Dynamics of the Great Lakes' Regional Climate Regimes

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Observations

The surface air (**Fig.1**) and water (**Fig.2**) annual warming trends of a number of the Great Lakes have been significantly greater than the warming trends of the surrounding land and atmosphere for the last couple of decades (Austin and Colman, 2007), especially those of their summer water temperature (not shown). The magnitude of these trends is also correlated with the lakes' bathymetry (**Fig. 3**).

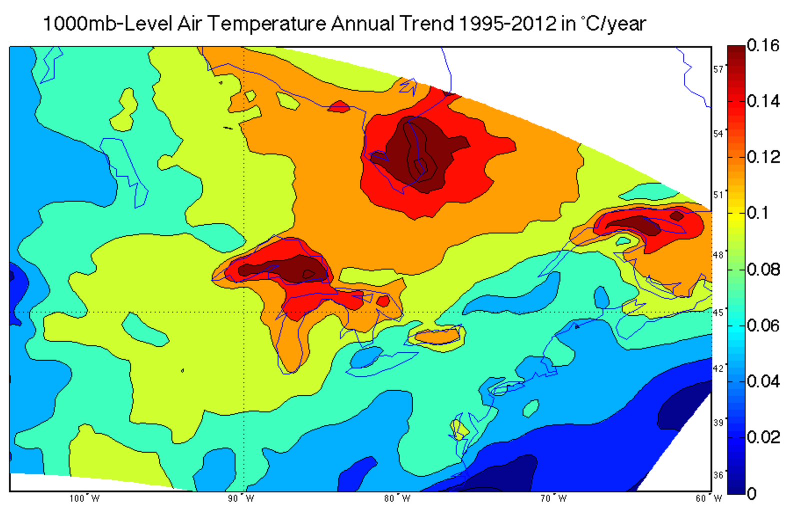

Figure 1. The spatial distribution of linearly warming trends in 1000-mb-level annual air temperature around the Great Lakes (at the center). The NARR reanalysis data for the years 1995-2012 is used.

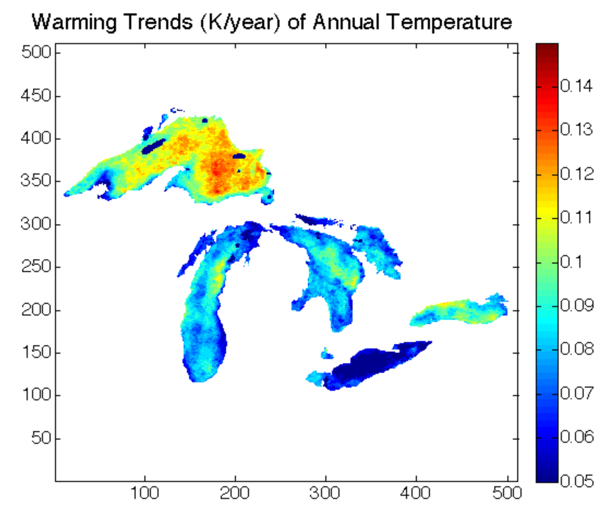

Figure 2. The spatial distribution of linearly regressed warming trends in annual surface water temperature of the Great Lakes, observed by the GLSEA satellite through the CoastWatch program for the years 1995-2012.

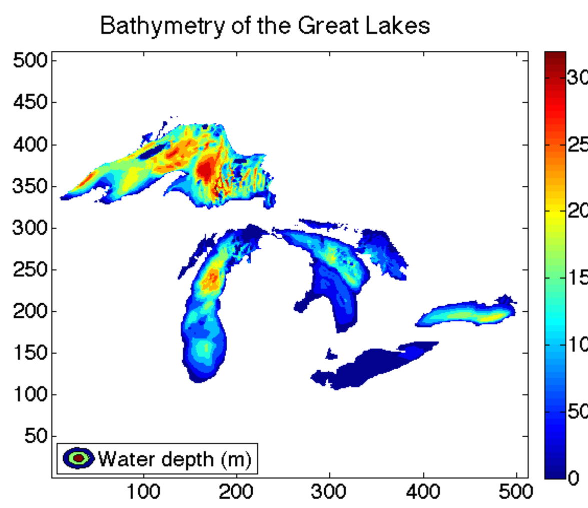

Figure 3. The spatial distribution of water depth in meters of the Great Lakes

Between the years 1977 and 1997, the maximum ice cover over Lake Superior was greater than 70% except for four winters, while between the years 1998 and 2013, the maximum ice cover over Lake Superior was in the range 0-70% except for two winters (not shown). The summer water temperature of Lake Superior also shows similar discontinuity before and after the year 1998 (**Fig. 4**), indicating that Lake Superior underwent a climate-regime change. Lake Erie, which is a shallow lake, however, does not exhibit such a discontinuous behavior (**Fig. 5**). Nor does Sparkling Lake, another shallow lake, located about 50 miles south of Lake Superior, although it exhibits a gradual trend (Lenters, 2015). We hypothesize that deeper lakes such as Lake Superior exhibit climate-regime changes more explicitly, and test the hypothesis with our model.

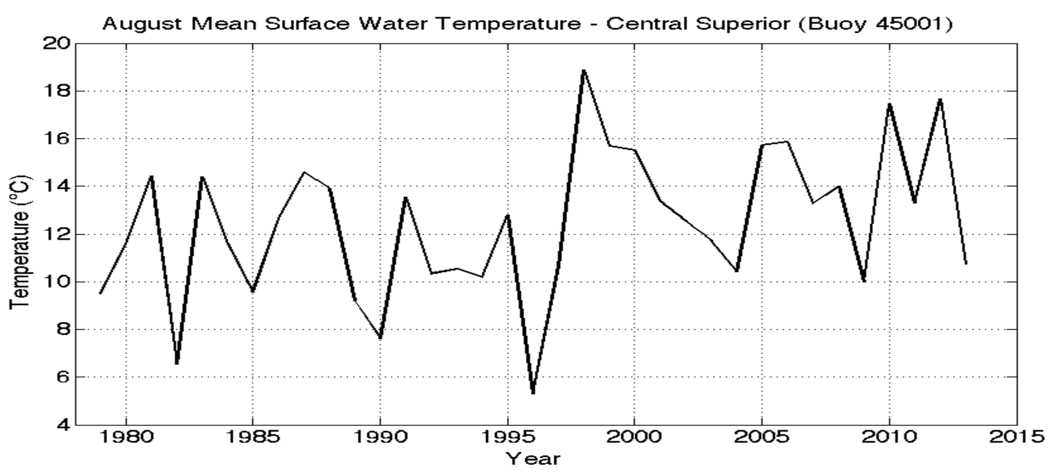

Figure 4. The time series of August mean surface water temperature at buoy station 45001 in central Lake Superior.

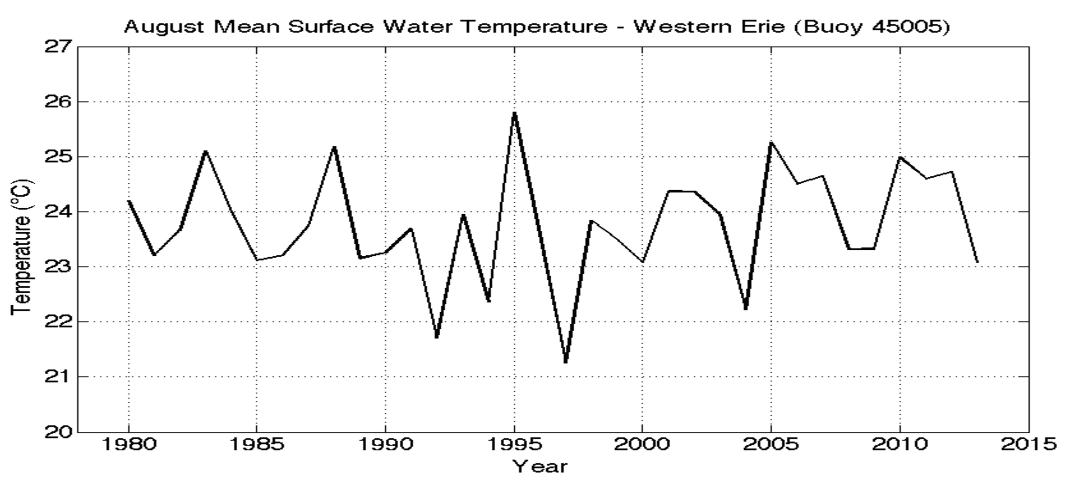

Figure 5. The time series of August mean surface water temperature at buoy station 45005 in western Lake Erie.

Lake–Atmosphere–Land Coupled Model

We consider a lake with three vertical columns of different depths, coupled with upper and lower atmospheres and surrounding land. The air mass in the lower atmosphere above the surface of each lake column or land has a distinct, uniform temperature (the illustration below). A Hostetler and Bartlein (1990) type 1-D lake model governs each lake column, and the columns do not exchange heat with each other horizontally. The lake exchanges heat with the atmosphere above them via sensible and latent heat fluxes, and the lower atmosphere air columns exchange heat horizontally. Periodic incoming shortwave radiation, upper-atmospheric temperature, and surface wind speed act as forcing. In addition, a linear trend of 0.04 K/year is imposed on the upper-atmospheric forcing, which mimics global warming. The temperatures of air masses in the lower atmosphere as well as that of land are determined by energy balance.

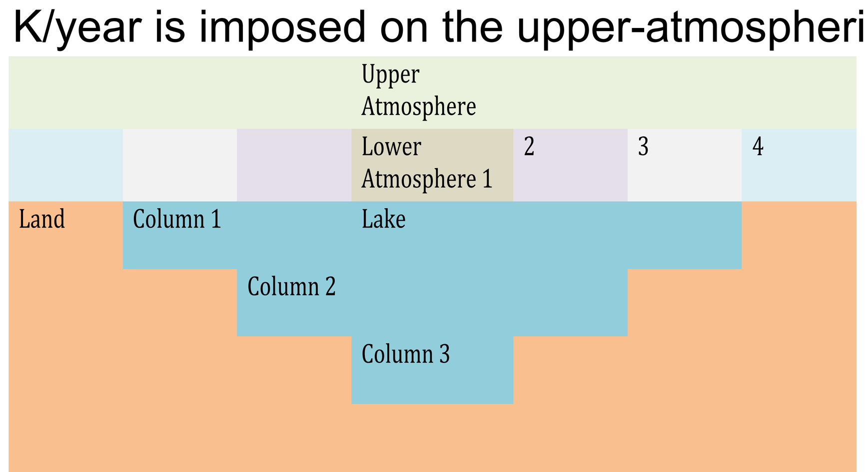

Figure 6 below shows how, in 1-D lake models that do not consider horizontal advection of water, lower atmosphere acts as a medium for interactions among lake points within a single lake. In the figure, the lake models 1A and 1B have identical three-column bathymetry, but the efficiencies of heat exchange between the air masses (see the illustration above) in the lower atmosphere differ. In particular, this efficiency is greater in the model 1A. Comparing the two models, we see that the more efficient heat exchange between air masses in the lower atmosphere is, the closer are the periods during which lake points of different water depths transition from being wintertime ice-covered to being perennially ice-free. A peak warming trend occurs concurrently with such a transition due to the ice-albedo feedback.

The figure also indicates that **the larger the depth of a lake column is, the stronger the magnitude of its warming-trend peak is. This is consistent with Figs 2 and 3.**

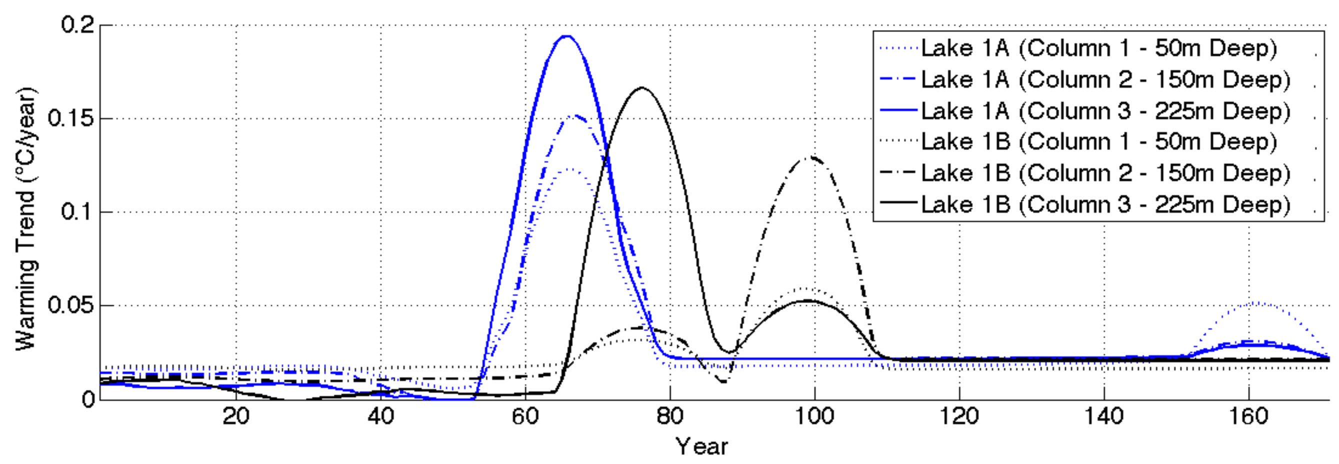

Figure 6. The 20-year warming trends in annual surface water temperature of various columns of Lakes 1A and 1B (their only difference is the efficiency of heat exchange between the air masses in the lower atmosphere, which is greater over 1A) as functions of year, given the upper-atmosphere forcing trend at 0.04 K/year.

Figures 7, 8, and 9 suggest the existence of more than one regional climate regime over the Great Lakes, with Lake Superior as an example, during their transition from wintertime ice-covered to ice-free state, with varying degrees of ice coverage among regimes.

The histogram of maximum ice cover over Lake Superior between the years 1973 and 2014 show two large peaks, one between 10% and 20% and the other between 90% and 100%, and one small, gentle peak between 30% and 70% (**Fig.7**). Each of these three ice regimes is associated with a distinct regime of summer water temperature (**Fig.8**). **Our 3-column lake models reproduce three such distinct regimes in the hysteresis plot of summer surface water maximum temperature versus upper air mean temperature** (**Fig.9**). By comparing hysteresis plots of lakes of different depths, our models also show that the range of upper air temperature in which more than one regime exist is smaller in shallower lakes than in deeper lakes, indicating more readiness of shallower lakes and more resistance of deeper lakes to transition from one regime to another (not shown). This explains why deeper lakes exhibit climate-regime changes more explicitly (**Figs. 4 and 5**).

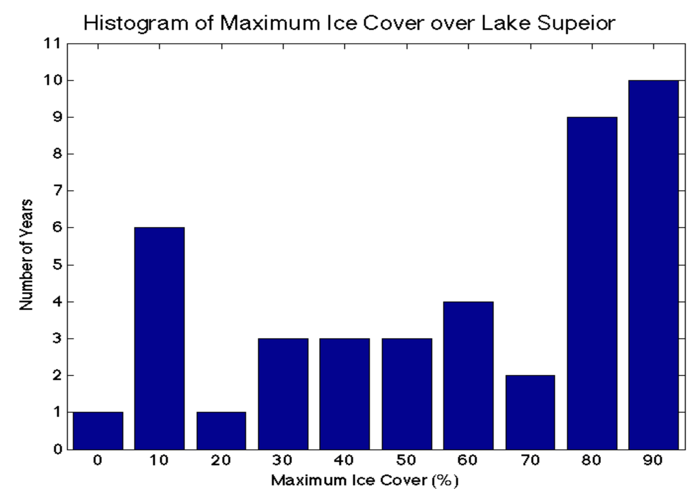

Figure 7. Histogram of maximum ice cover over Lake Superior for the years 1973-2014.

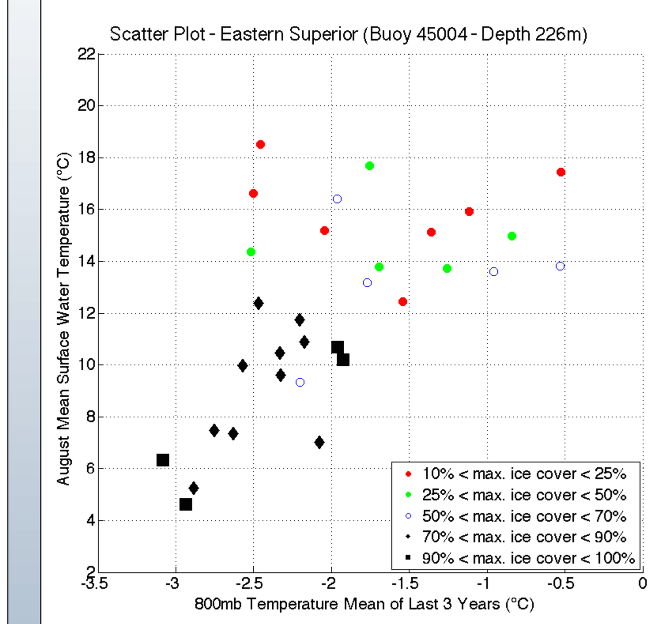

Figure 8. Scatter plot of August mean surface water temperature at buoy station 45004 in eastern Superior versus 3-year mean 800mb-level air temperature above the station, averaged between September 3 years ago and August. Different colors denote different maximum ice coverage of Lake Superior in winter a few months prior to August.

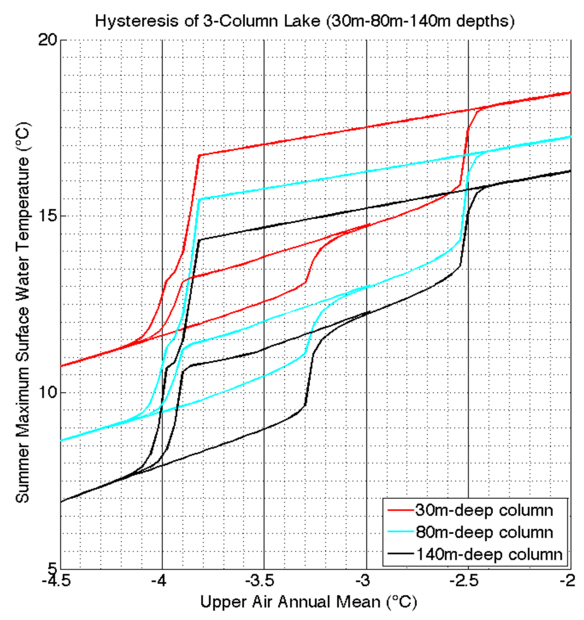

Figure 9. Hysteresis plot of summertime surface water maximum temperature of a 3-column lake (30m, 80m, and 140m deep each) versus annual temperature of the upper air forcing. Different colors correspond to different lake columns. For each lake column, three regimes exist in a range of upper air temperature.

Bibliography

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Hostetler, S. W. and P.J. Bartlein (1990), *Water Resources Res.* **26**, 2603-2612.

Lenters, J. (2015), private communication.

Acknowledgement. This research was supported by the NSF grant AGS-1236620.

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