Wind-driven interbasin exchange and hypolimnetic upwelling during wintertime in a large, deep lake (Lake Geneva)

Rafael S. Reiss, Ulrich Lemmin, D. Andrew Barry
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- Large embayments and distinct sub-basins are a feature of many lakes around the world, e.g., Lake Erie, Lake Huron, Lake Michigan, Lake Geneva, Lake Constance
 - Horizontal gradients in water quality between basins are common and can occur for many reasons, e.g., different mixing- or thermal regimes of adjacent basins with different depth, or different nutrient loads due to river inflow
- Interbasin exchange can have significant ecological consequences, both locally and basin-wide

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Increases in Great Lake winds and extreme events facilitate interbasin coupling and reduce water quality in Lake Erie

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Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

The role of circulation and heat fluxes in the formation of stratification leading to hypoxia in Green Bay, Lake Michigan

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J. Great Lakes Res. 24(1):145–151

Internat. Assoc. Great Lakes Res., 1998

Wind-Induced Hypolimnion Exchange in Lake Ontario's Kingston Basin: Potential Effects on Oxygen

William F. Ahrnsbrak* and Michael R. Wing

- Vertical convective overturning is an important process in the annual cycle of many lakes as it redistributes dissolved oxygen and nutrients
 - In deep, monomictic lakes, convective winter cooling often does not reach the deepest layers
 - Due to climate change induced warming, convective mixing is expected to become less efficient in the future
- In large, deep lakes, 3D processes, such as wind-induced upwelling of hypolimnetic water, may present important alternative deep-water renewal mechanisms, less susceptible to climate change

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LIMNOLOGY
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OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 66, 2021, 1168–1189
© 2020 Association for the Sciences of Limnology and Oceanography
doi: 10.1002/lno.11673

The setup and relaxation of spring upwelling in a deep, rotationally influenced lake

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Wintertime Coastal Upwelling in Lake Geneva: An Efficient Transport Process for Deepwater Renewal in a Large, Deep Lake

Rafael S. Reiss , U. Lemmin, A. A. Cimatoribus, D. A. Barry

- Shallow, western basin (*Petit Lac*, max. depth 75 m) completely destratifies every winter
- Deep, eastern basin (*Grand Lac*, max. depth 309 m) remains stratified throughout most seasons (thermocline depth 100 – 150 m), with complete vertical mixing occurring only during severely cold winters
 - Low dissolved oxygen and high nutrients concentrations in the deep hypolimnion
- Surrounding topography favors frequent, strong along-axis winds (*Bise* and *Vent*), both considerably affecting the lake's hydrodynamics

- Field measurement campaign at the confluence between the two basins during the winter 2018-2019 (see previous slide for location and mooring names)
 - 3 ADCP moorings with 10-m long vertical thermistor line attached on top (MV-N, MV-C, MV-S)
 - 1 horizontal thermistor line laid out on the lakebed (MH)
 - North-south CTD transects across the confluence
- 3D hydrodynamic modeling ([MITgcm](#)):
 - 113 m x 113 m Cartesian grid with 100 size-varying vertical z-layers (30 cm at the surface, ~5 m at the deepest point)
 - Realistic meteorological forcing from [MeteoSwiss](#) COSMO-1 model
- Lagrangian particle tracking based on velocity output of 3D model
 - Particles released in *Petit Lac* hypolimnion when model showed upwelling (time t_0)
 - **Backward** tracking: origin of upwelled water $t_{-2} < t_{-1} < \boxed{t_0}$
 - **Forward** tracking: fate of upwelled water $\boxed{t_0} < t_1 < t_2$
 - >200 000 particles released during the 2.5-day wind event

- Two-layer flow pattern at central and northern moorings (panels b, d)
- Epilimnetic currents towards *Grand Lac* ("outflow", red), balanced by hypolimnetic currents into the *Petit Lac* ("inflow", blue)
- Strong bottom inflow ($v_{\text{max}} \approx 27 \text{ cm s}^{-1}$) carrying cold hypolimnetic *Grand Lac* water into the *Petit Lac* for ~ 3.5 days
- Temperatures in hypolimnion at confluence (65 m depth) decreased to values found at 180 m depth
- Current reversal ~ 1.5 days after the wind stopped: bottom outflow and surface inflow ("relaxation", panels d, f)

- Interbasin upwelling and subsequent relaxation dynamics well reproduced by the 3D model
- Bottom inflow of upwelling cold *Grand Lac* water resulted in temporary doubling of the *Petit Lac* hypolimnetic volume (panels a, b below)
- Coriolis force strongly affected bottom inflow during upwelling and bottom outflow during relaxation (see thermocline tilting below). Confirmed by CTD transect at the confluence (not shown)

9 Dec 2018 04:00

10 Dec 2018 20:00

13 Dec 2018 13:00

- Backward tracking: upwelled water originated from below 150 m depth in the *Grand Lac* hypolimnion
- Forward tracking: upwelled water was transported more than 10 km into the *Petit Lac*, i.e., half of its total length, before returning back into the deep *Grand Lac* hypolimnion – all over the course of approximately one week
- Coriolis-induced rightward veering of the inflowing bottom currents caused coastal upwelling at the northern *Petit Lac* shore (see thermocline tilt on previous slide; details not shown here)

- *Vent*-wind induced interbasin upwelling of deep *Grand Lac* water into the shallow *Petit Lac* occurs several times every winter, providing an important mechanism for vertical and horizontal exchange in Lake Geneva. The resulting circulation is complex and strongly modified by the Coriolis force
- Upwelled *Grand Lac* water is transported far into the shallow *Petit Lac*, resulting in a temporary doubling of its hypolimnetic volume
- Simultaneously occurring coastal upwelling of *Grand Lac* water at the northern *Petit Lac* shore further enhances vertical and horizontal exchange between the basins (details not shown here)
- Temperature inversions in CTD profiles and low, model-based gradient Richardson numbers suggest mixing between upwelled *Grand Lac* water and surrounding “fresher” *Petit Lac* water (not shown here)
- Effect of stratification on interbasin exchange and upwelling between the *Grand Lac* and *Petit Lac* – i.e., the weakly stratified situation in early winter (~December) compared to the fully-mixed situation in late winter (~February/March) – is investigated in an ongoing study