Geostrophic currents in the Great Lakes

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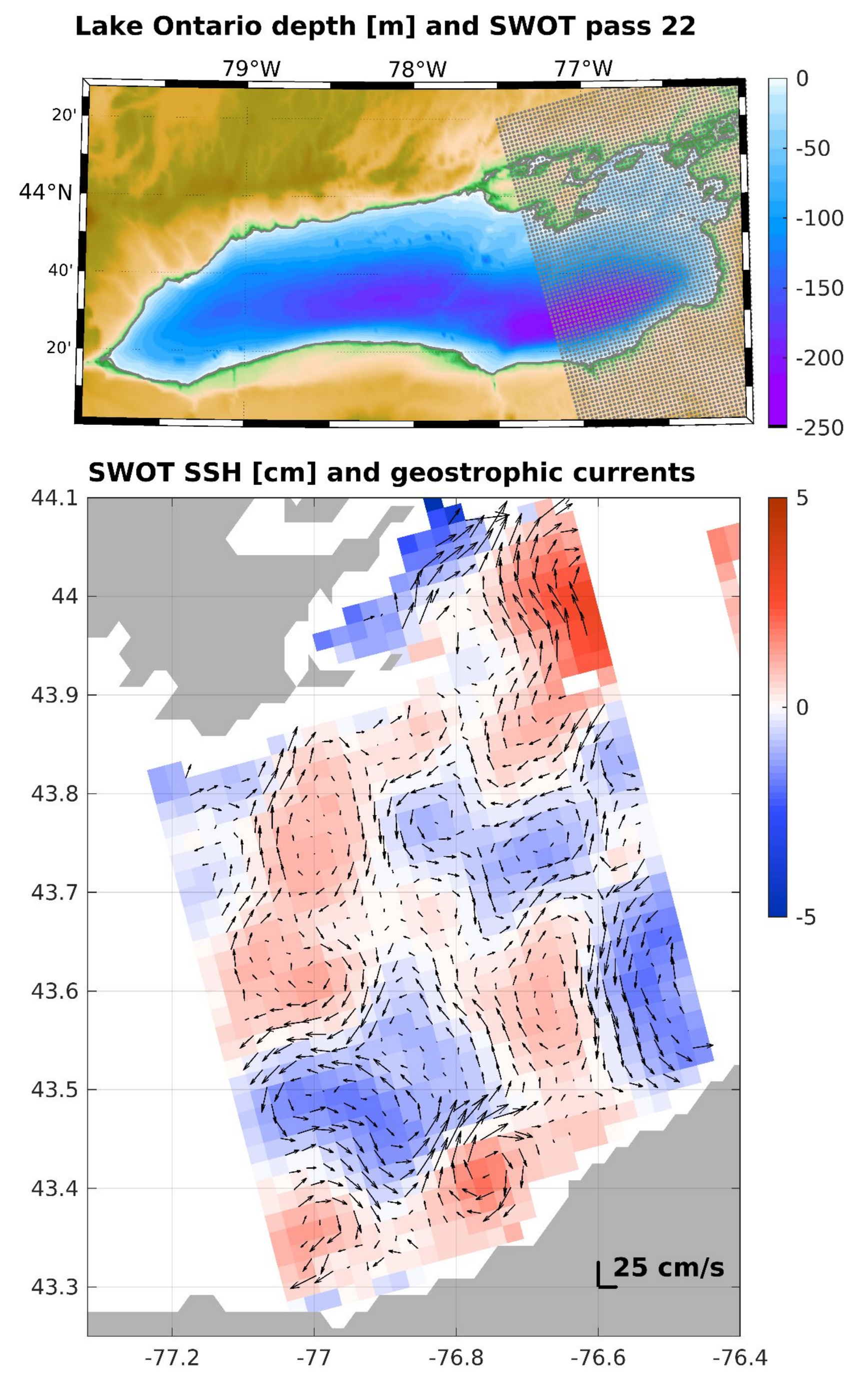
Abstract

Eighty-four percent of the surface freshwater in North America is contained in the Great Lakes. The widths of these lakes range from 80-500 km, which is much larger than a typical internal Rossby radius (3 km) during summer stratification. As a result, geostrophic circulation and eddies are common. Currents in the Great Lakes have only been characterized by coarsely-spaced, short-lived, in situ current meters (e.g., Beletsky et al. 1999) and largely unconstrained numerical models (e.g., Hui et al. 2021). Previous satellite altimeters have lacked the spatial resolution to map small-scale O(10-20 km) eddies. However, preliminary SWOT data reveal 20 km diameter eddies with 1-5 cm sea surface height (SSH) anomalies in eastern Lake Ontario consistent 10-20 cm/s geostrophic currents. The spectral slope of these SSH observations is k^{-4}, consistent with in situ measurements from Lake Superior, and geostrophic turbulence due to mixed-layer instabilities. Further calibration/validation of SWOT data in the Great Lakes requires detailed comparisons with in situ observations and the application of lake-specific dynamic atmosphere corrections.

SWOT Observations of Lake Ontario



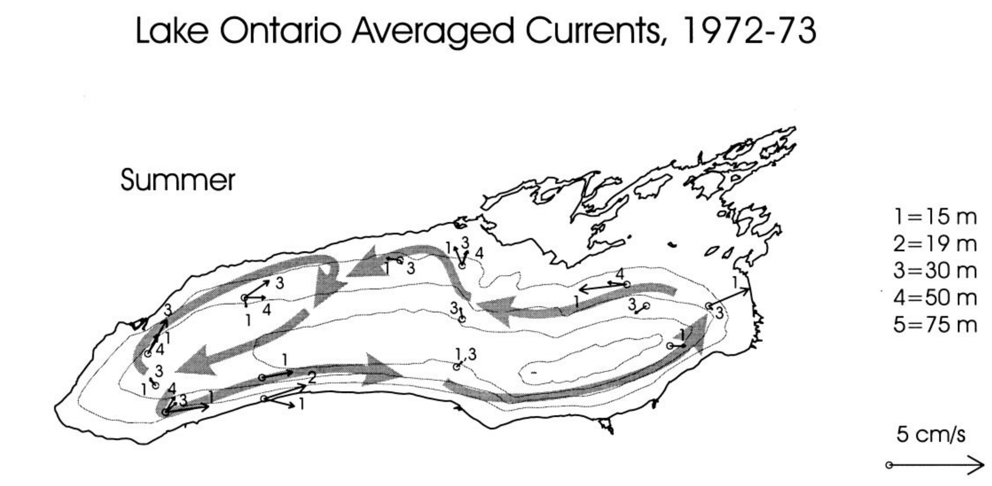
The 1-day calibration orbit sampled eastern Lake Ontario during April 2023. During this period, Lake Ontario was weakly stratified with an internal Rossby radius of about 0.5 km.

The SWOT data have not yet been corrected for wet troposphere, sea state bias, or dynamic atmosphere effects, which are not provided (by default) over the continents.

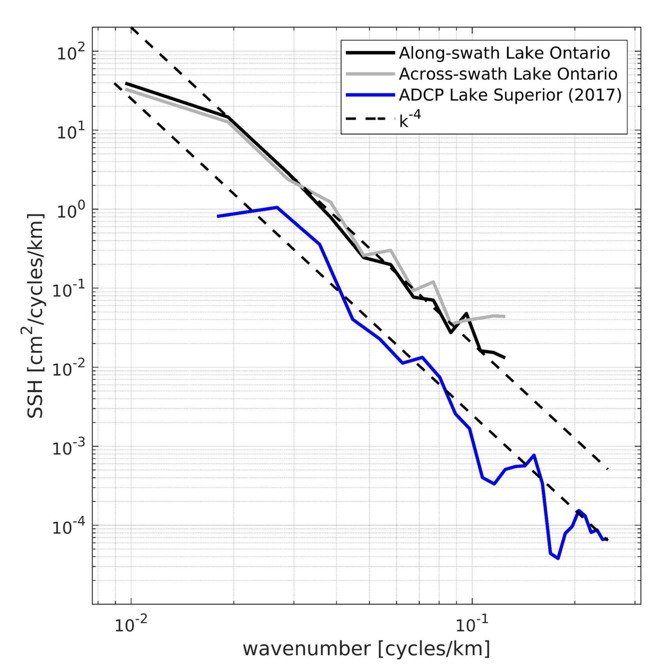
Top left: Lake Ontario has a nominal size of 310 km x 85 km and an average depth of 86 m. The SWOT pass 22 is shown in gray.

Bottom left: SWOT SSH, averaged over 17 cycles displays an eddy field with 10-20 km diameter eddies and 10-20 cm/s geostrophic currents.

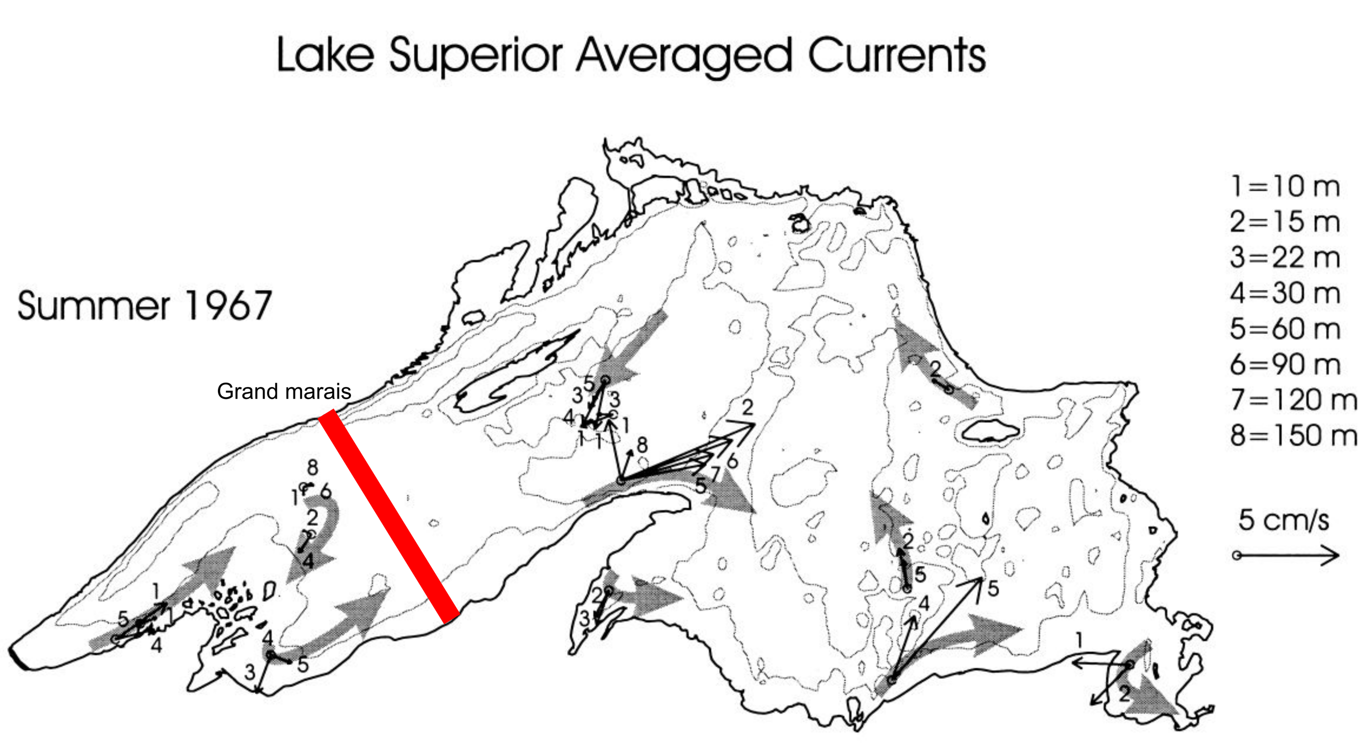
Bottom right: Along and across-swath SSH spectra have a k^{-4} slope, consistent with in situ observations from Lake Superior during August 2017 (see below) and geostrophic turbulence driven by mixed-layer instabilities. Increased energy in the SWOT vs in situ observations may be explained by stronger wind forcing and weaker stratification during April vs August.



Above: Mean currents based on historic current meters (Beletsky et al. 1999) lack the detail and complexity of SWOT observations.

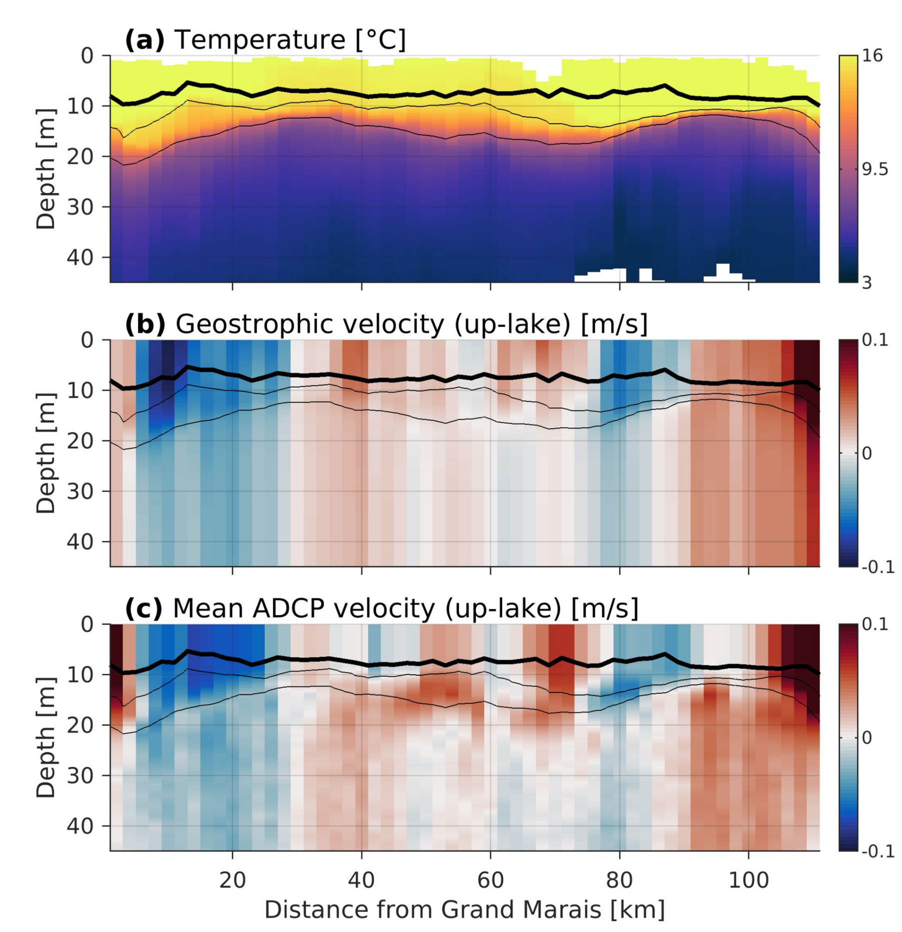


Direct observations of geostrophic currents in Lake Superior



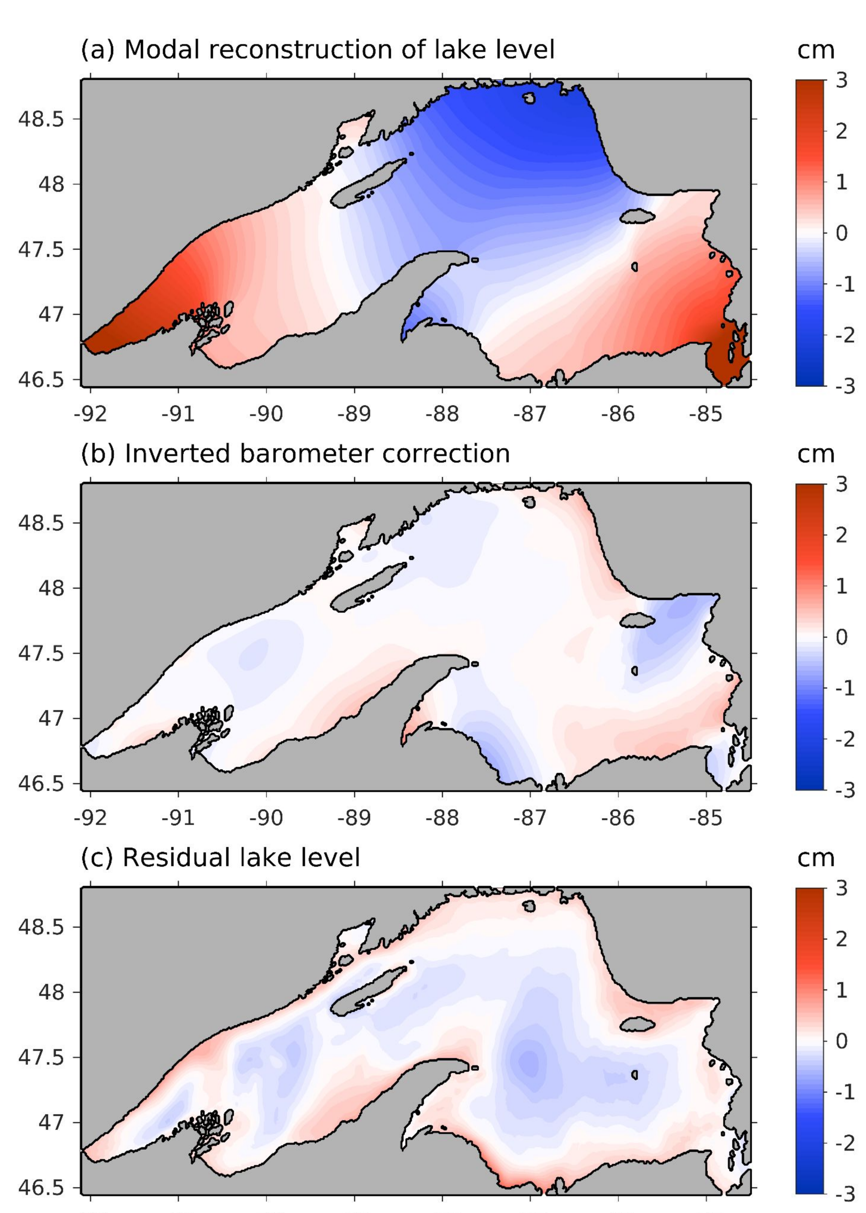
Left: Historical current meter observations (Beletsky et al. 1999) are largely incoherent and do not resolve the circulation of the lake. Seven cross-lake transects (red line) were conducted by the R/V Blue Heron during 6 days in August 2017. Observations included full-depth ADCP velocity profiles and more than 2,000 temperature profiles.

Right: Time-averaged temperature from the Lake Superior transect display a nearly two-layer structure with horizontal variability at scales of about 20 km. Geostrophic currents derived from temperature gradients agree well with the time-averaged ADCP currents (barotropic currents were matched from the ADCP). SSH spectra derived from the ADCP transect displays a k^{-4} slope (above), consistent with geostrophic turbulence.

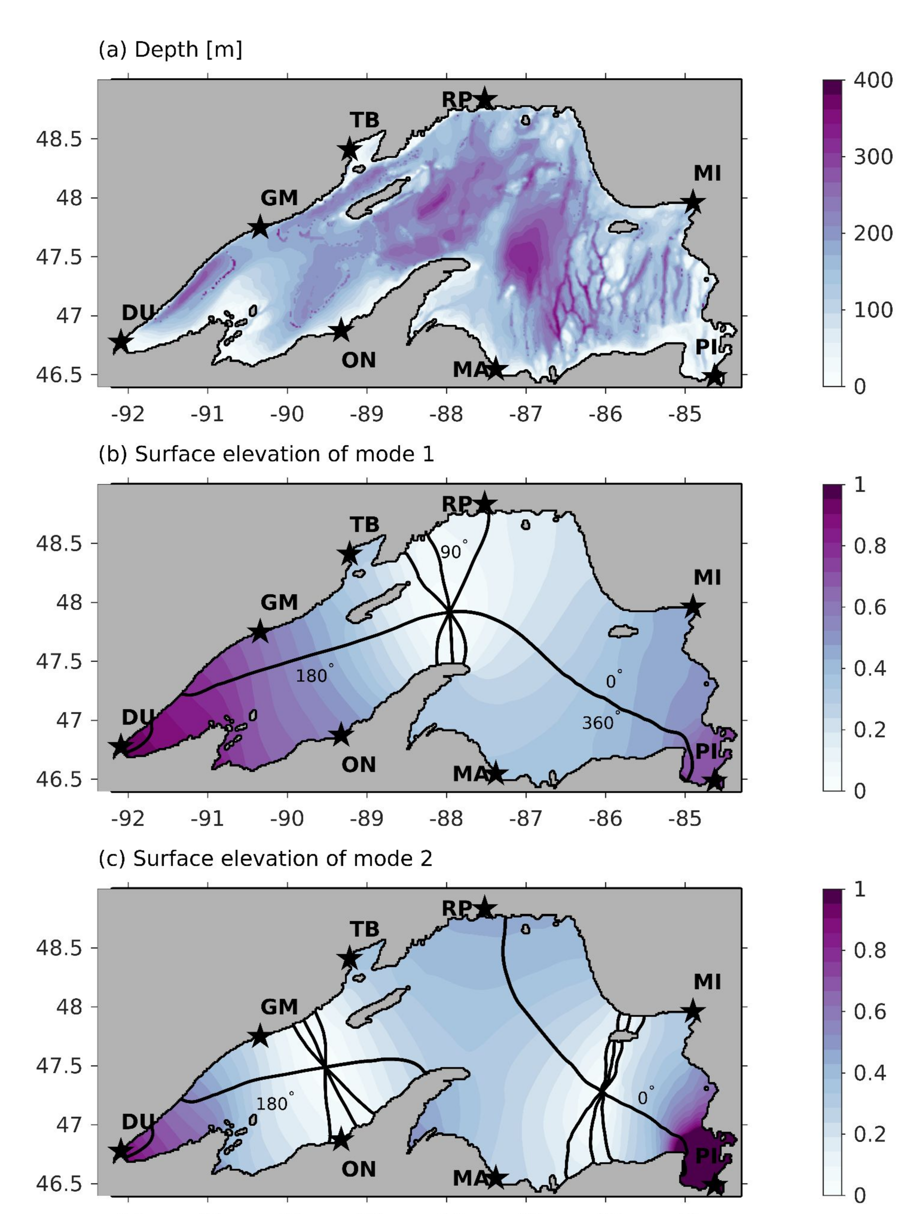


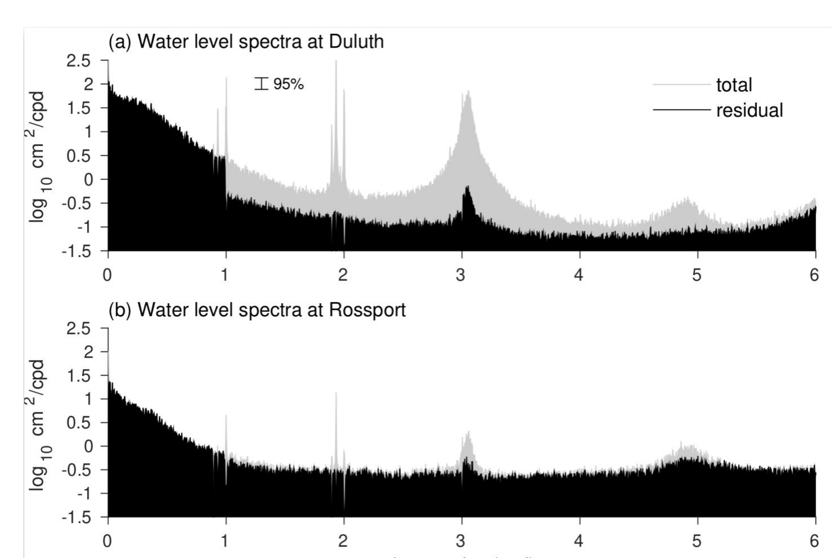
Tidal and dynamic atmosphere corrections in Lake Superior

Below: SSH comprises rapidly oscillating gravity modes (seiches), an inverted barometer response, and a residual quasi-geostrophic stream function. SSH is simulated here using the MIT general circulation model with atmospheric reanalysis forcing.



Below: Gravity modes are excited by tides, wind, and atmospheric pressure. These signals are recorded hourly at 8 lake-level gauges. The first mode is an east-west oscillation with 8 h period. The second mode is an east-west oscillation with two nodes and a 5 h period.



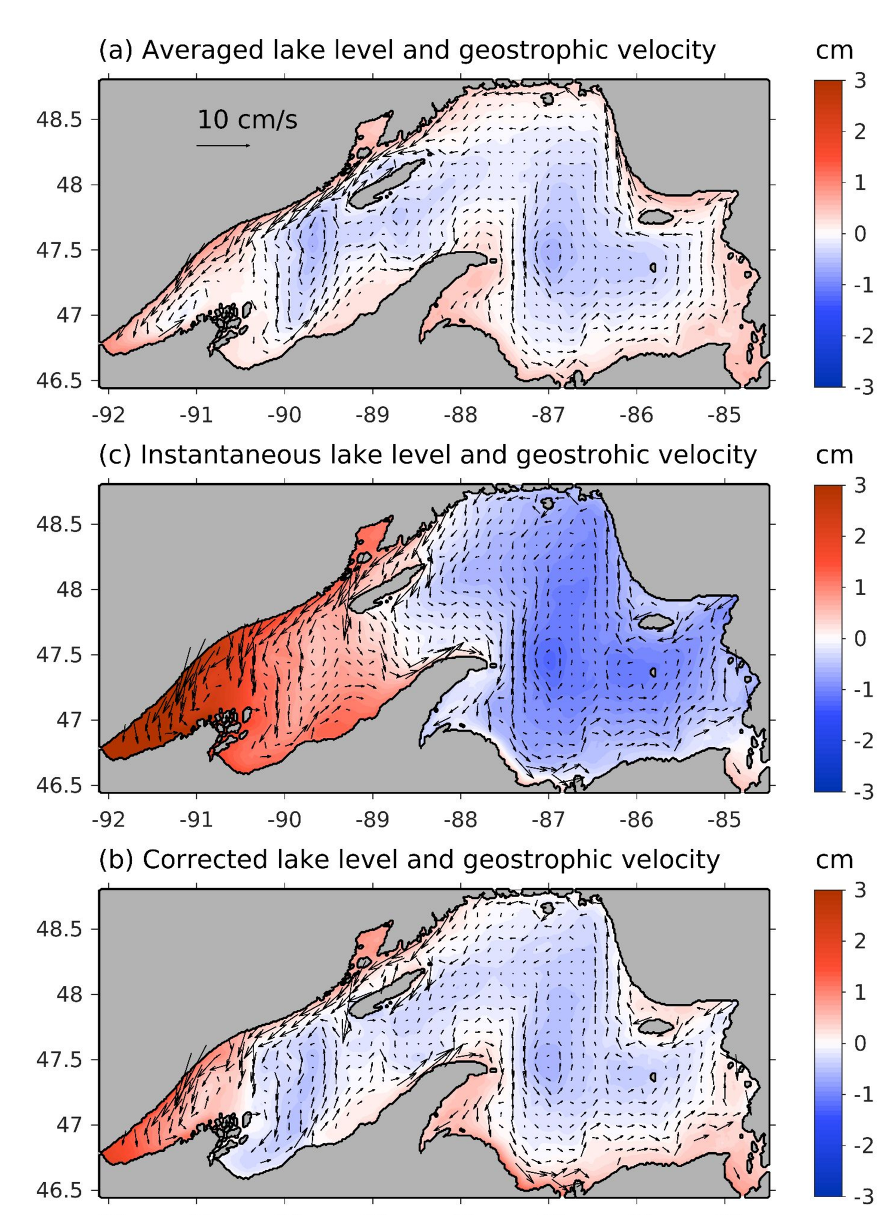


Above: Spectra from 50 years of hourly lake level data identify diurnal and semidiurnal tides at 1 and 2 cpd, and seiches at 3 and 5 cpd. Most tide (Sanchez et al. 1985) and seiche (Kelly et al. 2023) variability is explained by the first gravity mode (i.e., the residual in black is an order of magnitude smaller than the total in gray).

Removing the rapidly oscillating gravity modes from instantaneous measurements of SSH is a challenge for mapping geostrophic currents in enclosed and semi-enclosed basins. This can be done by (i) modeling the gravity modes as forced damped oscillators or (ii) fitting gravity modes to a network of water-level gauges.

In practice, the oscillator model predicts 96% of gravity mode variance in the MITgcm simulations, but noise in the model forcing (i.e., atmospheric reanalysis) makes lake-level gauges more accurate on time scales shorter than 1 day.

Below: Time-averaged SSH (a) in the MITgcm can be recovered from instantaneous SSH (b) by removing the gravity modes using a simplified dynamical model. The corrected SSH (c) provides estimates of geostrophic velocity that are consistent with time-averaged SSH.



Acknowledgments

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References

Beletsky, Dmitry, James H. Saylor, and David J. Schwab. "Mean circulation in the Great Lakes." *Journal of Great Lakes Research* 25.1 (1999): 78-93.

Hui, Yuan, et al. "Circulation in Lake Ontario: Numerical and physical model analysis." *Journal of Hydraulic Engineering* 147.8 (2021): 05021004.

Kelly, Samuel M, Maqsood Mansur, and Erica L. Green. "Predicting surface oscillations in Lake Superior from normal mode dynamics." *Journal of Physical Oceanography* (2023): under review.

Sanchez, Braulio V., Desiraju B. Rao, and Paul G. Wolfson. "Objective analysis for tides in a closed basin." *Marine Geodesy* 9.1 (1985): 71-91.

Conclusions

1. Preliminary SWOT observations from Lake Ontario reveal 1-5 cm SSH anomalies, 10-20 cm/s geostrophic currents, and a k^{-4} spectral slope consistent with geostrophic turbulence due to mixed-layer instabilities.
2. In situ observations in Lake Superior also reveal 10 cm/s geostrophic currents with a k^{-4} spectral slope.
3. Dynamic atmosphere and tidal corrections can be predicted from normal mode dynamics and lake-level gauges. Specialized corrections for wet troposphere and sea state bias are still needed.