GREAT LAKES HYDROLOGICAL IMPACTS OF $2xCO_2$ CLIMATE CHANGE[1]

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ABSTRACT: The Great Lakes Environmental Research Laboratory considered climate change impacts on North American Great Lakes hydrology by using recent atmospheric general circulation model (GCM) simulations of a doubling of atmospheric CO_2, available from the Goddard Institute for Space Studies. We made changes in historical meteorological data, similar to the changes observed in the GCM, and observed the impact of the changed data in hydrology models for basin moisture storage and runoff, over-lake precipitation, and lake heat storage and evaporation. While precipitation changes are uncertain, higher air temperatures generally increase basin evapotranspiration which decreases the snowpack, lowers runoff, shifts runoff peaks, and reduces soil moisture. There are larger amounts of heat resident in the deep lakes reducing buoyancy-driven turnovers of the water column, lowering ice formation, and increasing lake evaporation.
KEY TERMS: Great Lakes; Climate Change; Hydrology.

INTRODUCTION

The Environmental Protection Agency (EPA), at the direction of the U.S. Congress, coordinated several regional studies of potential effects of a doubling of atmospheric CO_2 ($2xCO_2$) on various aspects of society, including agriculture, forestry, and water resources (USEPA, 1988). Alternate scenarios were considered by making changes in historical data (air temperature, precipitation, humidity, wind speed, and cloud cover) similar to the changes observed in the atmospheric general circulation model (GCM) simulations of $2xCO_2$, observing the impact of the changed data in impact model outputs, and comparing outputs to model results obtained using unchanged data. The EPA supplied $1xCO_2$ and $2xCO_2$ scenarios to the Great Lakes Environmental Research Laboratory (GLERL) to assess steady-state and transient changes in Great Lakes hydrology consequent with simulated atmospheric scenarios from three recent GCM simulations. This paper outlines the hydrological models and their applicability, presents the methodology of linkage with the GCMs, and examines the results of that study for one GCM.

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The Laurentian Great Lakes and their surrounding basins cover 770,000 km^2 in the United States and Canada; see Figure 1. The lakes' surface areas comprise about one-third of the total basin area. Runoff, lake precipitation, and lake evaporation comprise the Great Lakes net basin water supplies; runoff is significant particularly during the snowmelt season, late March through early June. Because the lakes are so large, lake precipitation and evaporation are of the same order of magnitude as runoff. On a monthly scale, precipitation is fairly uniformly distributed throughout the year. Lake evaporation typically has the greatest effect during the late fall and winter months when cool dry air and warm water result in massive evaporation. Condensation on the cool lake surface from the wet overlying air occurs in the early summer. Net groundwater flows to each of the Great Lakes are generally negligible. Net basin supplies typically reach a maximum in the late spring and a minimum in late fall.

As water temperatures generally peak in August (September for Lake Superior) at 15 to 25 °C and drop to freezing or near-freezing during the winter, the water column in each lake "turns over" (deep lower-density waters rise and mix with heavier surface layers) twice a year as surface temperature passes through that of maximum density for water (about 4 °C). There is also extensive ice cover on most of the lakes during most winters. The large heat storage of the deep lakes forestalls and reduces ice formation and shifts the large evaporation response to fall and winter.

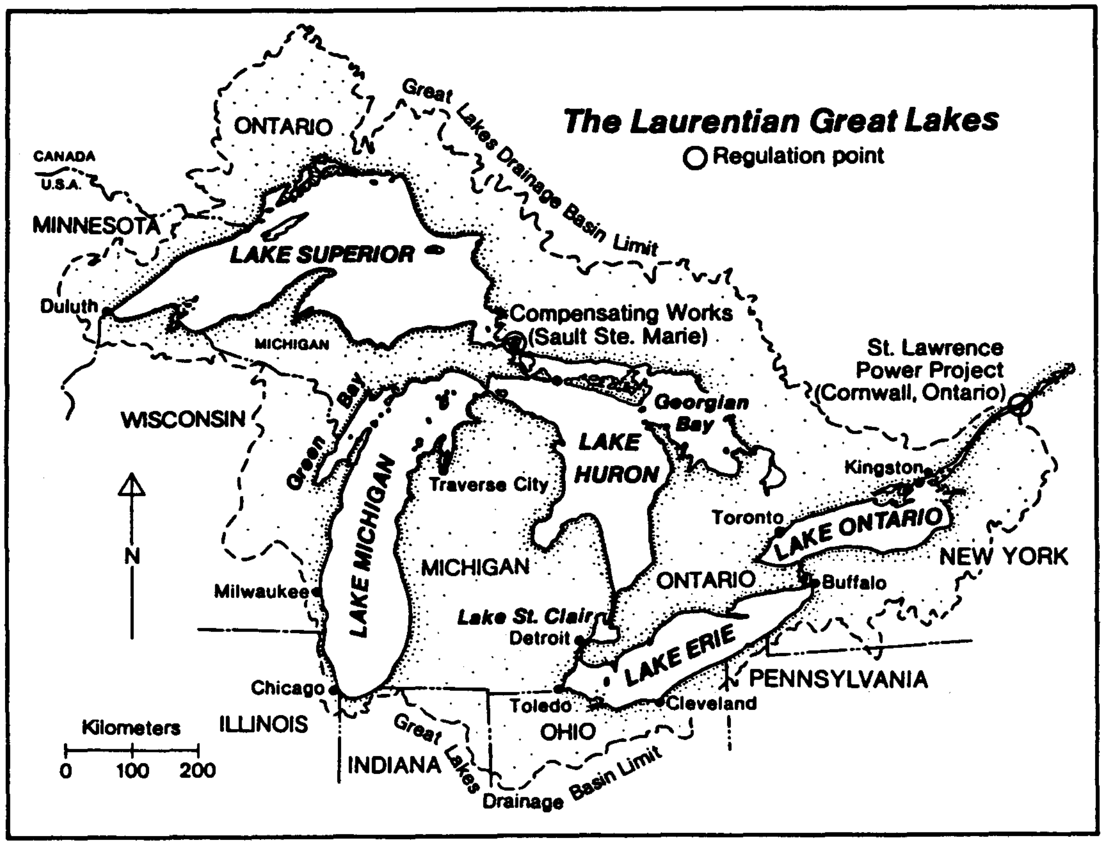

Figure 1. Location Map for the Laurentian Great Lakes.

The Great Lakes Environmental Research Laboratory has developed conceptual model-based techniques for simulating moisture storages and runoff from the watersheds draining into the Great Lakes, over-lake precipitation into each of the Great Lakes and Lake St. Clair (hereafter included as a Great Lake), and the heat storages and evaporation from each of the lakes. We model each of these components separately and combine them to estimate net basin supplies to Lakes Superior, Michigan, Huron, St. Clair, Erie, and Ontario for simulating the existing basin and lake storages of water and heat in response to possible meteorology.

The GLERL Large Basin Runoff Model (LBRM) uses daily precipitation, temperature, and insolation (the latter available from climatological summaries as a function of location) to determine daily moisture storages in the basin, evapotranspiration, and basin runoff (Croley, 1982, 1983a, b). The Great Lakes basin is divided into 121 watersheds, each draining directly to a lake, grouped into the six lake basins. The meteorologic data from over 1800 stations about and in the watersheds are combined through Thiessen weighting to produce areally-averaged daily time series of precipitation and maximum and minimum air temperatures for each watershed (Croley and Hartmann, 1985b). Records for all "most-downstream" flow stations are combined by aggregating and extrapolating for ungauged areas to estimate the daily runoff to the lake from each watershed. The LBRM was calibrated generally over 1965-82 to minimize the sum-of-squared-errors between model and actual daily flow volumes for each watershed (Croley, 1983b, Croley and Hartmann, 1984, 1985a).

The lack of over-lake precipitation measurements means that estimates typically depend on land-based measurements and there may be differences between land and lake meteorology. For the Great Lakes, where lake effects on near-shore meteorology are significant and the drainage basins have relatively low relief, the use of all available meteorologic stations throughout the basin is probably less biased than the use of only near-shore stations and no corrections are applied.

The GLERL lake heat storage and evaporation model uses daily air temperature, dewpoint temperature, wind speed, and cloud cover to determine lake heat fluxes and storage, surface temperature, and evaporation (Croley, 1989a). Daily meteorological over-land data from five to ten near-shore stations about each Great Lake were assembled and averaged for correction to over-lake data. The heat balance model was calibrated to give the smallest sum-of-squared-errors between model and actual water surface temperatures observed by satellite (available only on satellite passes over cloud-free conditions) during the calibration period of generally 1979-85 (Croley, 1989a).

Spatial resolutions finer than about 1000-5000 km^2 (the present average resolution of our hydrology models and their applications) are unnecessary and much could be done in assessing changes at resolutions of 100,000-1,000,000 km^2 with lumped versions of our models. This coarse spatial resolution is still much finer than the present GCM grids. Since we have daily models derived for other purposes, we use a daily resolution of data with our models even though weekly or monthly are adequate for this spatial scale (short-term fluctuations associated with storm movement are not addressed in this study).

It is entirely possible that the models are tied somewhat to the present climate; empiricism is employed in the evapotranspiration component of the LBRM and in some of the heat flux terms in the heat balance and lake evaporation model. Calibrations were performed under the present climate. The models are all based on physical concepts that should be good under any climate; but, the assumption is made that they represent processes under a changed climate that are the same as the present ones. However, the calibration and verification periods for the component process models include a range of air temperatures, precipitation, and other meteorological variables that encompass much of the changes in these variables predicted for a changed climate. Even though the changes are transitory in the calibration and verification period data sets, the models appear to work well under these conditions. Further assessments of the models for use with data outside the range of their calibrations are available elsewhere (Croley, 1989b).

METHODOLOGY

First, we simulated 30 years of "present" hydrology (the "base case" or "1xCO_2" scenario) by using historical daily average, maximum, and minimum air temperatures, precipitation, wind speed, humidity, and cloud cover data for the 1951-80 period in the hydrology models. The initial conditions were arbitrarily set but an initialization simulation period of 1 January 1948 through 31 December 1950 was used to allow the models to converge to conditions (basin moisture storages, water surface temperatures, and lake heat storages) initial to the 1 January 1951 through 31 December 1980 period. Then we conducted simulations with adjusted data sets.

EPA supplied ratios of "future" to "present" monthly absolute air temperature, specific humidity, cloud cover, and precipitation, and differences of "future" and "present" wind speed as Goddard Institute for Space Studies (Hansen *et al.*, 1983, 1988) atmospheric GCM predictions, at grid points spaced 7.83° latitude by 10° longitude, for a "future" atmosphere with twice the CO_2 content of the "present" atmosphere. Since the GCM does not produce wind speeds directly, speeds were derived indirectly from momentum terms; they are monthly averages that poorly reflect instantaneous values and they are vector averages instead of scalar averages. Since vector averages tend to be low, ratios are sometimes unrepresentative and differences were used instead. We applied these monthly ratios and differences to daily historic data sets to estimate 30-year sequences of atmospheric conditions associated with a changed climate, referred to as the "2xCO_2" scenario(s). The effect of this is to keep spatial and temporal (inter-annual, seasonal, and daily) variability the same in the adjusted data sets as in the historic base period. We inspected each of the 770,000 square kilometers within the Great Lakes Basin to see which of the model grid points it was closest to and applied the monthly adjustment at that grid point to data representing that square kilometer. By combining all square kilometers representing a watershed or a lake surface, we derived areally-averaged monthly adjustments to apply to our areally-averaged daily data sets for the watershed or lake surface, respectively (we used each monthly adjustment for all days of that month). We then used the 2xCO_2 scenario in a simulation similar to the base case scenario and then interpreted differences between the $2xCO_2$ scenario and the base case scenario as resulting from the changed climate.

Transfer of information between the GCM and our hydrologic models in the manner described involves several assumptions. Solar insolation at the top of and through the atmosphere on a clear day are assumed to be unchanged under the changed climate, modified only by cloud cover changes. Over-water corrections are made in the same way for both $1xCO_2$ and $2xCO_2$ scenarios, albeit with changed meteorology, which presumes that over-water/over-land atmospheric relationships are unchanged. Heat budget data from GCM simulations for Great Lakes grid points may not adequately describe conditions over the lakes due to their coarse resolution. Our procedure for transferring information from the GCM grid to our spatial data is an objective approach but simple in concept. It ignores interdependencies in the various meteorologic variables as all are averaged in the same manner. Of secondary importance, the spatial averaging of meteorologic values over a GCM grid box filters all variability that exist in the GCM output over that grid box.

BASIN HYDROLOGY

The average steady-state GISS annual $2xCO_2$ air temperatures are 4.3-4.7 °C higher than the base case, depending on the basin. Precipitation changes are much less consistent than air temperature changes between the different lakes ($2xCO_2$ precipitation ranges annually from 18% more to 7% less than the base case). The resulting over-land $2xCO_2$ evapotranspiration is higher than the base case, increasing fairly smoothly with latitude.

On the Superior basin, the average steady-state snowpack storage is reduced more than 50% by higher air temperatures during the winter; on the other basins, more to the south, the snowpack is almost entirely absent; see the Erie example in Figure 2. The snow season (period of freezing air temperatures) is shortened also two weeks to one month. The reduced snowpack causes smaller derived moisture storages in the soil zone, groundwater, and surface zones; in some cases the total is reduced more than 50% in Figure 2. Consequently, annual runoff is reduced in all cases, changing smoothly with longitude. Runoff peaks slightly earlier and with smaller magnitude under the $2xCO_2$ climate than under the base case as reflected by total moisture storage for Lake Erie in Figure 2.

LAKE HEAT BALANCE

The over-lake air temperature, humidity, and wind speed differ from over-land since the lower atmospheric layer is affected by the water surface over which it lies. In general, for the $2xCO_2$ scenario, the synergistic relationship that exists between over-lake air and water temperatures yields a general increase in both that follows the base case patterns, similar to over-land behavior. The average steady-state annual over-lake air temperatures are 4.9-5.5 °C higher. An increase with latitude is more pronounced than variation with size of the lake in terms of volume or heat capacity although Lake Superior not only has the largest rise in over-lake air temperatures but also has the largest rise relative to over-land air temperature rise, probably reflecting the large heat storage capacity influence on the air layer over the lake. Absolute humidities over the lakes are higher for the $2xCO_2$ climate while cloud cover and over-water wind speed have dropped after adjustment of over-land values for over-water conditions at increased water temperatures.

The heat budget gives rise to increased water surface temperatures as seen for Lake Erie in Figure 3. Since Lake Erie is a very shallow lake with little heat storage, the annual cycle of the $2xCO_2$ water surface temperatures follows a pattern very similar to the base case but several degrees higher. The average steady-state water surface temperatures on the lakes are 4.3-5.6 °C higher, reflecting again the general influence of heat storage capacity in a lake. The higher heat content of Lake Superior earlier in the year allows the $2xCO_2$ water surface temperatures to peak earlier than the base case; as over-lake Superior air temperatures are affected by the water temperatures, they also peak ahead of the base case.

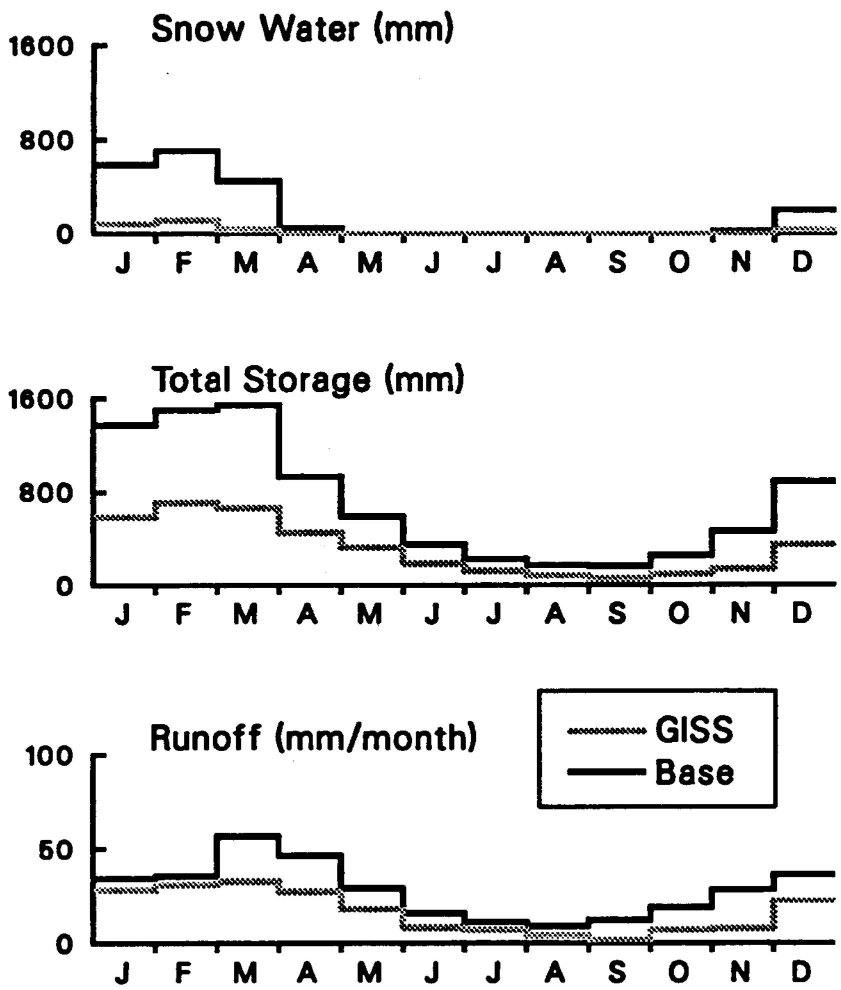

Figure 2. GISS Erie Over-Basin Averages

Large amounts of heat would then reside in the deep lakes throughout the year. All of the deep lakes (Superior, Michigan, Huron, and Ontario) show water surface temperatures that stay above 3.98 °C (at which water density is maximum) throughout the average annual cycle. This means that buoyancy-driven turnovers of the water column would not occur twice a year. Of course, one turnover per year is still possible while water temperatures are above 3.98 °C if the mixed layer deepens sufficiently and there are adequate winds (Hutchinson, 1957). It also means that ice formation will be greatly reduced over winter on the deep Great Lakes.

Water temperatures depend on the total heat balance of the lake with the atmosphere which, in turn, depends on changes in humidity, wind speed, and cloud cover in addition to air temperatures. As average air temperatures increase, the average water surface temperatures (in particular, the surface temperatures during the evaporation season of fall and winter) generally increase at lower rates and this rate further decreases as air temperatures rise. This can be noted from inspection of cool and warm years of the historical record. This is contrary to other works that set $2xCO_2$ surface temperature rises equal to air temperature rises for non-freezing temperatures (Cohen, 1986; 1987). However, evaporation computations are very sensitive to this assumption. At high air-water temperature differences, the effects of humidity and wind speed changes are secondary to temperature (and hence vapor pressure) differences and evaporation may be large even with offsetting humidity and wind speed changes. At lower air-water temperatures, the effects of humidity and wind speed changes become primary in determining the relative magnitudes of evaporation between the various scenarios.

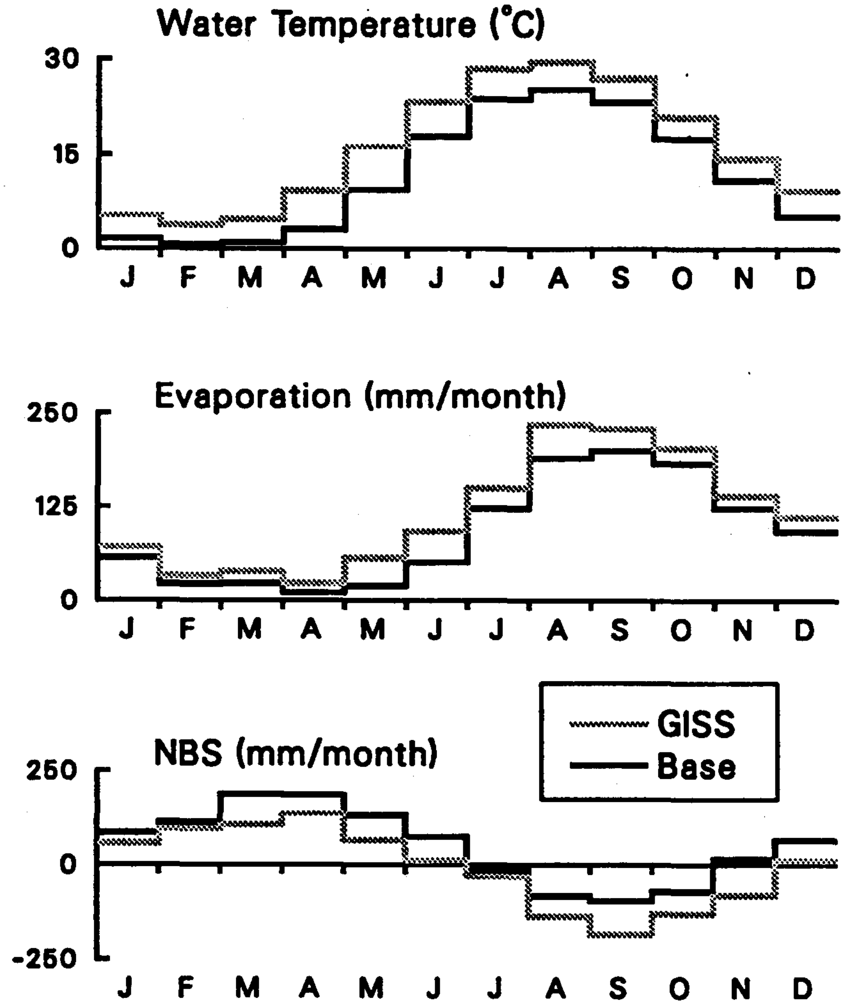

Figure 3. GISS Erie Over-Lake Averages

The higher water surface temperatures under the $2xCO_2$ climate result in increased annual lake evaporation and the shallow lakes have the largest absolute increase. While average humidities are up and average wind speeds are down (by themselves suggesting that evaporation drops), evaporation is higher. This is because the water surface temperature (and associated saturated vapor pressure at the surface) has increased sufficiently.

NET BASIN SUPPLY COMPONENTS

Over-lake precipitation, runoff, and lake evaporation sum algebraically as the net basin supply. Net basin supply is seen to be less under the $2xCO_2$ climate than under the base case; this is true throughout the year for Lakes St. Clair and Erie (see Figure 3 for Erie). It is nearly true on Lakes Huron (only January supplies are higher) and Ontario (only January and February are higher); Lake Michigan experiences increased net basin supplies during the winter under the GISS $2xCO_2$ scenario and Lake Superior has increased net basin supplies during the fall and winter. Table 1 summarizes the changes in the hydrologic and net basin supply components for the entire Great Lakes basin for three GCMs: the Goddard Institute for Space Studies (GISS) GCM discussed here, the Geophysical Fluid Dynamics Laboratory (GFDL) GCM (Manabe and Wetherald, 1987), and the Oregon State University (OSU) GCM (Ghan *et al.*, 1982). The changes from the base case are also expressed relatively in Table 1. The latter two studies were part of the EPA study not reported here. Net basin supplies to all Great Lakes are seen to drop between about one quarter to one half under the $2xCO_2$ scenario. Even though more heat is available under the GFDL scenario than under the GISS or OSU scenarios, evapotranspiration is lower because less water is available, as seen by inspection of the average precipitation. In the OSU and GISS scenarios, water availability is not as limiting and the higher air temperatures of the GISS scenario lead to higher evapotranspiration than in the OSU scenario even though more water is available under the OSU scenario.

SENSITIVITIES

Although the GISS, GFDL, and OSU steady-state scenarios show conflicting estimates of precipitation change, each shows increases in air temperatures that significantly reduce the snowpack, especially in the southern basins. Thus, even if precipitation increases more than suggested by the GCMs, the snowpack still will be much reduced under warmer winters. Similarly, soil moisture storage and runoff peak shortly after snowmelt and then drop throughout the summer and fall due to high evapotranspiration; each climate scenario produces earlier snowmelt and a longer period of evapotranspiration. Although soil moisture and runoff certainly vary with precipitation, they are most sensitive to it in midsummer when at their annual minimums. Thus, within the limits of precipitation produced by the GCMs, soil moisture and runoff scenarios are relatively insensitive to precipitation.

At small air temperature rises, the rise in water surface temperature and the vapor pressure difference with the atmosphere compensate for the smaller drop in wind speed and rise in atmospheric humidity; evaporation increases. For large air temperature rises, over-water air stability increases, they do not compensate, and evaporation may decrease. This turn-around point occurs in the range of the three climate-change scenarios considered here, giving uncertain evaporation

Table 1. Average Annual Steady-State Great Lakes Basin Hydrology and Net Basin Supply Components.

Scenario	Over Land Precipitation (cms)	Evapotranspiration (cms)	Basin Runoff (cms)	Over Lake Precipitation (cms)	Over Lake Evaporation (cms)	Net Basin Supply (cms)
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%

estimates. Note also increased over-water stability alters over-lake precipitation but this is ignored in the GCMs (because of their large scale the lakes do not appear) and therefore is not considered here.

SUMMARY

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

While precipitation over the entire Great Lakes changes less than 6% in all GCMs, the higher $2xCO_2$ air temperatures lead to about 20% higher evapotranspiration and 11-24% lower runoff with earlier runoff peaks since the snowpack is reduced up to 100% and the snow season is shortened from two to four weeks. This reduces available soil moisture by 50%. Under the warmer scenarios on some lakes, water availability limits evapotranspiration so that more occurs under wetter (and cooler) scenarios. Water surface temperatures peak earlier on Lake Superior; since the climate becomes similar to present-day climates on the southern lakes, the lake temperature behaves similar to present-day southern deep Great Lakes. There are larger amounts of heat resident in the deep lakes throughout the year. Also, buoyancy-driven turnovers of the water column, related to the passage of water temperatures through that at maximum density, occur only on the shallow lakes. Currently, they occur twice a year on all lakes. The lakes still might experience a single winter turnover if temperature gradients are small and winds are strong enough to induce turbulent mixing. Ice formation is greatly reduced over winter on the deep Great Lakes and lake evaporation increases between 26-44%. Over the entire Great Lakes basin, the three scenarios result in a 23 to 51% reduction of net basin supplies and they vary in the magnitude of the components of those supplies (particularly basin runoff and lake evaporation).

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