficients and sill elevations) could be improved. Different sill elevations would shift the "terminal" lines in Figures 7 and 8.

Finally, the results do not exactly represent past hydrology (for example, paleo-lake areas have not been incorporated) so that results should be interpreted as exploration on the question of what could be reasonably envisioned as the effect of various climate scenarios on the hydrology of the pre-development Great Lakes. This is an attempt to study the question of "What magnitude of drying and warming of the present climate might produce terminal lakes as a guide to possible climate that apparently produced hydrologic closure of at least some of the Great Lakes about 7,900 ^{14}C years BP?"

It is possible that other aspects of climate may have been a factor in lowering lake levels about 7,900 ^{14}C years BP. In a study of the oxygen isotopic composition of inorganic carbonate, cellulose from fossil wood, and lake sediments in southern Ontario, Edwards *et al*. (1996) show significant increases of mean annual temperature and summer relative humidity from 8,000 to 7,000 ^{14}C years BP. The early part of this interval is characterized as cold and dry; only the latter part is interpreted as warm and dry relative to the present climate. West of Lake Superior, a study of Lake Ann sediments adjacent to a Holocene sand dune field showed that dune (wind) activity started about 8,000 ^{14}C years BP and was associated with relatively severe drought conditions (Keen and Shane 1990). Thus future paleohydrological modeling focused on the 7,900 ^{14}C years BP Great Lakes low stand may need to explore potential impacts under cold/dry and windy conditions. Likewise, insolation would have been different at the time of the low stands than at present. For example, at 9, 000 ^{14}C years BP the average northern hemisphere summer solar radiation was up to 30 W m^{-2} greater and in winter it was a similar amount lower that at present (Kutzbach and Web 1993).

SUMMARY

A new empirical model of glacial rebound and comparison of past lake level indicators with outlet elevations showed that lake levels in the Huron and Michigan basins had fallen below their outlets about 7,900 ^{14}C years BP (Lewis *et al*. in press a, b). As glacial-isostatic depression of outlets was accounted for, the only alternate known process that could close the lakes is enhanced evaporation, reduced precipitation, or both, in a dry climate. These findings motivated us to explore temperature and precipitation excursions of the present climate that might close the Laurentian Great Lakes as a guide to better understanding possible conditions at 7,900 ^{14}C years BP. We demonstrate the possibility that changed climates could produce terminal Great Lakes by using present hydrology with natural (predevelopment) channel and outflow conditions. We first integrated existing comprehensive models for present-day large basin runoff applied to each of the 121 watersheds draining into the Great Lakes, models of present-day large-lake thermodynamics applied to the seven water bodies of the Great Lakes, water balances of the lakes and their connecting channels, lake area adjustments relating supplies (lake precipitation, runoff, and evaporation) to the water balance, models of natural outflows and channel flows, present-day hypsometric relations, and a water balance of all lakes and connecting channels. We tested the integrated model with historical meteorological data (1948-1999) and found it to be a reasonable model of Great Lakes water levels. We built alternate climates from the historical meteorological record by reducing precipitation by fixed ratios and increasing temperature by fixed increments. We applied the integrated hydrology model to these alternate climates, producing associated alternate lake level time series. The applications were made separately in the upper and lower Great Lakes basins as overflows from the upper lakes prior to and after 7,900 ^{14}C years BP were routed via the Ottawa and St. Lawrence rivers, bypassing the Erie and Ontario basins completely.

The changed climate scenarios used in this study were simple: spatially and temporally constant adjustments were applied to historical meteorology for each watershed and lake surface to estimate changed-climate meteorology for each watershed and lake surface. More complex climate change considerations in our study of terminal Great Lakes wait on improved paleoclimatic reconstructions. Our results are biased by the length of the historical meteorology record we used. Errors of approximation include linear adjustment of supplies for lake area, power equation hypsometric relations, and approximation of natural flow conditions and sill elevations for each Great Lake.

We modeled each alternate climate by repeating our 52 years of adjusted meteorology until there were no changes, in an effort to simulate steady-state conditions. It appears that Lake Superior would be a terminal lake if precipitation dropped 60% or more from the present *or* if air temperature increased 60/4.7 = 13°C or more above the present *or* some linear combination of the two, $4.7 + P > 60$ where T and P are temperature rise (°C) and precipitation drop (%), respectively. Likewise, it appears Michigan-Huron would be a terminal lake for $P > 63\%$ *or* $T > 14°C$ *or* $4.5T + P > 63$. Erie would be a terminal lake for $P > 51\%$ *or* $T > 11°C$ *or* $4.7T + P > 51$. Ontario would be a terminal lake for $P > 71\%$ *or* $T > 20°C$ *or* $3.5T + P > 71$.

Our study addresses only the question of climate change necessary to close the pre-development Great Lakes and does not represent past or present hydrology. We endeavored not to exactly model the hydrology of the lakes around 7,900 ^{14}C years BP, but to explore the potential magnitude of excursions in temperature and precipitation that could cause the lakes to drop so low as to become "terminal" lakes (with no outflow). Additional modeling could be done to accommodate the paleogeographic conditions of 7,900 ^{14}C years BP, such as incorporating changes in vegetation including those associated with changed lake areas. In addition, future modeling of the impacts of cold/dry and windier conditions as well as changed insolation are likely to be useful in understanding the Great Lakes low stands.

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