CLIMATIC IMPACTS OF IDEALIZED GREAT LAKES IN A GENERAL CIRCULATION MODEL

Brent M. Lofgren*
NOAA/Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan

1. INTRODUCTION

The Laurentian Great Lakes have a total surface area of approximately 245,000 km^2 and a total water volume of approximately 22,700 km^3. The resulting high thermal inertia causes them to have a greater persistence in temperature across the seasons than the rest of North America. Well-known short-term, localized phenomena resulting from this thermal inertia include lake-effect snow, lake breeze, and mid-lake cloud bands. Additionally, there are "lake-aggregate" thermal effects that can cause weakening, strengthening, or splitting of surface synoptic-scale systems (Sousounis and Fritsch 1994).

However, all of the phenomena mentioned above are episodic in nature, leaving us with the question of how the Great Lakes affect the average climate for a given month or season. This paper is concerned with the use of a general circulation model (GCM) to simulate the Great Lakes' effects on the budgets of water and energy in the surrounding area over climatic time scales. It will also deal with how the influence on energy fluxes due to the Great Lakes affect the long-term statistics of the atmospheric circulation.

A complementary approach to this problem would be to use a regional atmospheric model with a smaller domain and finer resolution. This approach would likely provide better representation of many relevant physical and dynamical mechanisms than a GCM, and we plan to use this approach in the future. However, the GCM can be run much faster than a regional model and provides an entree to the use of a regional model. It can help to identify some issues that need investigation using a regional model or direct observation.

2. MODEL FORMULATION

The atmospheric model used here is a version of the Geophysical Fluid Dynamics Laboratory (GFDL) GCM. The version used here has vertical resolution of nine unevenly spaced sigma layers, and uses rhomboidal-30 (R30) horizontal resolution (which transforms to a grid of 3.75° longitude by 2.25° latitude). See section 4 for caveats regarding the horizontal resolution. The main features of the dynamical component of this model are described in Gordon and Stern (1982).

A 1-dimensional (depth) lake thermodynamic model was used for the experimental run. Given the lake surface temperature and atmospheric conditions predicted by the components of the model, the net energy flux at the lake surface is calculated at each timestep and averaged over a 24-hour period. Near-surface winds are also averaged over the same period as an aging function. Average energy fluxes and winds are used with the superposition scheme of Croley (1989, 1992) to add and remove daily quantities of energy and gradually diffuse them downward in the lake. The lake model also includes a module to simulate ice formation (Croley and Assel 1994). The model differs among the lakes due to their mean depth and in the parameters that control the vertical diffusion, as calibrated by Croley and Assel (1994). Figure 1 illustrates the configuration of the idealized Great Lakes used for this study. The total surface area of the idealized lakes in this study is approximately 293,000 km^2. The larger box in Fig. 1 defines a region that will later be used for areal averaging of various quantities.

In a No Lakes (NL) simulation, the Great Lakes are depicted as land. This is the standard way of running the GFDL GCM at R30 resolution. The With Lakes (WL) case has lakes inserted as shown in Fig. 1. The lakes differ from the land in terms of surface albedo, surface roughness, unlimited supply of water, and thermal capacity, as explained in the previous paragraph.

3. MODEL RESULTS

3.1. Thermal state and fluxes

The way in which the lakes influence the atmosphere is highly dependent upon the evolution of their surface temperature. Figure 2 compares the surface temperature averaged over all four lake grid cells in the WL case with that over the same four grid cells in the NL case. The lake surface temperature is an average of the surface water temperature and the surface ice temperature, weighted by the areal coverage of each, making temperatures below the freezing point possible. The lakes in the WL case have a lower temperature than the corresponding land in the NL case during the spring and summer, up

*Corresponding author address: Brent M. Lofgren, NOAA/Great Lakes Environmental Research Laboratory, 2205 Commonwealth Blvd., Ann Arbor, MI 48105-1593; e-mail lofgren@glerl.noaa.gov.

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Front Cover: The 1 July soil wetness index anomaly (1988 minus 1987) from the Center for Ocean-Land-Atmosphere Studies' (COLA) offline version of the Simplified SiB land surface model is compared to the mean rainfall anomaly (1988-1987) for the preceding three months (April through June). Soil wetness index is a non-dimensional measure of moisture in the soil, where 0 denotes the wilting point, and 1 equals field capacity. Different hydrologic models can be compared directly, regardless of soil moisture parameterization, by converting each model's measure of soil water content to this dimensionless index. The signal of the 1988 springtime drought is very evident in the negative anomalies over the central and eastern U.S. In both the precipitation and soil wetness index maps. However, regional variations in climate, radiation, soil properties, and vegetation modulate the hydrologic response to the precipitation deficit.

Soil wetness index is one of the products of the Global Soil Wetness Project (GSWP), an ongoing modeling activity of the International Satellite Land-Surface Climatology Project (ISLSCP), a contributing project of the Global Energy and Water Cycle Experiment (GEWEX). COLA is one of about a dozen modeling groups which have taken the common ISLSCP forcing data to execute their state-of-the-art models over the 1987-1988 period to generate global data sets and perform model sensitivity studies. An intercomparison center has been established at the Center for Climate System Research, University of Tokyo for evaluating and comparing data from the different models. There is also a validation group which is validating the global products, either directly (by comparison to field studies or soil moisture measuring networks) or indirectly (e.g. use of modeled runoff to drive river routing models for comparison to streamflow data). Figure courtesy of Paul Dirmeyer, COLA, Calverton, Maryland.

Please refer to the following papers in this preprint volume for further information: Paper 7.11 (page 169) entitled, *Can Seasonal Climate Simulation Be Improved By The Gswp Soil Wetness Climatology?* and Paper P7.5 (page 335) entitled, *The Sensitivity Of Soil Wetness, Runoff And Surface Fluxes To Infiltration Properties*. By Paul Dirmeyer, Cola, Calverton, MD

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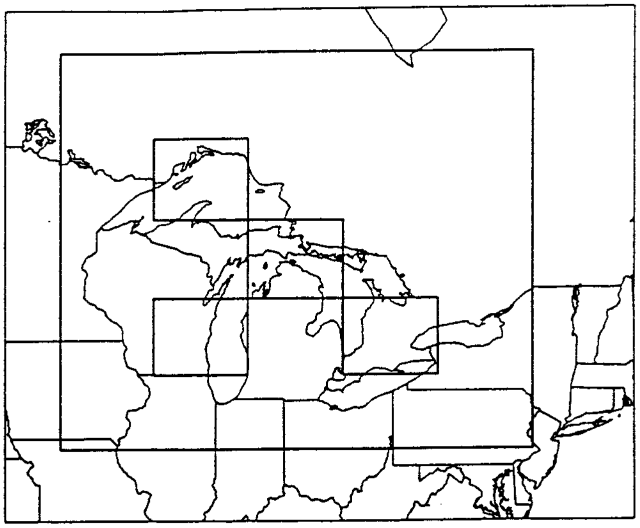

Figure 1. A map of the Great Lakes region overlaid by the positions of the four idealized Great Lakes used in this study, along with a surrounding region used for areal averaging in subsequent analysis.

to about 5° C lower during May. They have higher temperatures during the fall and winter, up to about 17° C higher during December. Annually averaged, the lakes are warmer than the land.

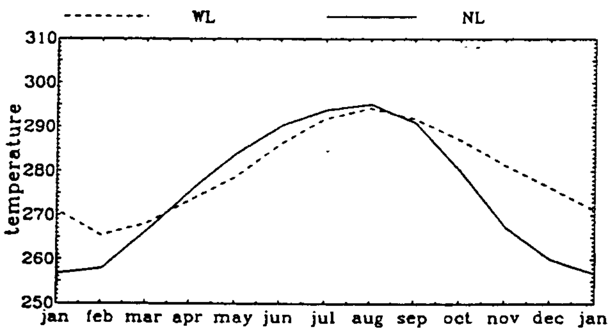

Figure 2. Comparison of the annual cycle of mean surface temperature (in degrees Kelvin) averaged over the four lake grid points in the WL case and over the same four grid points (now land areas) in the NL case.

Surface energy fluxes over the lakes (Fig. 3) are the source of any forcing of the atmosphere by the surface. This forcing is highly dependent on the presence or absence of the lakes. The net input of solar heat is much higher in the WL case during the spring and early summer. This is because of a combination of decreased cloudiness over the lakes and lower surface albedo. Net solar input is lower in the WL case during the autumn, when the lakes develop heavy low-level cloudiness. The net outgoing longwave radiation will not be remarked on here.

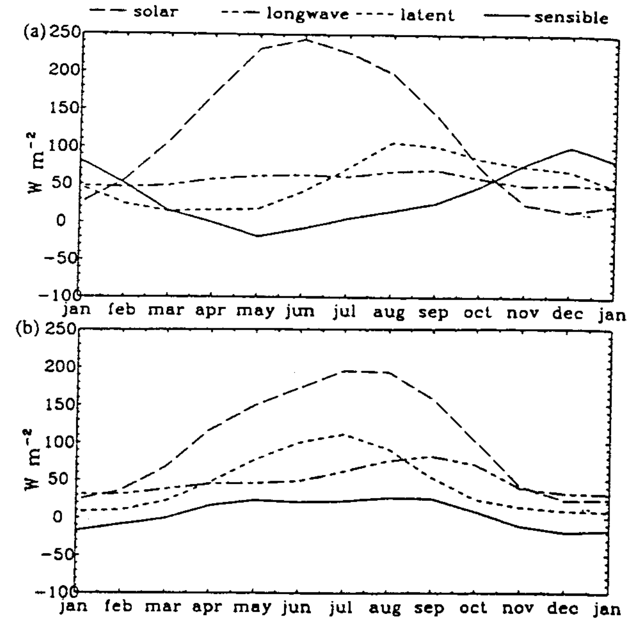

Figure 3. Annual cycle of surface energy fluxes (net solar radiation, net longwave radiation, latent heat flux, and sensible heat flux) averaged over (a) the four lake grid points in the WL case and (b) the same four grid points in the NL case.

The annual cycles of latent heat flux are out of phase between the two cases. The WL case has latent heat fluxes far exceeding the NL case during the fall and into the winter, but falling short during the spring and early summer.

Sensible heat flux is more dramatically out of phase between the two cases. The NL case has maximum sensible heat flux during May through September, and negative values in November through March. The WL case has a remarkably large maximum in December and January, and negative sensible heat flux in April through June. The outgoing sensible heat flux during November through January far exceeds the incoming solar radiation, dramatically displaying the hysteresis induced by the lakes' heat capacity.

It is also important to note that in the WL case, the sensible heat flux continues to increase long after the latent heat flux has been decreasing. The very high Bowen ratios (sensible heat flux divided by latent heat flux) during December through February suggest that the overlying air maintains a nearly saturated state, while the lake continues to contribute more heat. The boundary layer trapped under a capping inversion, with associated clouds, radiates heat outward but allows only slow detrainment of moisture from the boundary layer, but note that the character of the boundary layer within the model may be unrealistic.

In looking at the total water balance (Fig. 4), we average over the surrounding area (the larger rectangular area shown in Fig. 1), which includes land along with water. As in the results from the lakes alone (Fig. 3), the evaporation over the Great Lakes area (Fig. 4) decreases during the spring and early summer, and increases during the fall and winter due to the inclusion of the lakes. The changes in precipitation do not entirely follow these trends. The precipitation during the fall and winter increases by nearly as much as the evaporation. However, the decrease in evaporation during the spring and early summer is not accompanied by a decrease in precipitation over the Great Lakes basin as a whole. Thus, for the year as a whole, the inclusion of lakes results in an increase of precipitation minus evaporation of .049 millimeters per day. This corresponds to an increase in convergence of atmospheric water vapor flux. This increase in flux convergence occurs partially over the lakes, but more strongly over the surrounding land. The summertime increase in precipitation over the basin is due, at least partially, to very strong artificial diffusion of air cooled by the lakes in this region (see section 4).

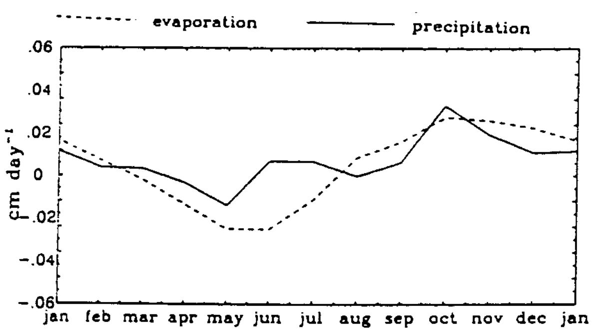

Figure 4. Annual cycle of precipitation and evaporation for the WL case minus the NL case, averaged over the Great Lakes area (see Fig. 1).

3.2. *Mean zonal winds*

Because of the thermal wind relation, we would expect that if the Great Lakes affect the meridional gradient of air temperature, they will also affect the zonal velocity associated with the jet stream. Figure 5a shows how the September, October, and November (SON) zonal wind changes due to the inclusion of the idealized Great Lakes. There is a dipole of increased zonal wind to the north of the mean jet core (not shown, located at about 50°N) and decreased to the south. The changes in zonal winds are due almost entirely to the accompanying changes in the mean temperature structure, shown in Fig. 5b, in accordance with the thermal wind relation.

The response in zonal mean wind during December, January, and February (DJF) is quite different, however. Fig. 6a shows the change in zonal winds due to the

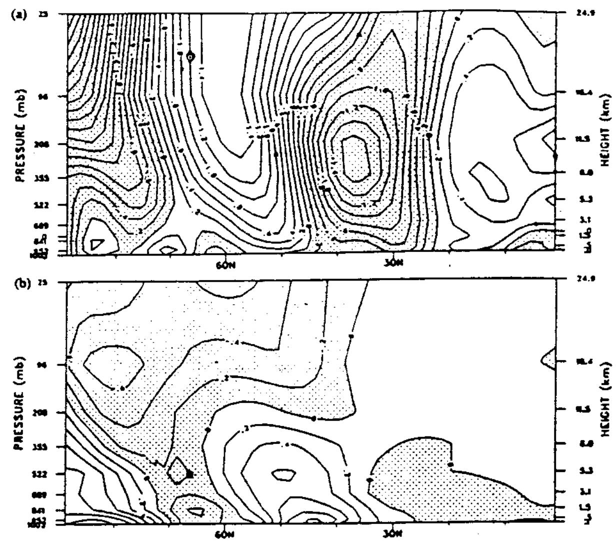

Figure 5. Latitude-height cross-sections averaged between 60° W to 100° W and over September, October, and November for the difference (WL case - NL case) in (a) zonal wind, and (b) air temperature at sigma=.99. In (a), the contour interval is .2 m/s. In (b) the contour interval is .2 degrees Kelvin. In both, values less than 0 are shaded.

inclusion of idealized Great Lakes. This effect is considerably less than that noted in SON (Fig. 5a).

Figure 6b shows the reason. Although the change in air temperature near the surface is more intense during DJF than during SON (Fig. 5b), its profile is much more shallow, yielding a lesser impact on the upper tropospheric jet. The additional sensible heat output from the lakes is unable to penetrate to greater heights in the atmosphere because of the enhanced static stability of the free atmosphere during the winter.

In both SON and DJF, the combination of reduced static stability of the free atmosphere and enhanced meridional temperature gradients acts to enhance baroclinic instability. Synoptic-scale variability in mean sea level pressure is enhanced to the northeast of the Great Lakes in the WL cases in both the fall and winter.

4. CAVEATS

Several caveats must be presented concerning the above results, applying to general circulation model results in general, specifically to the GFDL GCM, or to investigations of sensitivity to model perturbations applied at the limit of its spatial resolution.

The spectral transform method uses an effectively coarser resolution in its spectral space than in the grid space. Thus when a quantity is transformed from grid space to spectral space, it undergoes a strong instantaneous diffusion. For example, during the summer, sensible heat flux from the Great Lakes is reduced relative to the surrounding land, cooling the overlying air. This process is modeled in the grid space, but the temperature field is then transformed into spectral space, spreading that cooling effect over a wider region. Humidity, on the other hand, is calculated strictly in grid space, allowing the grid spaces surrounding the lakes to maintain higher humidities during the summer, in keeping with their warm surfaces. As the cool air diffuses into the high humidity areas, it artificially induces increased precipitation (Fig. 4).

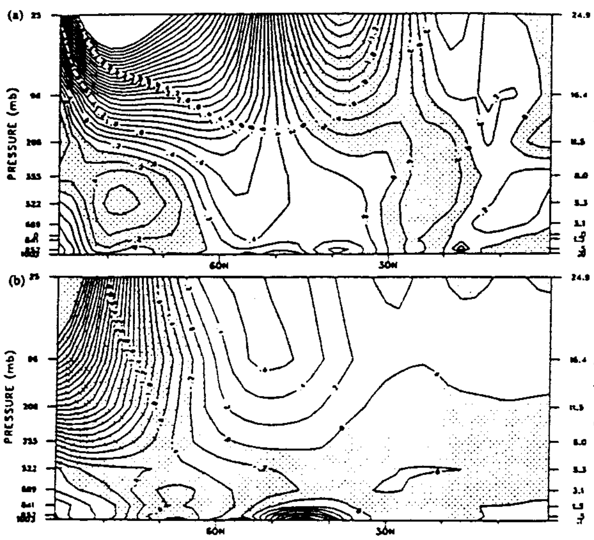

Figure 6. As in Fig. 5 except for December, January, and February.

Another consideration is the possibility of sensitivity to the parameterization of moist convection, which in this case uses a simple moist convective adjustment scheme. Also important, since it was mentioned that the cloud cover over the Great Lakes during the winter is similar to a classic cloud-capped boundary layer, is the use of prescribed mixing lengths in the boundary layer. This, along with poor vertical resolution, means that the model is incapable of representing the stability dependence of boundary layer fluxes.

Also, as is often the case in modeling studies, additional features of the simulated atmosphere have arisen which may or may not be spurious, such as large-amplitude changes in stratospheric winds and temperatures and some near-surface temperatures shown in Figs. 5 and 6. No physical mechanism is proposed for these. They may represent a discrete shift in the stratospheric circulation regime, which may or may not be accurately modeled.

5. CONCLUSIONS

The experiments discussed here are intended to illuminate some basic effects of the presence of the Great Lakes on hydrologic variables and atmospheric circulation at synoptic and larger spatial scales and over climatic time scales. Some of these hydrologic effects have been previously shown in studies such as Croley and Assel (1994), but additional information has been gained through coupling to an atmospheric model. Because of the idealized nature of the lakes used in these experiments and several caveats regarding the formulation of the model, the results given here are not to be taken as quantitatively exact answers.

The presence of idealized Great Lakes results in a phase shift in the annual cycle of latent and sensible heat flux from the lakes, in comparison to the land that would otherwise be there. The amplitude of the annual cycle of sensible heat flux also increases substantially.

Over a region encompassing the Great Lakes (referred to as the "basin", see Fig. 1), evaporation increases during the autumn and winter and decreases during the late spring and summer. During the autumn and winter, precipitation increases by a somewhat smaller amount than evaporation, and during the summer, precipitation decreases only slightly. In the annual average, precipitation minus evaporation increases, indicating that there is increased convergence of water vapor flux over this region.

The change in meridional temperature gradient induced by the presence of idealized Great Lakes intensifies the mean jet stream core and displaces it toward the north during the autumn and, to a lesser extent, during the winter.

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