Driving a 3-Dimensional Lake Dynamics Model Using a Global General Circulation Model: A Proof of Concept

GC33G-1445

Brent M. Lofgren[1], Michael Winton[2], Jia Wang[1], Eric J. Anderson[1], Haoguo Hu[3], Ayumi Fujisaki-Manome[3], James A. Kessler[3], Chuliang Xiao[3], and Gregory Lang1
[1]*NOAA Great Lakes Environmental Research Lab, Ann Arbor, MI* [2]*NOAA Geophysical Fluid Dynamics Lab, Princeton, NJ*
[3]*University of Michigan, Cooperative Institute for Great Lakes Research, Ann Arbor, MI*

GLERL Great Lakes Environmental Research Laboratory

Abstract

The spatial and temporal scales that can be investigated for global and regional aspects of the climate system are beginning to converge. Reducing the number of hand-offs of data among different models in a causal chain leading from anthropogenic greenhouse gases to an end-point impact (lake water levels, fish growth, etc.) reduces the opportunity for conceptual inconsistencies among models ("black boxes") in that chain. In contrast to the more conventional plan of using dynamically downscaled climate model output to drive regional phenomena associated with climate change, we are investigating the use of a 3-dimensional model of the Laurentian Great Lakes, driven directly by output from a general circulation model of climate with a global domain. The Great Lakes version of the Finite Volume Community Ocean Model with ice module (FVCOM-CICE) has been tuned for use on the Great Lakes, and currently has an operational version for short-term prediction. The Geophysical Fluid Dynamics Laboratory Climate Model version 4 (GFDL CM4.0) has been developed at that NOAA lab for multi-decadal projection of climate in the air-land-ocean system. Direct driving of FVCOM by output from GFDL CM4.0 will enable greater consistency of modeling than adding downscaling layers, and hence better conceptual fidelity among the pieces of the modeling system.

Statement of the Problem

Warming of the world has proceeded and will continue, but anticipated influences on specific systems, such as the physical system of the Laurentian Great Lakes, are still subject to considerable uncertainty. Our aim is to use output from global models of climate as drivers for a hydrodynamical model of the lakes, and explore the influence on characteristics such as ice cover, temperature and its temporal and spatial aspects, currents, up- and down-welling, and seiches. One particular aspect of the Great Lakes that contrasts with the oceans is that they have no permanent thermocline, but develop a new thermocline each year. Because fresh water has its maximum density at 4 °C, a weak temperature gradient can exist with the coldest water on the top of the column during the winter, but a stronger thermocline develops during the summer with the warmest water on top. Austin and Colman (2007) proposed that an earlier initiation of the formation of a thermocline builds on the trend toward warmer surface water by inhibiting vertical mixing while the water warms.

Phenomena such as more intense thunderstorms are expected under warming climate by theoretical arguments and have generally been observed, but are poorly resolved by climate models. Also, rotation of winds to a more easterly point of origin has been observed on Lake Superior, but this does not connect strongly with modeling results. Agreement between observations and models is a desired state in order to deduce causation by anthropogenic warming.

References

Anderson, E., A. Fujisaki-Manome, J. Kessler, P. Chu, J. Kelley, G. Lang, Y. Chen, J. Wang, 2018. Ice Forecasting in the Next-Generation Great Lakes Operational Forecast System (GLOFS), *J. Mar. Sci. Eng*, 123; doi:10.3390/jmse6040123

Austin, J. A., and S. M. Colman, 2007: Lake Superior summer water temperatures are increasing more rapidly than regional air temperatures: A positive ice-albedo feedback. Geophys. Res. Lett.,, 34, doi:10.1029/2006GL029021.

Goyette, S., N. A. McFarlane, and G. M. Flato, 2000: Application of the Canadian regional climate model to the Laurentian Great Lakes region: Implementation of a lake model. *Atmos.-Ocean*, 38, 481-503.

Lofgren, B. M., 2004: A model for simulation of the climate and hydrology of the Great Lakes basin. *J. Geophys. Res.,* 109, doi:10.1029/2004JD004602.

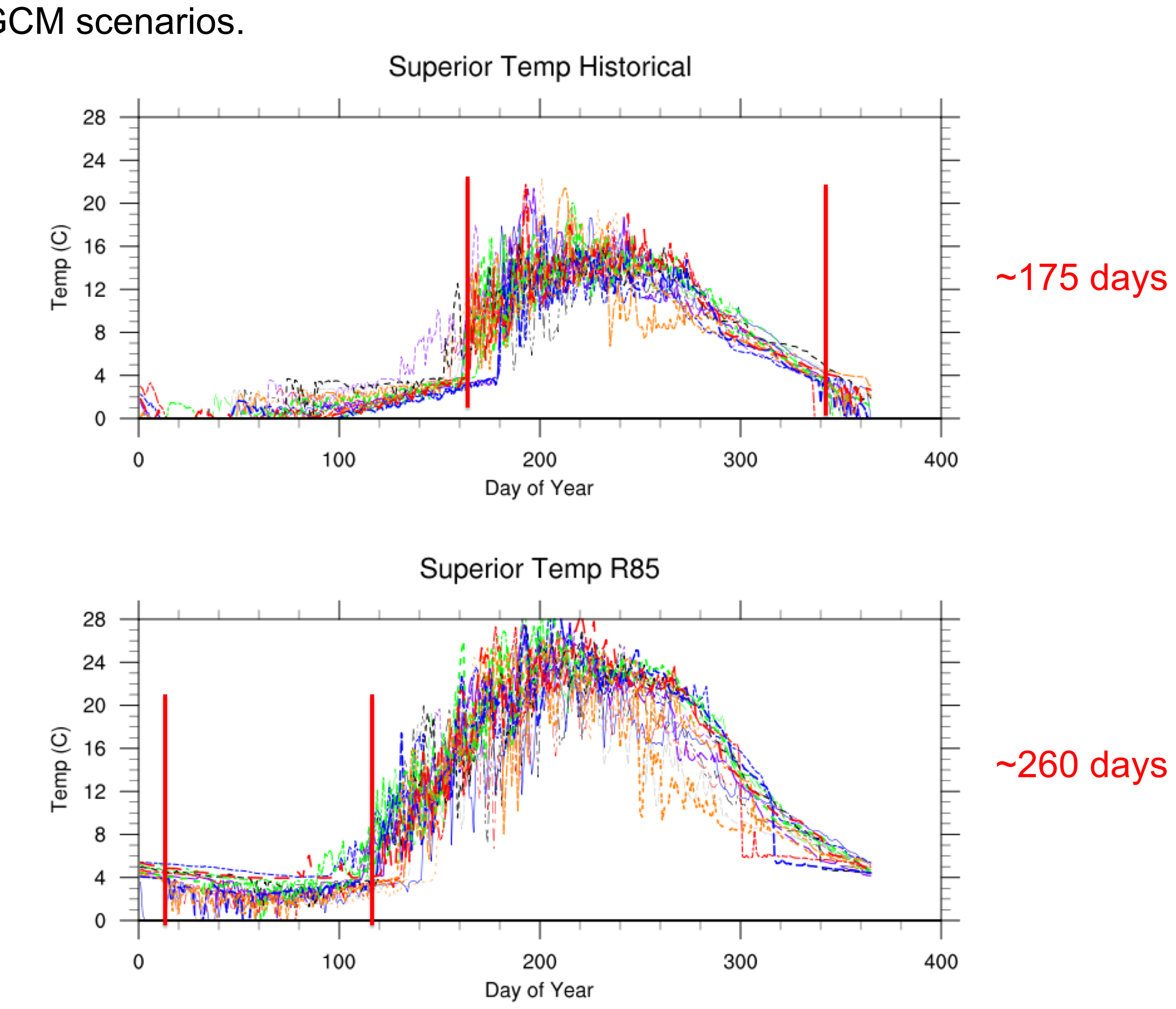
Mironov, D., E. Heise, E. Kourzeneva, B. Ritter, N. Schneider, and A. Terzhevik, 2010: Implementation of the lake parameterisation scheme FLake into the numerical weather prediction model COSMO. *Boreal Env. Res.*, 15, 218-230.

Xiao, C., B. M. Lofgren, and J. Wang, 2018: A dynamical downscaling projection of future climate change in the Laurentian Great Lakes region using a coupled air-lake model. *Atmosphere*., under review.

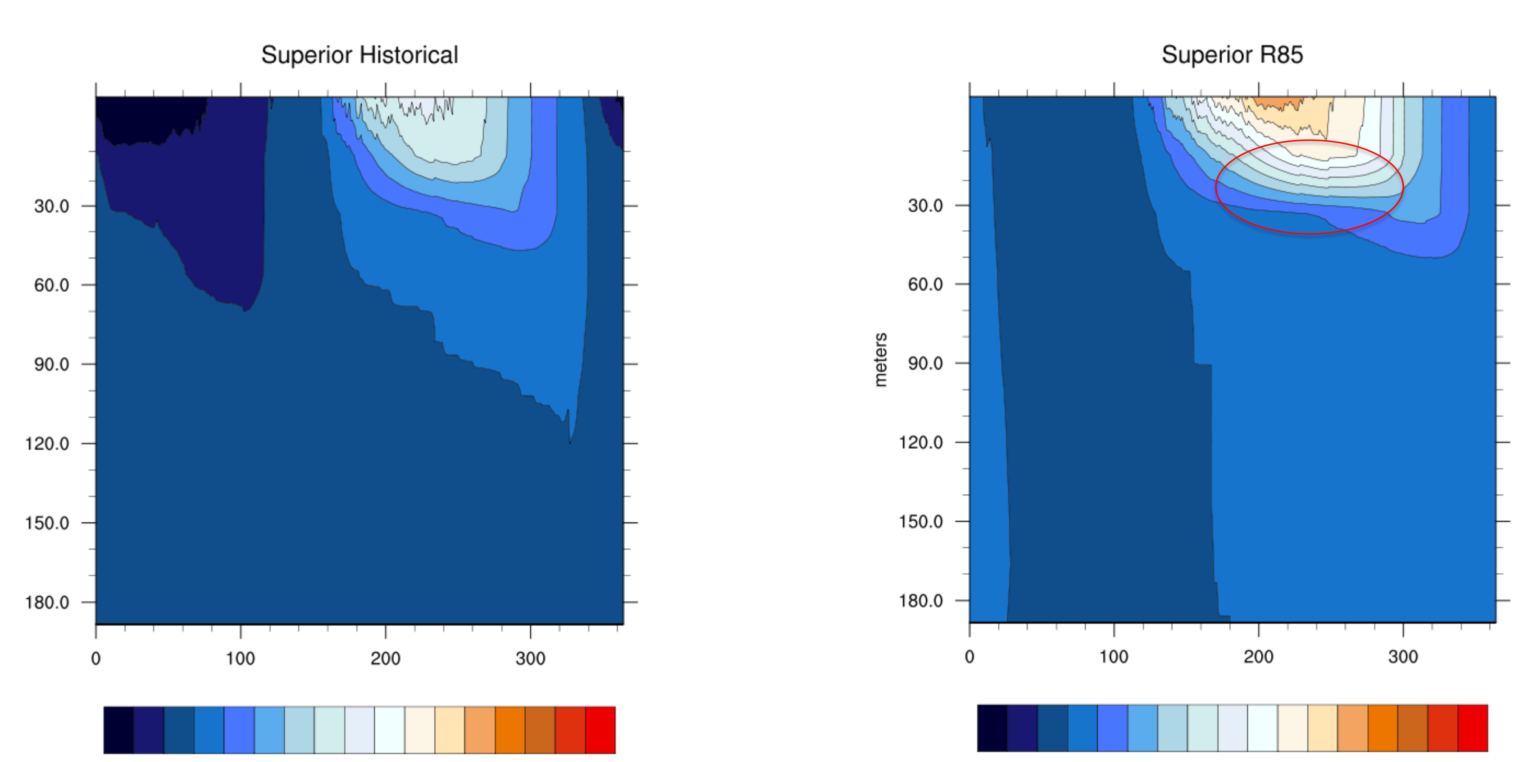
Previous Work

Simple models of vertical mixing of lakes as coupled to atmospheric models by Lofgren (2004) and Goyette et al. (2000) do not have a mechanism to inhibit vertical mixing in response to early initiation of a thermocline. The FLake model (Mironov et al. 2010) uses a canonical set of shape functions for the temperature profile, and is not well suited to lakes with a deep nearly-isothermal hypolimnion below the thermocline. Xiao et al. (2018) used the Weather Research and Forecasting (WRF) model including its lake component, WRF-Lake, which formulates lakes as individual columns with vertical diffusion of heat dependent on wind speed and explicit measures of static stability throughout the water column.

Global general circulation models (GCMs), generally with a horizontal discretization of about 1 degree in longitude and latitude, are not capable of good resolution of the Great Lakes, but can be set up to have rudimentary interaction with them. Our immediate goal is to create a one-way coupling system for GCMs to drive a model that simulates the hydrodynamics and thermodynamics of the Great Lakes under various GCM scenarios.



Time traces of surface water temperature for individual years of a WRF-Lake simulation. The top panel corresponds to a run using historical greenhouse gas concentrations between 1986 and 2005. The lower panel uses RCP8.5 concentration scenarios from 2081 to 2100. (Xiao et al. 2018)

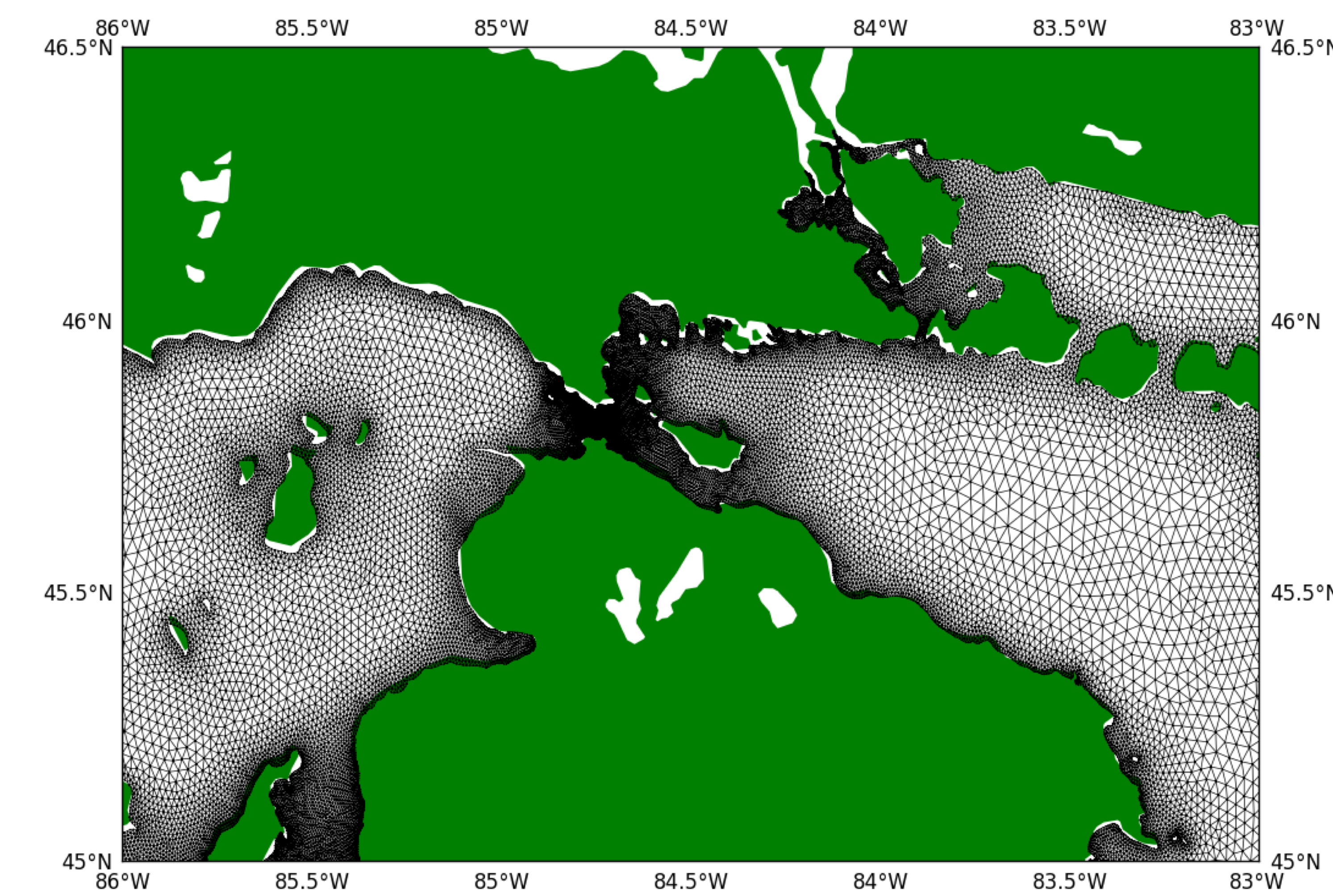


Mean annual cycle of water temperature profile from a WRF-Lake simulation. The left panel corresponds to a run using historical greenhouse gas concentrations between 1986 and 2005. The right panel uses RCP8.5 concentration scenarios from 2081 to 2100. The strong vertical temperature gradient is highlighted in the right panel by the red oval. (Xiao et al. 2018)

FVCOM

The Finite Volume Coastal Ocean Model (FVCOM) is a 3-dimensional hydrodynamic model that can be used for regional simulation of both salt water and fresh water. A Great Lakes version has been developed at GLERL (Anderson et al. 2018). It uses the finite volume form of horizontal discretization on a configurable unstructured grid. Great Lakes applications typically use 11 sigma layers in the vertical. FVCOM has been applied to short-term prediction and is being transitioned in stages to operational use. However, we wish to use it for multi-decadal simulations at time horizons up to a century away.

There has been concern about numerical instability of FVCOM's dynamical code, and the need to insert artificial diffusion to force stability. This problem has been corrected by Drs. Wang and Fujisaki-Manome, which should lead to stronger and more accurate thermocline features and overall model performance. Another enhancement is aimed at the simulation of ice, and this version is called FVCOM-CICE.



A sample unstructured grid with a domain covering the Straits of Mackinac (the juncture between Lake Michigan to the west and Lake Huron to the east). Grids will be much coarser when simulating all five Great Lakes over multiple decades.

Challenges and Future Plans

All new uses of models have technical difficulties to overcome, including this one. The transfer of data from one model into a set of variables and a format that another model will accept can be a challenge, and a mismatch between the height of data in the native spatial grid of one model and the expected height of input data for another model is one example of an incompatibility that causes difficulty but is not insurmountable. The default inputs of FVCOM-CICE include net heat flux at the surface, which is a direct thermodynamic driver, but may be at odds with turbulent fluxes of latent and sensible heat that would have been calculated directly by FVCOM. We will test and validate FVCOM-CICE in a one-way coupled mode, although the direct input of net surface heat flux will strongly constrain the thermodynamics of the model.

This project is intended to be a long-term collaboration between GLERL and GFDL, with the future incorporation of FVCOM-CICE as a component of future generations of GFDL's GCM. This sill require much work in software engineering, tuning, and evaluation. After completing this work for the Laurentian Great Lakes of North America, we will extend this to other large lakes worldwide.