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Climate Change Effects on Great Lakes Levels

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Abstract

The Great Lakes Environmental Research Laboratory has developed conceptual models for simulating moisture storages in and runoff from the 121 watersheds draining into the Laurentian Great Lakes, overlake precipitation into each lake, the heat storages in and evaporation from each lake, connecting channel flows and lake levels, and regulation of flows at control points. We determine net water supplies and levels for each lake to consider climate change scenarios developed from atmospheric general circulation models through linkages on air temperature, precipitation, humidity, wind speed, and cloud cover. Scenarios of a doubling of atmospheric CO_2 are considered by abstracting changes in linkages, making these changes in historical data, observing the impact of the changed data in model outputs, and comparing it to model results obtained from unchanged data. The implications of the climate change effects modeled herein suggest that new paradigms in water management will be required.

Introduction

The Environmental Protection Agency, at the direction of Congress, coordinated several regional studies of potential effects of a doubling of atmospheric CO_2 on various aspects of society, including water resources (EPA, 1988). As part of that study, we assessed changes in Great Lakes water supplies and levels consequent with simulated atmospheric scenarios. The Great Lakes system is ideal for studying regional effects of climate change because it possesses tremendous water and heat storage capabilities. This "memory" results in a filtering of most short-term meteorological fluctuations and in a response to longer-period fluctuations characteristic of climate change.

The Great Lakes system covers 770,000 km^2 in the U.S. and Canada, with the surface area of the 5 interconnected lakes com-

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prising about one-third of the total basin area. Because the lakes are so large, overlake precipitation and evaporation are of the same order of magnitude as basin runoff. The imbalance between net basin supplies (runoff + precipitation - evaporation) and other lake inflows and outflows results in rising and falling levels, with an overall range of about 1.8 m in annual levels. Outflows from Lakes Superior and Ontario are controlled by large dams and managed according to binationally-coordinated regulation plans.

Approach

Moisture storages and runoff are simulated by using GLERL's Large Basin Runoff Model, an interdependent tank-cascade model that employs analytical solutions of climatic considerations relevant for large watersheds (Croley, 1983). The model couples mass balances for snowpack, two soil zones, groundwater, and surface water with physically-based concepts of linear reservoir storages, partial-area infiltration, complementary evapotranspiration and evapotranspiration opportunity based on available supply, and degree-day determinations of snowmelt. Overlake precipitation is estimated by using overbasin precipitation; lake effects on near-shore meteorology are more significant than orographic effects throughout the drainage basin and use of only near-shore precipitation would bias overlake estimates.

Lake evaporation is simulated by considering overwater meteorology, stability effects on bulk mass transfer coefficients, ice cover, and a lake's heat balance and heat storage (Croley, 1988). Effects of past heat additions or losses are superimposed to determine a lake's surface temperature as a function of heat in storage. Water column turnovers and the hysteresis between heat in storage and surface temperature, observed in nature, occur as fundamental behaviors in the model.

Lake Superior outflows are determined by using Plan 1977 (ILSBC, 1982), designed to balance Lakes Superior and Michigan-Huron levels relative to their long-term averages while considering their normal variability. Level-pool routing through the unregulated lakes uses GLERL's Hydrologic Response Model, which solves a series of stage-fall-discharge equations for each of the connecting channels and continuity for each lake (Quinn, 1978; Hartmann, 1987). It also considers inter- and intrabasin diversions, ice and weed retardation of flows, and consumptive use rates. Lake Ontario outflows are determined by using Plan 1958-D (ISLBC, 1963), which first derives a basic regulated outflow, applies a seasonal adjustment, and then modifies the flows to comply with minimum and maximum outflow limitations.

To examine the impacts of climate change, we first simulate 30 years of "present" hydrology using historical daily maximum and minimum air temperatures, precipitation, wind speed, humidity, and cloud cover data for the 1951-1980 period; this is called the "base case" scenario. Initial conditions for the water supply component models were arbitrarily set, but a 2-year initialization period was used to allow the models to converge prior to the base case simulation. Lake level and outflow simulations were repeated with initial levels set to equal their averages over the 30-year period, until they were unchanging, to represent a "steady-state" simulation.

Ratios of "future" to "present" absolute air temperature, specific humidity, cloud cover, and precipitation, and differences of "future" and "present" wind speed were supplied by EPA as GISS (Goddard Institute for Space Studies), GFDL (Geophysical Fluid Dynamics Laboratory), and OSU (Oregon State University) atmospheric model predictions, for scenarios of a "future" steady-state atmosphere with twice the CO_2 content of the "present" atmosphere. We applied these ratios and differences to historic data sets to estimate 30-year sequences of atmospheric conditions associated with a steady-state changed climate, referred to as $2xCO_2$ scenarios. This approach keeps spatial and temporal variability the same in both adjusted and historic time series. We then used each $2xCO_2$ scenario in simulations similar to the base case scenario and interpreted differences between the $2xCO_2$ scenarios and the base case scenario as resulting from the changed climate.

Results

Precipitation changes under the $2xCO_2$ scenarios vary among lakes and scenarios, although they show consistent increases for the entire Great Lakes basin (Table 1). However, air temperature changes are consistently higher for all lake basins and all scenarios; the increases range from 4.3-4.6°C, 5.7-7.2°C, and 3.2-3.5°C for the GISS, GFDL, and OSU scenarios, respectively. The higher air temperatures lead to higher evapotranspiration and lower runoff to the lakes (Table 1), with earlier runoff peaks, since the snowpack is reduced by up to 100% and the snow season is shortened from 2 to 4 weeks. This also results in more than a 50% reduction in available soil moisture.

Table 1. Average annual steady-state Great Lakes basin hydrology and net basin supply components.

Scenario	Overland Precipitation m^3/s	Evapotranspiration m^3/s	Basin Runoff m^3/s	Overlake Precipitation m^3/s	Lake Evaporation m^3/s	Net Basin Supply m^3/s
BASE	13637	7727	6090	6499	5352	7237
GISS	13871 +2%	9317 +21%	4658 -24%	6747 +4%	6821 +27%	4584 -37%
GFDL	13725 +1%	9176 +19%	4714 -23%	6501 +0%	7685 +44%	3530 -51%
OSU	14483 +6%	9204 +19%	5438 -11%	6903 +6%	6745 +26%	5596 -23%

Although wind speeds drop and humidities increase consistently for all lakes and scenarios, the warmer climate increases water surface temperatures enough that lake evaporation increases substantially (Table 1). The warmer climate causes Lake Superior to behave like the southern Great Lakes under the present climate, and the increased heat storages keep Lakes Superior, Michigan-Huron, and Ontario above 3.98°C throughout the year. Buoyancy-driven water column turnovers thus do not occur on those lakes and ice formation is limited to near-shore areas.

Net water supplies to the lakes drop consistently for all lakes and scenarios (Table 1), although the magnitudes of the decreases vary greatly. This partly reflects reaching limits for some processes for some scenarios (e.g., moisture storage availability limited evapotranspiration increases under the GFDL scenario, air temperatures increases caused greater air stability and limited lake evaporation increases under the GISS scenario), but also reflects the potential for uncertainty in estimating climate change effects. Reduced supplies lead to lower levels for all lakes and scenarios (Table 2) and become so low on Lake Ontario that the regulation plan fails for all scenarios; the Lake Superior regulation plan fails in the GFDL scenario, which has the lowest supplies.

Table 2. Average annual steady-state lake levels differences.

	Scenario		
	GISS	GFDL	OSU
Lake	m	m	m
Superior	-0.46	*	-0.47
Michigan-Huron	-1.31	-2.48	-0.99
St. Clair	-1.21	-2.12	-0.87
Erie	-1.16	-1.91	-0.79
Ontario	*	*	*

* Regulation plan fails.

Implications

Climate change could dramatically affect Great Lakes ecosystem production. Wetland extents would be permanently reduced due to the direct lake level dependence, unsuitable offshore substrates, and steep offshore dropoffs of most wetlands, in addition to a resulting reduction in seeds and rhizomes for colonization (Manny, 1984). Increased water temperatures could result in general northward shifts in the geographical distribution of warm and cold water fish species, changes in abundance of species within fish communities, and changes in yields of different species (Meisner at al., 1987). Finally, with water temperatures remaining above 3.98°C throughout the year, water column turnovers in the fall and spring may occur only sporadically, if at all. Without turnover, hypolimnion chemistry would be altered; as oxygen is depleted, nutrients and metals are released from lake sediments and become available for uptake by organisms.

Recreation and commerce that depend upon reliable snow cover or instream flows may suffer total collapse throughout much of the Great Lakes region, especially in areas that are only climatically marginal for such activities at present. Agriculture faces mixed prospects, with increased air temperatures offering northward expansion, but also causing summer soil moisture deficits and increased insect and disease populations.

Efficient waterborne transportation and the recreational boating industry depend upon adequate depths in connecting channels and harbors. Under climate warming, decreased channels depths would require extensive dredging, posing serious problems associated with resuspended toxics and spoil disposal as many bottom sediments are highly contaminated. Many municipal and private harbors would likely have to cease operations. On the other hand, a decreased ice season could lead to an extended navigation season, contributing to better vessel utilization and decreases in stockpiling.

Decreased levels and flows under climatic warming would also lower hydropower production. This could be important, as hydropower is inexpensive and non-polluting when compared to its primary alternatives, fossil fuel or nuclear power. Because these alternatives also use lake water for cooling, climate warming could produce increased consumptive use of water, which would further exacerbate anticipated low levels. Presently, U.S. peak power demands occur in summer for cooling; climatic warming could increase these demands, making loss of hydropower production even more critical. On the other hand, climatic warming may substantially reduce peak demands for winter heating in Canada, making replacement of hydropower facilities nonproblematic.

A major thrust of water management under a warmer climate will likely be to keep water in the system. This will require extensive revision of the existing Lake Superior and Ontario regulation plans as well as possible regulation of Lakes Michigan-Huron and Erie. The debate over interbasin water diversions is also likely to intensify, with demands for increasing existing diversions into Lake Superior as well as considering new incoming diversions. In addition, efforts will likely be made to curtail water diversions out of Lake Michigan at Chicago, Illinois.

Low confidence in atmospheric model outputs and subsequent lake level estimates is probably a major obstacle to long-term con-

tingency planning that considers potential climate change impacts. In addition, other factors that are difficult to predict (e.g., economic, demographic, technological) are certain to complicate policy development. Although these climate change scenarios are highly uncertain, they highlight the need for policies to increase the region's resiliency to meteorologic uncertainty. Policies that protect the quality of existing water supplies, encourage efficient use of existing supplies, and adequately address present allocation conflict will provide advantages for future water management even if climate changes fail to materialize as expected.

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