Observations of Mesoscale SSH in the Great Lakes

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Driven to Discover

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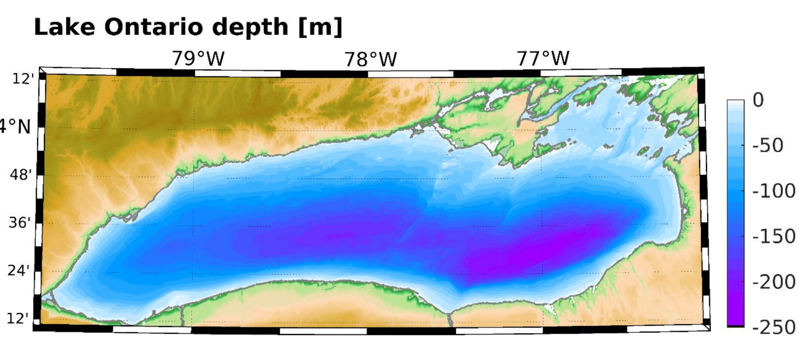
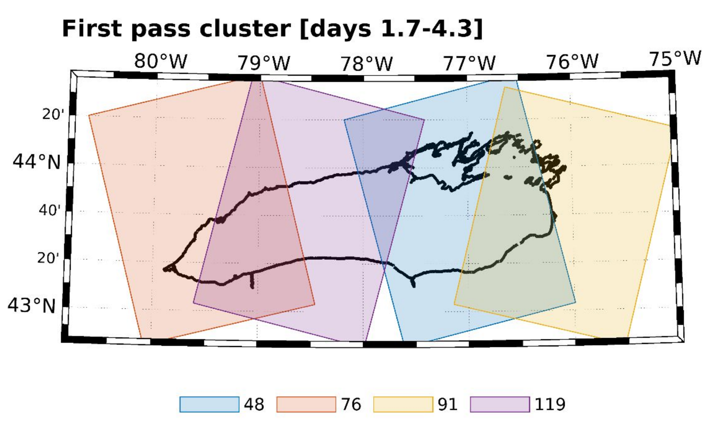
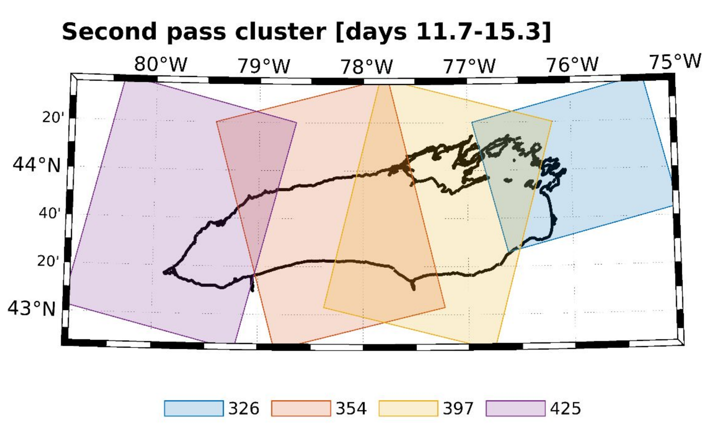
Abstract

SWOT (L3) observations of Lake Ontario are analyzed from Nov 2023 to Jun 2024 (cycles 7-16). During each 21-day cycle, the lake is sampled by two clusters of 4 tightly-spaced passes, effectively providing full-lake sea surface height (SSH) every 10 days. Lake Ontario has a 4.9 cycle/day east-west seiche that often reaches 10 cm. The seiche is removed using 8 in situ lake-level gauges. The first two EOFs of the gauge network are consistent with the first two basin-scale seiche modes, so that EOF amplitudes may be interpreted as seiche amplitudes and used as a high-frequency dynamic atmosphere correction (DAC). This correction removes 70% of the variance in the gauge network. SWOT data are corrected by (i) applying the DAC, (ii) removing the mean lake level and along-track median for each pass, and (iii) applying a 9-point median filter. The corrected data from each snapshot are objectively mapped onto a 2 km x 2 km lake-wide grid. The lake-wide map is then least-squares fit to 25 rotational basin modes, which explain a total of 10-50% of SSH variance. At times, the rotational modes reveal (i) a 10 cm/s basin wide circulation (in either direction) and (ii) a 10 cm/s double gyre circulation consistent with the topographically induced response to easterly wind. It is unclear whether the residual is due to altimeter noise, processing artifacts, or small-scale (<20 km) geostrophic turbulence and coastal trapped waves.



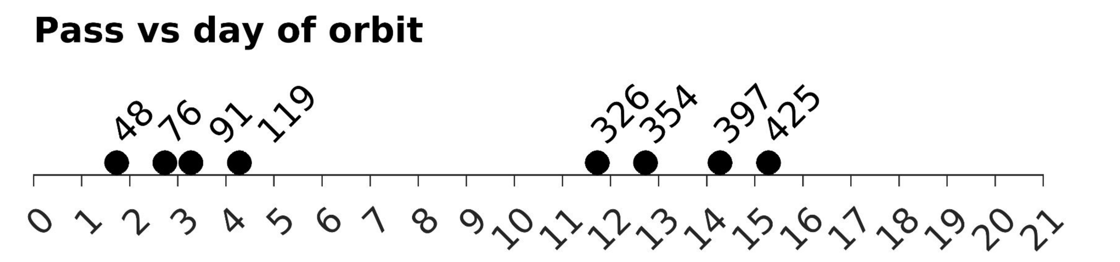


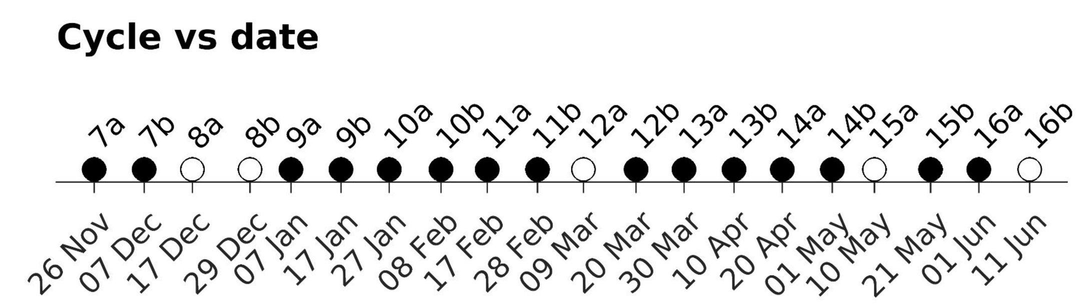


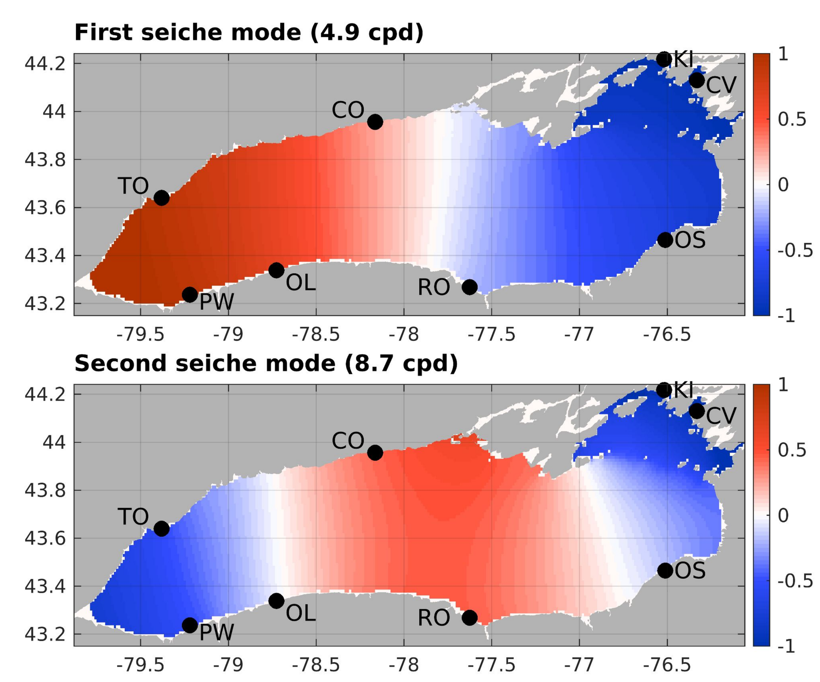
Lake Ontario during the 21-day Science orbit

Left: Lake Ontario is 310 km x 85 km with an average depth of 86 m. Eight SWOT passes cross the lake each cycle in two tightly-spaced clusters, providing two full-lake snapshots every 21 days. So far, the lake has been weakly stratified during the science orbit (Nov - Jun), corresponding to an internal Rossby radius < 1 km.

Below: The first cluster of passes ("a") occurs in days 1-5 and the second cluster ("b") occurs in days 11-16. A total of 19 clusters are analyzed over cycles 7-16, with 15 clusters returning good data over nearly the entire lake.



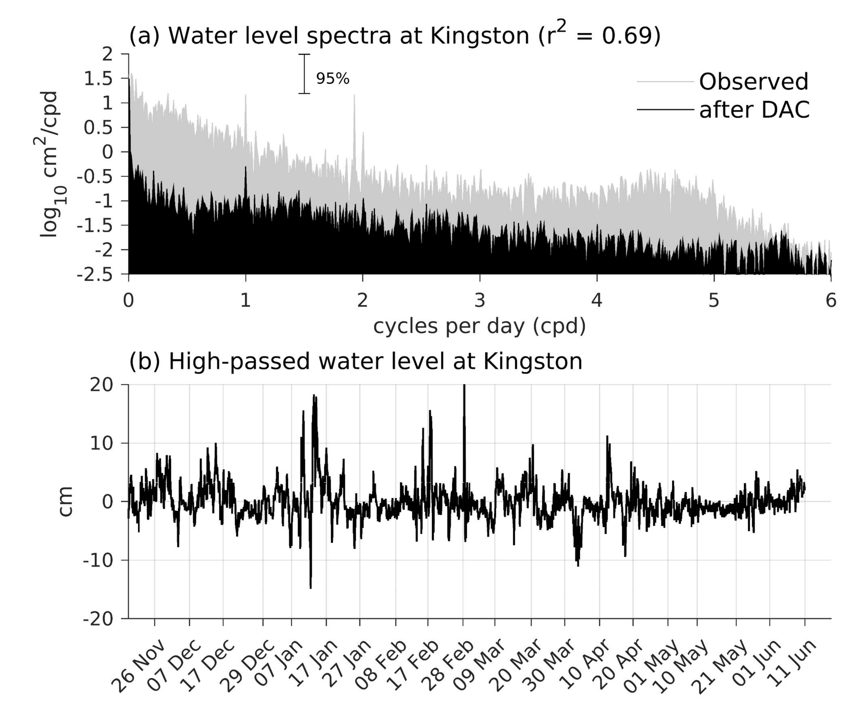




Removing Seiches and Tides from SSH

Left: The first two theoretical seiche modes (including rotation, Rao and Schwab 1976) have frequencies of 4.9 and 8.7 cpd. Eight lake-level gauges provide hourly water level. Barotropic tides in the Great Lakes are nearly equilibrium tides, and can be easily synthesized from seiche modes, with >90% of tidal variance being explained by the first mode (Sanchez et al. 1985).

Right: The lake-level spectrum from Kingston, ON (top) has tidal peaks at 1 and 2 cpd and a seiche peak near 5 cpd. Treating the gauge-network EOF amplitudes as seiche amplitudes provides a high-frequency dynamic atmosphere correction (DAC) for the entire lake (Kelly et al. 2024). The DAC reduces the water level spectrum at Kingston by an order of magnitude. The timeseries of lake-level (bottom) shows occasional short-lived 10 cm displacements due to strong winds.

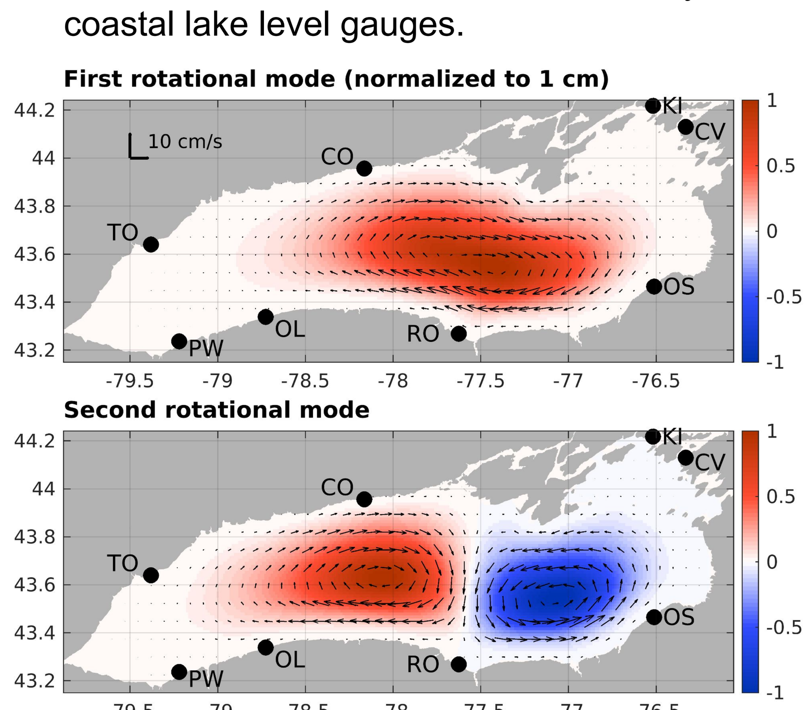


Observed Circulation Patterns

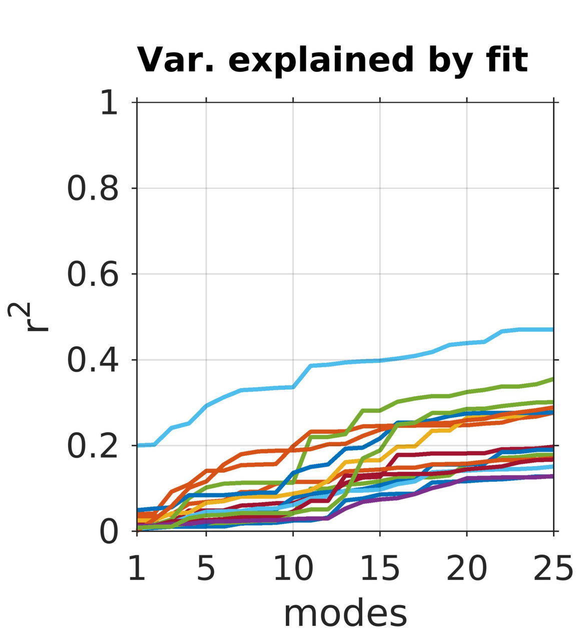
SSH L3 data from 19 clusters of passes were processed as follows:

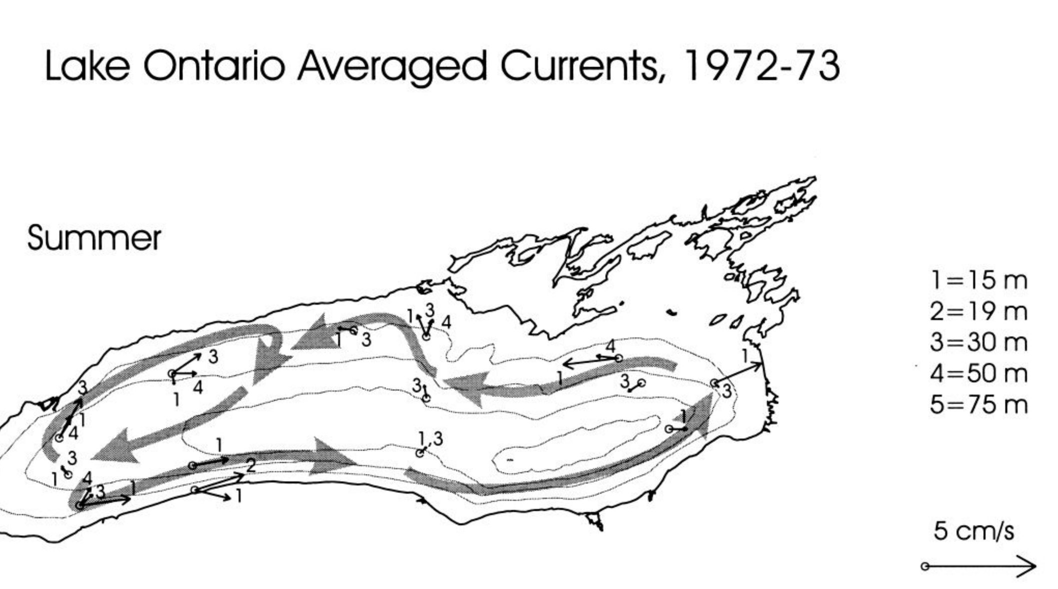
1. Data were corrected using the DAC above to remove tides and seiches
2. Mean lake level and each along track median were removed
3. Outliers were removed using a moving 9-point (2D) median filter
4. A lake-wide 2 km x 2 km map was created using objective analysis with a 5-km Gaussian covariance.
5. Time mean SSH (the geoid) was removed at each location.
6. Objectively mapped SSH was least-squares fit to 25 rotational modes to identify basin-wide flow patterns

Below: Rotational ("geostrophic" or "solenoidal") modes are excited by the wind stress curl (Rao and Schwab 1976). Rotational modes cannot be observed by coastal lake level gauges.



Below: Fitting rotational modes to of 15 objective maps indicates that most SSH variability is not associated with rotational modes. The slow convergence of explained variance indicates that basin-wide gyres are not particularly common.

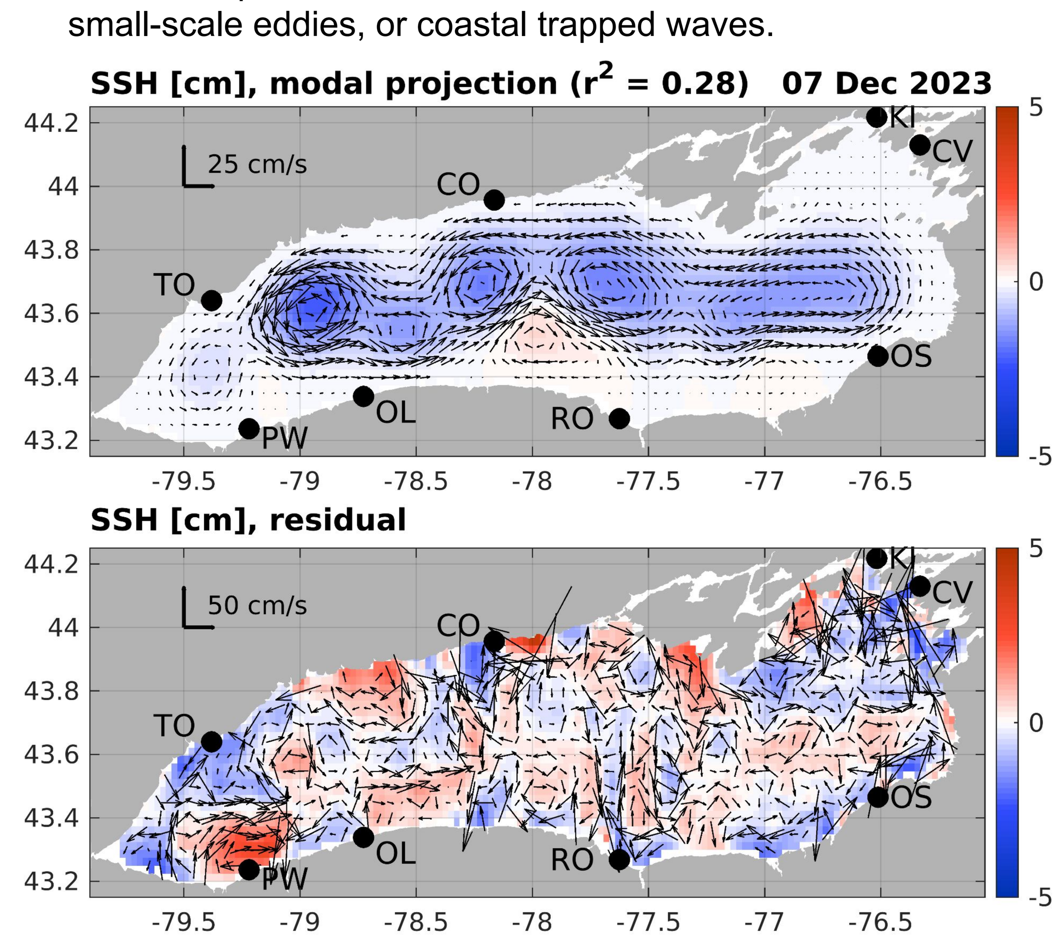


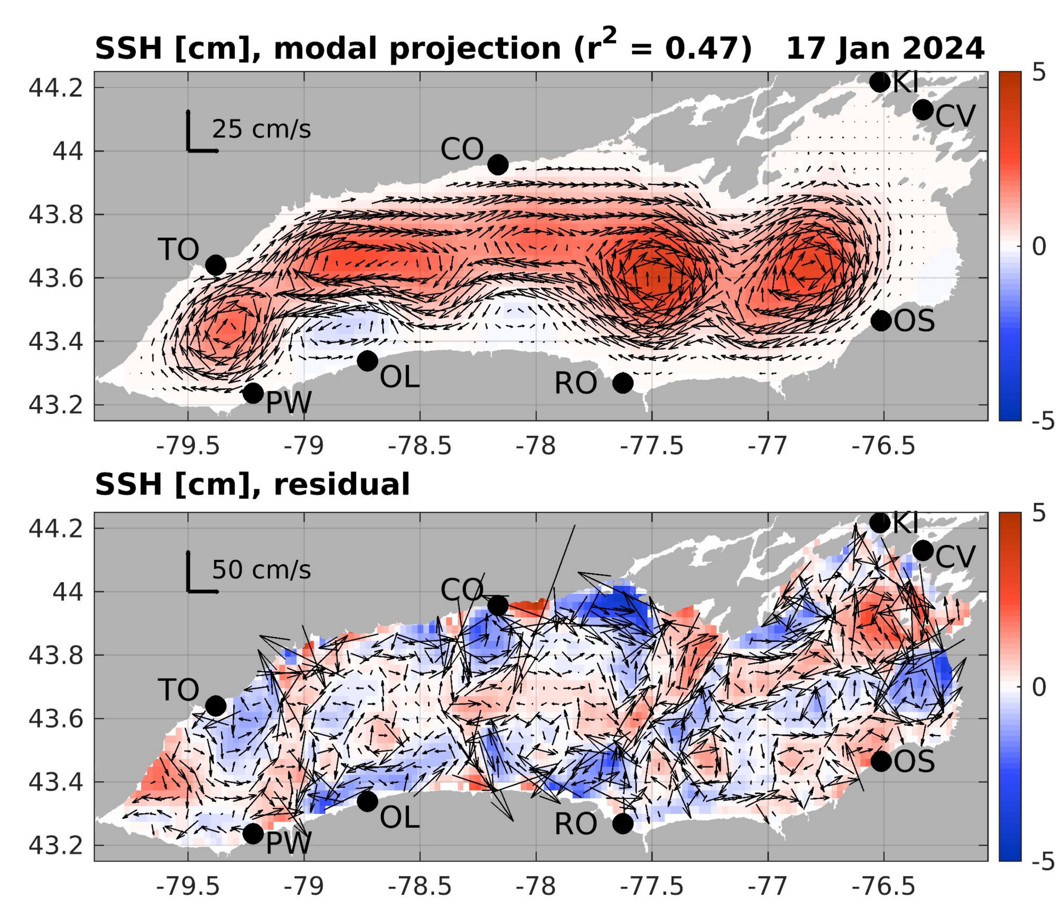


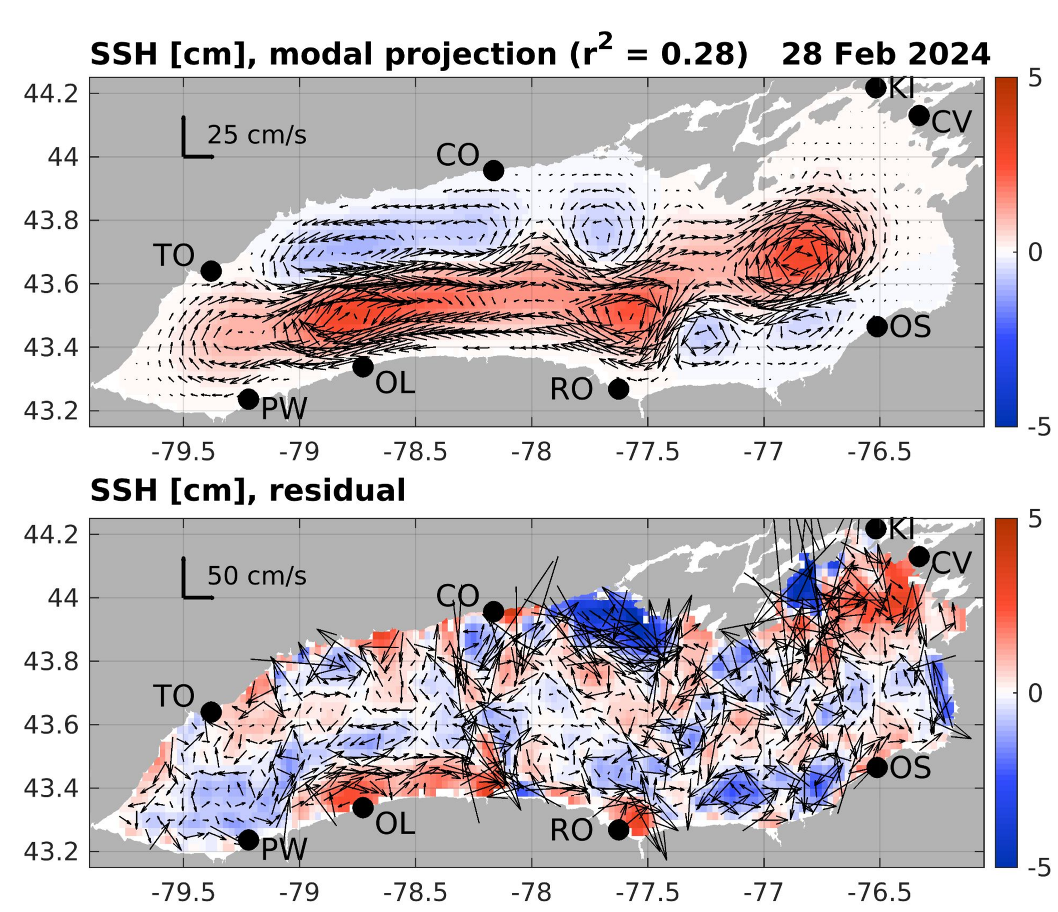
Left: Mean currents based on historic current meters (Beletsky et al. 1999) lack the detail of SWOT observations.

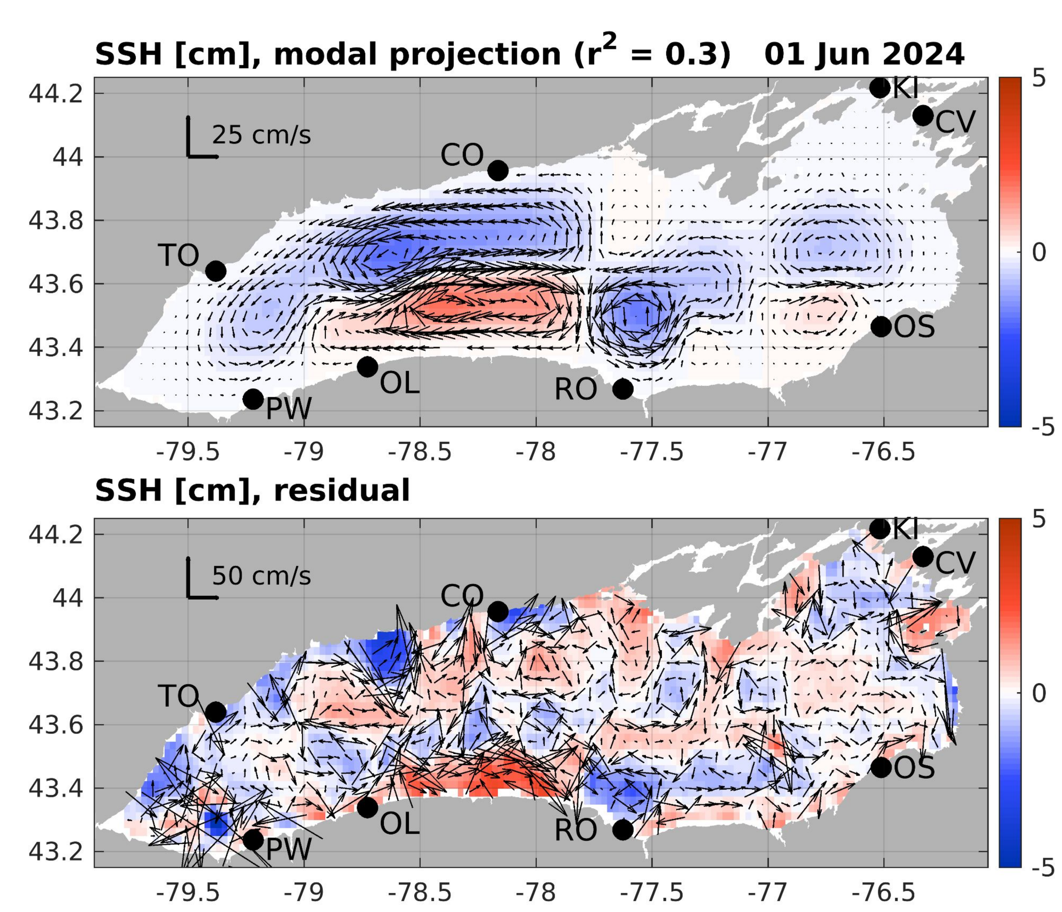
Below: Rotational modes explain 28-46% of SSH variance in the 4 snapshots shown here. On Dec 7 and Jan 17, the lake exhibits a 10 cm/s gyre in the counter-clockwise and clockwise directions, respectively. On Feb 28 and Jun 1, the lake displays a 10 cm/s double gyre consistent with downwind flow in shallow coastal regions and a return flow in the deep basin center.

In all 4 snapshots, the residual contains enhanced SSH variability at 5-20 km. This signal may be noise, processing artifacts, small-scale eddies, or coastal trapped waves.









Acknowledgments

Kelly was supported by NASA grant 80NSSC20K1331.

References

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Key Points

1. SWOT has collected 19 basin-wide snapshots of Lake Ontario since Nov 2023. After corrections, these data reveal 1-5 cm SSH variability implying 10-25 cm/s geostrophic currents.
2. Basin-wide rotational modes only explain 10-50% of SSH variance, but some snapshots reveal prominent single- and double-gyre circulations.
3. SSH that does not project onto rotational modes may be due to noise, processing artifacts, or small-scale (<20 km) geostrophic turbulence and coastal trapped waves.