Coupled Atmosphere-Surface Modeling of Lake Levels of the North American Great Lakes under Climate Change

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Abstract

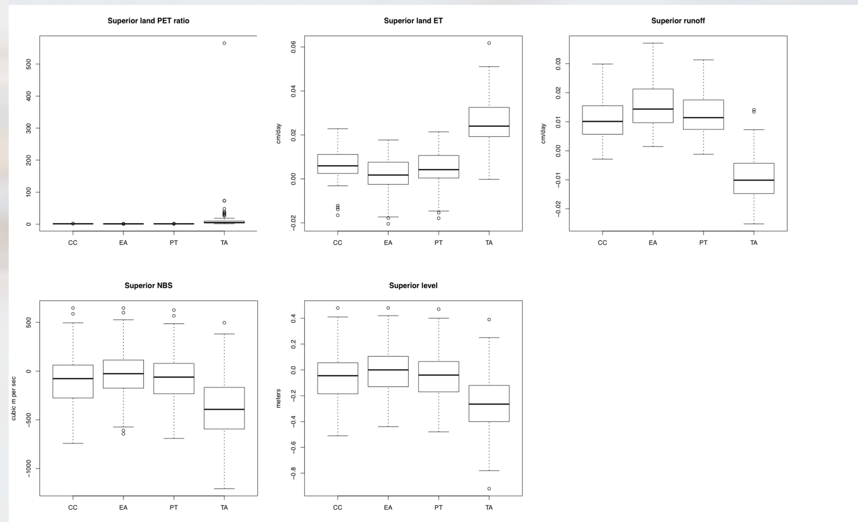
The influence of projected climate change on the water levels of the Great Lakes is subject to considerable uncertainty, and methods that have long been used to determine this sensitivity have been discredited. A strong candidate, albeit expensive, to replace problematic methods is to use outputs that result from dynamical downscaling of future climate simulations, focused on the hydroclimate of the Great Lakes basin. We have produced initial estimates of Great Lakes water levels in 21st century using the Weather Research and Forecasting (WRF) model, including its lake module, driven by lateral boundary conditions from the Geophysical Fluid Dynamics Lab Climate Model version 3.0 (GFDL CM3), under RCP4.5 and 8.5 scenarios. Future lake levels are influenced by the balance between projected general increases in precipitation and increases in evapotranspiration from both land and lake in the basin, driven primarily by the surface radiative energy budget and secondarily by air temperature. The net result was drops in lake level of up to 15 cm, in contrast to the results from much-used older methods, which often projected drops exceeding 1 m. Future plans include increased detail in the simulation of water flow overland and in river channels using WRF-Hydro, and full coupling of regional atmospheric systems with 3-dimensional dynamical lake implementation of the Finite Volume Community Ocean Model (FVCOM).

The Question

Great Lakes levels under climate change are influenced by changes in precipitation and evapotranspiration, in both the land and lake portions of the drainage basin. What is the net influence?

Problems with Previous Approaches

A methodology that has been used extensively in the past for projecting Great Lakes levels under climate change has been shown to exaggerate the influence of climate change by attributing evapotranspiration too exclusively to air temperature as a predictor or cause (Lofgren and Rouhana 2016).



The figure shows future changes in hydrologic variables for Lake Superior and its drainage basin under different versions of the long-used method. The original method, denoted TA, has potential evapotranspiration (PET) calculated using an exponential formula that is much more sensitive to air temperature than the 7% per deg C given by the Clausius-Clapeyron relation, leading to extreme increases in PET under future climate scenarios (upper left). Alternative methods based on the Clausius-Clapeyron relation (CC), the Priestley-Taylor equation (PT), and ratio of future to historical surface net radiation (EA) have changes in PET that are dwarfed by those in TA. Changes in actual ET, runoff from land, net basin supply, and lake level had less extreme, but still highly significant, contrast between the TA and other methods.

What is Net Basin Supply (NBS)?

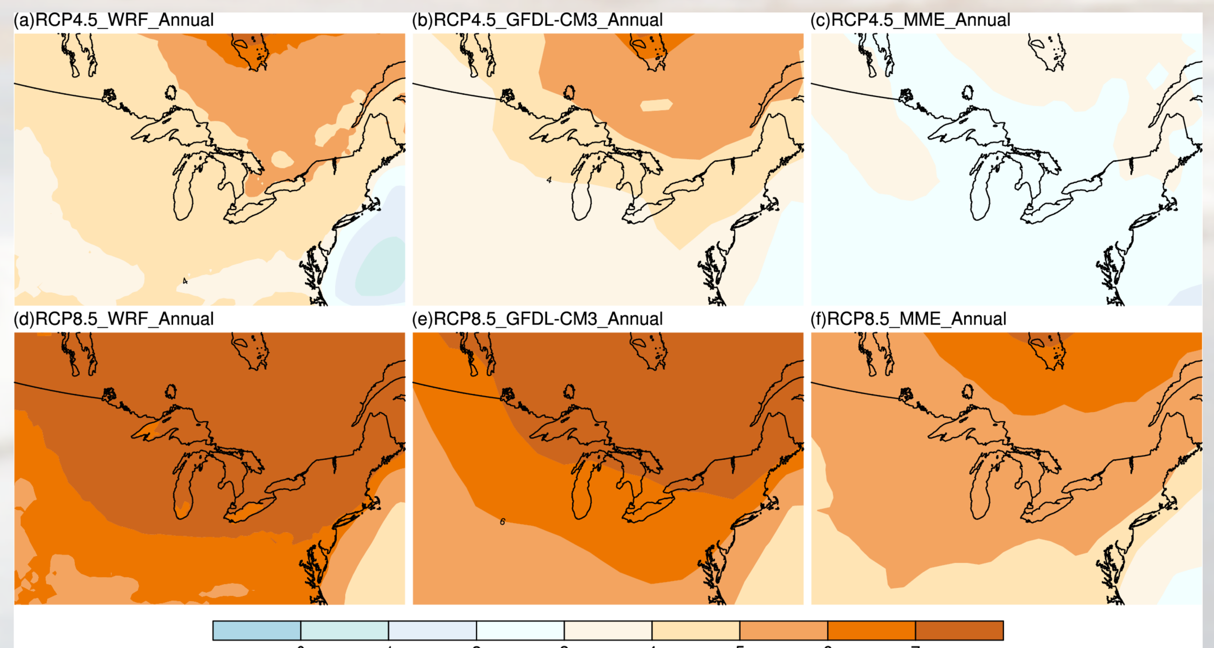
In the Great Lakes system, lake levels are driven by the balance among flow into the lake from the next Great Lake upstream, outflow to the next lake downstream, and input from the individual lake's own surface area and drainage basin. The latter is summarized as the NBS, defined as:

$$NBS = P - E + R$$

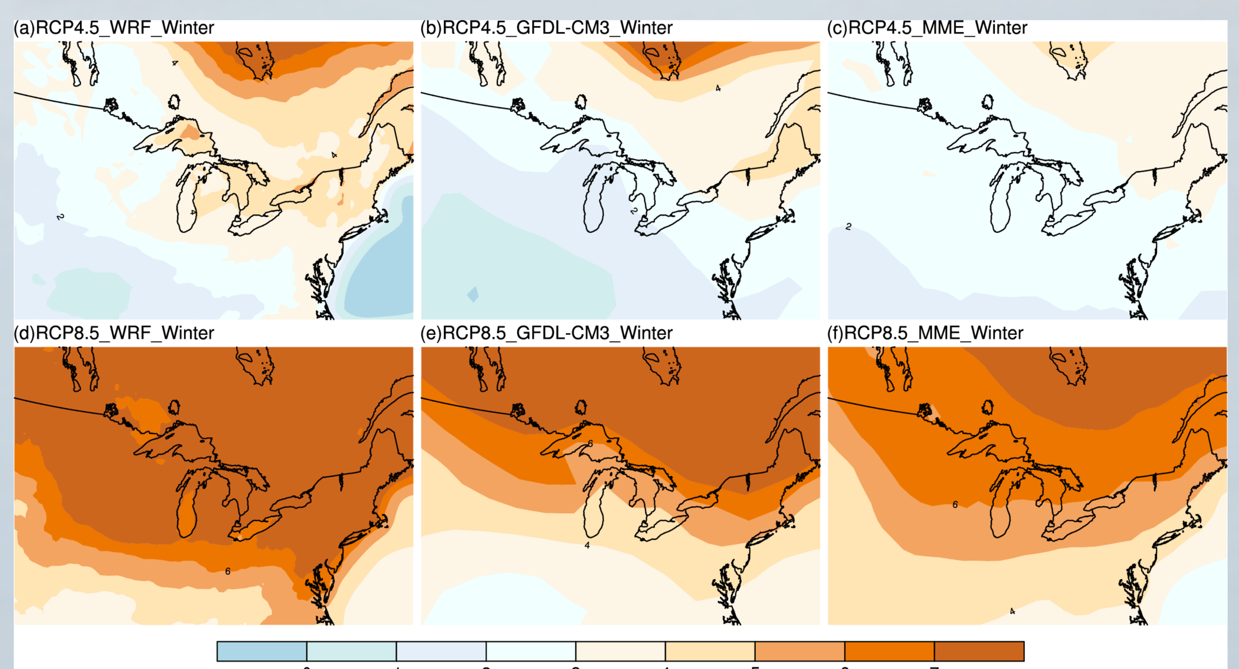
where P is precipitation directly over the lake, E is evaporation from the lake surface, and R is runoff from the land portion of the basin. Thus NBS is a key driving quantity, from which water flows between the Great Lakes and lake levels can be fully determined.

Regional Climate Modeling (Dynamical Downscaling) Approach

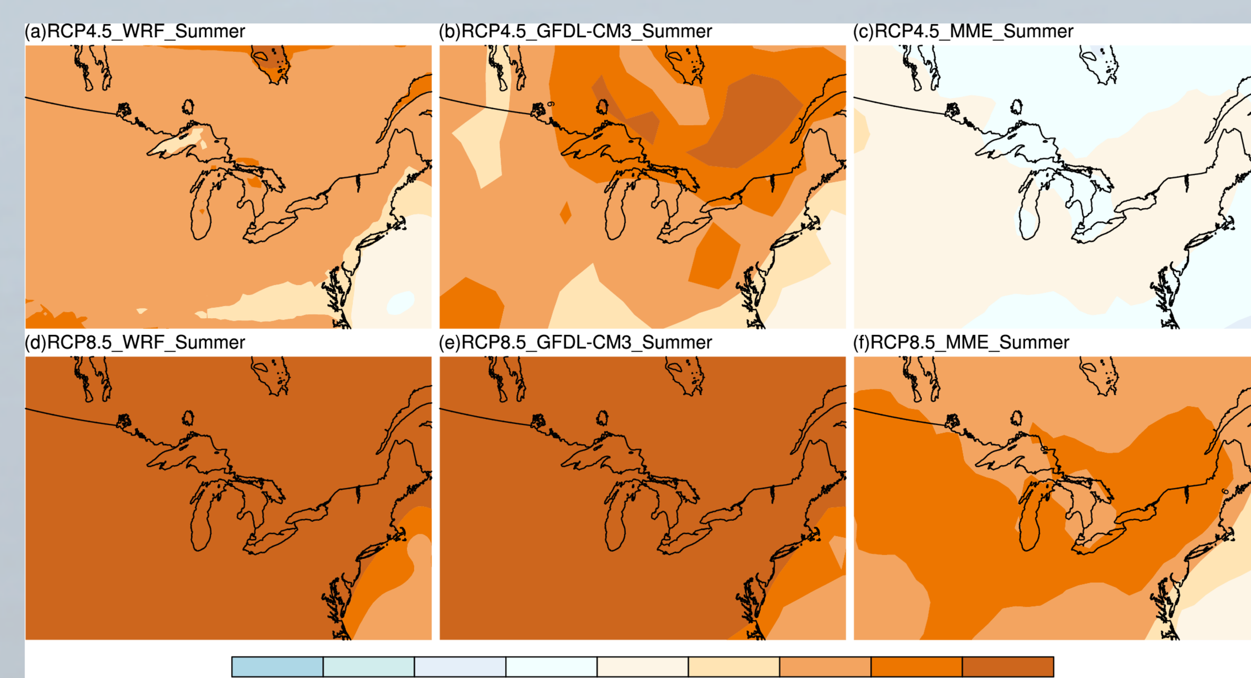
This study used the Weather Research and Forecasting (WRF) model, a regional model, in climate mode, for simulation of of atmospheric and surface processes. A module for a simple vertical diffusion formulation of lake temperatures (WRF-Lake) was enabled, as customized for the Laurentian Great Lakes (Xiao et al. 2016a). Boundary conditions for the WRF runs were specified from runs of the GFDL CM3.0 model for historical time (1977-2006) and future time (2007-2100) under both the representative concentration pathway (RCP) 4.5 and 8.5 scenarios.



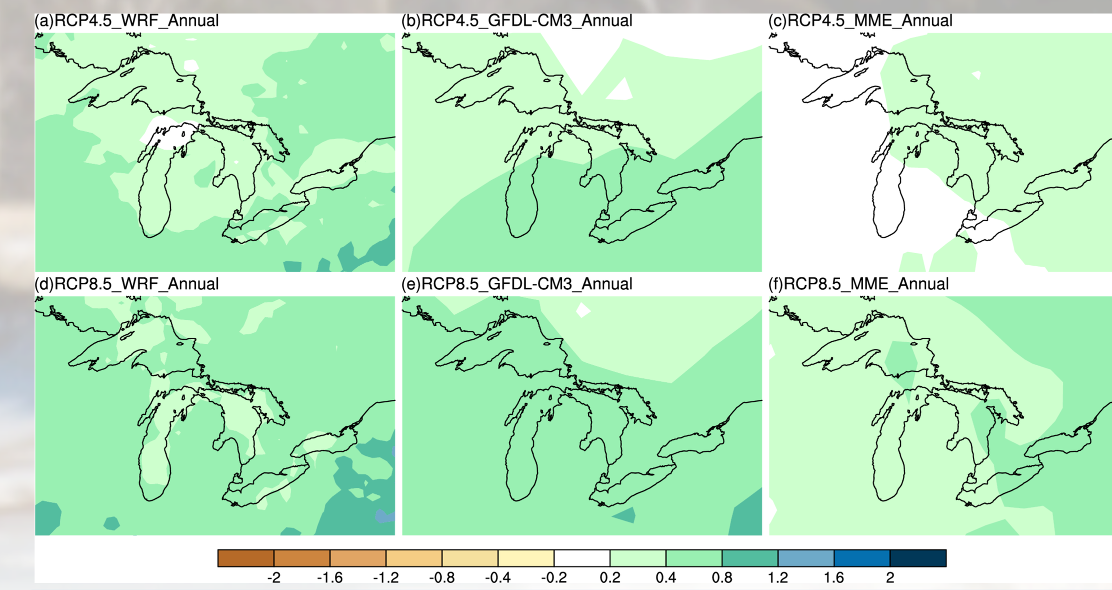
Change in annual mean surface air temperature (deg C) between historical and mid-21st century time periods from (a, d) WRF driven by GFDL CM3.0, (b, e) GFDL CM3.0 analyzed directly, and (c, f) analysis from the CMIP5 multi-model ensemble (MME). Panels a-c use the RCP 4.5 concentration scenario, while panels d-f use RCP8.5.



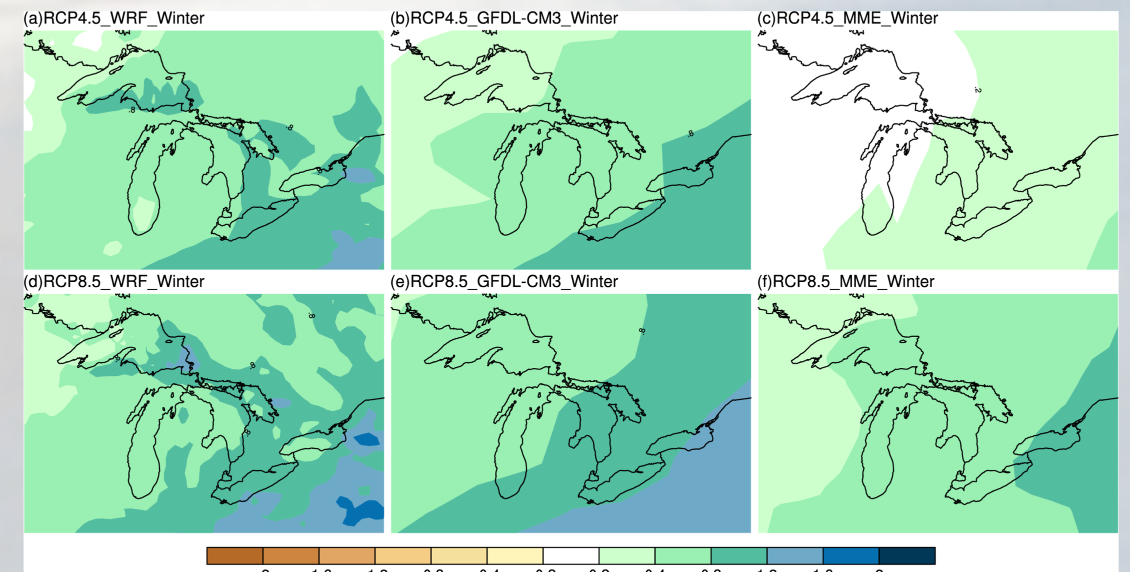
Change in winter mean surface air temperature (deg C) between historical and mid-21st century time periods.



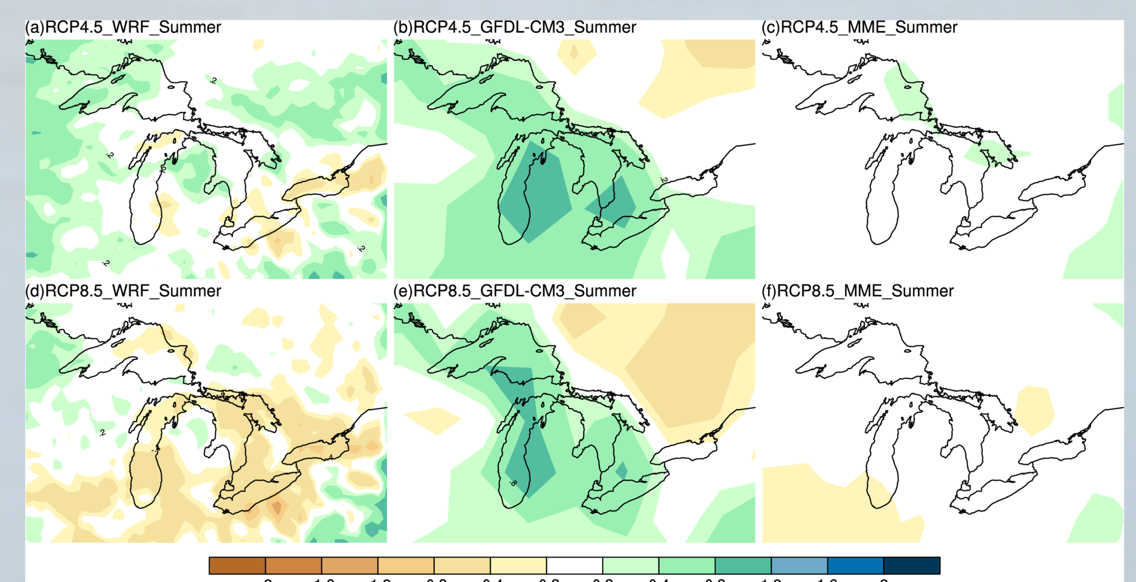
Change in summer mean surface air temperature (deg C) between historical and mid-21st century time periods.



Change in annual mean precipitation (mm/day) between historical and mid-21st century time periods.



Change in winter mean precipitation (mm/day) between historical and mid-21st century time periods.



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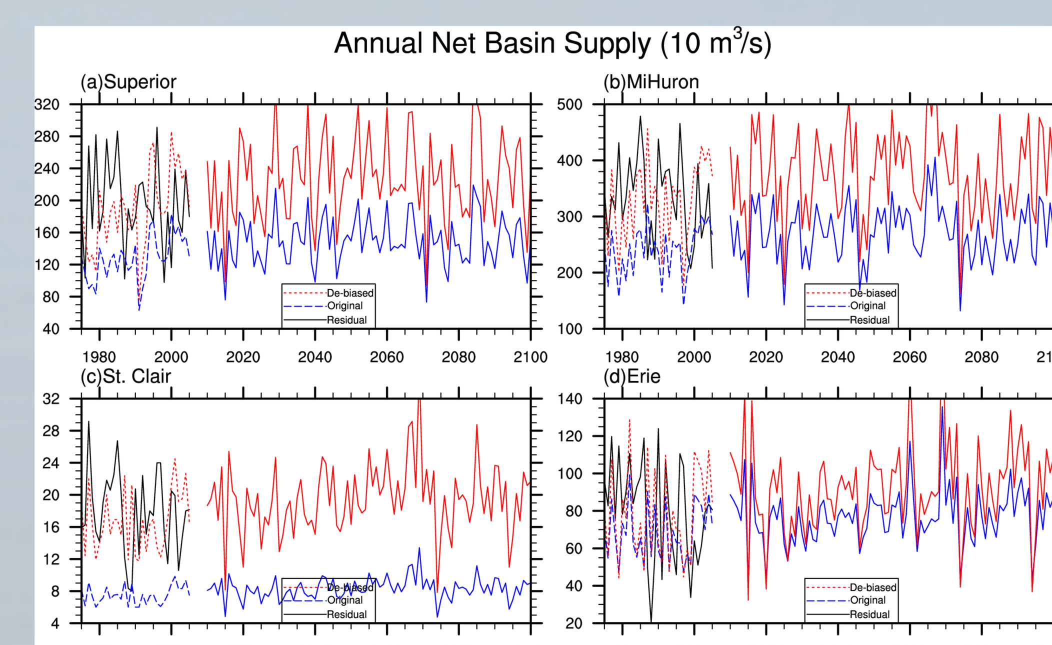
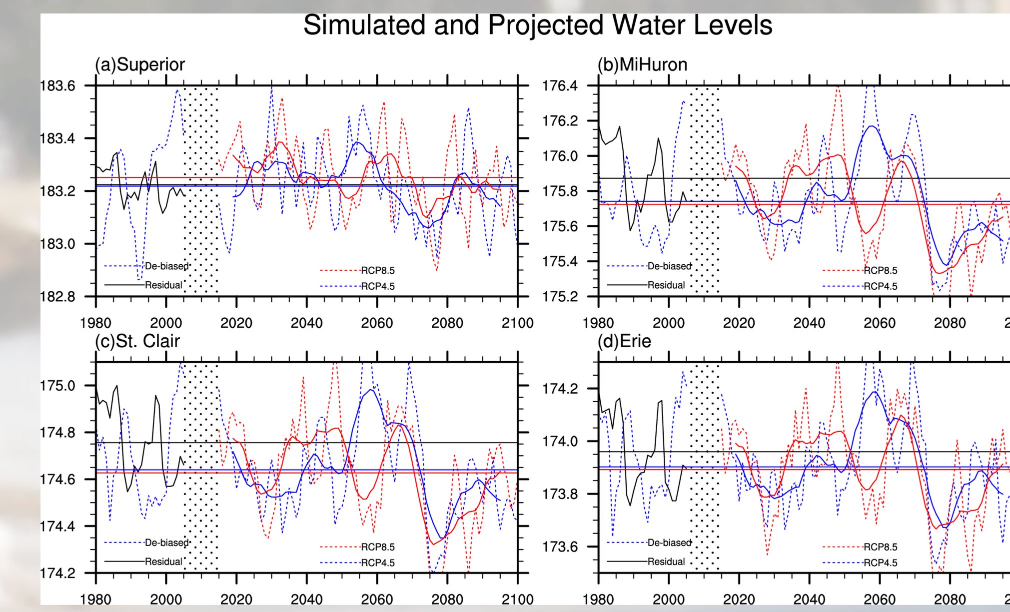


Time series of net basin supply (see text at left) for lake basins (10s of m3/s). Raw simulated values are shown in blue, and values de-biased by subtracting the mean difference from residual NBS values (best "observed" values) are in red.



Time series of lake levels (meters relative to IGLD85). Because of their connection at the Straits of Mackinac, Lakes Michigan and Huron are treated as one lake.

Tentative Conclusions

Future lake levels for the Laurentian Great Lakes have been projected using a limited range of model-generated scenarios. These model runs use regional climate modeling driven by output from global general circulation model simulations. The results found here show minimal mean changes in lake levels, with signal (i.e. changes in the mean values) of notably lesser amplitude than noise (interannual and interdecadal variation in lake level). This is at variance with the results of a long-used methodology for projecting lake levels under climate change, which relied excessively on air temperature as a predictor of land-based evapotranspiration.

Future Plans

- Additional GCM runs as drivers
- More careful de-biasing of NBS
- WRF-Hydro for stream routing
- Coupling to 3-dimensional lake dynamics model (FVCOM)

References

Lofgren, B. M., and J. Rouhana, 2016: Physically plausible methods for projecting Great Lakes water levels under climate change scenarios. *J. Hydrometeorol.*, 17, 2209-2223

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