Dynamics behind Recent Warming Trends of the Great Lakes

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AGU FALL MEETING San Francisco | 15–19 December 2014

Observations

The surface water annual warming trends of a number of the Great Lakes (**Fig.1**) have been significantly greater than the warming trends of the surrounding land and upper atmosphere for the last couple of decades (Austin and Colman, 2007), as seen in **Table 1**, and even twice greater during summer (not shown). The magnitude of these trends is also correlated with the lakes' bathymetry **(Fig. 2**).

	Annual Surface Warming Trend (°C/*year*)	Average Lake Depth (*m*)
Lake Superior	0.10±0.04	147
Lake Michigan	0.082±0.04	85
Lake Huron	0.076±0.04	59
Lake Erie	0.057±0.03	19
Lake Ontario	0.096±0.03	86

Table 1. Column 2: The linearly regressed warming trends in annual surface water temperature of each of the Great Lakes, observed by the GLSEA satellite through the CoastWatch program for the years 1995-2012. Column 3: The average depth of each of the Great Lakes.

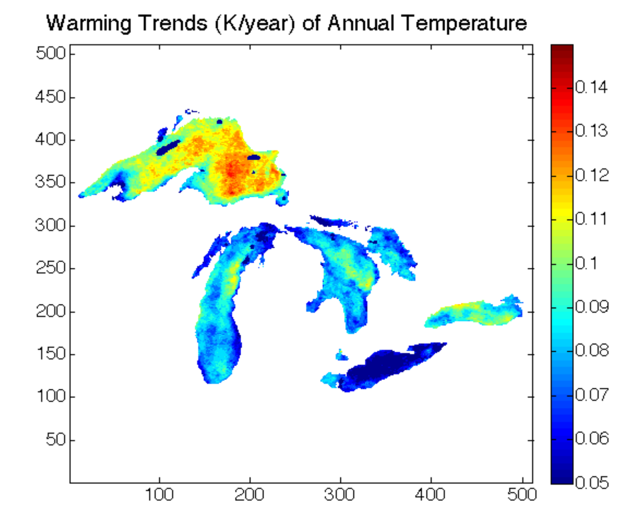


Figure 1. The spatial distribution of the linearly regressed warming trends in annual surface water temperature of the Great Lakes, observed by the GLSEA satellite through the CoastWatch program for the years 1995-2012.

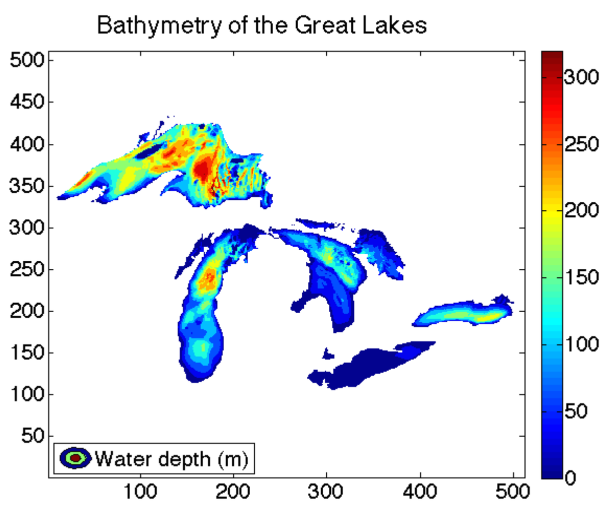


Figure 2. The spatial distribution of water depth of the Great Lakes

Lake-Only Model

Many existing lake models underestimate mixing of lake water when simulating the temperature of deep portions of the lake (Martynov et al., 2010, Subin et al., 2012, Bennington et al., 2014). This happens primarily during the period between when the temperature of surface water starts to warm in mid-winter and the spring overturn. Our *ad hoc* modification to a one-dimensional lake model of the Hostetler and Bartlein (1990) type is to enhance the value of minimum diffusivity during this period, especially when surface water temperature is slightly below 4ºC. The model so modified provides a better fit to observed seasonal evolution of the surface water temperature and ice cover when forced with the observed history of atmospheric surface variables (**Fig. 3**).

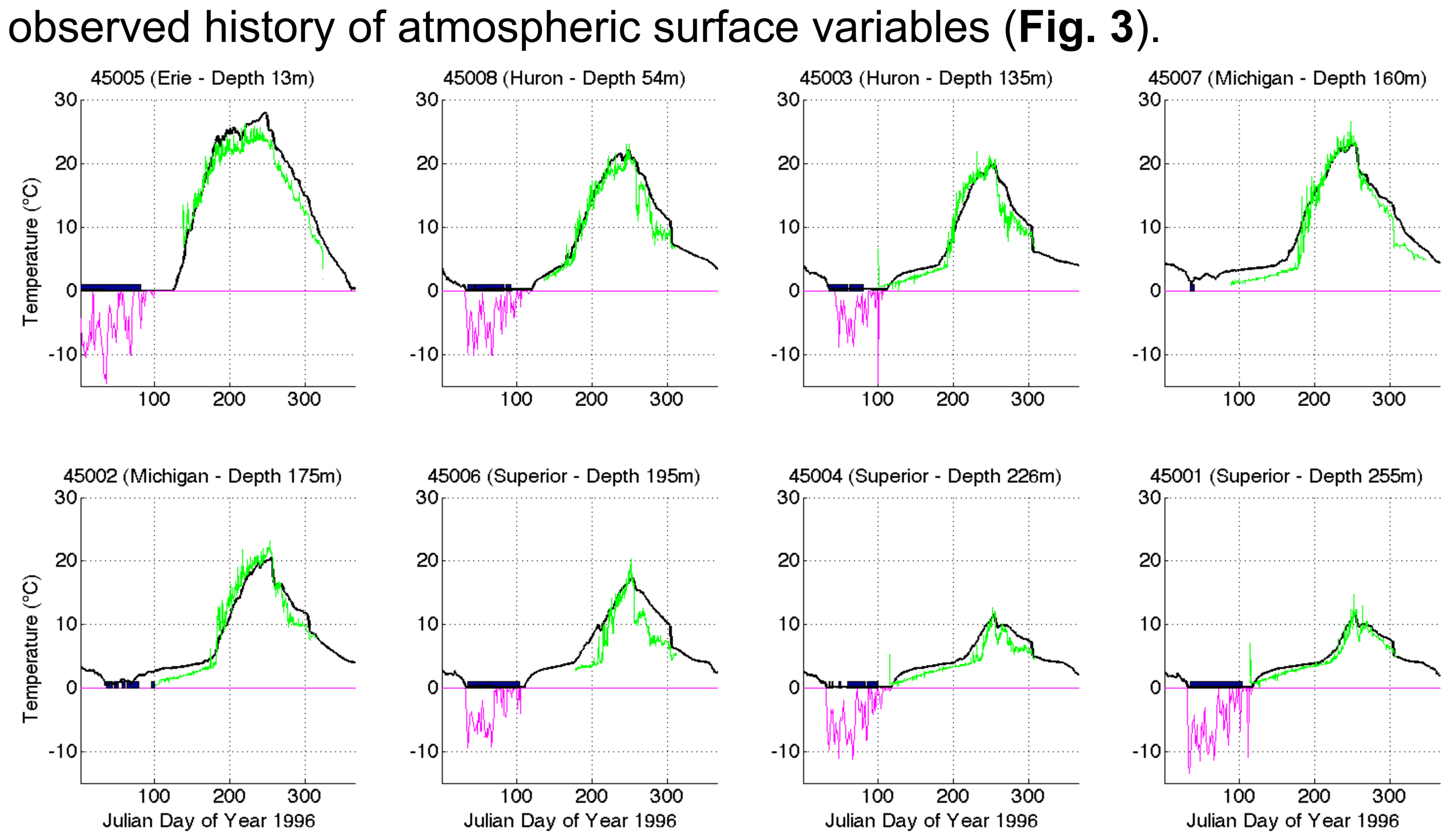
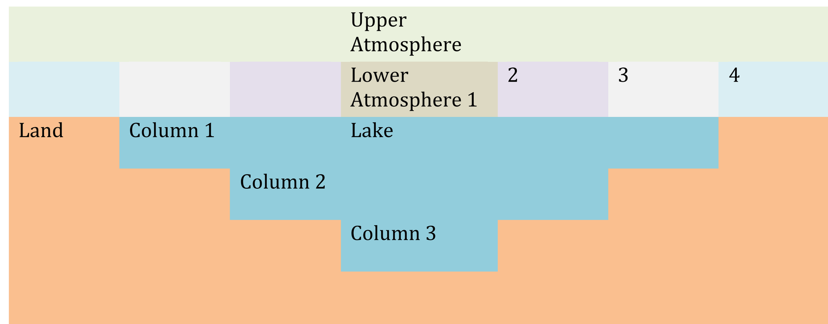


Figure 3. The surface water temperatures at various buoy stations during the year 1996. The green curves are the observed surface water temperatures, the dark blue bands mark the periods during which at least 10% or more of the region near the station was observed to be ice covered, the black curves are the model simulated surface water temperatures, and the purple curves are the model simulated ice temperatures.

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). The aforementioned 1D 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. The upper atmosphere acts as forcing, and the air temperatures of the lower atmosphere as well as that of land are determined by energy balance.



We construct a toy model with such three lake columns for each of the Great Lakes, so that each toy lake has average depth similar to that of the corresponding lake.

We vary the values of incoming shortwave radiation and upper-atmosphere long-term mean temperature among the toy models to account for the different geographic locations of the Great Lakes. **Figure 4** shows how surface water annual warming trends change as functions of time for toy models of the Great Lakes, given the upper-atmosphere forcing trend at 0.04 K/year. **Overall, the magnitudes and sequence of the peaks for individual lakes are consistent with observations.**

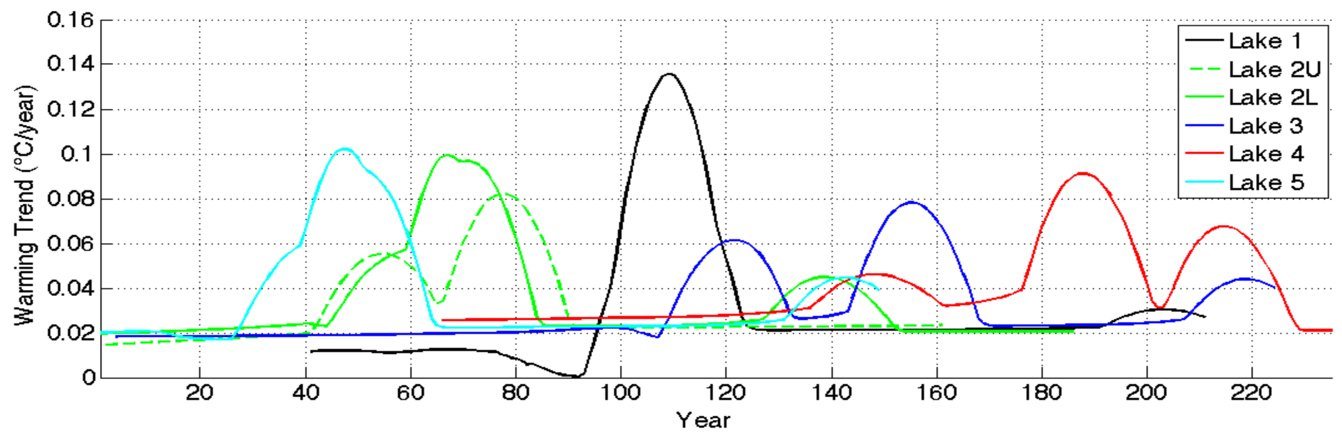


Figure 4. The 20-year warming trends in annual surface water temperature of the toy models of the Great Lakes, as functions of year, given the upper-atmosphere forcing trend at 0.04 K/year. Lake 1 – toy Superior. Lakes 2U and 2L - toy upper and lower Michigan. Lake 3 – toy Huron. Lake 4 – toy Erie. Lake 5 – toy Ontario.

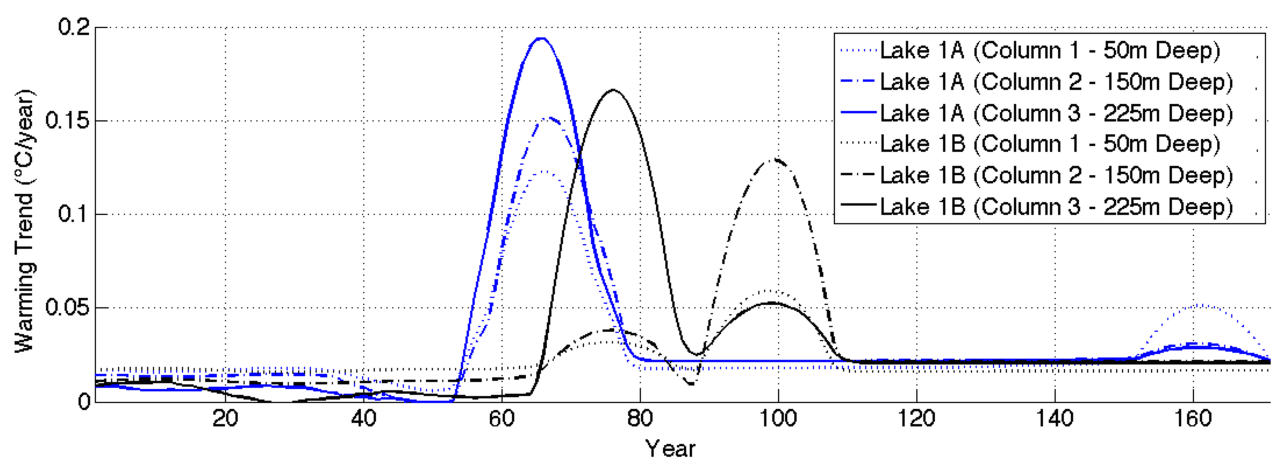


Figure 5. The 20-year warming trends in annual surface water temperature of various columns of Lakes 1A and 1B (both toy Superior but the efficiency of heat exchange between the air masses in the lower atmosphere is greater over 1A) as functions of year, given the upper-atmosphere forcing trend at 0.04 K/ year.

Figure 5 shows how, in 1D 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 these models;

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 ice-free. A peak warming trend occurs concurrently with such a transition due to the ice-albedo feedback.

The figure also indicates that **the heat transported in the lower atmosphere from shallower-lake to deeper-lake regions enhances the summertime surface warming of deep-lake regions further, thus helping explain the quantitative dependence of the surface warming rates on lake depth** (Figs. 1 and 2)**.**

Figure 6 suggests the existence of two regional climate regimes over the Great Lakes during their transition from wintertime ice-covered to ice-free state, namely the extensively ice-covered and lightly ice-covered regimes. Between the years 1977 and 1997, the maximum ice cover over Lake Superior was greater than 70% almost every winter, while between the years 1998 and 2002, the maximum ice cover over Lake Superior was in the range 20-40%. Numerical simulations of toy lakes with the upper-atmosphere forcing trend at 0.04 K/year and additional thermal and shortwave-radiation noises exhibit similar sudden changes in the amount of ice cover and the persistence of the regime once such a change occurs.

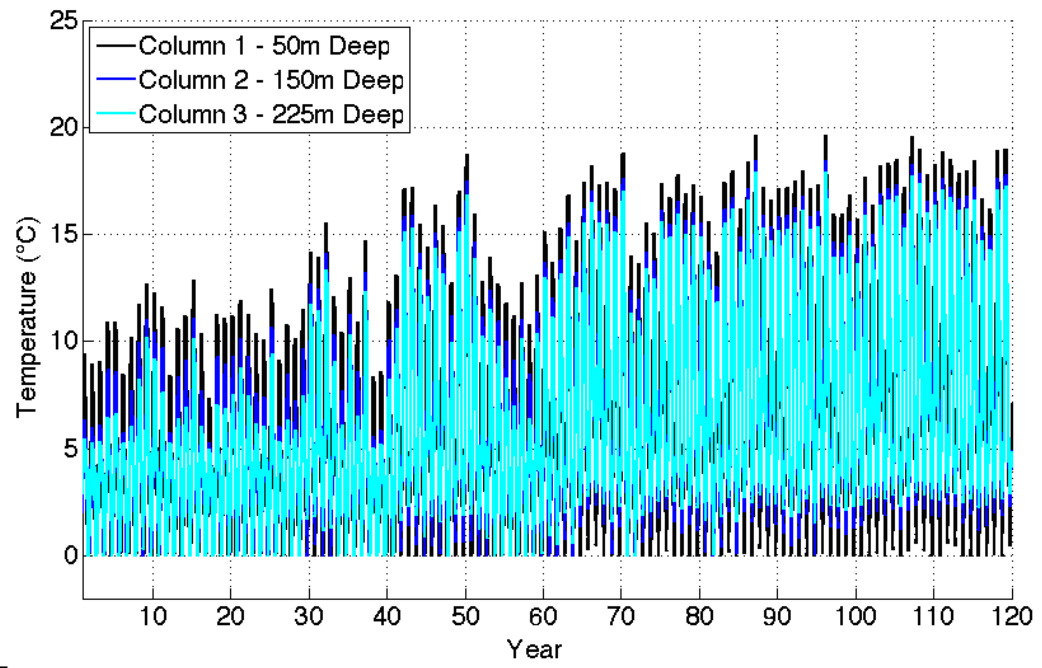


Figure 6. Surface water temperatures of Lake 1 (toy Superior), given the upper-atmosphere forcing trend at 0.04 K/year and additional thermal and shortwave noises. Column 1 – 50m deep, black curve. Column 2 – 150m deep, blue curve. Column 3 – 225m deep, light blue curve. The two regimes are evident in the evolution of the deep portion of the lake (light blue) between years 30 and 60.

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

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