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Multiple climate regimes in an idealized lake–ice–atmosphere model

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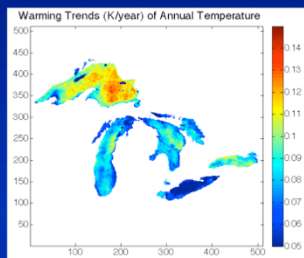
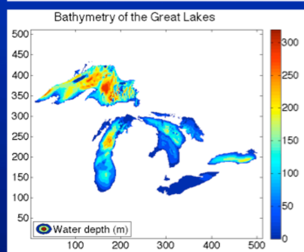
Motivation: Great Lakes' regional climate change

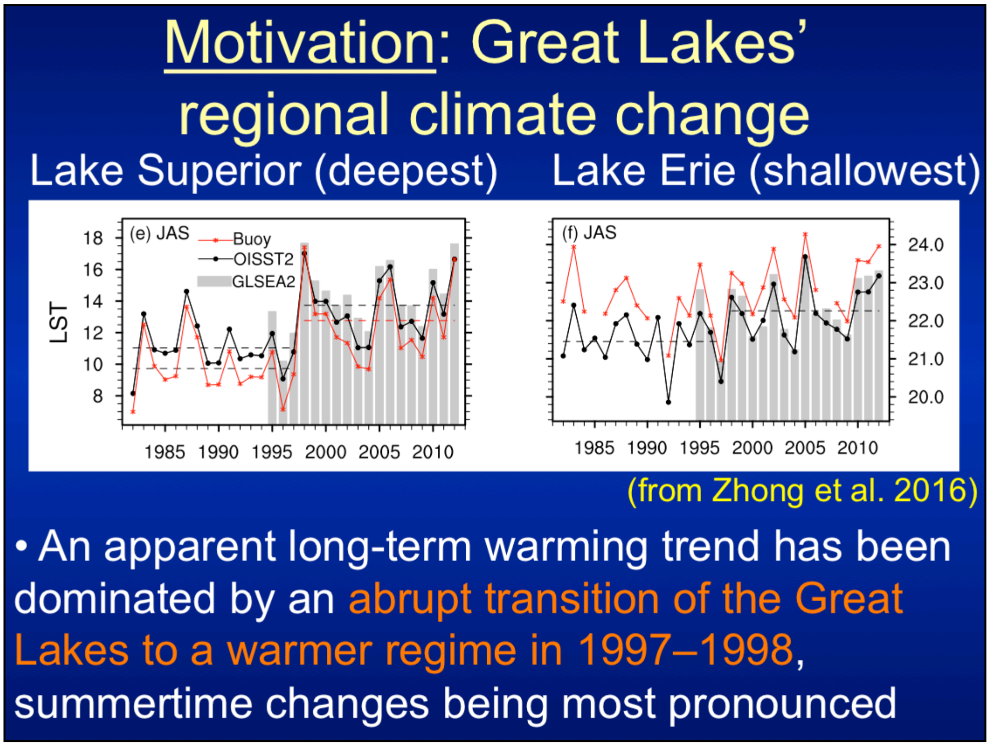




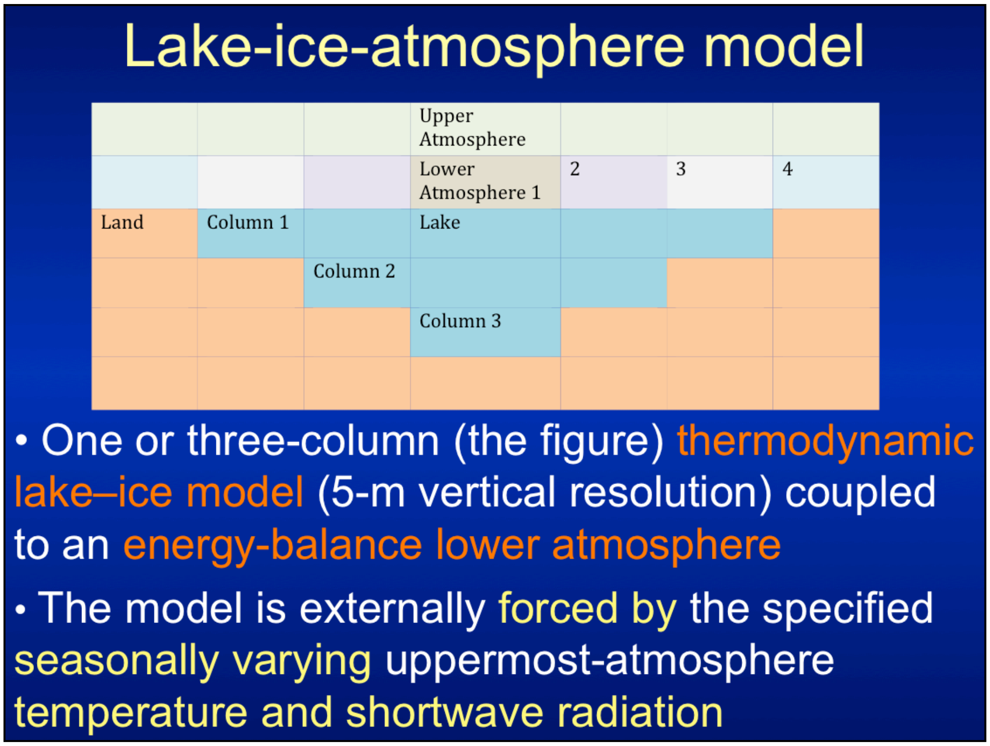
	Annual Surface Warming Trend $(^{\circ}C/year)$	Average Lake Depth (m)
Lake Superior	0.10 ± 0.04	147
Lake Michigan	0.082 ± 0.04	85
Lake Huron	0.076 ± 0.04	59
Lake Erie	0.057 ± 0.03	19
Lake Ontario	0.096 ± 0.03	86

- Great Lakes warm faster than surrounding land areas
- The pattern of warming trends correlates with lake depths

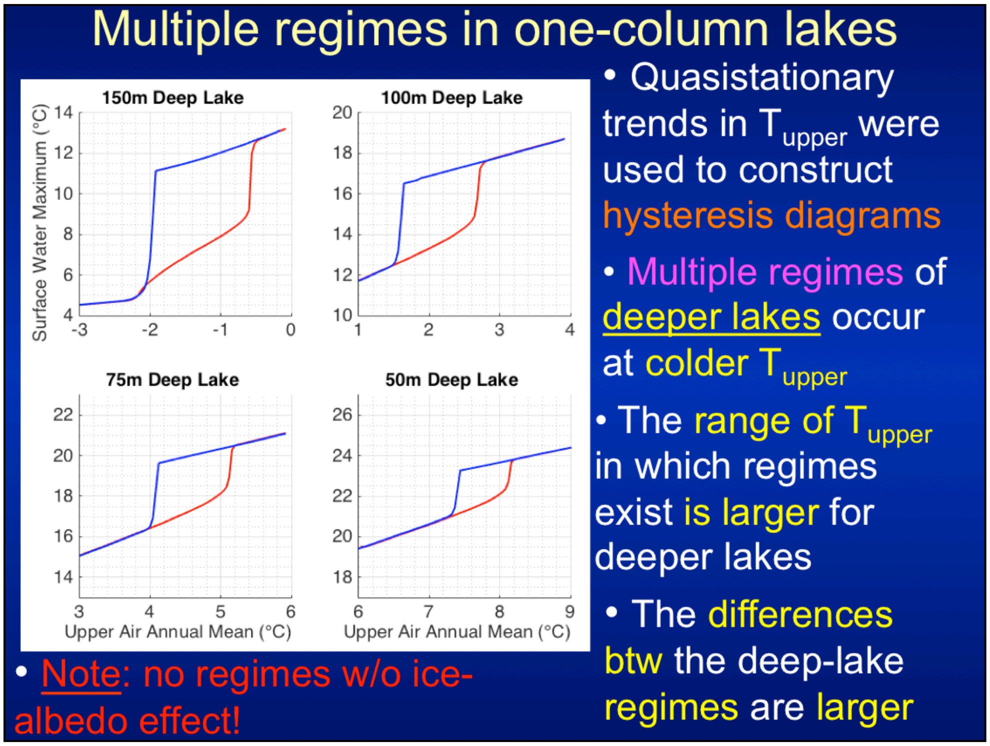
The surface water annual warming trends of the Great Lakes for recent decades have been significantly greater than the warming trends of the surrounding land (Austin and Colman 2007), and even more so in summer (not shown). The magnitude of these trends is correlated with the lakes' bathymetry within individual lakes and between the lakes.



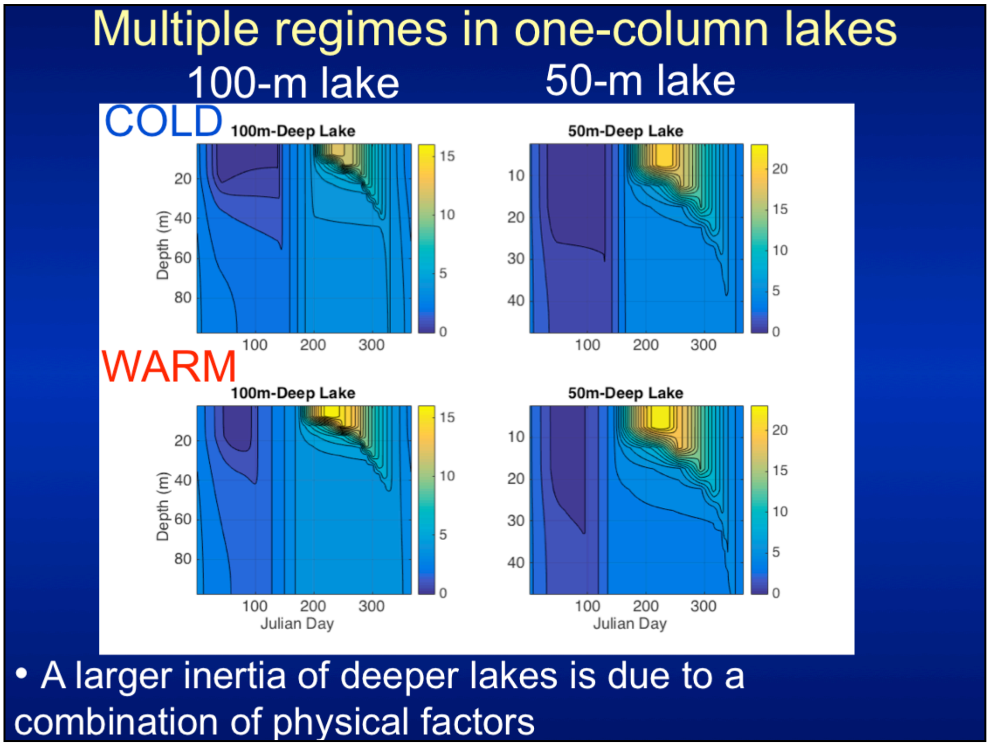
An abrupt regional climate change over Great Lakes may be indicative of its nonlinear nature.



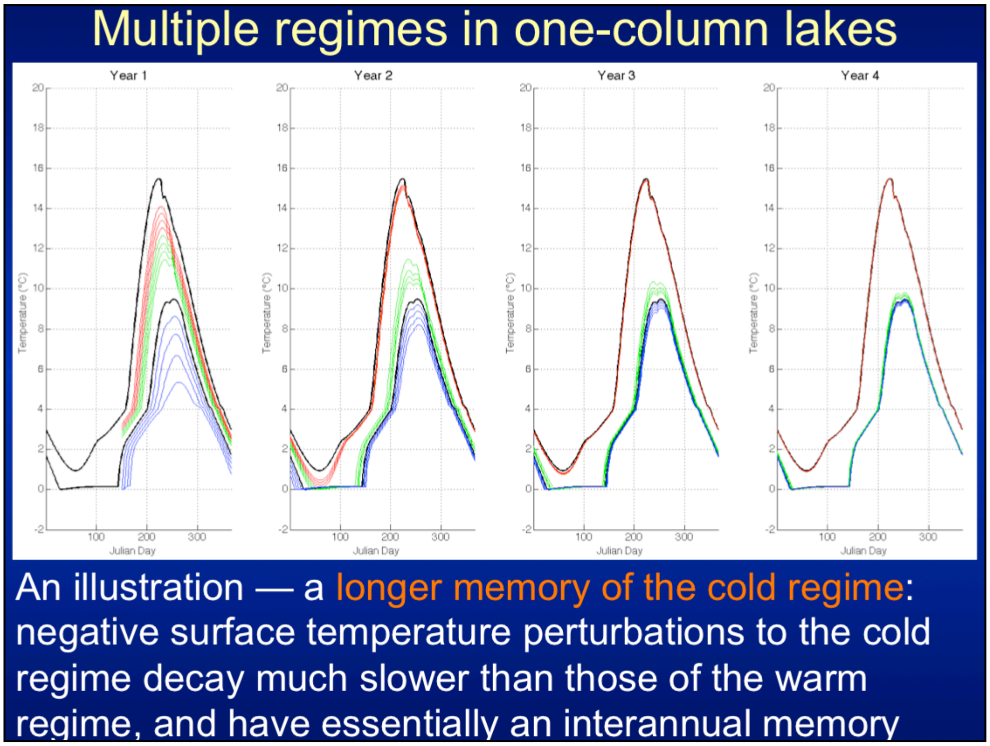
We attempt to understand the causes of the Great Lakes accelerated warming in an idealized coupled lake–ice–atmosphere model. The most general version of the model has a three-column configuration, with the thermodynamic lake and ice models (Hostetler and Bartlein 1990; Martynov et al. 2010; Subin et al. 2012; Bennington et al. 2014) coupled to an energy-balance lower atmosphere. The model is externally forced by the specified variable upper-atmosphere temperature and shortwave radiation.



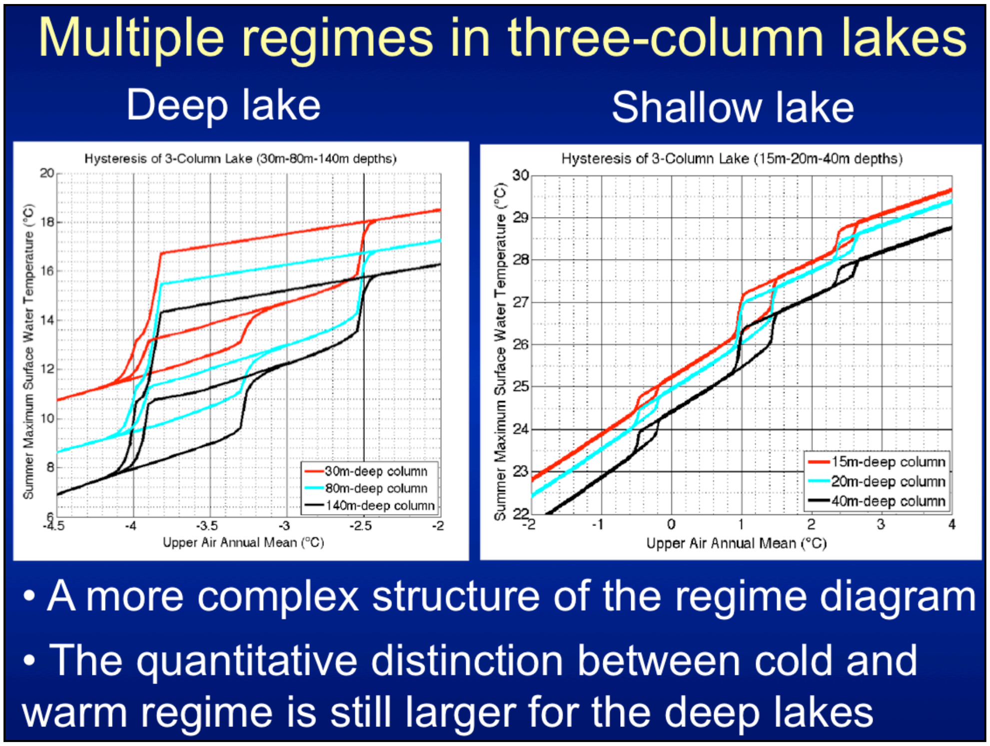
We start the discussion with one-column lake models, which have a uniform depth. Under identical seasonally varying forcing, these models exhibit multiple equilibrium seasonal cycles (regimes) in a range of the annual-mean upper-level atmospheric temperature *T*. We observe that: (i) the multiple regimes of deeper lakes occur at colder values of *T* forcing compared to the multiple regimes of shallower lakes; (ii) the range *T*max—*T*min of *T* in which the two regimes exist simultaneously is larger for deeper lakes; and (iii) the difference in the maximum summertime temperature between the two regimes is also larger for deeper lakes.



These properties are associated with a larger inertia of deep lakes, which arises via a combination of physical factors, including convective dynamics of the lakes and lake–atmosphere interaction modification by the seasonal ice cover, with both ice–albedo and insulating ice effects being important. The slide shows typical seasonal cycles of the lakes in cold and warm regimes, 100-m-deep lake on the left and a shallower, 50-m-deep lake on the right. Note the existence of the seasonal thermocline during summer and winter, separated by the periods of the spring and fall convective overturns which homogenize the lakes' temperature. The wintertime thermocline arises as seasonal forcing cools the water below 4 deg. C – which is the temperature at which the water density is maximal. As it starts to warm up in Spring and surface water reaches 4 deg. C, the Spring overturn starts and continues until the surface water warms above 4 deg. C, at which time the summertime stratified season starts. Note that the start of summertime stratification in the warm regime happens earlier than in the cold regime, and this is the mechanism by which the summertime mixed layer is able to warm up more during summer, due to its being heated up longer by the seasonal forcing. The difference in the start-date of the spring stratification between the warm and cold regimes is larger for a deeper, ultimately because the deep lake's convection is able to involve more water to participate in the surface heat balance, and hence is more sluggish in responding to seasonal forcing. Consequently, the maximum summertime temperature difference between the warm and cold regimes is larger for deeper lakes.



We quantify stability of the regimes by introducing perturbations (colored lines) to the cold and warm regimes (black lines) for the 100-m-deep lake. The warm-regime 'stable' perturbations exhibit non-uniform decay rates in the first year of the perturbation experiment (for example, the maximum summer temperature perturbations attained during year-1 are larger than initial perturbations; the same can be said about the perturbations of minimum temperature realized in the winter of year-2). These non-uniformities are due to changes in the mixed-layer depth throughout the year (see previous slide). The quick death of a warm-regime negative temperature perturbation occurs during days 60–100 of year 2, when the wintertime mixed layer is being heated by the seasonal forcing. On the other hand, the cold-regime's perturbations are insulated at that time by the presence of lake ice, and then are mixed throughout the entire water column, which only allows a slow heat loss to the overlying atmosphere.



The regime structure of the three-column models is more complex, with a possibility of three regimes which are characterized by wintertime ice coverage of either the entire lake, or two of its shallower columns, or the shallowest column only. In deep lakes, all three regimes can coexist over a certain range of annual-mean upper-air temperature. As this forcing increases, the deepest lake column eventually becomes ice-free and the system transitions to the two-regime region of parameter space. Further increase of the forcing leads to the transition to the warmest regime.

In shallower three-column lakes, the forcing ranges in which of the cold, intermediate and warm regimes occur do not overlap. As the forcing increases, the three model columns transition from their wintertime ice-covered to perennial ice-free states one by one, starting with the deepest and ending with the shallowest column. The quantitative distinctions between the regimes realized during these transitions is also much smaller than between the different deep-lake regimes, consistent with the results for single-column lakes of uniform depth.

Simulation of the Great Lakes warming

Warming-trend	Shallow col.	Intermediate col.	Deep col.	Overall
Lake 1	0.141/0.137	0.185/0.171	0.200/0.183	0.185/ 0.171
Lake 2	0.104/0.090	0.157/0.119	0.112/0.129	0.132/0.116
Lake 3	0.080/0.063	0.119/0.085	0.086/0.092	0.098/0.076

- Global warming is introduced as the 0.04 ºC/year linear trend in T_{upper}
- Lake-1: deep; Lake-2: intermediate: Lake-3: shallow
- Deeper lakes warm faster than shallow lakes, at rates consistent with observations
- Deep regions warm faster than shallow regions within individual lakes, also consistent with obs.

The model is able to simulate rapid warming of the Great Lakes in response to the linear 'global warming' forcing as a consequence of an abrupt transitions between cold and warm regimes. The warming rates and the dependence on lake depths are all consistent with observations.

Regimes as agents of the Great Lakes rapid climate change

- Our lake model exhibits, under identical seasonally varying forcing, multiple equilibrium seasonal cycles
- Cold/warm regimes are characterized by a pronounced/suppressed wintertime ice cover and cold/warm summer temperatures
- The gap between the cold/warm regimes increases with lake's depth, reflecting a dynamical inertia of deep lakes
- Under global warming, the attraction basin of the warm regime expands, and cold-to-warm regime transition may rationalize the observed rapid climate shift of Great Lakes, its dependence on lakes' depth, as well as the apparent correlation btw wintertime ice cover and next summer's temps.

Our results provide a nonlinear explanation of the recently observed rapid climate change in the Great Lakes region.

Discussion

- The lake regimes do arise due to ice–albedo feedback, but the dynamics may be completely different from the multiple regimes in Arctic sea ice (e.g., fresh water vs. salt water equation of state and convection, seasonal thermoclines etc.)
- The simulated winter-only ice regime is apparently stable for the mid-latitude lakes, while it is unstable for Arctic sea ice… The concept of regimes is arguably more applicable to explaining the lake regimes than the Arctic “regimes”.
- What’s the mathematical framework for multiple regimes and regime transitions under the seasonally varying forcing?.. Stochastic resonance? Others?

Bullets 1/2: Add that the common problem with idealized models simulating arctic ice regimes is the so called small ice cap instability, in which an equilibrium with ice cover in winter and no ice in summer is unstable. In this sense, the ice-albedo-related regimes may be more relevant for a description of mid-latitude lakes than for that of the arctic sea ice.

Bullet 3: Mention double-well potential framework. The properties of seasonally varying multiple equilibria are necessarily more complex than those of the systems under autonomous forcing. For example, we have noticed that the transitions between the regimes are most sensitive to the external forcing variability in winter, and less so in summer. Is it simply because the “hump” between potential wells becomes lower at that time? In general, is there a general mathematical framework that generalized the theory of multiple equilibria to the systems with seasonal forcing?

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