Near-surface Turbulence in Arctic, Temperate, and Tropical Inland Waters: Implications for Gas Fluxes

S. MacIntyre[1]

[1]*Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, CA, USA*

Penetrative Convection in Ice-covered Lakes

S. MacIntyre[1]* , R. Schwefel[2] , and A. Cortés[3]

[1]*Marine Science Institute and Dept. of Ecology, Evolution, and Marine Biology, University of California Santa Barbara, Santa Barbara, CA, USA*

[2]*Leibniz-Institute of Freshwater Ecology and Inland Fisheries – IGB, 12587 Berlin, Germany*

[3]*Department of Civil and Environmental Engineering, University of California at Davis, Davis, California, USA*

Thermobaric Processes Both Drive and Constrain Seasonal Ventilation in Deep, Seasonally Ice-Covered Lakes in Western Canada

E. Carmack[1*] and S. Vagle[1]

[1] *Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, British Columbia*

Abstract

The contrasting roles of seasonal stratification and seasonal ventilation are among the most important attributes of lake systems in defining their geochemistry, biology and response to climate forcing. The physical processes that regulate these processes are especially significant in very deep lakes, where the joint effect of temperature and pressure on water density becomes important. Although what constitutes 'deep' is subjective, we take this to mean lakes deeper than 200 m, and note that Western Canada has more than 15 such lakes, many of which are remote, seasonally ice-covered and endowed with inspirational beauty. Here we begin with a personal perspective on the Mackenzie River – Beaufort Sea system as a setting for hydrodynamical and biogeochemical processes. As a case study we then report on a year-long time series (2019–2020) of temperature from a mooring deployed in seasonally ice covered and dimictic East Arm of Great Slave Lake (614 m maximum depth), with a focus on the role of differential compression (thermobaricity) on both convection and stratification[1]. We speculate on effects of physical processes on geochemical and biologically processes based mainly on lake-wide data collected in the 1940's by D. S. Rawson[2]. Finally, we briefly report on other such lakes in Western Canada, some of which have only limited unpublished data sets, hoping to encourage more interest and opportunities in these remarkable systems.

info-PPNW2022@civil.ubc.ca

References

[1] Carmack, E. C., S. Vagle (2021), Thermobaric processes both drive and constrain seasonal ventilation in deep Great Slave Lake, Canada. *Journal of Geophysical Research: Earth Surface*, 126, e2021JF006288. https://doi. org/10.1029/2021JF006288.

[2] Rawson, D. S. (1950), The physical limnology of Great Slave Lake. *Journal of the Fisheries Research Board of Canada*, 8, 3–66. https://doi. org/10.4319/lo.2000.45.1.0159.

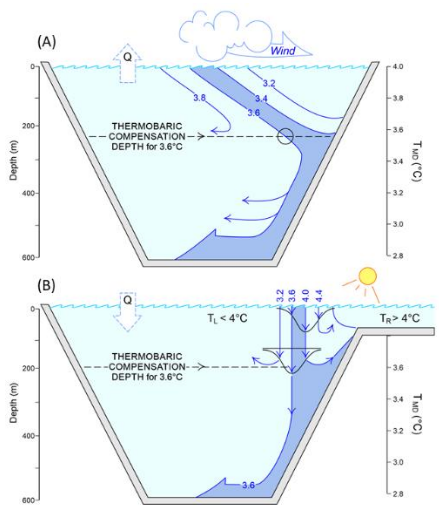


Figure. Conceptual models of deepwater ventilation by (A) wind-driven downwelling or internal seiche set-up in fall, and (B) convection within the proposed thermobaric thermal bar in spring.

* *Corresponding author, eddy.carmack@gmail.com*

Studying Circulation Processes with Lagrangian Methods

Rich Pawlowicz[1]

[1]*Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, B.C. Canada, V6T 1Z4*

Many of the physical processes we study in natural waters are driven by questions of the form "what is happening here", while most of the questions that non-scientists need answered are of the form "how do things get from one place to another". In an attempt to bridge this gap, I have started using cheap/expendable tracked drifters to study circulation processes. Not only has this resulted in plenty of interesting anecdotes, as drifter tracks illustrate a variety of surprising behaviors (including getting run down by ships, and running aground), but with enough drifters we can answer some interesting general questions. Is mean transport more important than its variability? Where do things like to wash ashore? What's the probability of grounding for items floating 20, 50, or 100m offshore? What are currents like near the shore compared to further away? The answers to these questions may improve modelling and policy (and they are fun to study).

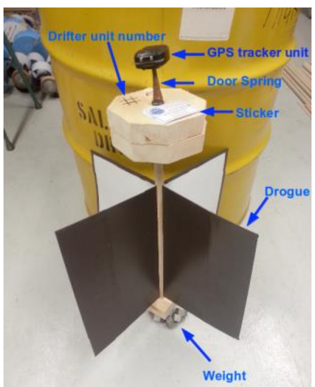


Figure 1: The Expendable Drifter

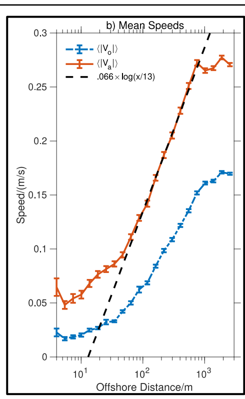


Figure 2: Evidence for a "logarithmic" boundary layer

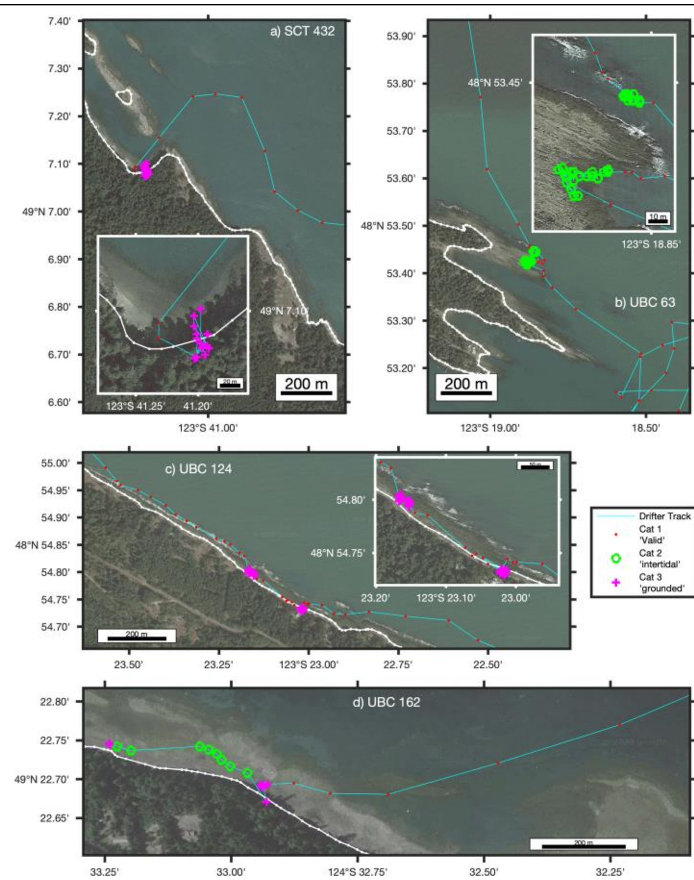


Figure 3: Examples of grounding behavior

[1] Pawlowicz, R., C. Hannah, and A. Rosenberger, Lagrangian Observations of estuarine residence times, dispersion, and trapping in the Salish Sea, *Est. Coastal Shelf Sci*., 225, 106246, 10.1016/j.ecss.2019.106246

[2] Pawlowicz, R., The Grounding of Floating Objects in a Marginal Sea, J. Physical Oceanography, 51, 537-551, 10.1175/JPO-D-20-0183.1

Micrometer world of natural waters – how it matters in practice

A. Wüest[1,2*]

[1] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, CH-6047 Kastanienbaum, Switzerland*

[2] *Limnology Center, ENAC, École Polytechnique Fédérale de Lausanne, EPFL, CH-1015 Lausanne, Switzerland*

Abstract

This presentation is a personal review of a specific topic that has accompanied me throughout my entire scientific work at Eawag and EPFL since the mid-1980s. It concerns the relevance of the smallest scales of aquatic processes for the entire bulk of the standing und usually stratified waterbody of lakes. When I began studying physical processes in natural waters, limnology and oceanography were called *factor-2 sciences*. Although the budgeting of water constituents is often possible within ranges of 20 to 30% accuracy today, the fundamental problem of adequate 3-dimensional representation remains. What fascinated and motivated me, throughout the entire time of my research and expert activity, was the ability that we continuously developed over time of using adequate system analysis, to estimate budgets, fluxes and process rates for water constituents over hundreds or thousands of cubic-kilometres with extremely small data sets, often acquired at sub-millimetre scales. Classical examples of key micro-scale processes are the molecular fluxes at the lake water boundaries to the atmosphere or bubbles[1] and to the sediment[2], density instabilities caused by molecular diffusion[3] or micro-scale motions of microorganisms[4].

In this presentation, I will show that all these examples are fascinating scientific phenomena on the one hand, but at the same time, they are also important environmental engineering topics as they are often related to real-world problems and offer the possibilities to interact with practice.

References

[1] McGinnis, D.F., J. Greinert, Y. Artemov, Y., S. E. Beaubien, and A. Wüest (2006). The fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? *Journal of Geophysical Research* **111**(C9): C09007, doi:10.1029/2005JC003183.

[2] Müller, B., L.D. Bryant, A. Matzinger, and A. Wüest (2012). Hypolimnetic oxygen depletion in eutrophic lakes. *Environ. Sci. Technol*. **46**(18): 9964–9971, doi: 10.1021/es301422r.

[3] Wüest, A., T. Sommer, M. Schmid, and J.R. Carpenter (2012). Diffusive-type of double diffusion in lakes – a review, p 271-284. Chapter 14 in W Rodi and M Uhlmann (eds), Environmental Fluid Mechanics: Memorial Volume in Honour of Prof. Gerhard H. Jirka, IAHR Monographs, CRC Press / Taylor&Francis Group, Karlsruhe.

[4] Sommer, T., F. Danza, J. Berg, A. Sengupta, G. Constantinescu, T. Tokyay, H. Bürgmann, Y. Dressler, O.R. Sepulveda Steiner, C.J. Schubert, M. Tonolla, and A. Wüest (2017). Bacteria-induced mixing in natural waters. *Geophysical Research Letters* **44**(18), 9424–9432, doi:10.1002/2017GL074868.

* *Corresponding author, e-mail: alfred.wueest@eawag.ch*

Vertical fluctuations induced by active carpets

G. Aguayo[1*], F. Guzmán-Lastra[2], A. J.T.M. Mathijssen[3]

[1] *Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile.*
[2] *Escuela de Data Science, Universidad Mayor, Santiago, Chile.*
[3] *Department of Physics & Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104, USA.*

Abstract

Active carpets are approximately 2-dimensional conglomerates formed by microscopic actuators, such as *E. Coli* or *Chlamydomonas*. These formations are found in natural waters, in the surface forming thin layers, or in interfaces [1]. A natural question is, are these formations beneficial for the actuators, in terms of energy consumption and survivance? Efforts have been made to clear some implications of these carpets. Guzmán-Lastra et al. [2], studied numerically those non-equilibrium systems and encountered phenomena like a self-cleaning effect and a generalized Fick's Law. The current work is focused on extending those results for various other carpet types and characterizing the different dynamics and time scales in the system, emphasizing the underlying numerical work. One of the results with particular importance, is the diffusivity on the water column, upon the carpets at different heights. This diffusivity directly relates to the generalized Fick's Law where we found that this proposed equation correctly predicts the equilibrium sedimentation profile of an ensemble of tracers and is also in good agreement with the particle capture rate of an active sink near a particle source.

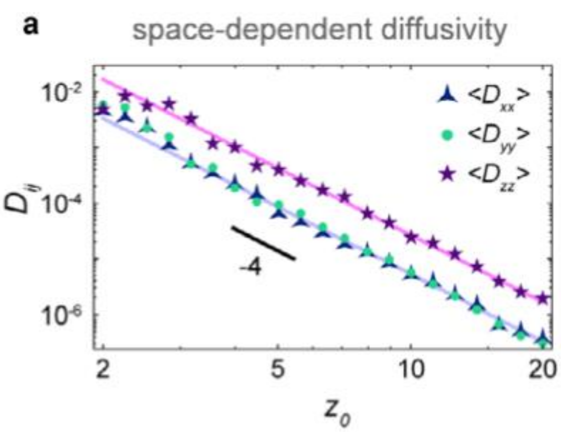


Figure a. Diffusivity coefficients as a function of height.

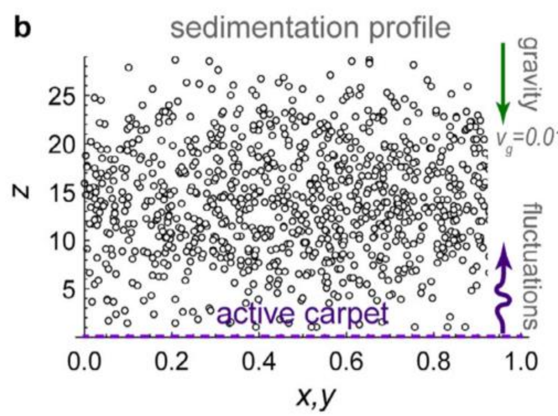


Figure b. Steady state sedimentation profile under an active carpet.

References

[1] Tobias Sommer, Francesco Danza, Jasmin Berg, Anupam Sengupta, George Constantinescu, Talia Tokyay, Helmut Bürgmann, Y. Dressler, O. Sepúlveda Steiner, CJ Schubert, et al. Bacteria-induced mixing in natural waters. Geophysical Research Letters, 44(18):9424–9432, 2017.

[2] Francisca Guzmán-Lastra, Hartmut Löwen, and Arnold JTM Mathijssen. Active carpets drive non-equilibrium diffusion and enhanced molecular fluxes. Nature communications, 12(1):1–15, 2021

* *Corresponding author, e-mail g.aguayo07@gmail.com*

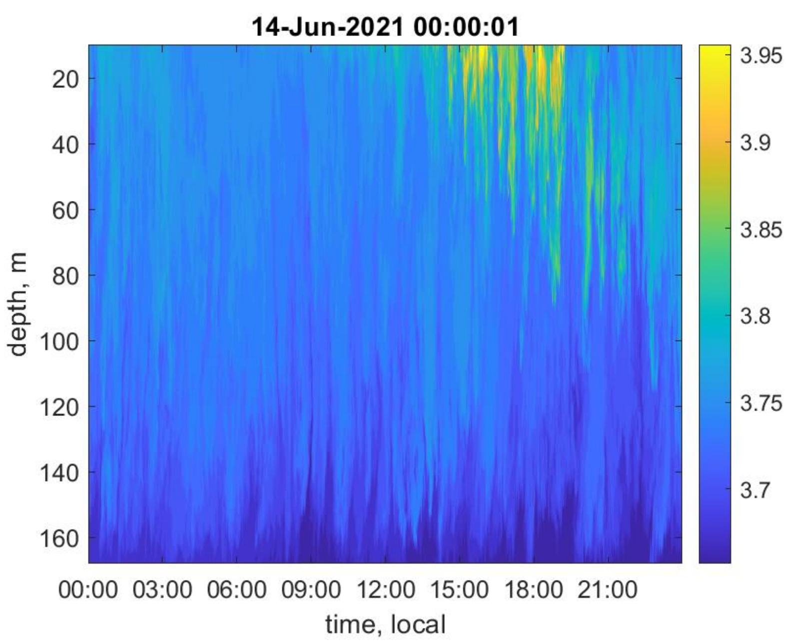
Characterizing radiatively-driven convection in a deep freshwater lake

J. A. Austin

Large Lakes Observatory, University of Minnesota, Duluth, Duluth, MN, USA

Abstract

For freshwater lakes that cool below the temperature of maximum in the late winter and spring, springtime heating due to incident shortwave radiation leads to radiatively-driven convection, in which warming near the surface results in convective circulation of the water column. At our field site in ice-free Lake Superior, this fully mixes the 185m-deep water column in less than six hours after sunup. Observations from gliders and from a large two-dimensional array of thermistors deployed on a two-point subsurface mooring in 2019, combined with Acoustic Doppler Current Profiler (ADCP) observations, show that the convective circulation results in sinking parcels of anomalously warm water with temperature anomalies on the order of 0.1K, horizontal scales on the order of tens of meters, and very sharp lateral gradients on the boundaries on the order of 1K/m over tens of centimeters. A large single-point mooring deployed in April 2021 to examine vertical structure of convective plumes (pictured) using a 1-dimensional array of 91 thermistors showed coherence over scales of 100m, with the depth of features deepening over the course of the day. Finally, ADCP acoustic backscatter data suggests that changes in stratification state from negatively stratified to neutrally stratified have a direct impact on zooplankton migratory behavior due to the impact of convection on the water column.



Noble Gas Thermometry in Lake Kivu Deep Water

Cornelis Schwenk[1,2,3,*], Sophie Negele[2], Florian Freundt[2], Charles M. Balagizi[4] ,Werner Aeschbach[2], **Bertram Boehrer[1,*]**

[1] Helmholtz Centre for Environmental Research, Magdeburg, Germany
[2] Institute for Environmental Physics, Heidelberg University, Germany
[3] now: Institute for Atmospheric Physics, Johannes-Gutenberg University Mainz, Germany
[4]Goma Volcano Observatory, Goma - RD Congo
[*]c.schwenk@uni-mainz.de, bertram.boehrer@ufz.de

Abstract

The deep waters of Lake Kivu host an enormous deposit of dissolved methane. About 40 billion cubic meters (representing a value of 30 billion EUR) have been found (e.g. Boehrer et al. 2019). The industrial exploitation has recently started. The deposit represents an important access to fossil energy for both adjacent countries, especially for Rwanda, which otherwise does not have access to fossil energy on its territory. However the enormous gas pressures have been feared to result in sudden large scale ebullition events “limnic eruptions” which would threaten the lives of about two million local inhabitants.

For planning economic exploitation and for ensuring safe conditions during operation of gas plants the hydrology of the Lake needs to be understood. For this purpose, also noble gases have been measured, in the hope these noble gases could indicate whether the lake had experienced large scale degassing events in recent history (i.e ~1000 years i.e. the age of the oldest water contained in the lake). Indeed, measurements showed that noble gases were depleted: neon by about 50% while argon and krypton were depleted by about 70% compared to atmospheric equilibrium at given conditions (Bärenbold et al. 2021). However the fact that neon was depleted the least indicated this was not (only) the result of degassing events.

In the presented study, we tested to which extent the observed depletion of noble gases could be explained by high formation temperatures of the inflowing groundwater. For this purpose, noble gas solubilities had to be accurately be determined to higher temperatures (up to 80°C from existing data starting from 0°C, Schwenk et al. 2022a). From these data, (1) the temperature of saturation could be deduced. As a consequence of the differing temperature behaviours between noble gases, (2) ratios of noble gas concentrations could directly be linked to formation temperatures. Finally, (3) simultaneous least square fitting of formation temperatures and excess air with the special software packet PANGA, allowed conclusions about formation temperatures and missing gas portion (Schwenk et al. 2022b).

All three approaches consistently indicated a formation temperature of Lake Kivu deep water at 65°C. At this temperature, all interpreted noble gases are close to saturation indicating that the presently contained water in Lake Kivu has not experienced a large scale ebullition. It is concluded, that the deep water of Lake Kivu is most probably formed on the northern slopes, which are of volcanic origin and so porous that no surface drainage of precipitation happens. Precipitation hence percolates through the aerated soil and meets the groundwater table at a temperature of about 65C. The hydraulic head facilitates the intrusion at great depth into the basin of Lake Kivu.

References

[1] Boehrer, B., Tümpling, W., Mugisha, A., Rogemont, C., Umutoni, A. (2019). Reliable reference for the methane concentrations in Lake Kivu at the beginning of industrial exploitation. *Hydrology and Earth System Sciences*, 23, 4707-4716.

[2] Bärenbold, F., Schmid, M., Brennwald, M. S., Kipfer, R. (2020). Missing atmospheric noble gases in a large, tropical lake: The case of Lake Kivu, East-Africa. *Chemical Geology*, 532, 119374.

[3] Schwenk C., Freundt F., Aeschbach W., Boehrer B. (2022a): Extending Noble Gas Solubilities in Water to Higher Temperatures for Environmental Application, *Journal of Engineering and Chemical (accepted).*

[4] Schwenk C., Negele S., Balagizi C.M., Aeschbach W., Boehrer B. (2022b): High Temperature Noble Gas Thermometry in Lake Kivu, *Science of the Total Environment (accepted).*

Flow Structure and Scaling of Radiatively Driven Convection in a Freshwater Lake

Yun Chang and Alberto Scotti
Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill, USA

The water in mid- to high-latitude lakes in spring is usually between 0 and 4 ^{o}C, in which freshwater density increases with increasing temperature. As solar radiation penetrates a lake, the near-surface water becomes warmer, denser, and sinks (radiatively driven convection, or RDC). This talk addresses scaling and overall flow structure of RDC by looking at mid-latitude deep lakes. Sinking velocity scale W is formulated as a simple function of water temperature, solar radiation, photic zone extent, and lake depth, which indicates the Rossby number can be as low as 2. Order of magnitude analysis suggests that the nontraditional Coriolis parameter should also be considered. The Stratified Ocean Model with Adaptive Refinement (SOMAR) is used to simulate RDC and verify the proposed W. With time-independent radiation, the horizontal scale of convection cells suitably normalized grows linearly with time. This relation is then used to infer the horizontal scale forced by diurnal solar radiation. Rotation reduces the horizontal scale by a factor of 1.5, and induce a large-scale circulation. W scaling agrees well with measurement in Lake Michigan. This framework can be applied to plan and analyze future observations.

Penetrative convection modifies the dynamics of a gravity current

T. Doda[1,2*], H. N. Ulloa[3], C. L. Ramón[4], D. Bouffard[1]

[1] Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, Kastanienbaum, Switzerland
[2] Limnology Center, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
[3] Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, USA
[4] Department of Civil Engineering, University of Granada, Granada, Spain

Abstract

Gravity currents are flows driven by spatial water density differences. In lakes, downslope gravity currents contribute to the littoral-pelagic exchange of heat, dissolved compounds and particulate matter. Their dynamics are understood from laboratory studies in quiescent environments. However, ambient natural waters can be turbulent, which may modify the behaviour of gravity currents. Here, we investigate thermally driven gravity currents, aka thermal siphons, induced by differential cooling in sloping water bodies. In contrast to the classic gravity current that propagates through a quiescent environment, thermal siphons develop in the presence of penetrative convection triggering specific dynamical flows. From high-resolution velocity and temperature measurements in the sloping region of a wind-sheltered lake (Rotsee, Switzerland), we explore how penetrative convection modifies the dynamics of thermal siphons. We identify two phases (Fig. 1): a nighttime convective (C) phase, during which convective plumes interact with the gravity currents, and a daytime relaxation (R) phase, during which convection weakens and thermal siphons intensify. The thickness of gravity currents fluctuates vertically over ~2 m during the C-phase but becomes constant during the R-phase. This change of current dynamics is associated with a weakening of convective mixing (one order of magnitude increase of the convective Richardson number between C- and R-phases). The convective penetration depth δ_c overcomes the shear interface thickness δ_S during the C-phase, implying that convective plumes erode the current interface and reduce the bottom stratification. We suggest that penetrative convection reduces any tracer's lateral transport by mixing the downslope flow vertically with the upper ambient water. By delaying the time of maximal transport to daylight conditions, convective mixing modifies the traditional perception of thermal siphons as a nocturnal transport process.

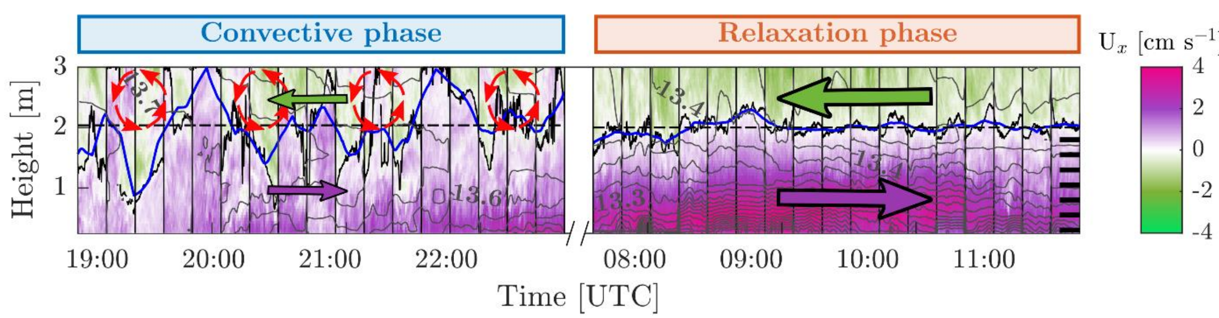


Figure 1 – High-resolution cross-shore velocity captured in the sloping region of Rotsee (4 m depth), as a function of time and height above the sediment, during the convective and relaxation phases. The gravity current is shown with positive (purple) velocity, and its upper interface is depicted by black (instantaneous) and blue (smoothed) lines. Grey lines are 0.02 °C-spaced isotherms, linearly interpolated between thermistors (black ticks on the right vertical axis). Vertical black lines delimit each measurement burst. Red arrows and horizontal arrows illustrate convective plumes and the thermal siphon, respectively.

* *Corresponding author, e-mail tomy.doda@eawag.ch*

Assessment of climate change impacts over the thermal behaviour of a small-polimitic-tropical lake

B.P.S. Duarte[1*], R. Scarati[2], L.F. Amorim[1], A.A.B. Magalhães[1] and J.C.M. Bernardino[3]

[1] Graduate Students, Hydraulics and Environmental Engineering Department, School of Engineering, University of São Paulo, São Paulo Brazil
[2] Associate Professor, Hydraulics and Environmental Engineering Department, School of Engineering, University of São Paulo, São Paulo, Brazil
[3] Assistant Professor, Hydraulics and Environmental Engineering Department, School of Engineering, University of São Paulo, São Paulo, Brazil

The occurrence of stratification and mixing events reflects the thermal behaviour within the vertical layers of lakes and reservoirs, in response to daily or seasonal variations. These variations depend on the lake's morphology, atmospheric regional patterns and in and outflows presents on the lake, influencing, in its turn, the physical, chemical and biological processes of these environments. Small-tropical lakes are essential in many tropical cities due to its multiple uses. However, the study of these tropical environments is still scarce and restricted, but of great interest for local decision-makers, especially in face of climate change scenarios. In this context, this study aims to apply mathematical modelling to represent a small-polimitic-tropical lake and assess its thermal behaviour variations and tendencies for two climate change scenarios, an optimistic and a pessimistic one. The case study was focused on the Hedberg Dam, a 0.23 km²-4.5m depth pond, built in the beginnings of the 19th century, located about 90 km from Sao Paulo city, in Brazil. Its hydrological catchment area is partially protected by the Floresta Nacional de Ipanema, with sparse urban infrastructure and intense agricultural and pasture occupations. The mathematical modelling software applied was the General Lake Model (GLM)[1], a one-dimensional hydrodynamic model, which uses a deterministic, mechanistic, time-dependent and numerical solving approach. With an hourly time-step, the model used morphology characteristics, atmospheric variables and inflow as input data. High-frequency thermal sensor data were used for the calibration and validation of the model, performed during the years 2017 and 2018 and 2019 and 2020, respectively. The obtained results were considered reliable, as the model represents well the daily and seasonal patterns observed in the Hedberg Dam. For the climate change scenarios, the Eta regional climate model was used, with a 20 km spatial resolution, being downscaled by the HadGEM2-ES and MIROC5 models. The chosen scenarios represent the RCP 4.5 (optimistic) and RCP 8.5 (pessimistic), proposed by the IPCC, which indicate the increase in mean global temperature by the end of the century of 1.8°C and 3.6°C, respectively. The scenarios were simulated between 2021 and 2100 and their results assessed as three sets of data, near future (2021 – 2039), mid-term future (2040 – 2069) and distant future (2070 – 2100). Applying the Lake Analyzer tool, four parameters were assessed throughout the scenarios: the Schmidt Stability, epilimnion and hypolimnion temperatures and the thermocline depth. Results indicate the increase in Schmidt Stability values for the distant future, correlating with the notably increase in the epilimnion temperature, yet mildly increase in the hypolimnion temperature. This points to higher number of mixing and stratification events and longer stratification periods as well, leading to a different thermal behaviour and its implications to the lake water quality.

References

[1] Hipsey, M. R.; Bruce, L. C.; Boon, C.; Busch, B. et al. (2019) A General Lake Model (GLM 3.0) for linking with high-frequency sensor data from the Global Lake Ecological Observatory Network (GLEON). *Geoscientific Model Development*, *12(1)*, 473-523.

* *Barbara Pozzan dos Santos Duarte, e-mail: barbara.pozzan.duarte@usp.br*

Lock exchange induced by cooling below the temperature of maximum density

K. A. Everard[1*] and G. A. Lawrence[1]

[1]Department of Civil Engineering, Faculty of Applied Science, University of British Columbia, Vancouver, Canada

Whether a lake is ice covered or not is an important piece of information to understanding not only the energy balance of the lake, but also that of the atmospheric boundary layer, making knowledge of ice-on an important variable both for studies on lake ecosystems and for weather and climate modelling. We propose a simplified model for prediction of ice-on which builds off the work by [1]. In our model, we consider a 2D lake at an initially uniform temperature of 4°C with a simplified geometry representing the presence of a littoral zone and a deeper basin (Figure 1). The model problem is initiated with a full night of uniform radiative heat loss at the lake surface which is then mixed during a windstorm strong enough to vertically mix both basins. The resulting differential cooling sets up a lock exchange (see Figure 1). The lock exchange continues until the next mixing event. This problem is pursued iteratively until the surface water reaches 0°C. This model allows us to investigate the impact that differential cooling and lock exchange might have on the timing of ice-on. We investigate the model's dependence on two geometrical parameters, h/H and l/L, and compare ice-on predictions of the model with observations at Base Mine Lake.

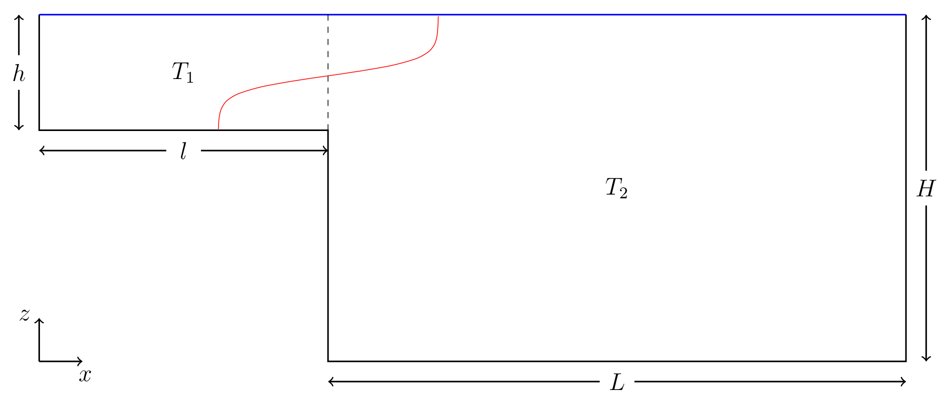


Figure 1. Schematic of exchange driven by differential cooling. T_1 is the average temperature of the littoral zone and T_2 is the average temperature of the deeper basin. The red curve is a representation of the exchange that takes place when $T_1 < T_2 < 4$℃.

Reference

[1] Toffolon, M., L. Cortese, D. Bouffard (2021), SELF v1.0: a minimal physical model for predicting time of freeze-up in lakes, *Geosci. Model Dev., 14*, 7527-7543, doi:10.5194/gmd-14-7527-2021.

Short-term patterns of summer arsenic cycling in a temperate, polymictic lake

S. Fung[1,2*], A. Horner-Devine[2], R. Neumann[1]

[1] *Hydrobiogeochemistry Group, Civil and Environmental Engineering, University of Washington, Seattle, WA, USA*
[2] *Environmental Fluid Mechanics Group, Civil and Environmental Engineering, University of Washington, Seattle, WA, USA*

Abstract

Summertime internal loading of arsenic in temperate, polymictic lakes overlaps with periods of peak primary producer growth and poses risks to ecosystems and surrounding populations. Our previous work describes the physical and biogeochemical mechanisms that lead to seasonal patterns of arsenic concentrations in Lake Killarney, a shallow, arsenic contaminated lake near Seattle, WA. Specifically, we found that arsenic concentrations in surface waters were highest in mid-summer when sediment temperatures were elevated, and that alternating stratification and mixing led to pulses of arsenic into the upper water column. However, short-term dynamics that contribute to these longer patterns are still not well understood. To advance knowledge about the timescales of arsenic cycling within shallow, polymictic lakes, we conducted an intensive two-month field study during summer 2019 to investigate whether there were higher frequency patterns underlying the previously observed cycles. We collected surface and bottom water samples for arsenic analysis every 6 hours along with high frequency temperature profiles and measurements of surface and bottom water dissolved oxygen. Significantly, we found that bottom water arsenic concentrations exhibited diel oscillations, with concentrations peaking in the early afternoon when bottom water DO concentration and water column stratification strength reached their daily peaks. Diel oscillations in bottom water arsenic were most extreme within longer periods of stable stratification. In this work, we show how photosynthesis, stratification, and meteorological forcing contribute to forming these daily patterns in arsenic concentrations. We also apply our data toward understanding rates of arsenic scavenging and resorption within the water column, processes that are challenging to quantify in natural systems. Parsing out the mechanisms controlling pathways of arsenic transport in shallow lakes is essential for determining the residence time of dissolved arsenic in the lake waters, and thus of the length and degree of biotic exposure to legacy arsenic contamination.

* *Corresponding author, e-mail samfung@uw.edu*

Convection under lake ice: turbulent kinetic energy budget and mixing anisotropy

G. Kirillin[1*], S. Bogdanov[2], S. Volkov[1]

[1] *Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany*
[2] *Northern Water Problems Institute, Karelian Research Center, Petrozavodsk, Russia*

Abstract

Generation, transport, and decay of turbulence in natural fluids remains one of the fundamental unresolved questions in environmental fluid dynamics. Recent developments of the modern autonomous measurement systems, such as muti-beam acoustic velocity profiling, allow an insight into the mixing dynamics on both energy-containing and viscous dissipative scales beyond a simple comparison of production-dissipation of the turbulence kinetic energy (TKE) in a small volume. Ice-covered freshwater lakes create specific low-turbulent environments with relatively simple forcing, and can be considered as large-scale natural lab facilities for investigation of turbulence in terms of non-stationarity and anisotropy. We combined multi-beam acoustic current profiling (ADCP) in different configurations accompanied by point-based acoustic Doppler velocity (ADV) measurements to explore the "anatomy of turbulence" in these environments. By using two coupled ADCP devices in an original setup we measured all 6 components of the Reynolds stress tensor. The estimated horizontal stress u'v' exceeded other components up to an order of magnitude, demonstrating an important role of u'v' in horizontal homogenization of the convective flow and in the 3-d redistribution of mixing energy, which can be easily underestimated. The resulting direct estimate of the non-stationarity term in the TKE revealed its contribution to the TKE budget and explained the previously observed delay between the generation and dissipation of the turbulent energy. Analysis of the Reynolds stress tensor in terms of the anisotropy invariants demonstrated that the decay of convective turbulence is accompanied by turning near-isotropic mixing to two-component axisymmetric turbulence. We also demonstrate that small-volume ADV measurements fail to capture the TKE characteristics in convective flows, while remain reliable for estimation of the dissipation rates at the Kolmogorov length scales and can be applied in combination with other methods for evaluation of mixing dynamics.

[*] *Corresponding author, e-mail georgiy.kirillin@igb-berlin.de*

Gravity Currents in the Cabbeling Regime

A. P. Grace[1*], M. Stastna[1], K. G. Lamb[1], and K. A. Scott[2]

[1] *Department of Applied Mathematics, Faculty of Mathematics, University of Waterloo, Waterloo, Canada*
[2] *Department of Systems Design Engineering, Faculty of Engineering, University of Waterloo, Waterloo, Canada*

Abstract

Recently, the understanding of the dynamics of flows beneath ice cover has garnered much interest in the geophysical fluid dynamics community [1]. Much focus has gone into characterizing vertical flows beneath ice and their impact on lake dynamics [2], while less has gone into characterizing the impact of horizontal flows beneath ice. The study of horizontal flows under ice cover is still in its relative infancy, but we know they can play a major role in the transport of nutrients, as well as impacting CML temperature [3]. In this talk, we describe one such example of the interactions of horizontal flows and vertical flows induced from freshwater cabbeling (the mixing of parcels with equal density but different temperature). This talk presents numerical simulations of the evolution of freshwater gravity currents (canonical examples of horizontal density driven flows) where intruding and ambient temperatures are on different sides of the temperature of maximum density. A setup like this might occur in the springtime from a riverine inflow [4], or by differential heating in littoral regions of a lake[2,4]. We will highlight how the initial intrusion flows along the upper surface of the domain and mixes with ambient water, and due to cabbeling, generates a coherent bottom current. We will introduce a control parameter (essentially the inverse of the non-dimensional temperature of maximum density), which is key to the evolution of the system, and we will show how the maximum horizontal extent of the initial intrusion varies with it. We show that for some cases, the maximum extent of the initial intrusion controls some of the important characteristics of the coherent bottom current. Finally, we will highlight some of the key characteristics (head height and temperature distribution) of the bottom current.

References

[1] Powers, Stephen M., and Stephanie E. Hampton. "Winter limnology as a new frontier." *Limnology and Oceanography Bulletin* 25.4 (2016): 103-108.

[2] Bouffard, Damien, and Alfred Wüest. "Convection in lakes." *Annual Review of Fluid Mechanics* 51 (2019): 189-215.

[3] Ulloa, Hugo N., et al. "Differential heating drives downslope flows that accelerate mixed-layer warming in ice-covered waters." *Geophysical Research Letters* 46.23 (2019): 13872-13882.

[4] Tsydenov, Bair O., Anthony Kay, and Alexander V. Starchenko. "Numerical modeling of the spring thermal bar and pollutant transport in a large lake." *Ocean Modelling* 104 (2016): 73-83.

---

[*] *Corresponding author, e-mail andrew.grace@uwaterloo.ca.*

Observations and predictions of deepening of the surface mixed layer during Autumnal turnover in a small, deep, temperate lake with seasonal ice-cover

K. Graves[1*] and B. Laval[1]

[1] *Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada*

Abstract

Inspired by [1], and using the methods presented by [2], we investigate the deepening of the surface mixed layer (SML) during Autumnal turnover in a small, deep, temperate lake with seasonal ice-cover.

We use thermistor chain and CTD measurements to make observations of water temperature and salinity, and estimate the buoyancy frequency (N). We pair these observations with in-situ meteorological data to estimate the surface buoyancy flux (B_0) and the Monin-Obukhov depth (L_m). The surface mixed layer thickness (h_{ml}) is estimated from the temperature profiles from the thermistor chain and the CTD, and from these estimates, the deepening rate of the h_{ml} (dh_{ml}/dt) is then directly calculated. dh_{ml}/dt is also predicted using observations and a semi-empirical expression for the deepening rate [2]

$$\frac{d_{hml}}{dt} = \frac{(1+2A)B_0}{h_{ml}N^2} \tag{1}$$

where A is an entrainment coefficient and N is directly below the h_{ml}. We compare the predicted dh_{ml}/dt from (1) with the value estimated from temperature observations from CTD and thermistor chains.

Observations of Autumnal cooling show that the surface layer temperature (T_s) cools with time, and as T_s approaches the temperature of maximum density ($T_{md} \approx 4$ °C), B_0 decreases and approaches zero. When T_s cools to and below T_{md}, B_0 changes sign and stabilizes the water column. This is when convectively driven h_{ml} deepening stops. By comparing L_m to the h_{ml} prior to when deepening stops, it is seen that Autumnal deepening is mostly due to convection, with only a couple of days where $L_m > h_{ml}$.

Both the observations and predictions show that at the beginning of Autumnal cooling, the SML deepens slowly, as it must erode the stratification of the metalimnion (the region of strongest stratification). The deepening continues slowly until the SML has eroded the seasonal thermocline (location of greatest N^2). Once through the seasonal thermocline, dh_{ml}/dt increases. Again, once the SML has eroded the metalimnion and enters the hypolimnion, there is a significant decrease in N^2 and dh_{ml}/dt increases. Once the SML reaches the hypolimnion, predictions and observations differ. (1) predicts that the SML deepens to the bottom in approximately one day, whereas observations show that, depending on the definition of the SML, the SML did not reach the bottom.

While we have previously discussed the effect of N^2 on dh_{ml}/dt, (1) is a balance of B_0, h_{ml} and N^2. It is this balance, as well as their timing, that determines whether a lake turns over. We also show that while the CTD is coarser in time, the fine spatial discretization provides a better estimate of N^2 than can be achieved from the thermistor chain. However, both measurements demonstrate that the prediction of dh_{ml}/dt is greatly affected by the selection of h_{ml} which determines the value of N^2 used in (1).

References

[1] Bouffard, B., and A. Wüest (2019), Convection in Lakes, *Annu. Rev. Fluid Mech.*, *51*(1**)**, 189-215, 10.1146/annurev-fluid-010518-040506.

[2] Zilitinkevich, S. (1991), Turbulent Penetrative Convection, Avebury Technical.

[*] *Corresponding author, e-mail kellygraves@civil.ubc.ca*

Thermal circulation in an arctic pond

Stephen M. Henderson[1], Sally MacIntyre[2],

[1] *School of the Environment, Washington State University (Vancouver), Vancouver, WA, U.S.A*
[2] *Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, U.S.A*

Abstract

In arctic tundra environments, millions of small lakes and ponds constitute a potentially significant greenhouse gas (CH_4 and CO_2) source, and influence heat transport in the rapidly evolving landscape. Observations presented here suggest that rapid early-summer bottom-water renewal in a 1.5-m-deep pond (68.626°N,149.597°W) was dominated by thermal overturning circulation, rather than by wind-driven overturning or vertical turbulent mixing. Water velocities and rates of viscous dissipation of turbulent energy (ε) were estimated using three pulse-coherent Nortek Aquadopp ADCPs, while temperature stratification was measured along three vertical profiles using 41 RBR Solo-T temperature loggers. Each night during early summer, surface cooling and free convection generated a mixed layer of minimal stratification and relatively intense turbulence ($\varepsilon \leq 3 \times 10^{-7}$ W/kg) within 1 m of the surface. Each day, stratification re-developed, inhibiting mid-pond turbulent mixing beneath a thin (often <0.5-m-deep) surface layer. At greater depths, daily cycles of cooling and warming were also observed ($\pm$ 2°C), but strong stratification separated upper and lower layers (Figure 1, left). During both day and night, this stratification prevented significant turbulent mixing within the near-bed layer (gradient Richardson numbers $\gg$1, and estimated buoyancy Reynolds numbers <1). Each night, in a layer extending 10 cm above the gently sloping bed near the pond's inlet, temperatures were colder than those in underlying sediments, or those near the pond's deepest point (Figure 1, right). We infer that these relatively cold waters were likely created by surface cooling in very shallow regions of the pond or the adjacent wetland, and cascaded down the bed to renew bottom waters. Assuming that such cascading of near-bed waters was responsible for deep-water cooling, a bottom-water heat balance suggests about 100 m^3/day of bottom water renewal, sufficient to overturn the pond in a few days, despite the absence of deep-pond turbulent mixing (Figure 2; groundwater inflow and outflow may also play a role). This thermal overturning circulation may influence heat transport and biogeochemical cycling.

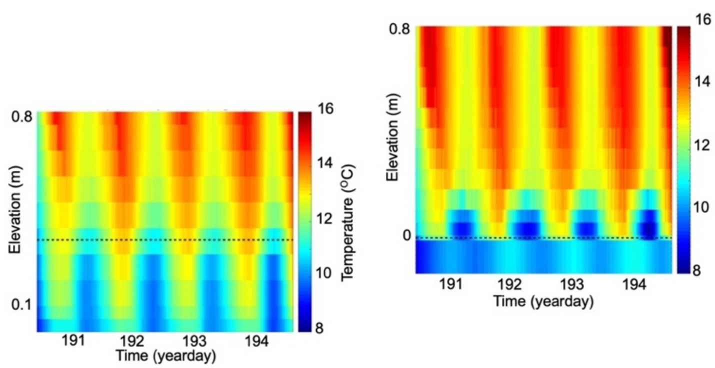


Figure 1: Daily temperature fluctuations observed near the pond's deepest point (left) and above the sloping bed near the inlet (right). For reference, horizontal dashed line in both panels indicates the depth of the bed at the inlet site.

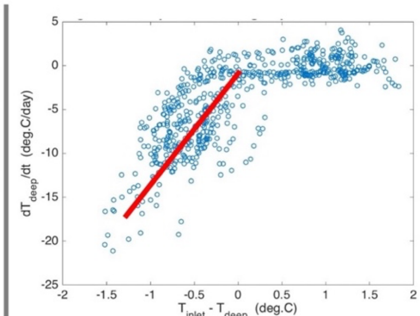


Figure 2: Half-hourly mean rate of deep-water warming versus temperature difference between cascading inlet water and deep water. Line indicates $VdT_{deep}/dt = Q(T_{inlet} - T_{deep})$, where V= deep-water volume and Q = flux of cascading water.

[1] *Corresponding author, e-mail steve_henderson@wsu.edu*

Weakening of inverse stratification in northern lakes

J. Jansen[1*], R. I. Woolway[2], Z. Tan[3]

[1] *Department of Ecology and Genetics – Limnology, Uppsala University, Uppsala, Sweden*
[2] *School of Ocean Sciences, Bangor University, Bangor, UK*
[3] *Pacific Northwest National Laboratory, Richland, Washington, US*

Abstract

Inverse stratification is a defining feature of northern lakes in winter. This thermal state is broadly defined by a 0-4 °C vertical temperature profile, and enables the development of chemical gradients and ecological niches that shape winter food webs. Importantly, the strength of the density gradient modulates the extent and velocity of density-driven currents under ice, including downslope flows and radiatively driven convection. A recent modelling study [1] has shown that the duration of the inverse stratification period is rapidly declining as a result of warmer winters. This work represents a next step, investigating changes in inverse stratification strength.

In this study we present a unique dataset of lake water temperature observations from North America and Scandinavia (11140 lakes, 1960-2021) to assess long-term changes in inverse stratification strength. We find that the surface-bottom density gradient has weakened significantly in the last 60 years, and that this is caused primarily by warming of surface waters below the ice (Figure 1). A 1D process-based model (ALBM [2]) is used to identify potential drivers of the surface temperature trend in a subset of 787 trend lakes with ≥15 years of observations. We will present the new dataset and discuss preliminary modelling results.

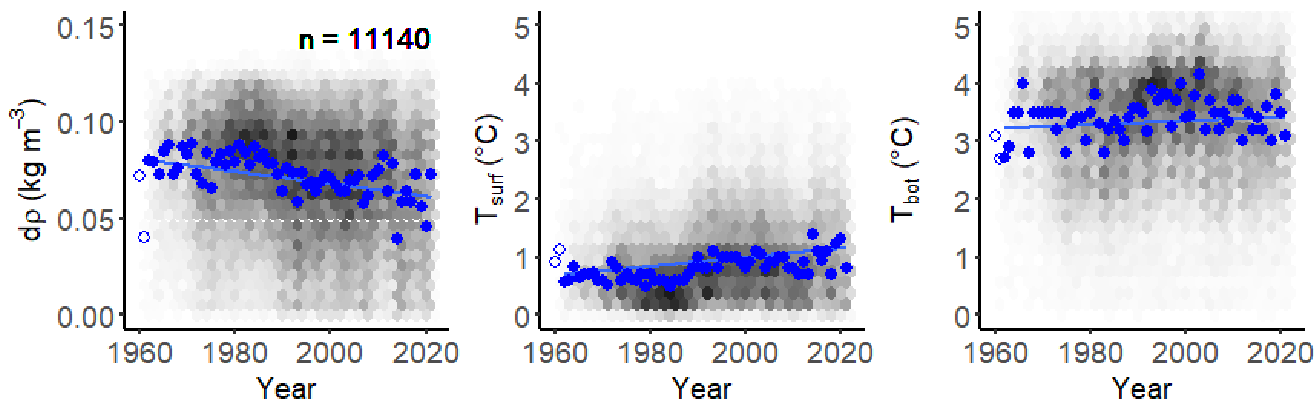


Figure 1 – Annual medians of the lake-averaged vertical density gradient *dρ*, surface water temperature and bottom water temperature (blue dots) from 11140 lakes between 1960 and 2021 during the period of inverse stratification between November and May. The sample density is shown as grey hexagons.

References

[1] Woolway, R.I., Denfeld, B., Tan, Z., Jansen, J., Weyhenmeyer, G.A. and La Fuente, S. (2021), Winter inverse lake stratification under historic and future climate change. Limnol. Oceanogr. Lett. doi:10.1002/lol2.10231

[2] Tan, Z., Zhuang, Q., and W. Anthony, K. (2015), Modeling methane emissions from arctic lakes: Model development and site-level study, J. Adv. Model. Earth Syst., 7, 459– 483, doi:10.1002/2014MS000344.

[*] *Corresponding author, e-mail joachim.jansen@ebc.uu.se*

Radiatively driven convection plumes in a deep, unstratified lake

K. Larrieu[1, 2*], A.L. Forrest[1,2], J.B.T. McInerney[1,2], A.M. Friedrichs[1,2] and J.A. Austin[3,4]

[1] *Department of Civil and Environmental Engineering, University of California Davis, Davis, CA, USA*
[2] *Tahoe Environmental Research Center, University of California Davis, Davis, CA, USA*
[3] *Department of Physics and Astronomy, University of Minnesota Duluth, Duluth, MN, USA*
[4] *Large Lakes Observatory, University of Minnesota Duluth, Duluth, MN, USA*

Abstract: Radiatively driven convection (RDC) occurs in freshwater below the temperature of maximum density wherein volumetric heating of surface waters by solar radiation creates a diurnal, spatially distributed, destabilizing buoyancy flux. This process has typically been studied under ice-covered conditions, but it can also occur in open water during springtime warming leading up to overturn, and in such systems it may serve as the dominant process driving mixing of heat, nutrients and phytoplankton[1,2]. Despite the ecological significance and unique physical dynamics of RDC, little is understood regarding the lateral heterogeneity and three-dimensional structure of the process.

This study examines data collected with an autonomous underwater glider during a period of active RDC in Lake Superior (Fig. 1a). Spring storms on Lake Superior after ice-off lead to nearly isothermal conditions during the RDC period, resulting in an ideal environment for the study of convective plume development in unstratified conditions[3]. Conductivity, temperature and depth (CTD) measurements reveal plumes as distinct regions of anomalously warm downwelling water with width scales on the order of 100 m and temperature anomalies of ~ 0.1 ℃. Shear and temperature microstructure measurements indicate turbulence kinetic energy (TKE) dissipation rates exceeding 10^{-8} W/kg, orders of magnitude greater than laterally adjacent quiescent waters (Fig. 1b). A heuristic method for delineation of plumes is used to characterize width scales and properties. Observed plume widths are found to be consistent with theoretical scales imposed by Coriolis forces and water depth. Implications for transport of heat, turbulence, and phytoplankton are discussed. These observations demonstrate that RDC can dominate mixing dynamics even in deep, open water systems.

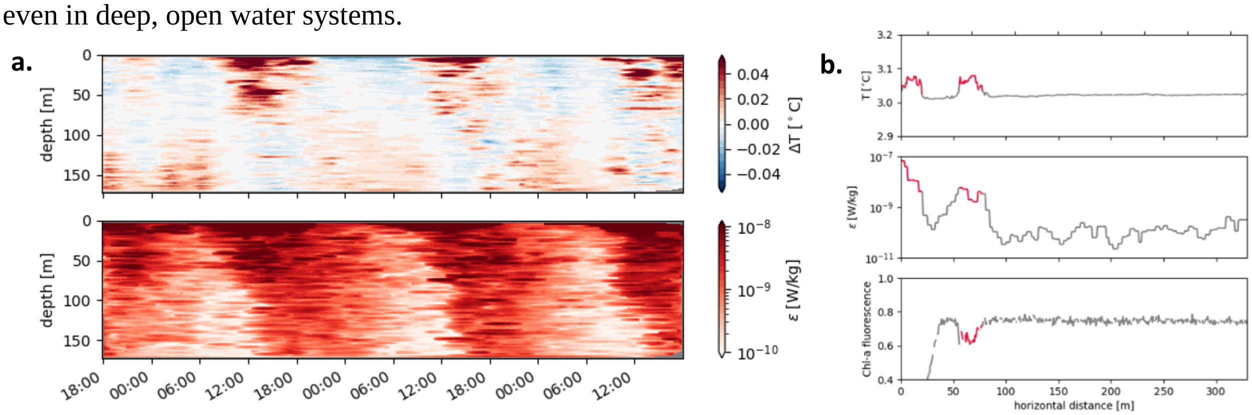


Figure 1: (a) Temperature anomalies and TKE dissipation rates (ε) observed during the glider deployment in Lake Superior. (b) Example profile of temperature, ε, and chlorophyll-a fluorescence in convective plumes (red) surrounded by quiescent water (grey).

References

[1] Austin, J. A. (2019). Observations of radiatively driven convection in a deep lake. Limnology and Oceanography, 64(5), 2152–2160. https://doi.org/10.1002/lno.11175

[2] Cannon, D. J., Troy, C. D., Liao, Q., & Bootsma, H. A. (2019). Ice-Free Radiative Convection Drives Spring Mixing in a Large Lake. Geophysical Research Letters, 46(12), 6811–6820. https://doi.org/10.1029/2019GL082916

[3] Titze, D. J., & Austin, J. A. (2014). Winter thermal structure of Lake Superior. Limnology and Oceanography, 59(4), 1336–1348. https://doi.org/10.4319/lo.2014.59.4.1336

* *Corresponding author, e-mail kglarrieu@ucdavis.edu*

Schmidt Stability formulation of mixing energetics in lakes.

B. Laval[1*], J. Olsthoorn[1,2], K.Graves[1], J. Wang[3]

[1] Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada
[2] Now at Department of Civil Engineering, Queen's University, Kingston, Ont., Canada
[3] Key Laboratory of Tibetan Environment Changes and Land Surface Processes (TEL) /Nam Co Observation and Research Station (NAMORS), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China.

Abstract

We present a vertical 1-D conservation of energy formulation for enclosed basins written in terms of Schmidt's Stability. The only energy fluxes considered are thermal and mechanical (wind) at the basin surface. Using a Schmidt Stability formulation for energy allows us to directly consider the effects of surface energy fluxes on the background potential energy contained in water column stratification. A comparison of the evolution of Schmidt Stability calculated from thermistor chain observations, with that predicted from surface fluxes and estimates of mixing efficiency allows for a diagnosis of processes controlling the seasonal evolution of thermal stratification. Furthermore, separating thermal fluxes into penetrating (i.e. optical band or shortwave radiation) and non-penetrating (i.e. non-optical band or longwave radiation, sensible and latent) heat flux provides insight into the relative contributions by these fluxes. To illustrate the utility of this energy formulation we apply it to 1-year of field observations of a small, deep, temperate lake with seasonal ice-cover.

[*] *Corresponding author, e-mail Bernard.Laval@ubc.ca*

Wind, waves, and currents on the Great Lakes: Expanding the observational network via small, scalable "Spotter" buoys

J. D. Lenters[1*], and C. Lenard[1]

[1] *Great Lakes Research Center, Michigan Technological University, Houghton, MI, USA*

Abstract

In recent years, Spotter buoys from Sofar Ocean have become a popular tool for wave data collection on the oceans and Laurentian Great Lakes. These low-cost, easily deployable buoys collect a variety of limnological data, including wave height, direction, and period, as well as surface water temperature and vertical temperature profiles. The buoys also estimate wind speed and direction from the observed wave spectra and can be deployed as drifters to measure lake and ocean currents. With the advent of Spotter buoys on the Great Lakes in April of 2020, the number of observational sites on Lake Superior roughly doubled in a span of just two years. This has led to a wealth of new wave data on the Upper Great Lakes, along with a few applications in which the Spotter buoys have been used as drifters to help characterize lake circulation and also provide water safety information for commercial shipping and recreational boaters. In this presentation, we provide an overview of recent Spotter buoy data collected on Lake Superior and northern Lake Michigan, including examples of large wave events, complex drifter tracks, coastal upwelling, and an assessment of wave-derived wind velocity estimates via comparison with shore-based anemometers.

[*] *Corresponding author, e-mail* jdlenter@mtu.edu

A rotational gravity current in the Strait of Georgia

Mina Masoud[1*], B. Rich Pawlowicz[1]

[1] *Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, 2207 Main Mall, Vancouver, B.C. Canada, V6T 1Z4*

Abstract

Gravity currents often occur in stratified waters, as dense water flows downwards to the bottom of lakes and ocean basins, and over longer time scales can be significantly affected by Coriolis effects. However, the study of such currents in nature is often difficult because they are intermittent. Here we describe a very predictably intermittent gravity current in the Strait of Georgia, Canada, which occurs as part of the deep renewal of its bottom waters. We analysis and interpret several datasets measured at deep part of the Strait of Georgia to describe the structure of the gravity currents driving deep renewal, averaged over the renewal periods. The results show strong evidence of deep-water renewal events based on episodic fluctuations in the oceanographic characteristics. Renewals occur as a ∼30m thick layer extending along the right hand slopes of the Strait and currents are primarily along-isobath at speeds of up to 20cm s^{-1} with a small downhill component. We also develop an analytical model with a depth-dependent eddy viscosity which provides a good description of the vertical structure of the "mean" gravity current. The model confirms a clockwise rotation of current vectors with height, partly driven by boundary layer dynamics over a scale of a few meters, and partly by Coriolis forces in the near-bottom linear density gradient.

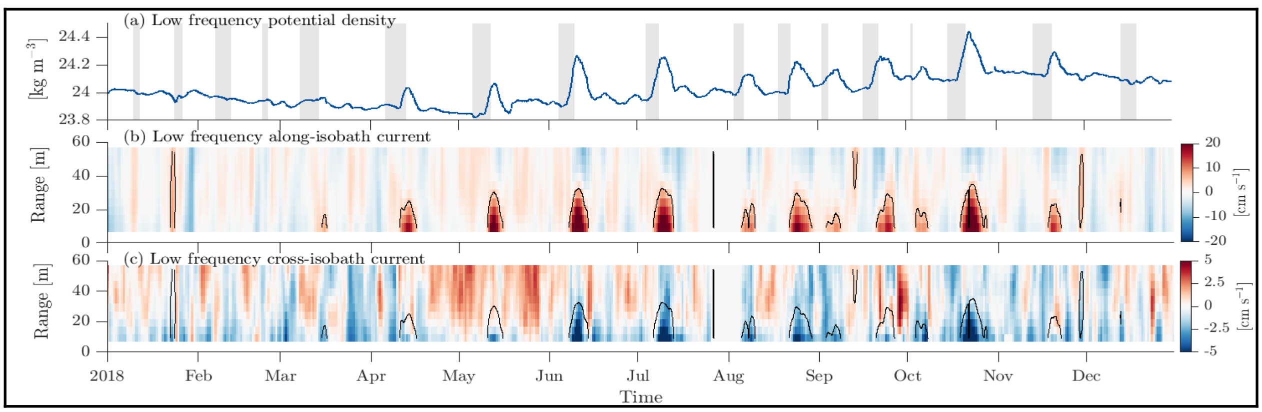


Figure 1. Central node observations in 2018.

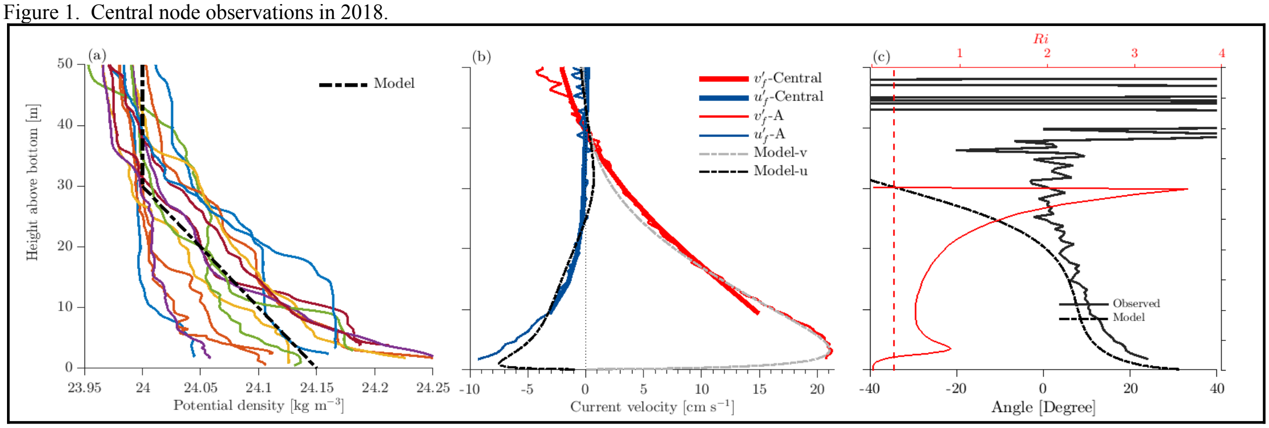


Figure 2. Structure of the renewal current. (a) Density anomaly taken from towyo sections. (b) Current velocities. (c) Observed and modelled downhill rotation angles and the Richardson number with a value of ¼ indicated by the vertical line.

* *Corresponding author, mmasoud@eoas.ubc.ca*

Bottom boundary layer mixing, strain-induced periodic stratification, and lateral advection, driven by internal waves in a small lake

Jeffrey R. Nielson* and Stephen M. Henderson

School of the Environment, Washington State University (Vancouver), Vancouver, WA, USA

Abstract

Seiche-cycle variations in turbulent mixing, bottom mixed layer entrainment, and offshore advection from the sloping bottom boundary layer (BBL) were measured in the metalimnion of a small lake using pulse-coherent acoustic Doppler current profilers and thermistor strings. Over an initial 74-day deployment, structure function estimates of turbulent dissipation, and two different models of mixing efficiency, revealed that >80% of near-bed turbulent buoyancy flux occurred during the downslope flow phase of the internal seiche (10–24 h period) [1]. During downslope flow, thin bottom mixed layers formed and slowly thickened over hours. Mixed-layer thickening was consistent with a newly developed entrainment closure, in which the effect of strain-induced periodic stratification (SIPS) is proportional to the ratio between layer thickness and a modified Monin-Obukhov length that quantifies a SIPS-induced buoyancy flux. Transitions to the upslope flow phase of the internal seiche were marked by arrivals of sharp, non-breaking (nearly horizontal) cold fronts, which displaced the mixed layers that had formed during the previous downslope phase, lifting them from the bed. The detached mixed layers then flowed offshore above fronts. A second deployment partially resolved the extent of the resulting jet-like intrusions as they transported water from the BBL into the thermocline base, and revealed seiche-coherent vertical propagation from the bed to the base of the surface mixed layer. When averaged over multiple seiche cycles, the separated jets were responsible for a substantial mean lateral flux (1.9 m^3s^{-1}) into the interior at thermocline depths. Mean lateral flux estimates from both ends of the lake suggest flushing times of 2–3 days in the thermocline and overlying surface layer.

References

[1] J. Nielson and S. Henderson (2022, in press), Bottom boundary layer mixing processes across internal seiche cycles: Dominance of downslope flows, *Limnol. Oceanogr*.

* *Corresponding author, e-mail jeffrey.nielson@wsu.edu*

Aggregation of microplastic and biogenic particles in upper-ocean turbulence

M. Rahmani[1,2*], A. Gupta[3], L. Jofre[4]

[1] *Department of Mathematics, The University of British Columbia, Vancouver BC V6T 1Z2, Canada*

[2] *Department of Chemical and Biological Engineering, The University of British Columbia, Vancouver BC V6T 1Z3, Canada*

[3] *Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, U. P. 208016, India*

[4] *Department of Fluid Mechanics, Technical University of Catalonia - BarcelonaTech, Barcelona 08019, Spain*

Abstract

Plastic particle pollution has posed serious environmental challenges to seawater systems worldwide. It is estimated that there are at least 5 trillion plastic pieces in the oceans, with their weight exceeding 250,000 tons (1). Although microplastics have small sizes (<5mm) and their density is commonly lower than the density of seawater, they can settle from the surface to deeper layers of the ocean and spread in the entire ocean through their aggregation with biogenic particles that are denser than seawater. The aggregation and biofouling processes have been hypothesized to be responsible for the disappearance of a significant amount of microplastics from the ocean surface (2).

In this talk, we discuss numerical simulations of the aggregation of microplastic and biogenic particles in upper-ocean turbulence. The range of particle properties (size and density) and mixture characteristics (turbulence intensity and particle number densities) studied here correspond to realistic scenarios, relevant to the transport of microplastics in marine systems. In particular, we focus on the flow and mixture conditions encountered in the surface boundary layer (top region) of oceans, in which microplastics and biogenic particles have been experimentally observed to interact and form aggregates.

Equations of motion of the background turbulent flow are solved using direct simulations on an Eulerian frame of reference, while the equations of motion of microplastic and biogenic particles are integrated in time on a Lagrangian frame of reference, assuming a Stokes drag law. After each aggregation event, the aggregating particles are replaced by a new particle which properties are computed based on the composition of the particles within the aggregate. The main findings are that (i) microplastics can be found in a large fraction of aggregates in scenarios with different diameter and number density ratios between microplastic and biogenic particles, (ii) microplastic-containing aggregates will sink to the deeper ocean layers particularly in situations where the biogenic particles are larger, and (iii) the Stokes numbers of aggregates can be significantly different from the Stokes numbers of the initial individual microplastic and biogenic particles. In addition, by examining the collision mechanisms, a model for the collision rate that reproduces the computational results is proposed.

References

1. Eriksen, M., L.C. M. Lebreton, H.S. Carson, M. Thiel, C.J. Moore, J.C. Borerro, F. Galgani, P.G. Ryan, And J. Reisser, (2014), Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea, *PloS one,* 9 (12), e111913.
2. J. Michels, A. Stippkugel, M. Lenz, K. Wirtz, and A. Engel (2018), Rapid aggregation of biofilm-covered microplastics with marine biogenic particles, *Proc. R. Soc. London, Ser. B,* 285 (2018) 20181203.

* *Corresponding author, e-mail* mrahmani@math.ubc.ca

Epilimnetic turbidity in a glacier-fed reservoir

D. M. Robb[1*], R. Pieters[1,2], G. A. Lawrence[1]

[1] *Department of Civil Engineering, University of British Columbia, Vancouver, Canada*
[2] *Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada*

Abstract

We have been investigating the seasonal variation of turbidity in Carpenter Reservoir, located in southwest British Columbia, Canada. This long (~50 km) and narrow (~1 km) hydroelectric reservoir is fed by glacial inflow that is cold and turbid. There is concern that this turbidity limits light availability in the reservoir and, in turn, limits biological productivity. To address these concerns, and to investigate the processes that control turbidity in the surface waters, we conducted a two-year field study in conjunction with theoretical analysis and hydrodynamic modelling.

Thermal stratification during summer isolates the epilimnion from plunging glacial inflows. These inflows travel along the bed of the reservoir until they reach the deep outlets at the downstream end of the reservoir near the dam. As a result, the epilimnion is relatively clear during summer, despite the high glacial load into the reservoir. Epilimnetic turbidity decreases exponentially during summer due to the settling of suspended particles from the epilimnion into the hypolimnion. In addition to the decline in turbidity during summer, we observe a variation in turbidity along the length of the reservoir.

Turbidity is highest at the upstream end of the epilimnion nearest to the plunging glacial inflow, and lowest at the downstream end of the epilimnion near the dam. Meteorological measurements, thermistor chain data and numerical simulations indicate that strong down-valley winds set up basin-scale internal motions, which lead to a small turbidity flux entering the epilimnion at the upstream end of the reservoir, setting up a longitudinal gradient in epilimnetic turbidity. The variation of turbidity along the length of the epilimnion depends on wind-driven fluxes at the upstream end of the epilimnion, longitudinal dispersion along the length of the epilimnion and particle settling out of the epilimnion. Basin-scale internal motions oscillate with a dominant period of 4 days, corresponding to the natural seiche period, and with higher frequency internal motions coinciding with daily wind pulses.

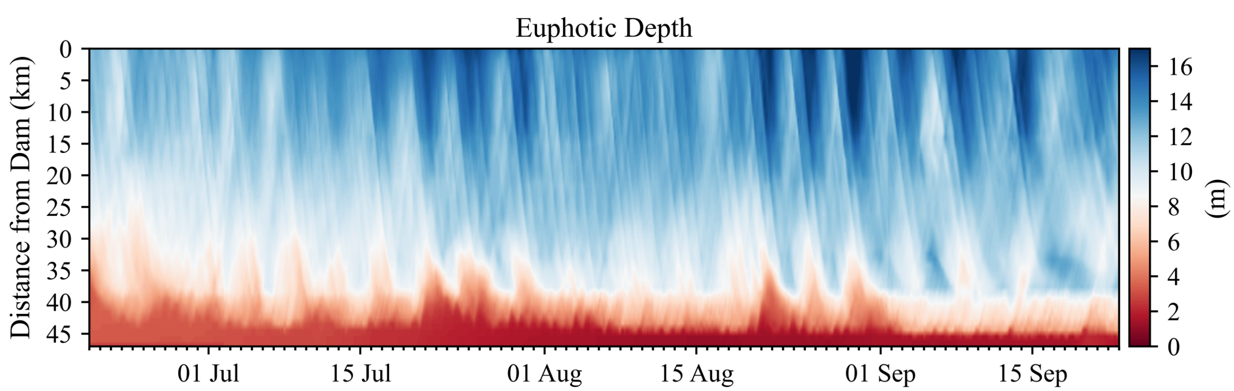


Figure: Simulated euphotic depth as a function of distance along the length of the reservoir and time.

* *Corresponding author, drobb@eoas.ubc.ca*

Glider-based turbulence measurements in Lake Geneva

O. Sepúlveda Steiner[1,2*], A. Forrest[3], J. McInerney[3], B. Fernández Castro[2,4], A. Wüest[1,2] and D. Bouffard[1]

[1] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, Kastanienbaum, Switzerland*
[2] *Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair, Institute of Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland.*
[3] *Civil & Environmental Engineering, University of California – Davis, Davis, CA, USA,*
[4] *Ocean and Earth Sciences, National Oceanography Centre, University of Southampton, Southampton, UK*

Abstract

Buoyancy-controlled autonomous underwater vehicles (aka gliders) allow the investigation of vertical and horizontal variability of physical and biogeochemical water properties. The recent integration of microstructure sensors into gliders has represented a qualitative breakthrough for quantifying the spatial and temporal variability of ocean turbulence and mixing. However, there have been very few deployments of gliders in lakes to date. During the summer of 2018, we explored the spatial variability of turbulence in Lake Geneva (309.7 m max. depth, 582 km^2 surface) using a G2 Slocum glider (Teledyne Webb Research; Figure 1A). In addition to the standard CTD and water quality payload, the glider was equipped with a microstructure turbulence package (MicroRider – RSI, Canada). The sampling strategy consisted mainly of repeated L-shaped transects (Figure 1B) from 0 to 100 m depth in the interior and one interior-coastal mission. Estimates of the dissipation rates of turbulent kinetic energy (TKE) and thermal variance were obtained from temperature microstructure by fitting the Batchelor spectrum to the measured spectra of temperature gradient fluctuations. Additional field measurements of currents with traditional moorings revealed the predominant presence of internal Poincaré waves. In the interior, the microstructure analysis indicates mild TKE dissipation rates in the surface and thermocline (~10^{-8} W kg^{-1}), which weakened towards the deep interior (~10^{-11} – 10^{-10} W kg^{-1}). Further analyses show that, although the internal dynamics generated horizontal variability (Figure 1C), interior mixing was extremely low in the thermocline region (mixing efficiency $\Gamma << 0.2$) due to the strong stratification with Cox numbers ≤1. In the coastal region, the measurements revealed a striking enhancement of turbulent dissipation above the sloping topography, which we attribute to the development of centrifugal instabilities. This study offers novel spatially-distributed measurements in a large lake and highlights the distinct turbulence characteristic of the interior and coastal regions.

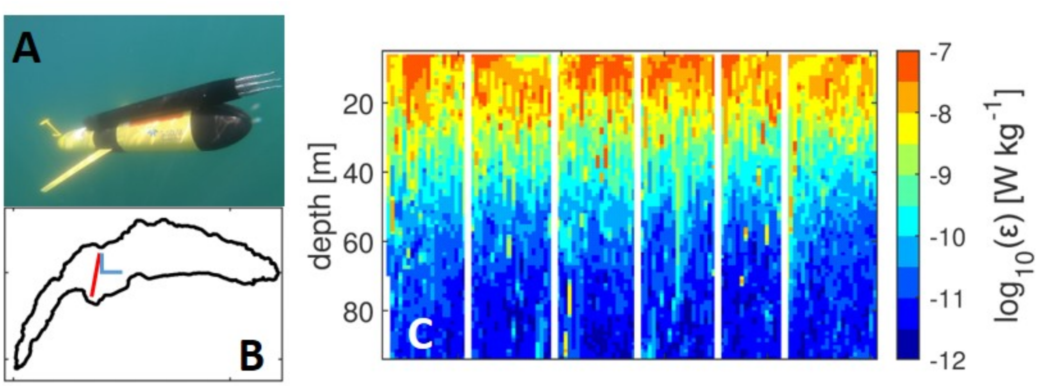


Figure 1: (A) Teledyne G2 Slocum glider equipped with the RSI-MicroRider. (B) Study site showing the performed transects. (C) TKE dissipation rate (ε) from three consecutive L-shaped transects performed on 30 July 2018.

[*] *Corresponding author, e-mail oscar.sepulvedasteiner@eawag.ch*

The comparison between cylindrical and gaussian bathymetry in ice-covered lakes

F. Sharifi[1,2*], R. Hinkelmann[2], and G. Kirillin[1]

[1] *Department of Ecohydrology and Biogeochemistry, Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany*

[2] *Department of Planning Building Environment, Institute of Civil Engineering, Technical University of Berlin, Berlin, Germany*

Abstract

We present preliminary results on the simulation of three-dimensional flow in ice-covered lakes with the Regional Ocean Modeling System (ROMS). We used idealized conical and cylindrical bathymetries to compare the effect of lateral boundaries on circulation in ice-covered lakes. To simulate the ice-covered conditions, the surface temperature was set to 0℃, with a linear initial stratification within the water column to 4℃ at the bottom. The water salinity was set to zero. Two major scenarios were explored: (i) flow caused by molecular viscosity at sloping boundaries in a stratified fluid that creates macroscopic up-slope current, and (ii) gravity currents along the bottom slope due to heating of the lateral edges. We discuss the representativeness of a hydrostatic Boussinesq model for weakly energetic flows, dominated by viscous forces and rotation in enclosed ice-covered domains, and the role of model spatial resolution and boundary conditions for a successful simulation of such flows.

* *Corresponding author, Fatemeh.sharifi@igb-berlin.de*

Effects of Spatial Heterogeneity and Temporal Variability of Meteorological Variables on the Mass and Energy Exchange of Inland Waters

U. Spank[1*], M. Hehn[1], M. Mauder[1], M. Koschorreck[2], and Ch. Bernhofer[1]

[1] *Chair of Meteorology, Faculty of Environmental Sciences, Technische Universität Dresden, Tharandt, Germany*
[2] *Department Lake Research, Helmholtz Centre for Environmental Research – UFZ, Magdeburg, Germany*

Abstract

The correct quantification of the mass and energy exchange between inland waters and the atmosphere is of great importance for both scientific and practical issues. Exact direct measurements are possible, but expensive and technically challenging. Thus, different gradient approaches, such as the 'turbulent boundary layer' (TBL) approach, provide the methodological backbone to determine diffusive gas fluxes, energy fluxes, and evaporation rates from inland water utilizing easy–to–measure limnologic and atmospheric variables. However, the reliability of such approximations depends on (i) the parameterization of the transfer coefficient and (ii) the representativeness of input data. Thus, the question arises whether estimates of mass and energy fluxes derived from point measurements are actually representative for the entire surface of a lake or reservoir, given the heterogeneity and variability of limnic and atmospheric conditions.

In order to enhance our capabilities to determine fluxes from inland waters, the atmospheric impact on the mass and energy exchange are intensively studied in our DFG-funded project "MeDIWA". We investigate how meteorological drivers change along the fetch and how diurnal variations and short-term events, such as squalls, affect limnic conditions in the water and the fluxes at the water surface. In particular, we aim (A) to quantify the effects of spatial and temporal variations of atmospheric variables on the mass and energy exchange and (B) to develop suitable approaches to address these variations in common methods to compute mass and energy fluxes from inland waters.

At Bautzen reservoir in Lusatia (Germany), two long-term experiments have been performed to study the mass and energy exchange between the water surface and the atmosphere under different weather and limnic conditions. The fluxes have been observed on different scales of space and time utilizing micro-meteorological and different limnological measurement methods. A floating outdoor laboratory equipped with an eddy covariance measurement system and several other meteorological, hydro-chemical, and hydro-physical sensors have been used for continuous measurements of fluxes and variables that are unaffected by land surfaces. In addition, three additional satellite platforms with a simplified set-up have been utilized to detect the spatial variations of atmospheric and limnic conditions along the fetch. In our conference contribution, we will present the data and results from our first season of measurements. We aim (1) to demonstrate the importance of taking into account the spatial and temporal heterogeneity of driver variables when exchange processes at the water surface are to be described representatively, as well as (2) an overview of the technical challenges and difficulties in measuring reliable and representative flux data.

Microswimmers colonizing an obstacle immersed in a Stokes flow

H. N. Ulloa[1*], T. Faúndez[2], B. Espinoza[3], R. Soto[2] & F. Guzmán-Lastra,[4†],

[1] Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia, USA
[2] Departamento de Física, FCFM, Universidad de Chile, Santiago, Santiago, Chile
[3] Centro de Modelamiento Matemático, FCFM, Universidad de Chile, Santiago, Chile
[4] Escuela de Data Science, Facultad de Estudios Interdisciplinarios, Universidad Mayor, Santiago, Chile

Abstract

Microswimmer colonization of suspended solid particles immersed in fluids is a biophysical process occurring in natural and human-made aquatic systems, and it is relevant for a wide range of applications in environmental, sanitary, and industrial engineering. Here, we are motivated to examine the interplay between the motility of microswimmers and a background flow to determine the colonization rate of microbes on suspended solid obstacles. For that, we perform numerical experiments of active Brownian particles interacting with a single cylindrical obstacle facing a Stokes flow. We examine highly and weakly persistent microswimmers, which represent extreme cases of bacteria used in experiments to investigate biofilms formation on solid surfaces. For tuning our "microorganisms" swimming skills, we control the self-propelled swimmers velocity, u_0, the mean Stokes flow speed, U_∞, and the obstacle radius, R. Our experiments work as follows. Initially, the cylindrical obstacle has no swimmer on its surface. We then inject swimmers at a constant mass rate until a quasi-steady number of microbes are in contact with the obstacle. The latter is quantified by the mean coverage of the cylindrical surface λ_{trap} and the relaxation time to reach the steady-state, τ_{trap}. We found two regimes: (1) "Brownian deposition" is attained when swimmers velocity is smaller than the mean flow speed. In this scenario, microbes can diffuse across the streamlines and settle around the obstacle, coating the entire perimeter, eventually forming multiple layers. In the second case, (2) "Direct interception" occurs when the swimmers' speed is larger than the mean flow, allowing microbes to reach the obstacle by direct swimming. In the latter scenario, microbial colonizers form approximately one layer on the obstacle's surface. We found that λ_{trap} decreases with u_0 and R, yet the dependence with the mean flow U_∞ is non-monotonic. Indeed, an optimal coating of the immersed obstacle is achieved for intermediate magnitude flows, given by the crossover of two regimes. The existence of an optimal flow velocity to reach maximum colonization rate is a relevant finding for understanding how this process can occur in nature and for designing applications for microbial growth or filtration.

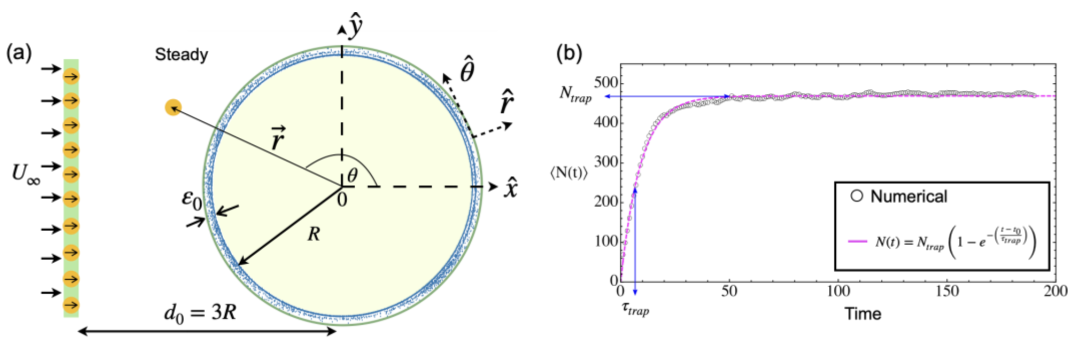


Figure 1 – (a) Schematic of microswimmers colonising a cylindrical obstacle immersed in a Stoke flow. (b) Numerical results. $\langle N(t)\rangle$ is the average number of microbes on the obstacle's surface as a function of time. Circles denotes numerical results; solid curve denotes an analytical model.

* *Corresponding author, e-mail ulloa@sas.upenn.edu*
† *Corresponding author, e-mail francisca.guzman@umayor.cl*

The Influence of the Coriolis Force During Upwelling in Lakes of Moderate Size

Sergio A. Valbuena[1,2*], Fabián A. Bombardelli[1], Alicia Cortés[1,2], John Largier[3,4], Derek C. Roberts[2,5], Alexander L. Forrest[1,2], Geoffrey Schladow[1,2]

[1] *Department of Civil and Environmental Engineering, University of California, Davis, California, USA*
[2] *UC Davis Tahoe Environmental Research Center, Incline Village, Nevada, USA*
[3] *Department of Environmental Science and Policy, University of California, Davis, California, USA*
[4] *UC Davis Coastal and Marine Sciences Institute, Bodega Bay, California, USA*
[5] *San Francisco Estuary Institute, Richmond, California, USA*

Abstract

Upwelling can drive impacts of ecological nature and exert changes in the water quality. Conceptual models generally classify the lake response during active wind forcing into either an Ekman upwelling model (rotational) or a 2D, closed basin (non-rotational) conceptual model. The non-rotational model is broadly applied to predict and address flow structures and, by extension, water quality dynamics in rotationally influenced lakes of moderate size despite the Coriolis force influence. Nonetheless, in stratified water bodies, the upwelling response to winds may exhibit flow dynamics that cannot be described by applying a single conceptual model. Here, we present the results of numerical simulations with the three-dimensional numerical model Si3D of a lake of moderate size (Lake Tahoe, California-Nevada, USA), validated using field observations at 20 locations around the lake. We focus on analysing the effects of the Earth's rotation on the flow dynamics during active upwelling and after the wind weakens. Upwelling was observed at upwind boundaries and at along-wind shores (shores to the left of the wind direction at Lake Tahoe) due to Ekman-driven divergence on the offshore flow of the surface layer. Ekman transport developed in the pelagic zone and resulted in baroclinic pressure gradients non-parallel to the wind direction. During wind forcing on the downwelled shores, alongshore currents developed in response to wind forcing parallel to the coastline. Following the weakening of the wind forcing, migration of the thermal front towards the upwelled zone initiates the relaxation stage of the upwelling event, and rotational effects altered the flow dynamics across the lake. Furthermore, accompanying the rotational internal wave field, high-speed cyclonic alongshore currents were observed. The counterclockwise currents were found to be in quasi-geostrophic balance with jet-like velocity profile, and followed the characteristics of coastal jets often observed in large lakes and the coastal ocean. The observed coastal jet exhibited peak velocities of up to 35 cms^{-1}. These strong cyclonic currents likely generate horizontal alongshore transport of constituents during the upwelling relaxation and play a relevant role in the water quality along the well-known upward motions of nutrients on the upwelled zone. Our work allows us to conclude that active upwelling in rotationally influenced lakes of moderate size describes flow structures that can be summarized as the combination of the dynamics predicted by both the 2D, closed-basin model, and the rotational upwelling conceptual model.

[*] *Corresponding author, e-mail savalbuena@ucdavis.edu*

Holmboe instabilities in an arrested salt wedge

Adam. J.K. Yang[1*], E.W. Tedford[1], J. Olsthoorn[1,2] and G.A. Lawrence[1]

[1] *Environmental Fluid Mechanics, Civil Engineering, University of British Columbia, Vancouver, BC, Canada*
[2] *Hydrotechnical Engineering, Civil Engineering, Queen's University, Kingston, ON, Canada*

Abstract

Instabilities in stratified shear flow are important in estuaries, lakes, and the ocean. In stratified shear flows where the thickness of the density interface is often less than that of the velocity interface, the Holmboe instability can arise [1]. The Holmboe instabilities that form on an arrested salt wedge have been investigated in the laboratory. The flow is characterized by three regions. Near the tip of the salt wedge there is little Holmboe wave activity; immediately downstream mostly positive waves form; further downstream both positive and negative waves are present (Fig. 1). The appearance of these regions is determined by the spatial variation of the background mean flow. We predict the growth, wavelength, phase speed, and steepness ratio of the Holmboe waves by applying linear stability theory to the mean flow field.

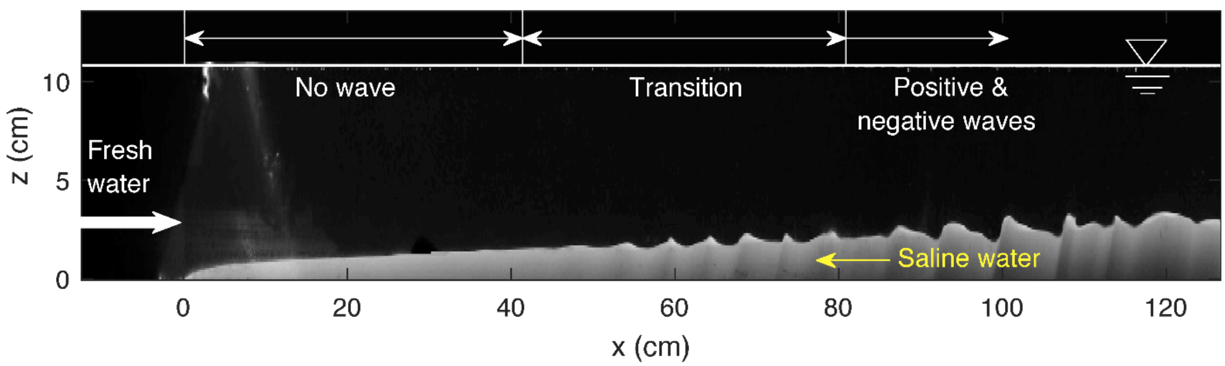


Figure 1. A laser-induced fluorescence image of the salt wedge. The top fresh water (dark) moves to the right and the bottom salt wedge (bright) is arrested [2]. The Holmboe waves form at the density interface. The upward pointing cusp is a positive wave and the downward pointing cusp is a negative wave.

References

[1] Lawrence, G. A., Browand, F. K. and Redekopp, L. G. (1991), The stability of a sheared density interface, Physics of Fluids A: Fluid Dynamics, 3(10), 2360-2370.

[2] Yang, A. J. K., Tedford, E. W., Olsthoorn, J., and Lawrence, G. A. (2022). Asymmetric Holmboe instabilities in arrested salt-wedge flows. Physics of Fluids, 34(3), 036601.

* *Corresponding author, e-mail jyangay@mail.ubc.ca*

Methane ebullition regulated by atmospheric pressure variation

Kai Zhao[1*], Edmund Tedford[1], Gregory Lawrence[1]

[1] *Department of Civil Engineering, University of British Columbia, Canada*

Abstract

Lakes emit greenhouse gas into the atmosphere and ebullition is often the dominant pathway. However, most ebullition surveys in lakes have focused on the weekly and monthly changes in ebullition. Ebullition is rarely monitored at hourly or sub-hourly time scales. This limits our understanding of the high-frequency variations in ebullition and the physical factors that influence these variations.

We present high-frequency acoustic ebullition data during ice-cover and open-water seasons in a mining-pit lake. During ice-cover we sample ebullition once every hour, whereas during the open-water season we sample ebullition every 1 min to 30 min. Our results show that during ice-cover ebullition is regulated by atmospheric pressure variations and ebullition events enhance lake turbidity at depth. During the open-water season, atmospheric pressure variations still play a dominant role regulating ebullition, but water level fluctuations can also affect ebullition.

We show that ebullition intensity is proportional to the pressure deficit below a pressure threshold. During ice-cover, this pressure threshold is approximately constant and close to the average atmospheric pressure. During the open-water season, we adopt a varying pressure threshold that accounts for variations in water level. Finally, we investigate ebullition using a physics-based model. Our preliminary results show that ebullition events occur when bubbles grow to a critical size at which point bubbles begin to rise through sediment. Bubble growth is a result of methane exsolution from porewater and is modulated by pressure variations.

* *Corresponding author, zhaok1@student.ubc.ca*

High-resolution Hydrodynamic Measurements and Simulations in an Amazon Floodplain Lake

Wencai Zhou, John. M. Melack, Sally MacIntyre

Earth Research Institute, University of California, Santa Barbara, California, USA

Shallow, warm water lakes undergo daily cycles of stratification and mixing with important ecological consequences. As part of an investigation of Amazon floodplain lakes, we deployed sensors to measure thermal structure and adapted a 3-dimensional hydrodynamic model (AEM3D) to link physical and biological processes. In Lake Janauacá, water level fluctuated up to 13 m, and water temperatures varied from 28 to 37 ºC over two years of study. Vertical temperature profiles were obtained with RBR Solo® thermistors (accuracy of 0.002 ºC, recording at 0.1 Hz) deployed on taut-line moorings in the main lake and in a bay. With light winds, stratification developed in the top 0.5 m of the water column in the morning with near-surface buoyancy frequencies reaching 60 to 120 cycles per hour. Nocturnal mixing reached as deep as 6 m, with convection contributing 90% when winds were light and approximately 50% on the few occasions when wind speed reached ~ 5 m s^{-1}. To be able to capture the stratification, horizontal resolution of the AEM3D simulations was 100 m and 5 m in the main lake and bay, respectively, with 0.1 m vertical resolution in both. Model performance of AEM3D was evaluated based on root-mean-square-errors, percent relative errors and correlation coefficients computed from measured and simulated temperatures and buoyancy frequencies. The model satisfactorily reproduced the key hydrodynamic processes, including diurnal stratification, nocturnal mixing and basin-scale internal waves. Simulated near-surface rates of dissipation of turbulent kinetic energy (ε) varied from below 10^{-8} m^2 s^{-3} at low winds (< 1 m s^{-1}) to above 10^{-5} m^2 s^{-3} at moderate winds (> 5 m s^{-1}). Under prevailing wind, ε in a downwind direction was higher than that in an upwind direction, and ε also differed between margins where herbaceous plants grew and open water.