The Puppet Master: Climate-driven physical processes are increasingly controlling lake ecosystem changes in our "Anthropocene" world

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Abstract

Historically, when biological limnologists studied algal dynamics (and especially algal blooms), chemical variables (most notably nutrients like P and N) were the focus. Over the last few decades, there has been increased emphasis on biological interactions (such as top-down controls by grazers). However, more recently, rapidly changing physical processes that are often linked with climate warming (such as shifts in thermal stratification, reduced wind speeds, and/or decreased ice cover) can likewise explain these rapid biological changes occurring "below the water line"[1]. For example, paleolimnological studies, linked with water quality monitoring, continue to show that algal blooms are occurring in lakes where surface-water nutrient levels are not increasing[2] or, in several cases, are in fact declining. Less ice cover and/or enhanced thermal stratification (i.e. the "longer summer") may be a key factor linked to these late-summer algal (often cyanobacterial) blooms[1,3]. Similarly, numerous Arctic lakes, which are on the frontline of climate change, have crossed key aquatic thresholds largely driven by changing ice cover and other climate-related variables[4,5,6]. Many Arctic water bodies are now fundamentally different than they were just a few decades ago. Collectively, these changes may cascade throughout the food web which may lead to important changes for local Indigenous populations as well as to the global community.

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Epoch in a Lake: How Crawford Lake Became the Golden Spike of the Anthropocene

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Abstract

In the summer of 2023, a small lake in southern Ontario, Crawford Lake, made news headlines around the world when it was announced as the Global Boundary Stratotype Section and Point (GSSP) "Golden Spike" candidate of the proposed Anthropocene epoch. In essence, this meant that it was selected, out of a short list of 12 sites globally, as the best location on the planet to provide evidence for how human actions have changed planetary systems. In this talk, I will present the background and path by which this unassuming lake made its way to worldwide fame, and discuss what is coming next in this story, including ongoing work in developing a museum exhibition about the lake.

Under-Ice Processes in Lakes Across Latitudes

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Abstract

In seasonally and permanently ice-covered lakes, winter is not a time of ecological dormancy, but of dynamic activity. This talk explores the physical, chemical, and biological processes that unfold beneath lake ice, with a focus on how ice cover shapes the limnological trajectory of lakes year-round. From light penetration governed by ice clarity to heat budgets and convective mixing, under-ice conditions control biological production, gas dynamics, and biogeochemistry. Drawing from experimental manipulations and long-term observations at Long Term Ecological Research (LTER) sites in Wisconsin and Antarctica, I'll discuss how winter processes may have lasting carry-over effects into open-water seasons. As ice regimes shift globally, under-ice physics may offer the first signals of broader lake responses to climate change. The increasing availability of high-resolution winter datasets opens new opportunities to interrogate under-ice processes and revise physical limnology paradigms.

Impacts of climate change on thermal and oxygen dynamics in a pristine deep lake, Lake Taupō

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Abstract

Climate change significantly impacts freshwater ecosystems, influencing water quality indicators such as water temperature and dissolved oxygen (DO). We applied a 3D hydrodynamic model (AEM3D), coupled to biogeochemical module (iWQ), catchment model (TopNet), and climate scenarios (CMIP6), and also used observations to examine thermal and DO changes in Lake Taupō, the largest oligotrophic lake in Australasia. Atmospheric warming (1992–2022) correlate with increased heat content and enhanced stratification, affecting water temperature and DO. Surface waters warmed significantly at a rate of 0.065 $°Cyr^{-1}$, and summer DO concentrations declined at -0.008 $mgL^{-1}yr^{-1}$. Reduced bottom DO concentrations were observed in the mid-lake, dropping below fish habitat thresholds (7 mgL^{-1}). Increasing summer nitrogen concentrations and high Chl*a* corresponded with elevated temperature, indicating the link between nutrient dynamics and thermal conditions. Global climatic phenomena (La Niña) influenced significant warming during periods of Niño indices ≤ -1. Simulations under high (SSP370; Fig1a) and low (SSP126) emissions scenarios predicted prolonged hypolimnetic hypoxia by century's end (Fig1b). Catchment model simulations over the century showed significant declining DO and flow rates in inflows, with rising temperatures. These findings highlight the complexities of climate change effects on Lake Taupō's ecosystem, emphasizing the need for adaptive management strategies.

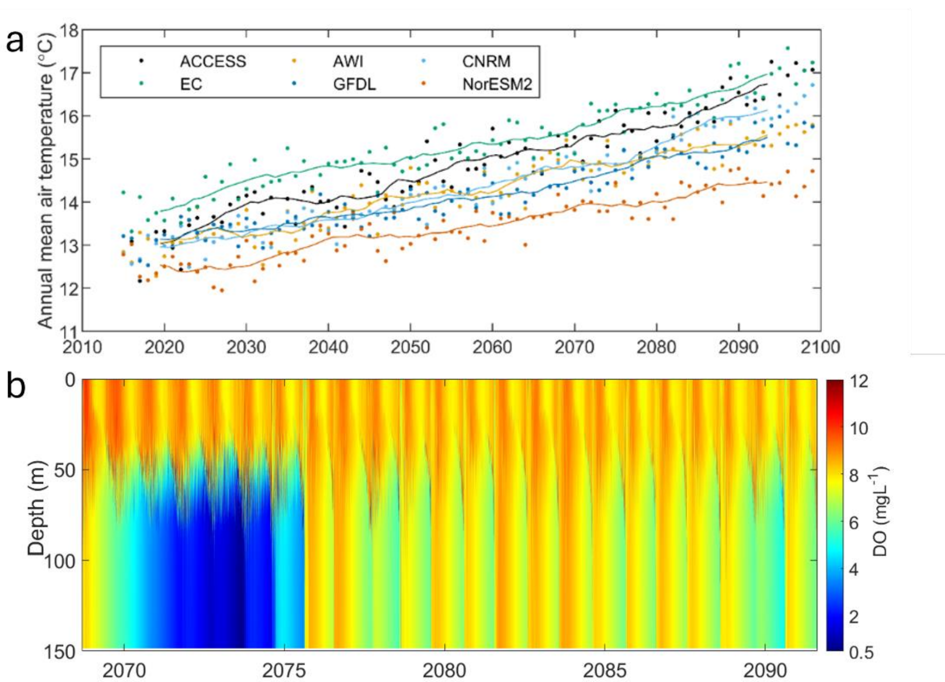

Figure 1. (a) Predicted mean annual air temperatures under SSP370 (the lines are a 10-year moving average; (b) water column DO at mid-lake under SSP370 and EC (GCM downscale).

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Surface CO_2 Gradients Challenge Conventional CO_2 Emission Quantification in Lentic Water Bodies under Calm Conditions

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Abstract

Lakes are hotspots of inland carbon cycling and are important sources of greenhouse gases (GHGs), such as carbon dioxide (CO_2). The significant role of CO_2 in the global carbon cycle makes quantifying its emission from various ecosystems, including lakes and reservoirs, important for developing strategies to mitigate climate change. The thin boundary layer (TBL) method is a common approach to calculate CO_2 fluxes from CO_2 measurements in water and air as well as wind speed. However, one assumption for the TBL method is a homogeneous CO_2 concentration between the measurement depth and the water surface, where gas exchange takes place. This assumption might not be true under calm conditions, when microstratification below the surface slows vertical exchange of gases. We used a floating outdoor laboratory to monitor CO_2 concentrations in 5 cm and 25 cm depth as well as in the air, wind speed, and water temperature profiles for one week in Bautzen Reservoir, Germany. While we found homogeneous CO_2 concentrations in both depths during wind speeds above 3 m s^{-1}, we observed a vertical gradient during wind still nights. The observed concentrations temporally ranged from undersaturation to supersaturation in 25 cm and 5 cm depth, respectively. Fluxes calculated from the measured concentrations would therefore change from negative to positive, depending on the measurement depth. Simultaneous Eddy Covariance measurements showed that even the measurements close to the surface underestimated the actual CO_2 fluxes. Oxygen measurements support our hypothesis that plankton respiration at the water surface causes a periodic CO_2 concentration gradient from the surface to the underlying water. Until now, the depth of CO_2 measurements has not been questioned, as long as measurements were done in the upper mixed layer and close to the surface. Our results provide evidence that representative measurements of CO_2 in the water strongly depend on depth and time of measurements. Further research will require novel methods to measure fine scale CO_2 concentrations and processes at the water surface.

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A framework for lake proxy system model calibration to optimize field data collection and to guide quantitative interpretation of paleoclimate proxies

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Abstract

Lakes preserve proxies for past temperature and precipitation in their sediments, and can provide valuable, high-resolution climate information about times warmer than today. However, proxy values often encapsulate multiple climate processes, many of them specific to the lake environment. Proxy system models (PSMs), which simulate how a climate signal is encoded in a proxy, are useful tools for quantitatively interpreting proxy records. PSMs can translate climate variables into proxy values, allowing for comparison with Global Climate Models. However, lake PSMs require calibration to the study site, which involves tuning several parameters and comparing model output to observations. In this way, calibration can be difficult if time and resource limitations, or remote study sites, preclude collection of continuous observations. To address this challenge, we test the PRYSM v2.0 lake environment submodel's ability to simulate two well-monitored lakes in western New York State and provide guidelines for calibration. Bear Lake is an open-basin, dimictic lake with a maximum depth of 8 meters, and Red Pond is a closed-basin, meromictic kettle lake with a maximum depth of 18 meters. The PRYSM v2.0 lake environment submodel is a one-dimensional model that simulates lake energy, hydrology, and isotopic balance [1][2]. We apply the Sobol method, a variance-based sensitivity analysis, to identify necessary parameters for modeling different variables, reducing the number of parameters that require calibration. Through a series of calibration experiments, we test the kinds of observations (lake water temperature and stable oxygen and hydrogen isotope values; surface vs. profiles) and the best season to collect them to yield optimal calibration. For example, we find that a single lake temperature profile collected during the late ice-free season can provide sufficient observations for lake PSM temperature calibration with limited model bias. Results from this study can guide optimized fieldwork for collecting observations and can streamline model calibration. Using the lake PSM and our calibration framework, we can quantitatively interpret proxy records of temperature and precipitation for our study sites in the Laurentian Great Lakes region.

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A Screening Method to Identify Extreme Events Affecting Drinking Water Quality.

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Abstract

When considering the impacts of hydroclimatic extreme events on drinking water provision, it is both the magnitude of runoff and materials entering a water supply, and also the time of transport and ongoing transformation of these from input to water supply withdrawal that ultimately affect water quality. With ongoing climate change these processes will be regulated through changes in watershed runoff response and waterbody hydrodynamic processes. These in turn will be affected by not only the magnitude of individual events, but also the historical sequence of events that can impact regulatory processes. There is a need to better understand such interactions in order to fully evaluate the effects of climate change on drinking water supplies.

The MEWS project (https://mews-water.com/), is attempting to evaluate the future impacts of extreme events on the water quality of Lake Mälaren, Sweden's 3rd largest lake that supplies drinking water to over two million consumers. The lake's complex morphometry requires the use of a 3D approach to simulate transport. However, this modelling is too slow to allow evaluation of long-term climate scenarios. Here we test a screening method to identify potentially important events in long-term climate records that can be further analysed in detail with 3D modelling. A simple lumped parameter hydrologic model (GWLF) is used to estimate the storm event runoff response, while a 1D hydrodynamic model (GOTM) is used to estimate water column stability. We expect a relationship between the seasonality of runoff response and thermal stratification. We hypothesize that deviations from this relationship will identify events of interest. Initial results from this analysis will be presented.

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The role of a lateral constriction in controling water exchange and oxygen distribution in a two-basin lake

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Topographic constraints, such as sills or constrictions, play a critical role in regulating water exchange between different basins, often creating complex circulation patterns that influence the transport and distribution of sediments, nutrients, and oxygen. This study examines the inter-basin exchange in Lake Zug (Switzerland), where two basins, a shallow northern basin (100 m deep) and a deeper southern basin (180 m deep), are connected by a lateral constriction. Lake Zug is meromictic, remaining stratified throughout the year, with anoxic conditions prevailing below approximately 120 m. Consequently, the shallow northern basin remains well-oxygenated, while the bottom 60 m of the southern basin is characterised by anoxic water. Past fine-scale measurements have revealed the presence of oxygen intrusions at depth, suggesting episodic oxygen supply to the anoxic zones of the southern basin (Figure 1).

We hypothesise that the constriction between the basins influences lateral inter-basin exchange, thereby controlling the oxygen supply from the oxic northern basin to the deep anoxic zones of the southern basin. The primary aim of this study is to identify the dynamics within each basin and determine the nature of the hydraulic control exerted by the constriction. By identifying the physical mechanisms that drive inter-basin exchange, this study seeks to clarify the factors influencing oxygen supply in the southern basin and its impact on the vertical zonation of redox processes. A combination of field measurements, including temperature, oxygen, turbidity, and velocity, and a 3D numerical model are employed to investigate both lateral and vertical transport in the lake. Preliminary findings on the dynamics of Lake Zug, with a focus on the physical processes at the constriction, will be presented.

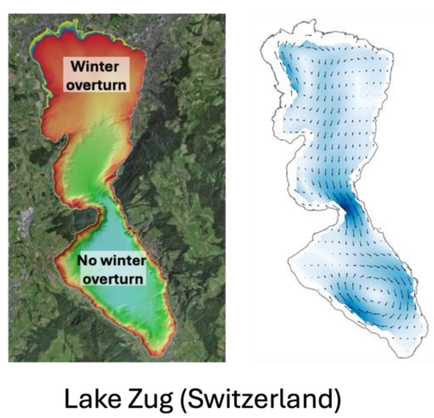

Figure 1. (Left) Bathymetric map of Lake Zug showing how the shallower (max depth 100 m) north basin is separated from a deeper (max depth 180 m) south basin. (Right) Example of current modelled with MITgcm highlighting the increase in velocities in the constriction

A predictably intermittent rotating gravity current in the Strait of Georgia, Canada

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Abstract

During the summer, the deep waters of the Strait of Georgia, Canada, are renewed by pulses of overflowing heavy water, each lasting about 4-5 days, occurring on a predictable timetable about 4-11 times in a summer. This gravity current oxygenates the deep water and also moves sediment from its initial settling areas under a turbid river plume, at depths of 100-300m, down to the bottom of the Strait at more than 400m. Coriolis effects trap the current on the right side of a broad V-shaped valley, so that it forms a sheet flow about 5 km wide and 20-30 m thick, moving deeper at an angle of only about 20 degrees relative to isobaths. However, its motions are also affected by ambient tides so that it speeds up and slows down on tidal time scales, which results in intermittent suspension and settling of bottom sediment. Recently, field measurements were made to investigate the structure of the current along its flow (Fig. 1). Although previous modelling suggested that the current could end in a feature reminiscent of a hydraulic jump, with slower, thicker downstream flow, these new observations suggest instead that enhanced mixing in a field of large-scale bottom ripples up to 10m high may govern the fate of this current.

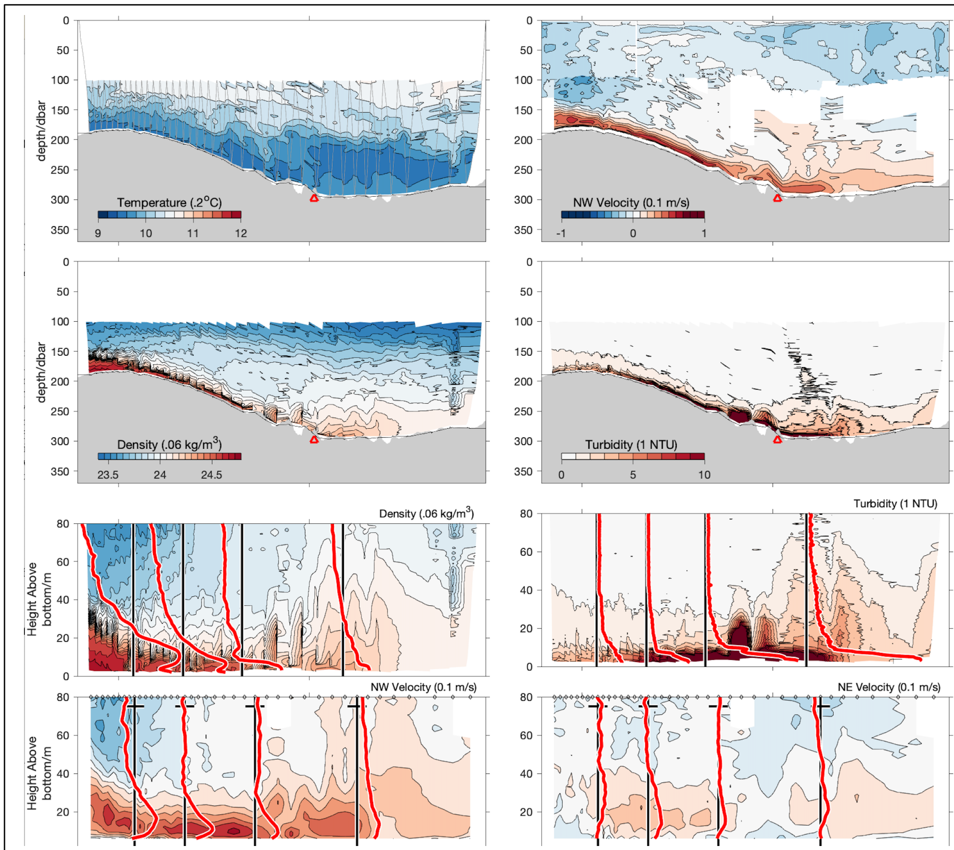

Figure 1: Observations along the gravity current axis. Upper 4 subplots are: temperature, along-axis current, density, and turbidity, all in depth coordinates. Lower 4 subplots show density, turbidity, and along and across-track currents but here plotted as height above bottom to emphasize the near-bottom structure. Profiles of the relevant parameters (in red) at locations marked by the black lines are superimposed on the contour plots.

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North-South interbasin exchange at Chautauqua Lake, New York

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Abstract

Algae blooms are often modeled or forecasted using zero or one-dimensional models. However, satellite images of surface chlorophyll in many lakes, including Chautauqua Lake, eastern New York State, suggest the influence of horizontal transport.

Chautauqua Lake is split into two basins, a hyper-eutrophic basin in the South and meso-eutrophic in the North, with Bemus Bay at the center connecting the two basins. Remote sensing observations highlight the presence of a band of high chlorophyll concentration, associated with blooms, in the North basin that may originate from the South basin (Figure 1).

As a complex shoreline exacerbates the non-uniform spatial distribution of dissolved elements and physical processes in a lake ([1],[2]), we investigate the water exchange taking place through Bemus Bay. Using a hydrodynamic simulation, validated against measurements of water temperature and currents, we quantify the volume of water from both bays going through the entrances of the bay, depending on weather and stratification conditions. We assess the role of baroclinic and barotropic water currents in the modulation of the water exchange through the bay and how these processes may contribute to spatial heterogeneity and mixing of algae between basins.

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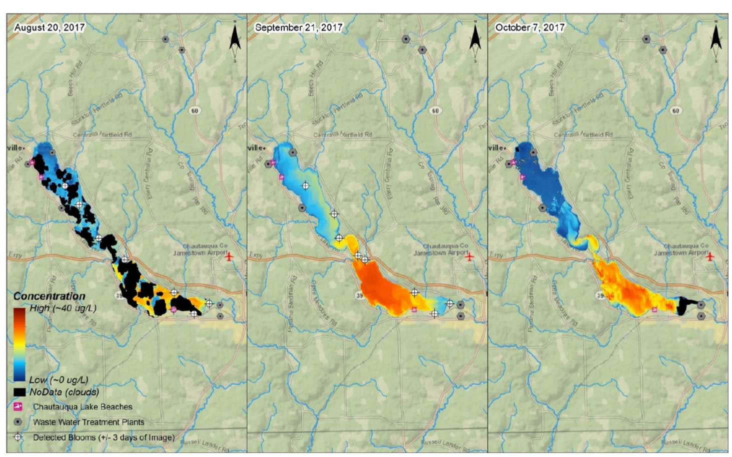

Figure 1: Estimated surface Chlorophyll concentration of Chautauqua Lake from satellite images. Source: [3]

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Physical-biological interactions in the benthos: Dislodgement of Walleye eggs.

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Abstract

The relationship between organisms and hydrodynamics in benthic habitats remains challenging, especially at small spatial scales pertinent to many organisms, e.g., O(mm) for fertilized eggs of commercially important fish species. This is due, in part, because the interaction of hydrodynamics and substrate roughness is also complex, but it has been conceptualized in two dimensional flows by roughness flow regimes (isolated, wake interference, and skimming flow) or roughness types (*k*- and *d*-type). We examined the effect of different roughness flow regimes/roughness types and roughness heights (*k*) on the dislodgement of walleye (*Sander vitreus*) eggs (2 mm diameter, $\varnothing$) using a wall jet apparatus to generate 2D flow over characteristic roughness. We expected that lower wall shear stress (τ_w) would be required for dislodgement in more-exposed/less-sheltered roughness type/flow regimes (i.e., *k*-type/isolated roughness flow) and when $k \leq \varnothing$ (Figure 1). Surprisingly, the opposite was found, indicating that other mechanism(s) are also responsible for egg dislodgement on these rough surfaces. Hydrodynamic sheltering occurred when flow was directed over exposed eggs ($k \leq \varnothing$) adjacent to roughness elements effectively increasing their width, and thus requiring higher τ_w for rolling and then ejection. When $k > \varnothing$, eggs dislodgement likely occurred via the lower pressure in the eddies recirculating in the groove width between roughness elements, rather than due to τ_w. These results indicate the relevance of heterogeneous sorting and sizing of substrate elements to provide suitable spawning habitats in benthic environments.

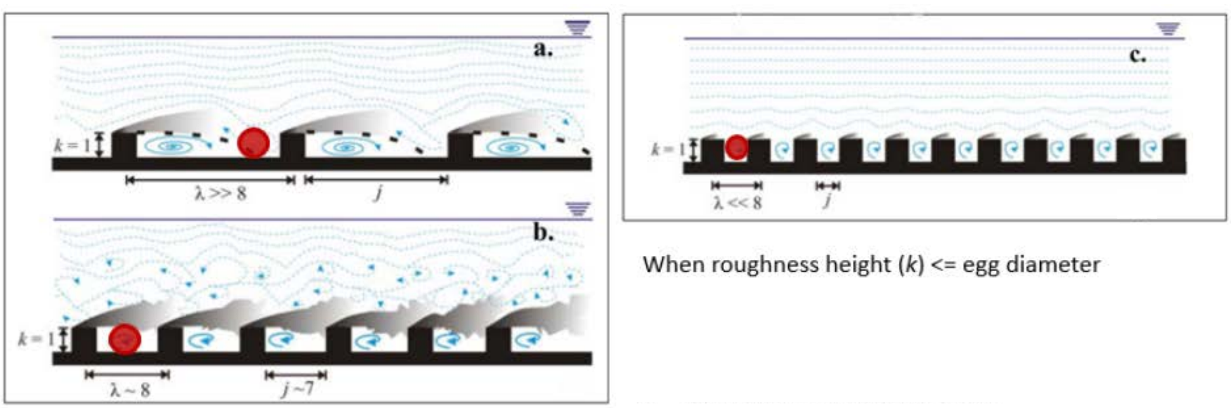

Figure 1: schematic of the experimental conditions examined in the study examining walleye egg (red circles) dislodgement under (a) isolated roughness flow (*k* – type roughness), (b) wake interference flow (*d* – type roughness), and (c) skimming flow (*d* – type roughness). Legend: *k* roughness height, λ roughness spacing, *j* groove width, vectors indicate flow patterns from left to right.

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Layers and interfaces in stably stratified waters: A DNS perspective

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Abstract

Flows in stably stratified natural waters often develop self-organized layers and interfaces. Using direct numerical simulations (DNS), we investigate the dynamics of these layered flow structures and the instability mechanism driving their emergence. These simulations provide fresh insights into the interplay between stratification, turbulence, and mixing, with implications for physical-biogeochemical interactions in natural aquatic environments.

We first examine turbulence in a stratified wake and find that the flow evolves toward a locally critical state [1], forming spontaneous shear layers. Decomposing the flow into components above and below the Ozmidov scale, we observe high-dissipation regions clustering around a critical Richardson number. Despite an order-of-magnitude decay in the strength of bulk turbulence, this self-organized state persists, facilitating two-way energy transfer—including kinetic energy backscatter—reminiscent of self-organized criticality in other complex systems [2].

Next, we analyze the impact of layering on mixing efficiency by tracking the irreversible flux coefficient, which quantifies the ratio of turbulent potential to kinetic energy dissipation [3]. As the wake flow transitions into the layered state, the flux coefficient stabilizes between 0.45 and 0.49 before eventually declining as viscosity dominates the dynamics. This plateau coincides with a specific range of Ozmidov-to-Thorpe length scale ratios, aligning with previous studies (e.g., [4]). Conditional sampling against the local Richardson number further reveals a universal flux-gradient relationship, supporting the "constant-power" mixing scenario proposed in prior theoretical work [5].

Finally, we investigate a mechanism driving layer formation by analyzing the breakdown of a columnar Taylor–Green vortex array under strong stratification [6]. Linear stability analysis identifies the zigzag instability as the dominant mode, with the fastest-growing vertical wavenumber scaling as the inverse Froude number. DNS confirms that this instability efficiently transfers energy from vertically uniform vortices to a preferred vertical scale, providing a direct pathway for layer formation.

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On the Reynolds-Averaged and Large Eddy Simulation methodology for active tracers

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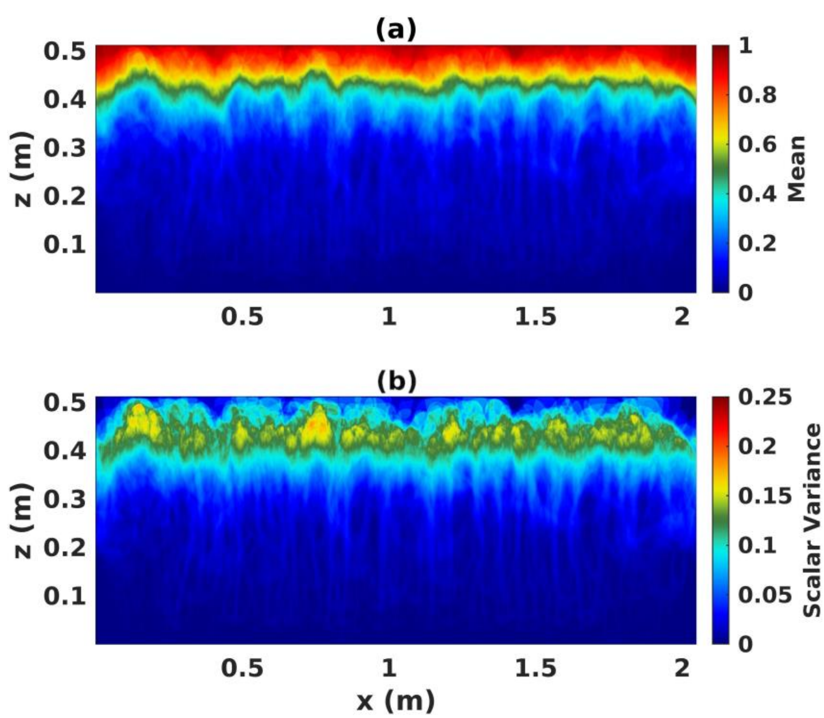
Abstract

The size of all but the smallest lakes implies that numerical modeling efforts must be interpreted as something other than "Direct Numerical Simulation". In practice this often means that an eddy viscosity and eddy diffusivity are used, but the form and structure of the underlying equations both remain unchanged. When reactive tracers are considered the application of either the RANS or LES derivation procedure leads to new terms, which may lead to surprising effects. Using the well-studied logistic form of a reaction with two equilibrium points (i.e. the form that appears in the well-studied Fisher equation) we demonstrate the calculation of the new terms, and provide physical interpretations for both methodologies. In the case of RANS the new terms imply that mean concentration is drained by the variance of the fluctuations, as shown in the figure below. In the case of LES the problem is further complicated by the need to choose a filter. Motivated by pseudospectral simulations, we use a spectral filter with varying properties and discuss to what extent local balances are possible. We conclude with speculation on other contexts, such as strong cabbeling, where the type of nonlinearity observed in the reaction problem may modify the way in which RANS and LES are applied to the lake setting.



The mean (a) and variance (b) of the active tracer in a 50 ensemble member RANS simulation of Rayleigh-Taylor turbulence.

New Insights Into Deep Mixing in Crater Lake, Oregon

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Abstract

Crater Lake, Oregon, is a deep (594 m) caldera lake in the Cascade Mountains, USA. Previous studies on deep mixing in the lake were based primarily on temperature measurements taken at various depths with thermistors mounted on a mooring in the deepest part of the lake, supplemented with occasional CTD casts. In 2013, an automated profiling instrument was installed in the deep lake, incorporating a suite of sensors and providing daily profiles at ~1 m resolution. In addition, in Sept. 2023 an extra mooring with thermistors was deployed for the first time in the southern side of the lake, at a water depth of 340 m. Here we report on preliminary analyses of three different deepwater mixing events, as observed at these three sites.

[1] Strong, southerly (~10 m/s) winds occurred Feb. 29-Mar. 5, 2024. Temperature (T), salinity (S) and dissolved oxygen (DO) near the bottom of the lake (i.e., 570 m) temporarily changed by as much as -0.23 C, -0.0014 PSU, and +0.05 mg/L, respectively, on Mar. 3 (Fig. 1a-c). At 530 m and above, relatively little immediate change was observed. These results suggest a thermobaric instability formed in early March, likely near the northern side of the lake, with a “slug” of colder, fresher, higher-oxygenated water descending from the upper lake and flowing along the bottom where it encountered the profiler mooring in the deepest part of the lake (i.e., near-horizontal advection at the mooring site). The in situ density, ρ, of this new water at the bottom was ~1.5 x 10^{-3} kg/m^3 greater than the water present before the event (Fig. 1d). That water eventually mixed out, but a net change in T, S, DO and ρ remained in the deep lake. [2] In late Jan./early Feb. 2024, the lake was nearly isothermal. Strong easterly winds occurred across Jan. 30-31. This appeared to have caused downwelling at the profiler mooring, deepening the pycnocline (starting at about 300 m) by about 200 m locally. T, S and DO temporarily changed (Fig. 2 a-c), although ρ at depth actually decreased (Fig. 2d). Within a week, the system appeared to relax again, with relatively little net change in T, S, DO or ρ. [3] We will also discuss some observations suggesting a potential turbidity current that carried down some upper lake water to the deep lake in late November 2023 (not shown here).

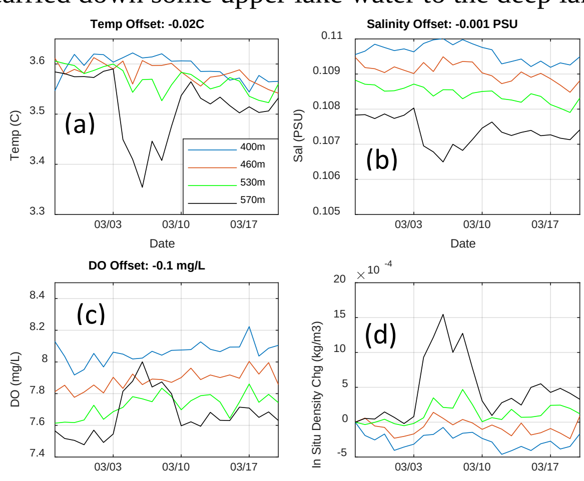

Fig. 1 (a) T, (b) S, and (c) DO and (d) change in ρ at 400, 460, 530 and 570 m for early March 2024 event.

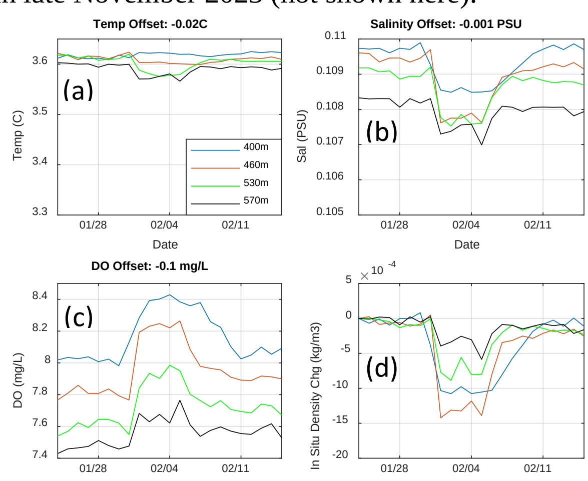

Fig. 2 (a) T, (b) S, and (c) DO and (d) change in ρ at 400, 460, 530 and 570 m for early February 2024 event.

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Parsimonious Modelling of Thermobaric Mixing in a Deep Lake

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Abstract

Thermobaricity can be understood as the temperature dependence of the compressibility of water. It is known to have a significant impact in many deep lakes. Despite this, it is often not implemented numerically in lake models, only in combination with external forcing [1].

Motivated by Lake Shikotsu, Hokkaido, Japan, which portrays an excellent example of thermobaricity controlled deep water circulation [2], we created a simplified 1D model without any external forcing, except the surface temperature input. Also, we excluded salinity, used a simple bathymetry without shallow areas, and did not consider any inflows to prevent any competing influences and avoid any expendable complexity. For stability considerations, we used the in-situ density and where able to access the stability in form of the Brunt-Väisälä frequency.

The model recreated the deep water renewal only induced by thermobaricity. We identified three phases of the deep water renewal: (1) mixing from the surface to a depth with similar temperature, (2) mixing from the crossing of the temperature profile with the line of the temperature of maximum density to a depth with similar temperature, and (3) from the same crossing to the bottom. Additionally, we investigated the influence of previous deep water renewal events and of the surface temperature on the current deep water renewal. The results of the model emphasize the necessity and the feasibility of the implementation of thermobaricity in lake models to ensure correct behaviour of the deep water renewal. Our approach of using the in-situ density is straight forward, offers a simple solution and can be easily customized. [3]

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Thermobarically stratified lake: theoretical aspects, consequences for deep water circulation and observations

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Abstract

Deep water circulation in deep lakes of the temperate and cold climate zone is affected and often controlled by thermobaric effects. Thermobaric effects derive form the fact that the thermal expansion of water depends on pressure or – which is tantamount – on the temperature dependence of compressibility. As a consequence temperature stratified lakes can show temperatures considerable lower than 4°C in their deepest layers. Until now this effects has been greatly neglected, and numerical modelling of thermobaric effects have hardly ever been attempted.

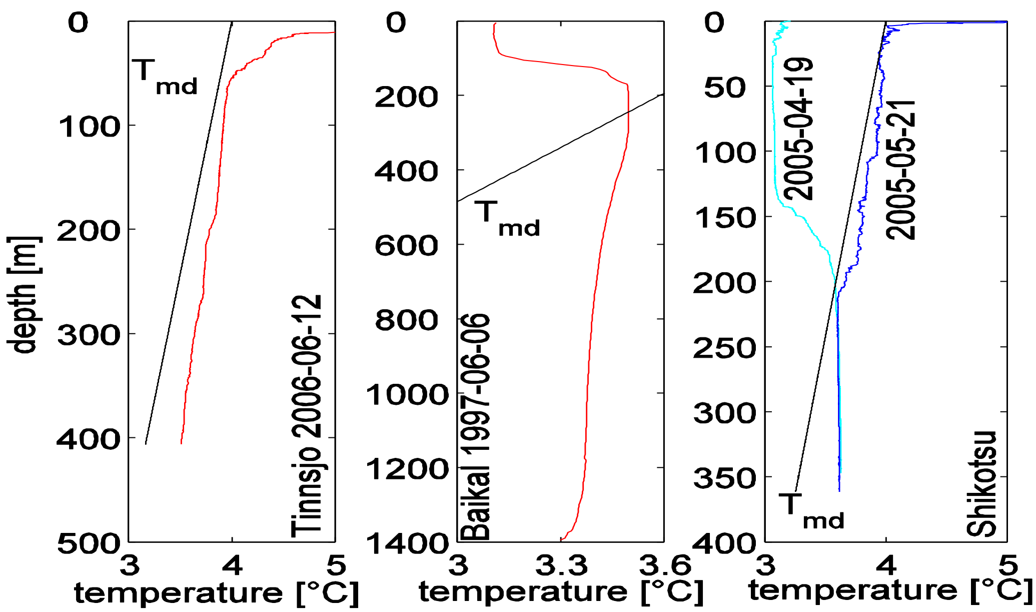

Fig. 1: *temperature profiles from three thermobarically stratified lakes (from [1])*

In this contribution, the fundamental theoretical ideas behind thermobaricity are shown. The convenient physical quantity of potential density is lost for stability considerations and other quantities must be implemented. We show a few examples of thermobarically stratified lakes and draw conclusions about various ways of replacing the deep water. Despite the continuous stable density stratification and the complex paths of water into the abyss, thermobarically stratified lakes appear to be well ventilated. We show similarities and differences between temperature profiles of various lakes, and what this indicated about the deep circulation. A more detailed understanding of the deep circulation under thermobaric conditions would greatly profit from numerical modelling that include this effect.

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Multi-year 3D lake modelling in a large northern lake

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Abstract
To fill the knowledge gaps in the northern lakes and assess their responses to the accelerated warming in arctic regions and rapid change in landscape, a multi-year three-dimensional lake model is developed in the Great Slave Lake, one of the world's largest and deepest lakes. Forcing by meteorological data from ERA5 climate model and observed inflow/outflow data, the hydrodynamic and thermodynamic processes in the lake were simulated.

The temperature profiles collected from 6 stations during 1998-2001, revealing the mixing scheme and thermal characteristics in various locations in the western basin of Great Slave Lake, were used to evaluate the temperature simulation. The remote sensing images were used to evaluate the ice cover simulation spatially. The inter-annual comparison of the lengths and components (black/white ice) of ice cover explain the overall warming effect on the lake not only in the winter but also the following open water season. The multi-year modelling of ice cover could benefit the ice phenology and future winter limnology studies. This modelling tool can be further coupled with the large-scale hydrological model, benefitting water resources management in the Mackenzie River Basin.

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Thermobaric Instability in a deep Fjord-Type Lake, Quesnel Lake, Canada

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Deep lakes in temperate climates store about 50% of the world's surface liquid freshwater, yet their deep circulation remains poorly understood and inadequately modeled. These lakes experience extreme hydrostatic pressures that affect circulation through compressibility which decreases the temperature of maximum density with depth. This phenomenon, known as thermobaricity, complicates understanding because subtle processes occur around a changing temperature of maximum density. This leads to two challenges: understanding the sequence of events that drives circulation at such depths and accurately incorporating them into lake models. In previous field studies, oxygen and temperature measurements have been used to demonstrate but not fully explain hypolimnetic ventilation. 1D models have been utilized recently for their simple inputs and capacity for long-term simulations, though they overlook key factors such as non-uniform wind fields and bathymetry. Accurate wind modeling is particularly crucial, as wind is hypothesized to induce thermobaric instability triggering hypolimnetic ventilation. This study aims to better understand deep ventilation in freshwater lakes by focusing on Quesnel Lake (maximum depth of 511 m) using two decades of field observations and a 3D numerical lake model (AEM3D).

Field observations were used to assess deep ventilation, focusing on timing and the sequence of events leading to ventilation by analyzing data from two moorings within the East Arm (M9 and M14, located at 500 m and 400 m water depth, respectively). ERA-5 Reanalysis dataset was used for longwave radiation input but proved inadequate for wind data as it does not resolve the lake's complex topography. We use the AEM3D model for hydrodynamic modeling, known for its effectiveness in simulating basin-scale wind-induced internal waves and circulation in stratified lakes. AEM3D solves the Navier-Stokes and scalar transport equations under the hydrostatic assumption while utilizing a wind-mixing algorithm that mixes unstable potential density gradients. We initialize AEM3D model with temperature data from the two most extensively monitored years (2007 and 2024) and use meteorological data obtained from Dock Point station located at the narrowest section of the East Arm.

Moorings at the deepest section of the lake reveal a series of significant cooling events in January linked to windstorms combined with sub-freezing air temperatures (down to -23°C). After a constant warming from May, these events consistently (occurred in January of each of the 20 years of observations) reset the bottom temperature (order of 0.3°C) and indicate an interaction with the surface water. When the water profile is statically unstable, cooling events either manifest as a sequential vertical descent of cool water plumes from top to bottom or a sudden horizontal intrusion of colder water at deeper depths. In January 2007, these series of events led to a net cooling of around 0.25°C at the deepest point of the lake (M9) and 0.4°C at M14. In 2007, cooling occurred almost simultaneously at M9 and M14, whereas in 2024, the event was first observed at M9 and then three days later at M14 (18 km distance). Various hydrodynamic model runs were analyzed, differing in factors such as salinity and the use of maximum versus average wind speeds. Some simulations accurately capture the timing of the cooling event, whereas others better reproduce its total magnitude. Model results show that cold, shallower water (<150 m) exposed to sub-freezing air temperatures descends to depths below 350 m, eventually reaching 500 m after the windstorms, supporting the hypothesis of thermobaric instability occurring during inverse stratification.

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Internal Kelvin and Poincaré waves and the bottom boundary layer in Lake Biwa

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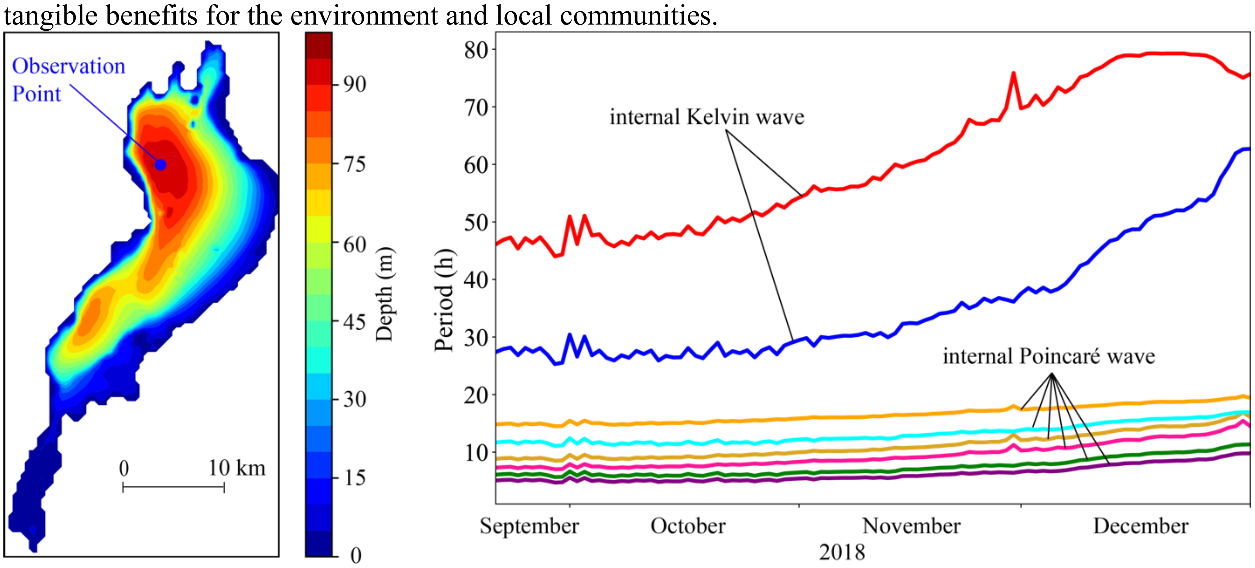
Abstract

In deep-water lakes, such as Lake Biwa, global warming impacts anoxia near the lake bottom, significantly affecting water quality and ecosystems. Stratification is one of the key factors controlling the occurrence of anoxia, and linear internal waves yield seasonally changing stratification. Therefore, we aim to investigate internal Kelvin and Poincaré waves, which are crucial for the epilimnion and hypolimnion thickness, using the vertical water temperature and dissolved oxygen profiles obtained from field observations. We applied the frequency equation considering the Coriolis force to elucidate the properties of internal waves theoretically. The high reproducibility of its equation was confirmed through numerical simulations using the three-dimensional environmental hydrological model with the agreement of the internal Kelvin and Poincaré waves observed in the field, providing a solid foundation for practical applications. Furthermore, the revelation that the elliptical cylinder assumption has greater accuracy than the circular cylinder for real lakes is a significant finding that enhances the practicality of our research. These results are not just theoretical, but they also provide important insights for the rapid estimation of internal wave periods using the frequency equation. Additionally, by analyzing the vertical water temperature distribution and dissolved oxygen distribution in the bottom boundary layer of Lake Biwa, we found that the thickness of the bottom boundary layer is thicker in spring, becomes thinner towards summer, and thickens again towards winter, corresponding to changes in the energy dissipation rate within the bottom boundary layer, indicating that the dissipation rate of turbulent energy decreases and increases during the formation and destruction of stratification. These findings can be directly applied to improve the understanding and management of deep-water lakes, especially in the context of climate change, leading to tangible benefits for the environment and local communities.



Left figure: Bathymetry of Lake Biwa. Right figure: Periods of internal Kelvin and Poincaré waves obtained from the frequency equation with the elliptical cylinder assumption.

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Summertime Upwelling Events in Multi-Arm Fjord-Type Lakes: A Case Study of Quesnel Lake

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Abstract

During summer, lakes typically stratify, forming a warm epilimnion above a cold hypolimnion. This thermal stratification increases downstream river temperatures compared to watersheds without lakes. However, processes such as upwelling disrupt this thermal structure by bringing cold hypolimnetic water to a lake's surface and into its outflows. This rapid temperature change can potentially harm downstream ecosystems, including temperature-sensitive summer salmon migrations.

Upwelling occurs in thermally stratified lakes when wind forcing is sufficiently strong, sustained, and aligned with the lake's morphology. Upwelling is more likely during the weak stratification that occurs at the beginning and end of the stratification season, and is more pronounced near lake boundaries where outflows originate. The geometry and bathymetry of a lake can amplify or dampen upwelling responses, while surrounding topography influences wind patterns, further complicating upwelling dynamics. These factors are particularly significant in fjord-type lakes, which have complex shapes and are often located in mountainous regions.

Quesnel Lake is a fjord-type lake in British Columbia, Canada. It is the source of the Quesnel River, which feeds into the Fraser River, one of the world's most productive salmon-bearing systems. The lake has a Y-shaped geometry with three arms (West, North, and East) and a shallow sill (35 m depth) in the West Arm, which separates the West Basin from the Main Basin. While the Main Basin contains 97.7% of the lake's volume and reaches a maximum depth of 511 m, the West Basin is shallower (maximum depth of 108 m) and drains into the Quesnel River. The smaller size of the West Basin and its separation from the Main Basin influence upwelling dynamics and their impact on downstream temperatures.

This study uses nine years (2016–2024) of mooring and meteorological data to investigate the role of lake geometry in upwelling events in Quesnel Lake and their effect on the Quesnel River. Moorings and meteorological stations deployed across all three arms captured spatial variations in temperature and wind patterns. Temperature loggers, Acoustic Doppler Current Profiler data, and wind measurements were used to identify upwelling events in the West Basin, assess the influence of basin geometry, categorize upwelling types, and to analyze the river's response.

Observations show that upwelling occurs multiple times each summer despite strong stratification. It is correlated with strong winds (exceeding 80th percentile) and aligned with the lake's thalweg, typically causing Quesnel River temperatures to drop by over 5°C within two days.

Two primary upwelling patterns were identified: synchronous upwelling, where upwelling occurs at the same time across the entire West Basin, and progressive upwelling, during which upwelling progresses from east to west across the West Basin. During upwelling events, the most pronounced cooling occurs at the head of the river and within the West Basin, where the lake's narrowing and shallowing amplify the cooling signal, highlighting the role of lake geometry in controlling the magnitude of upwelling. These findings also provide insights into the complex interactions between lake hydrodynamics and river ecosystems.

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Cabbeling-driven lateral instabilities on a vertical portion of the thermal bar

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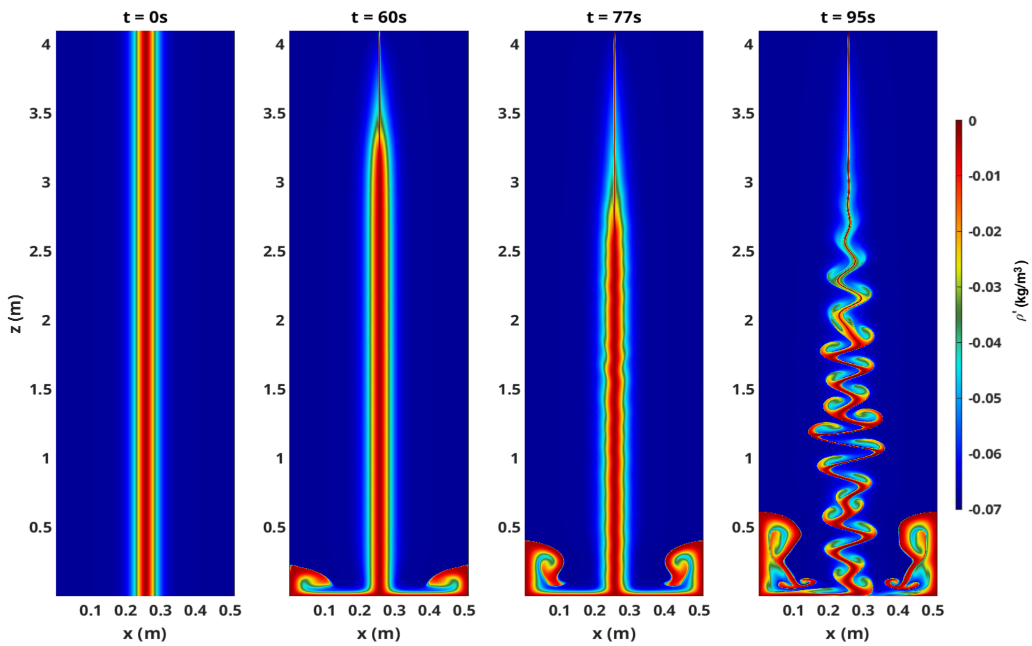
Abstract



Strong cabbeling occurs when two parcels of water combine to create a parcel that is of greater density than either initial parcel. It drives the thermal bar, one of the mechanisms of deep-water renewal in dimictic lakes during the spring and autumn [1]. Strong cabbeling exists because water attains a maximum density at a temperature of approximately 4ºC (at atmospheric pressure). As discussed in [2], a special situation arises when half (lengthwise) of the domain is nºC lower than the temperature of maximum density, and the half is nºC higher. In the first panel of the attached figure, we plot the resultant density field (to be specific, the fluctuation about the maximum density) in a numerical simulation with free-slip boundary conditions. The densest water occurs in the centre, and hence plunges symmetrically into the left and right halves of the domain. By *t = 77*s and *t=95*s an instability has formed in the centre of the domain, which is enhancing the lateral mixing of heat. Using direct numerical simulations, we investigate this cabbeling-driven instability in thermobaric and non-thermobaric contexts (the latter being depicted above). We will also discuss implications for mixing in dimictic lakes.

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Evaluating the effectiveness of destratification aeration on spatial-temporal distributions of manganese in a drinking water reservoir

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Abstract

Manganese (Mn), an abundant trace metal in rocks and sediment, is a significant problem for drinking-water treatment within the UK, USA and other regions. Global and national recommendations and regulations are commonly set for Mn, and steps to remove Mn are typically part of the treatment process in standard drinking-water plants. However, treatment of water with elevated Mn concentrations is often difficult due to the complexity of Mn redox kinetics. To combat on-going and emerging drinking-water taste and odour issues with Mn and other contaminants (e.g., algal toxins), many water utilities are using in-situ oxygenation or aeration systems to i) improve source water in lakes and reservoirs and ii) decrease the need for costly and potentially harmful chemicals during treatment (Bryant et al., 2011; Ming et al., 2024). Resultant shifts in key biogeochemical and physical processes are still poorly understood though, often leading to inefficiently managed reservoir systems (Austin et al., 2019; Slavin et al., 2022).

This study explores how an engineered destratification (i.e., aeration mixer) system influences the transport and removal of Mn within Blagdon Lake, a lowland drinking-water supply reservoir in southwest England. Based on an extensive, interdisciplinary set of field measurements, Mn dynamics and other relevant biogeochemical sediment and water processes were characterised over a focused three-year period (2017-2019, including additional follow-up data through 2022), including water-column sampling and profiling, sediment trap and core analyses, and a wider catchment-scale investigation. Results show that aeration contributed to maintaining a mixed, destratified water column throughout the summers, leading to high DO levels and decreased concentrations of total and soluble Mn in source water. Increased sediment Mn retention paired with decreased water-column Mn concentrations were observed within the key aeration zone located near the reservoir outtake to the treatment plant. Ultimately, results highlight that while aeration operations may be successful for meeting some reservoir management goals (e.g., decreasing intake Mn concentrations), maintaining full destratification often requires natural, wind-driven events. Furthermore, comparison across regional reservoirs highlights the influence of local geology and sediment dynamics on water quality, reinforcing the need for tailored, site-specific reservoir management, including aeration operation and sediment loading.

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Modelling the impact of changing water clarity on lake stratification across Maine

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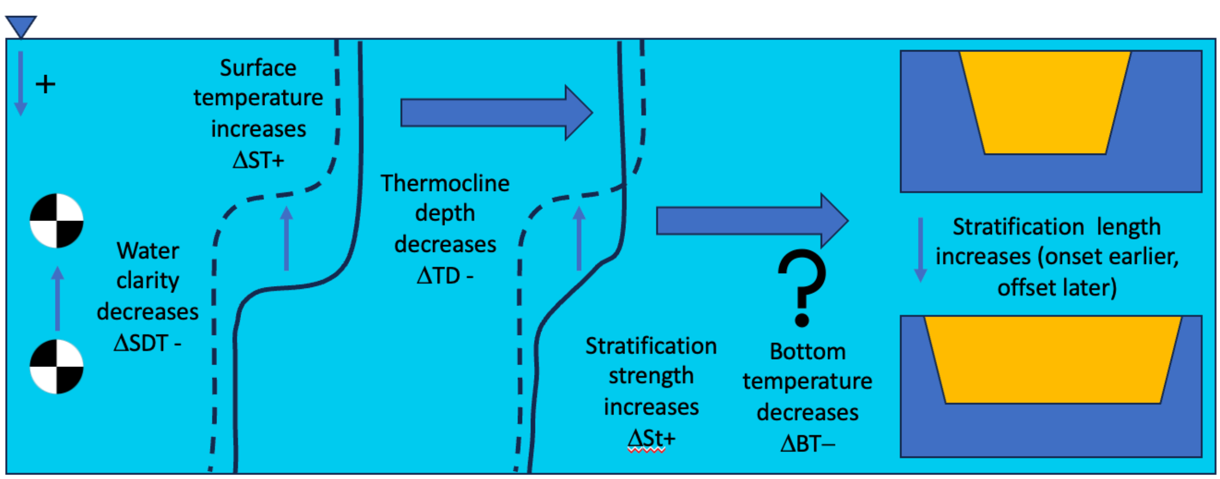
Abstract

Water clarity in lakes is an important driver of stratification. Across Maine, water clarity (measured by Secchi disk transparency (SDT)) has been declining over the past 50 years. As water clarity decreases, previous work on individual lakes has shown that surface temperatures will increase, thermocline depth will decrease, and stratification strength will increase. It is expected that different lake morphologies will be impacted by lower water clarity differently. In this study, we used the 1-D General Lake Model (GLM) to investigate how stratification changes with changing water clarity in ~50 lakes across the state of Maine. The lakes were modelled using data from the Lakes of Maine database, which is maintained by the Maine Department of Environmental Protection and contains over 50 years of volunteer and state collected data on over 6000 lakes. A subset of these lakes was selected that were deeper than 10 m, had an available hypsograph, and had at least 10 temperature profiles. In total, 54 basins were modelled. Global model calibration was done using part of the dataset and then validated on the remainder. Once models were calibrated, SDT was varied from 2-10 m (every 0.5 m) for each lake for each simulation year and stratification metrics were calculated. In total, > 42,000 model simulations were conducted. For each metric (thermocline depth, surface temperature, benthic temperature, volume averaged temperature, Schmidt stability, stratification onset and offset, and stratification length), the gradient of the metric to SDT was computed to represent the sensitivity of each parameter to water clarity in each lake. As hypothesized, all lakes showed a shallower thermocline, warmer surface temperature, and stronger stratification with shallower SDT. Most lakes showed a cooler bottom temperature with shallower SDT, likely due to the earlier stratification onset data seen across all lakes. Most lakes showed a later stratification offset date with shallower SDT; combined with earlier onset, all lakes showed a longer stratification length. The sensitivity of each of these parameters to changes in SDT varied between lakes and was linked to morphology.



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Breathing life into ocean dead zones using excess oxygen from the super-green hydrogen economy

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Abstract

Oxygen depletion in aquatic ecosystems accelerates biodiversity loss, greenhouse gas emissions, toxic algal blooms, and other water-quality hazards. Dead zones with low oxygen exist in both freshwater and marine environments and are expected to grow with continued eutrophication and climate heating. Small-scale oxygenation to improve water quality is common in freshwater systems, but large-scale oxygenation of ocean dead zones [1] is rare. Fortuitously, renewable energy from green hydrogen production may enable us to breathe life into suffocating ocean dead zones [2]. The electrolysis of seawater generates hydrogen gas, with oxygen gas as a by-product. Excess oxygen can be used to oxygenate ocean dead zones, creating substantial synergies and co-benefits during the coming clean-energy transition. In this presentation, we describe the potential feasibility of this approach for large-scale oxygenation of the Chesapeake Bay by combining land use, watershed and estuary models [3] with a model of the multi-modal energy system [4] within a system-of-systems convergence paradigm [5, 6]. Ocean dead zones are just one of a large class of interdependent societal challenges of the Anthropocene, all of which need to be framed and addressed using an integrated and holistic approach [6].

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Hydrodynamic modelling of Great Slave Lake using NEMO

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Abstract

The subarctic region of northern Canada, including the Mackenzie River Basin, is experiencing profound impacts from climate change. Over the past few decades, the region has warmed at unprecedented rates—up to four times the global average—leading to significant consequences for regional hydrology, ecosystems, and human activities. A key feature of the Mackenzie River Basin is Great Slave Lake, the second-largest lake in the Northwest Territories and the deepest in North America. With over 60% of the territory's population residing along its shores, the lake is a vital ecological and societal resource. To better understand and predict the effects of climate change, we have recently configured a climatological model [1] to assess its impact on water surface levels, providing critical insights for long-term water resource management.

Despite its size and importance, numerical modelling of Great Slave Lake has been hindered by the lack of accurate bathymetric data. To address this gap, we collaborated with the Department of Fisheries and Oceans to develop the first complete bathymetric map of the lake. By integrating historical naval charts and field sheets with additional sounding data, we created a high-resolution simulation domain optimized for the Nucleus for European Modelling of the Ocean (NEMO), with a 1 km horizontal resolution and 30 vertical layers. The NEMO model was selected for its widespread use in oceanographic and limnological studies, including its adoption by Environment and Climate Change Canada (ECCC) for operational forecasting in the Laurentian Great Lakes.

This talk will discuss the parameterization of surface fluxes and vertical mixing in the lake model, as well as the configuration of atmospheric forcing, surface runoff, river inflows and outflows, and ice dynamics. Preliminary results indicate that the NEMO model robustly simulates lake processes, showing strong agreement with observed temperature profiles. Seasonal thermal stratification is closely linked to the ice cycle, while wind-induced mixing plays a key role in circulation. A cyclonic circulation pattern is observed, characterized by prominent gyres in the main basin. Ongoing work [2] focuses on further calibration and sensitivity analysis of key parameters to enhance model accuracy and improve its application for future water resource management.

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Hydrodynamic Modelling of a Fluvial Lake: Influence of Seasonal Submerged Aquatic Vegetation on Circulation and Nutrient Dynamics

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A three-dimensional hydrodynamic model (AEM3D: Aquatic Ecosystem Model) with a spatial resolution of 200 × 200 m was developed for Lake Saint-Pierre, a fluvial lake along the Saint Lawrence River, to investigate lake-wide circulation, water temperature dynamics, and hydraulic retention time. The lake experiences seasonal growth of submerged aquatic vegetation (SAV), which provides critical habitat for fish, birds, and invertebrates, while also influencing bottom roughness and transport dynamics. The model was driven by atmospheric reanalysis forcing and incorporated eight major riverine inflows, one outflow, and spatiotemporal variations in bottom roughness based on observed SAV growth patterns. Model performance was evaluated using field observations from 2004 and 2024, including water temperature, directional velocity profiles, surface water elevations, and data collected by a YSI EcoMapper autonomous underwater vehicle. Circulation analysis revealed that lake-wide hydrodynamics are primarily governed by riverine inflows, fluvial bathymetry, and seasonal changes in bottom roughness associated with SAV, which begins growing in May, peaks in September, and detaches in October. Flow remained concentrated along the main navigation channel throughout the season. Hydraulic retention time in the southern portions of the lake ranged from approximately 1.5 to 3 days, corresponding to areas directly influenced by local riverine plumes. This finding is consistent with the simulated distributions of passive tracers released from the Yamaska and Saint-François Rivers, major sources of phosphorus, suggesting limited dispersion and largely confined plumes along the southern shoreline. These results underscore the significant role of SAV growth patterns in shaping regional water circulation and nutrient transport, as well as in influencing potential zones of algal bloom formation in a fluvial lake. This study demonstrates hydrodynamic modeling under the influence of seasonal SAV in Lake Saint-Pierre and provides a foundation for future water quality assessments under changing hydrological or climatic conditions.

Title: Hindcasting a century of winter thermal conditions in the upper Great Lakes

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Abstract

Only recently have multi-year, whole year time series of whole water column thermal structure been available for the Laurentian Great Lakes. These data show that the formation of winter stratification and thermal structure in general across the great lakes varies in character not just between lakes, but interannually within individual lakes. An analysis of heat content and Schmidt stability shows that there is an empirical threshold that must be exceeded for winter stratification to form; specifically, the heat content of the water column must drop to at least -1GJ/m2 relative to the temperature of maximum density before winter stratification can form. Further, there is a strong relationship between winter (December-February) air temperature and minimum heat content, although the sensitivity of heat content to DJF air temperature varies between lakes. Combining this relationship with the stratification formation threshold means that whether a lake stratifies in a given year or not can be predicted using average DJF air temperature. Finally, a recently compiled record of sub-basin averaged daily air temperatures for the Great Lakes can be used to hindcast winter stratification status in the upper great lakes from 1897 to the present. This analysis suggests that Lake Superior has been and remains reliably dimictic, Lake Huron is in the process of transitioning from forming winter stratification to cooling below the temperature of maximum density but not forming stratification, and Michigan experiencing more frequent years in which it does not cool to the temperature of maximum density. There is a great deal of interannual variability on top of the long-term trend towards warmer stratification status, and lakes, especially Huron and Michigan, display different behavior from year to year. This makes putting labels like “dimictic” or “warm monomictic” on these lakes difficult in any meaningful sense.

Meromixis in Brackish Pit-Lakes with Ice Cover

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Abstract

Pit-lakes are of interest because they are often deep, have a small surface area, are sheltered by pit walls, and have just a little salt (0.5 to 3 g/L). At mid to high latitudes, the exclusion of salt from the ice can result in a freshwater cap with sufficient salinity stratification to supress spring and fall turnover, resulting in meromixis [1, 2]. However, such systems are susceptible to mixing deeper, especially in fall, transporting some water from depth into the surface layer.

Here we examine the evolution of meromixis in the Zone 2 pit-lake at the Colomac mine site, Northwest Territories, Canada (Figure 1). The pit-lake was intentionally destratified using aeration to enhance biological remediation of contaminants [3] providing a unique opportunity to observe the formation and long-term evolution of meromixis. Zone 2 pit-lake was meromictic in the first year after aeration and a small chemocline developed over subsequent years. The pit-lake was vulnerable to mixing as the surface layer cooled through the temperature of maximum density, and we describe how high or sustained winds during this window in time deepens the chemocline. Understanding these processes is important to characterizing the transport of contaminants from the deep water to the surface, and to planning closure and managing water quality at mine sites [1-4].

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Figure 1. Colomac Zone 2 pit-lake just before ice-on.

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Divergent oxygen trends in ice-covered lakes

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Abstract

Dissolved oxygen (DO) is an essential resource in ice-covered lakes, regulating water quality and biodiversity, including the survival of economically important fish species. Most of the world's lakes seasonally freeze, often resulting in oxygen depletion as ice cover inhibits water column ventilation and snow cover limits photosynthesis while respiration continues. Widespread shortening of ice cover duration in a warmer world might improve winter oxygenation by decreasing the duration of under-ice oxygen depletion, but this hypothesis remained untested. Here we performed a systematic analysis of 6.6 million physical and chemical observations from 19645 lakes in the Northern Hemisphere during 1960–2022. We analysed long-term trends in volume-weighted mean (or whole-lake) dissolved oxygen concentrations (DO_{vw}). Contrary to expectations, under-ice DO_{vw} trends ranged from significantly negative in small lakes (surface area <10 ha) (-0.14 ± 0.05 mg L^{-1} decade^{-1}) to significantly positive in large lakes ($\geq 10^4$ ha) (0.11 ± 0.03 mg L^{-1} decade^{-1}). This divergence with lake size emerged partly because ice cover periods have shortened 2.2 times faster in large lakes compared to small lakes. Hierarchical modeling revealed that in smaller lakes, aeration in fall was incomplete even under isothermal conditions (full mixing), such that increasingly oxygen-depleted conditions in summer carried over to the ice-cover season. As a result of this cross-seasonal ecological memory, under-ice hypoxic zones have expanded. Oxygen trended most negative in small eutrophic and humic lakes with high seasonal oxygen depletion rates. In larger lakes ($\geq 10^3$ ha), negligible summer deoxygenation, prolonged ventilation in fall and shortening of the oxygen drawdown period in winter explained positive DO_{vw} trends. However, in the vast majority of seasonally ice-covered lakes, which are small, continued climate warming is likely to exacerbate deoxygenation.

Impact of Ice Cover Composition on Radiatively Driven Convection in Lakes

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Abstract

Lakes that experience winter ice cover are not quiescent due to buoyancy driven flows within the water column. For instance, as winter progresses into spring, a significant increase of solar radiation can generate circulation near the ice-water interface that transports nutrients and phytoplankton to the surface triggering the development of blooms during or soon after ice cover [1]. The ice composition is a key control mechanism of this, where highly transparent black ice allows more light to propagate into the water column compared to opaque white ice (figure 1). Climate change is predicted to lead to an increased variation of ice quality [2], hence, it is important to investigate how this change in composition impacts convection which further dictates other biophysical processes. To tackle this, a simple model (figure 2) is developed that couples ice composition and solar radiation to the incompressible Navier-Stokes equations under the Boussinesq approximation assuming a fixed ice boundary with no melting to investigate the impact of ice quality. This is numerically solved on a small domain where it is found that higher proportions of white ice within the ice cover delay the onset of convection, even potentially prohibiting it, which could have ecological implications.

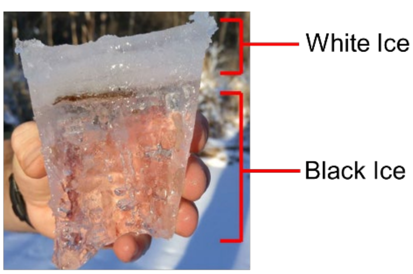

Figure 1: Black and White Ice within the ice cover. Adapted from [1]

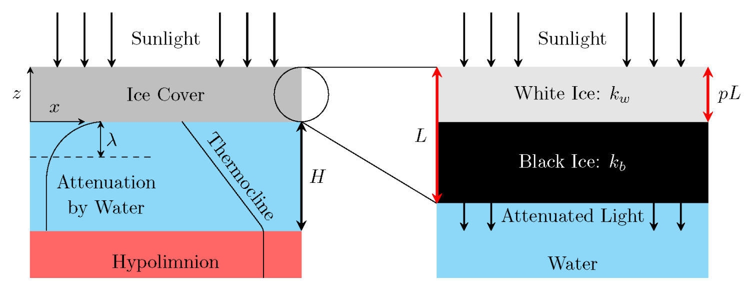

Figure 2: Schematic of the ice-covered water column. Incoming light penetrates and is attenuated by the ice cover. The transmitted light is subsequently attenuated by the water as it filters through the water column.

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Laboratory Model of Stratification and Circulation Under Lake Ice

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Abstract

We examine under ice circulation and suppression of spring turnover in brackish lakes with ice-cover. Exclusion of salt from the ice destabilizes the water column during ice growth, but then stabilizes the lake in spring by providing a fresh water cap during ice melt. We use observations from mine pit-lakes (Colomac Zone 2 pit-lake and Syncrude Base Mine Lake), and laboratory experiments to characterize these processes.

Laboratory experiments were conducted in a walk-in freezer containing an open tank filled with brackish water (S=0.4 g/L). We describe the circulation starting with convection and cooling in the 'fall' when the air temperature was below freezing (-15 °C), as well as the formation of reverse stratification and the onset of ice cover. The salt excluded at the base of the growing ice generated salt-fingers that transported salt downward [1]. To simulate spring, the freezer was then set to 10 °C, and we observed melting of the ice and development of a fresh water cap. These experiments simulated the expected circulation in a brackish lake subject to ice cover. The experiments compare well with the field results where the fresh water cap was observed to inhibit spring turnover and reduce re-oxygenation of the deep water.

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How winter inverse temperature stratification and thermal biology influence the depth distribution a cold water fish - lake trout

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Abstract: Here we ask the question where fish choose to sit in relation to the available inverse thermal stratification between of 0-4°C that is available under lake ice. We already know that lake trout can sit more shallow than bass in the winter, which is likely due to lake trout choosing colder temps and bass slightly warmer temps. The depth of the preferred isotherm will change between lakes that are cyrostratified and cryomictic. Larger lakes generally experience more wind driven mixing, so tend to be cryomictic with cold mean temperatures and a deep 2°C isotherm. There is also considerable year to year variability in wind driven mixing, so the mean temperatures of the water column, and the depth of 2°C isotherm can change considerably. Even two lakes next to each other can have different thermal profiles depending upon the relative date of ice. Here we use acoustic telemetry of Lake Trout from 6 different lakes over multiple years to explore the variability in thermal habitat usage for several years that range from cyrostratified and cryomictic thermal profiles. We find that much of the variability in Lake Trout winter habitat usage is explained by the changing physics of winter inverse stratification.

Future scenarios of under-ice irradiance in Swedish lakes

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Abstract

The thermal structure of a lake and the light-dependent organisms living in its waters rely heavily on irradiance, which becomes particularly critical during winter as it is the only external source of energy capable of penetrating the ice cover. The amount of irradiance reaching the water beneath the ice is greatly dependent on the composition and thickness of the ice and snow cover. Snow has the greatest impact on irradiance attenuation and reflectance, followed by white, and then black ice, which allows the most irradiance to penetrate. As future climate conditions are expected to alter the duration, thickness, and type of ice cover, under-ice irradiance will also change, consequently affecting the lake's physical dynamics and its ecosystem. To evaluate these changes, not only must the future thicknesses of ice and snow and the incoming irradiance be known, but also their attenuation coefficients and reflectance. Then, the under-ice irradiance can be estimated using the Beer-Lambert law, which describes the exponential attenuation of irradiance as it passes through the ice cover. Obtaining consistent reflectance and attenuation coefficients from the literature is challenging due to their high variability and sparse observations. To account for this variability, a Bayesian model has been developed after collecting and homogenizing a global dataset, providing a probabilistic framework for estimating these parameters. By incorporating data from diverse lake environments, the model provides a robust and generalizable estimation of the optical properties of ice and snow, enabling the extension of these values to unmonitored lakes more reliably than using case-specific literature values. We then obtained continuous ice quality data using the *air2ice* model (unpublished, presented at PPNW23, Brescia), an extension of the hybrid data-driven/physically-based *air2water* model (Piccolroaz et al., 2013), which uses air temperature and precipitation as inputs to predict daily lake surface water temperature and ice thickness and quality. By analyzing historical data and reconstructed ice conditions for some Swedish lakes, where data on chemical, physical, and biological parameters, as well as ice quality and thickness, are available for decades, we first aim to identify potential correlations between under-ice irradiance and chemical and biological parameters. This understanding is then applied to assess the potential impacts of future climate change scenarios (using ISIMIP3b meteorological forcings to predict future ice conditions) on under-ice irradiance levels and, consequently, on light-dependent organisms in the lake.

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Methane Bubbles in Lake Ice

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Abstract

Base Mine Lake (7.9 km^2, 57° 1'N, 112° 31'W) is a pit lake in the oil sands region of northern Alberta, Canada. The lake consists of a 10 m water cap, on top of approximately 40 m of fluid fine tailings [1, 2]. Within the underlying fluid fine tailings, methane bubbles are generated that rise through the water cap throughout the year. These bubbles can transport particles (turbidity) and residual hydrocarbons from the tailings into the water column.

We examine methane bubbles in CT (computed tomography) scans of ice cores collected from Base Mine Lake. These cores provide a horizontal and temporal record of ebullition during the period of ice growth (approximately 90 days). These records show that ebullition is highly variable horizontally (between cores) and is episodic in time, making it challenging to calculate the lake-wide flux. The mean void ratio in the ice was ~ 0.5%. Ebullition was also compared to fluxes computed using methane eddy-covariance and bubble traps. The flux estimated from the voids in the ice was approximately 1/20th of that from the eddy-covariance and bubble traps. We will discuss the possible reasons why bubbles in the ice cores underestimate the methane flux.

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Can satellite SAR be used to retrieve information about wind, waves and currents in medium-sized lakes?

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Abstract

Many limnologists have a dream: to directly measure water movement across the entire lake, in order to understand how it is associated with the redistribution of mass and heat, which eventually governs almost all physical and ecological dynamics. Traditional *in situ* measurements, although providing high temporal resolution, are inherently limited by their spatial coverage. In contrast, remote sensing techniques offer extensive spatial data but often capture only surface phenomena and may suffer from low temporal frequency. In addition, optical methods for estimating surface velocity require two images (e.g., based on water temperature, turbidity or Chl-a maps) captured at short intervals, which greatly limits their practical application. In this contribution we discuss the potential of Synthetic Aperture Radar (SAR) imagery to retrieve instantaneous information on wind, waves, and surface currents. While this approach has been used in oceans, seas and very large lakes (e.g., the Laurentian Great Lakes), we explore its novel application in medium-sized lakes, where complex orographic boundaries, limited fetch, and strong temporal variability challenge the usual assumptions that are used in larger systems. As a case study, we use the perialpine Lake Garda in Italy and rely on SAR data from the Italian COSMO-SkyMed constellation.

We exploit SAR data to extract information on water movement at the lake surface by processing backscatter amplitude and Doppler anomaly measurements through Geophysical Model Functions (GMF) to reconstruct the wind field and Surface Radial Velocity (SRV), and to disentangle the effect of wave propagation from the underlying surface currents. The accuracy of these estimates in systems that are characterised by large spatial gradients, such as medium-sized lakes, is still unknown and their uncertainty potentially large. Validation is therefore crucial, and we are trying to obtain valuable information by integrating traditional *in situ* measurements (thermistor chains, ADCPs, wavemeters, floating drifters) and a modelling chain composed of three numerical models: the Weather Research and Forecasting (WRF) model forces the Delft3D hydrodynamic model and its two-way coupled wave model SWAN (Simulating Waves Nearshore).

Preliminary results [1] indicate that the wind field retrieved from SAR data exhibits a spatial distribution and magnitude coherent with the WRF model outputs, whereas the SRV shows only qualitative agreement with the hydrodynamic simulations. An intensive field campaign is planned in spring 2025, and we aim at valorising such information to better understand the potential and the limits of SAR-derived estimates of wind, waves and currents in medium-sized lakes.

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The influence of velocity shear on sediment transport in particle-laden flows

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Abstract

The vertical transport of sediment in particle-laden flows is influenced by both settling-driven convective instability (Rayleigh–Taylor) and stratified shear instabilities (Kelvin–Helmholtz) [1]. Using direct numerical simulations, we investigate how these competing mechanisms regulate sediment transport out of the surface mixed layer under varying shear strengths. In the absence of shear, the Rayleigh–Taylor instability enhances vertical sediment transport, with effectiveness increasing with Stokes settling velocity and decreasing with stratification strength (Fig. 1). Under weak shear conditions (velocity difference $\Delta U <$ 0.05 m/s), vertical transport remains dominated by Rayleigh–Taylor-driven convection, leading to enhanced effective settling velocities. However, under strong shear ($\Delta U >$ 0.05 m/s), rapid growth of Kelvin–Helmholtz instabilities suppresses the Rayleigh–Taylor instability, significantly reducing effective particle settling and mass transport rates. These findings highlight the critical role of shear dynamics in shaping sediment transport pathways.

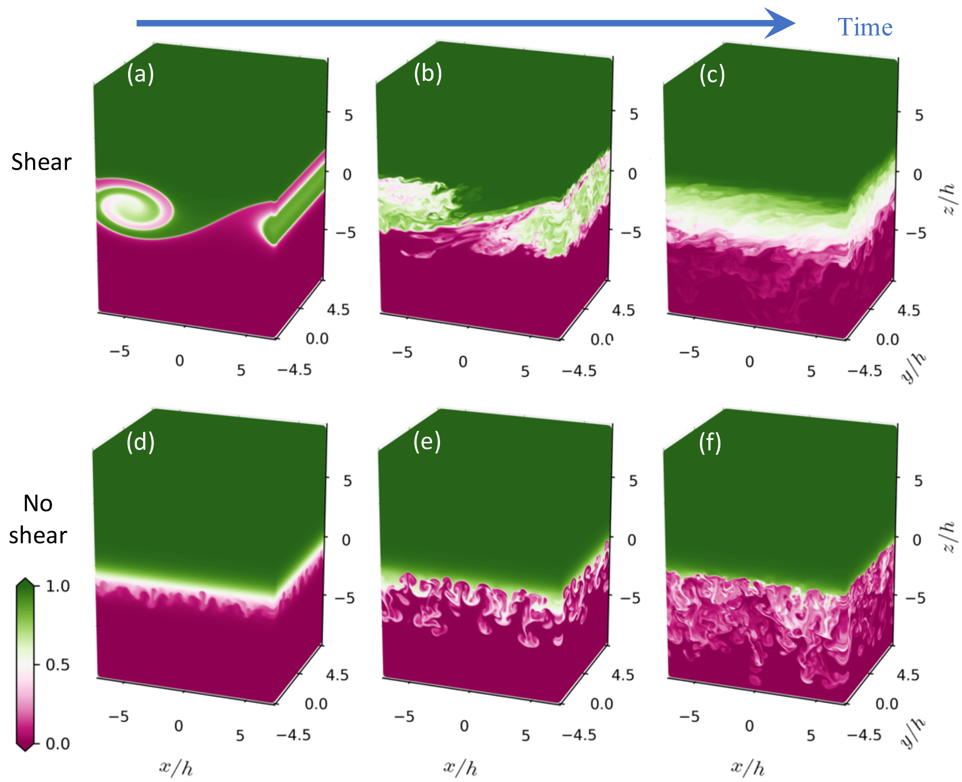

Fig. 1. Evolution of the three-dimensional normalized sediment concentration at representative times: (a)-(c) in the presence of velocity shear, $\Delta U = 0.91$ m s^{-1} at $t = \{20,25,35\}$ and (d)-(f) without shear, $\Delta U = 0$ at $t = \{35,40,45\}$.

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Light attenuation due to preferential orientation of non-spherical particles in waves and shear flow

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Abstract

Particles are a key component of the aquatic light climate that contributes to the attenuation of light in the water column. Near the water surface, wave and shear flows induce a preferential orientation of non-spherical particles (see figure 1a) that alter their inherent optical properties and the resulting attenuation of light (see figure 1b). This theoretical study focuses on how particle shape and the corresponding preferential orientation due to waves and shear impacts the light climate in an aquatic environment. We use homogeneous spheroid particles with the anomalous diffraction optical approximation to examine the effect of orientation on light attenuation. Our theoretical results show that the preferential orientation by waves and shear tends to increase the projected area of the spheroid compared to random orientation. For particles comparable in size and shape to algae, diatom colonies, or microplastics this corresponds to increased light attenuation by approximately 25% (see figure 1c). For smaller bacteria-sized particles the orientation corresponds to a decrease in light attenuation by approximately 20%. This idealized framework enables preliminary investigation of how preferentially aligned particles by waves and shear can impact light attenuation in the water column.

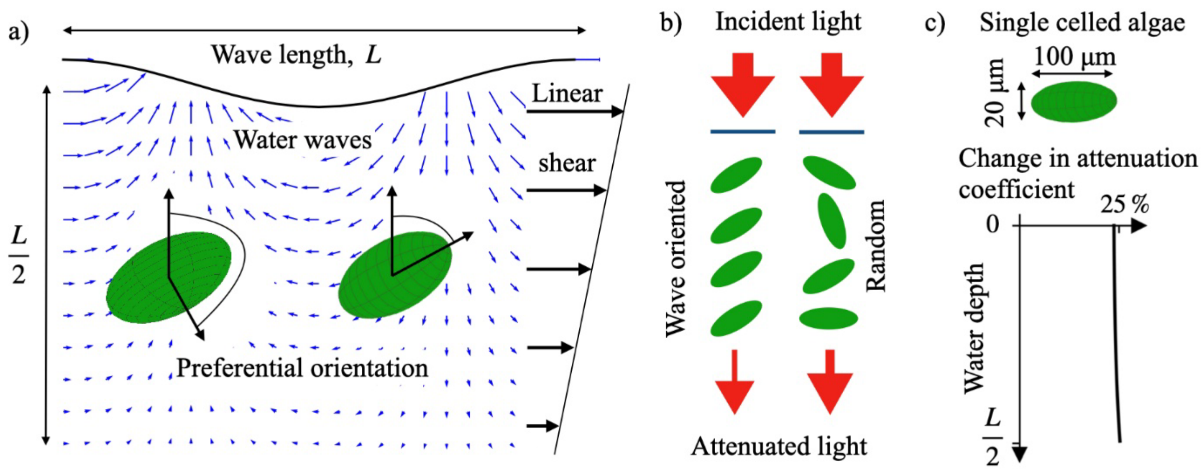

Figure 1: Illustration of the effect of orientation on light attenuation: a) preferential orientation of particles in waves and shear combined flow, b) attenuation of light of particles oriented by the flow compared to the random orientation case, c) change in attenuation coefficient for an example algae-like particle.

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A Simple Model for Vertically Propagating Seiches

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Abstract

In small lakes and ponds, seiches sometimes propagate vertically[1,2], a phenomenon not represented by classic seiche models. Propagation results when bottom boundary layer dissipation prevents strong internal wave reflection from lakebeds. Here, a simple model is developed to simulate vertical seiche propagation, and tested against observations from a small pond. The model solves coupled, linearized conservation equations for mass and momentum in three layers: an upper mixed layer, a continuously stratified interior, and a bottom boundary layer. Oscillating winds generate flows in the mixed layer, tilting the thermocline. Thermocline tilt generates internal waves that propagate through the interior. Coupling between interior and bottom boundary layers determines a complex reflection coefficient relating the energy of upward- and downward-propagating waves. The full model predicts a transfer function relating the amplitude of seiche motions to wind stress fluctuations. The transfer function displays peaks at resonant seiche frequencies, which weaken and broaden as boundary layer dissipation increases. The phase between wind and seiche oscillations transitions as the frequency increases from below- to above-resonance. These predictions are tested against observations of winds and velocity profiles in a small pond.

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Optimizing Floating Solar Configuration Design to Mitigate Environmental Impact on Freshwater Reservoirs

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Abstract

Renewable energy deployments can help meet net zero targets. Amongst these, photovoltaic sources are forecasted to dominate the global energy supply by 2050, with exponential growth in the deployment of Floating Photovoltaic Panels (FPVs). Despite the rapid pace of FPVs deployment, little is known about physical, chemical, and ecological impacts on hosting waterbodies, and potential mitigation options. Consequently, there is a pressing need for tools that will allow us to predict impacts on water bodies and help the design of potential future installations. In response, this study investigates how the thermal structure of a freshwater body responds to multiple FPVs array configurations - including 'light island' geometries, i.e., gaps within the array - and percentage coverages using the three-dimensional numerical modelling software package Delft3D-FLOW. We simulate how the strength and duration of thermal stratification vary over time and space and find that the magnitude of the FPVs' impacts on water temperature and water column physical properties vary seasonally and depend on the percentage coverage of the lake surface and the number, size and spatial distribution of light islands. These results provide insights to guide management options for impact mitigation whilst building an understanding of the environmental impacts of FPVs.

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Floating Photovoltaics on Lakes: What Coverage is Needed to Counteract Climate Change Effects?

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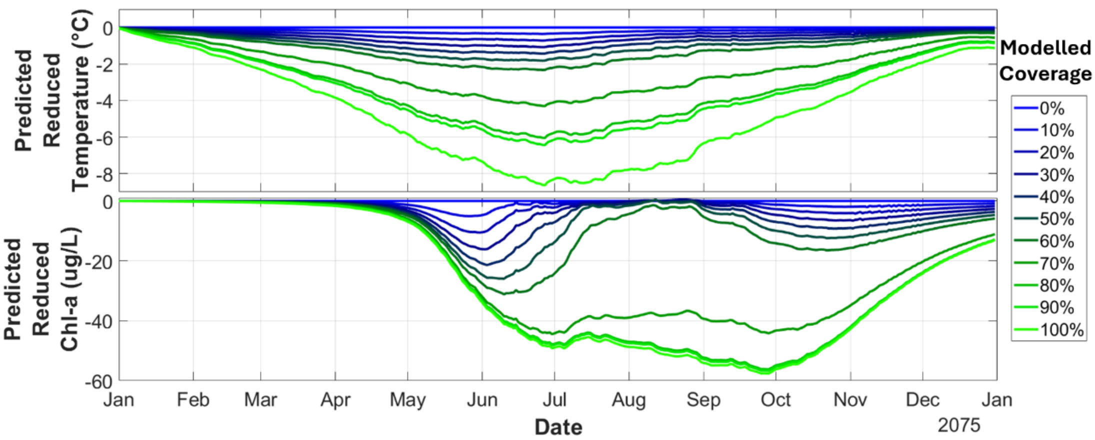
Abstract

Anthropogenic climate change threatens lake ecosystems and prompts decarbonisation efforts. Floating photovoltaics (FPVs) are a technology that could potentially mitigate lake warming and decrease phytoplankton bloom frequency by lowering solar and wind impacts on the covered lake surface and reducing reliance on fossil fuels, presenting a way to resolve both problems while also reducing land use conflicts. FPV arrays can vary significantly in position on the water body (e.g. changing hydrodynamics beneath the array), array design, and proportion of the water surface covered. Using a modelling tool designed to rapidly assess FPV configurations for project development and observational data from Queen Elizabeth II Reservoir (QE2), London, UK - where an FPV array has been installed since 2016 - we identify which configurations most effectively mitigate climate change effects on the reservoir ecosystem and water quality. The tool employs the MyLake model to simulate the impact of multiple FPV configurations, varying coverage from 0% to 100%, under multiple projected climate scenarios. For comparison, we also present observational water column data taken from close to the FPV array to illustrate the influence on the water body of the current 4.5% FPV coverage. Our model results show that with greater coverage, the cooling effects and phytoplankton reduction of FPVs are magnified, with coverages > 70% and > 20% sufficient to counteract climate-induced effects on temperature and algal concentrations, respectively. However, at high % coverages, other issues may arise, such as reduced winter water temperatures. Observations from the QE2 suggest that a low % cover FPV array did not affect water proximal to the FPV. There has been an apparent reduction in algae since the FPV was installed, but this is also seen in two neighbouring water bodies, suggesting an alternative influence beyond the FPV array. This indicates that, as reported in the literature, lower coverages do not substantially affect the water quality. Thus, findings suggest smaller FPV coverages (≈5%) can be widely implemented without disrupting lake conditions. In contrast, more extensive coverages can address warming and phytoplankton blooms but require more careful planning as simulations of significant coverages showed drastic alterations to the water body, e.g. near zero simulated chlorophyll-a. FPVs are an emerging technology that could counteract the effects of climate change but may require tailored designs for more significant coverage.



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Investigating the effects of wind on floating particles

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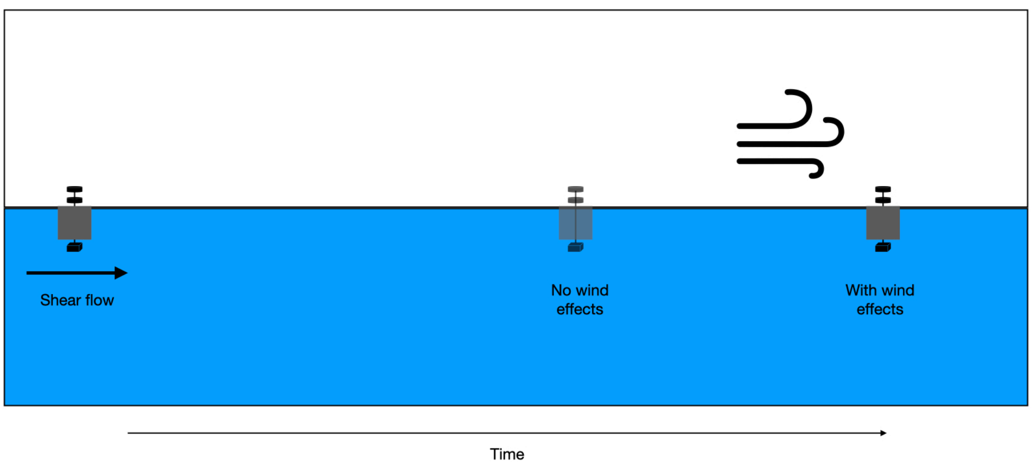
Abstract

Drifters are used to track near-surface ocean currents. Recently, focus has been shifted to making drifters smaller and with different designs to increase efficiency and reduce cost. However, a floating object does not necessarily follow the path of the water. This 'slip'/'leeway' arises primarily due to wind effects and inertia (since drifters have mass). Effects of the wind on such drifters are not well documented. There have been studies in the past aimed at analyzing observational datasets and modelling boundary layer effects (due to wind, drag and Stokes drift) on some drifters launched during the TReX experiment (Pawlowicz et al., 2024). We report on the development of modelled drifters in a shallow-water numerical model which involves wind effects. We investigate the effects of wind shear on floating particles using the developed model. We explore various test cases such as gyres and unstable jets in our analysis. Finally, we comment on the potential speed up of the runtime when the computation is carried out using a graphical processing unit (GPU).



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Wave Basin Experiments to Quantify Sediment Transport From Localized Beach Nourishments in Idealized Wave Conditions

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Climate change is driving an increase in storm frequency and along with rising water levels this will cause higher rates of shoreline erosion in lakes and oceans. A common approach for protecting coastal areas is to nourish regions with large volumes of sand distributed along the beach. While this approach protects infrastructure and preserves recreational areas, it can be inefficient due to the high frequency and cost of nourishment required and impacts on the natural environment. Another approach involves adding localized beach nourishments updrift of the area being impacted by erosion. This allows sediment to naturally redistribute over time, with a lower nourishment frequency and potentially lower impact on the natural environment. While this technique has been implemented into large scale field applications such as the Sand Engine in the Netherlands, detailed measurements collected in laboratory studies can be used to investigate the optimal offshore locations for localized sand nourishments. Using the wave basin at Queen's University on a beach with a 1:10 slope, and regular waves generated by a paddle oriented at an oblique angle to the shoreline, a series of localized sand-pile tests are performed to study the effect of the initial nourishment location on sediment transport. The sand piles are strategically distributed across the nearshore region to better understand the impact varying locations have on the transport rates and mechanisms, quantified using high-resolution LIDAR observations and geo-rectified camera images. The results contribute to better understanding wave-driven sediment transport and morphological evolution in beach nourishment projects.

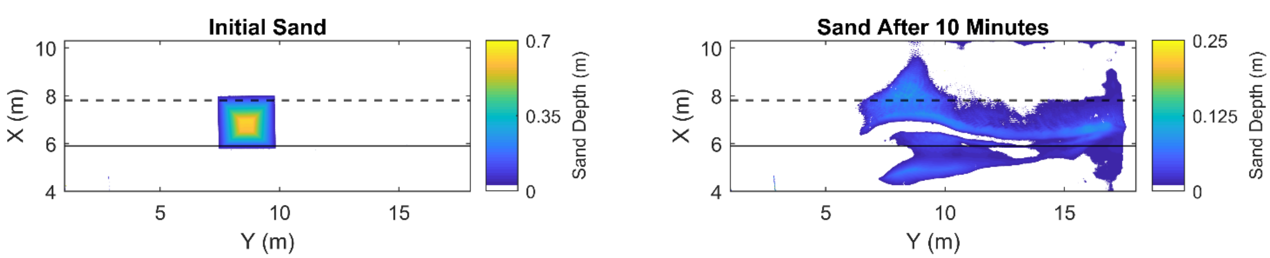

Figure 1 - Processed LiDAR scans showcasing sediment transport after a 10 minute test

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Application of machine learning to improve hydrodynamic and surface water quality modelling

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Abstract

Process-based coupled hydrodynamic-biogeochemical models are widely used to simulate surface water quality processes in lakes. Despite extensive efforts by users, model calibration remains subjective and often computationally intensive. This challenge arises from the complexity and interdependence of model parameterizations, which require extensive manual tuning to match simulations with field observations. Uncertainties and data gaps in nutrient and phytoplankton inputs further complicate model setup process. To address these challenges, we developed a machine learning (ML) based approach for model parameter calibration and gap-filling of tributary input files. The ML framework was applied to a three-dimensional Aquatic Ecosystem Model (AEM3D) model of Lake Erie, where the lake frequently suffers from a range of water quality issues including invasive species, harmful algal blooms, hypoxia, and climate change. This framework minimizes the root-mean-square error of simulated state variables in comparison to field observations and estimates the nutrient and phytoplankton concentrations in eleven major riverine inputs. This automatic and computationally efficient approach enhances model accuracy, reduces subjectivity in calibration and improves model representation of ecosystem services.

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Observing surface water currents and plastic pollution transport using GPS-tracked drifters in Georgian Bay, Lake Huron

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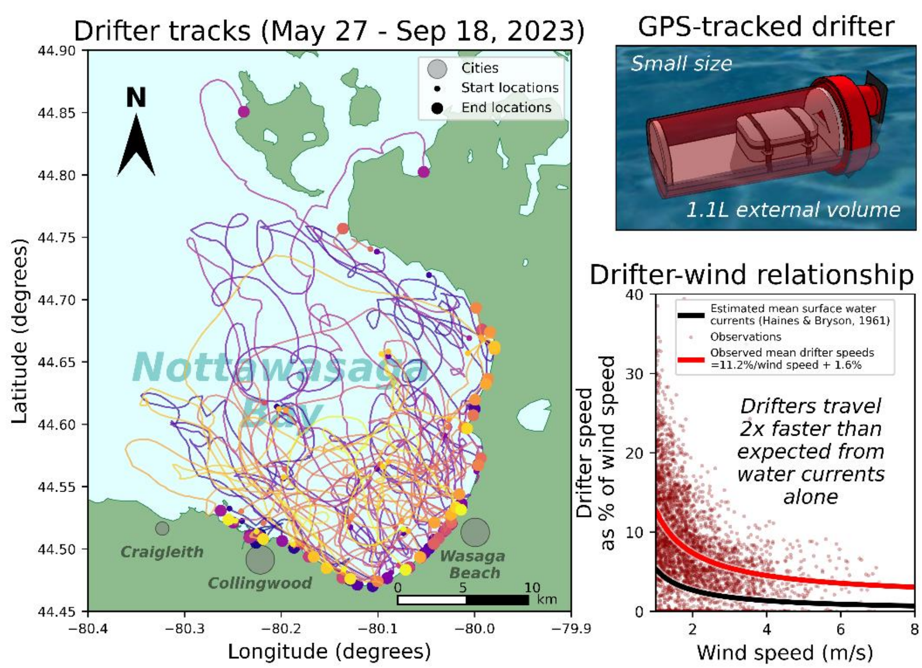
Abstract
To understand and observe plastic pollution transport in large lakes with limited existing empirical knowledge of water currents, GPS-tracked bottle-drifters were released in Nottawasaga Bay of Georgian Bay. During the summer of 2023, 67 usable drifter datasets were collected from 20 GPS-tracked drifters deployed over 8 rounds of deployments from May through September. From the release of our drifters, we learned that most drifters entering Nottawasaga Bay were retained within the bay but typically travelled tens of kilometers over several days before reaching shore. We observed evidence of a strong northwesterly near-shore surface water current exporting 2 drifters out of northern Nottawasaga Bay. Clockwise-spiraling water currents demonstrated inertial motions caused by Earth's rotation (Coriolis effect) during periods of low wind. Drifters demonstrated strong wind-dependent transport and travelled twice as fast as would be expected from water currents alone. The use of drifters allowed us to identify spatial patterns of plastic pollution transport and accumulation to inform natural resource and habitat conservation efforts.



Graphical abstract. *Left:* Observed drifter tracks during the summer study season of 2023 (May 27 - September 18). A time-lapse animation can be viewed here: https://youtu.be/HVGTaywbXU8. *Top Right:* Three-dimensional rendering of GPS-tracked bottle drifters. *Bottom Left:* Relationship between observed drifter speeds and wind speeds compared to expected water current speeds.

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The characteristics of the seasonal internal waves and the effectivenesses on the Lake Trout habitats: A near shore study in Lake Ontario

Zheng (Zac) Zhu, Mathew Wells, and Jon Midwood

Abstract: Internal waves, which occur at the interfaces of water layers with different densities, play a important role in the dynamics of the lake environment. However, in the Lake Ontario, there is a gap between the characteristics of the internal waves and their impacts on the fish habitats as well as their effects on the ecological balance and fisheries management. This study focused on a 200-kilometer-long western shoreline of the Lake Ontario and ultilized data from April to October 2023, and we analyzed the spatial and temporal patterns of internal waves and their correlation with the Lake Trout occurrence. Our results showed that temperature changes driven by the internal waves have a strong connection with the Lake Trout distribution patterns. The finding underlines that it is important to consider internal waves dynamics when further investigating fish habitats and sustainable fisheries management.

Bubble Facilitated Bitumen Transport

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Abstract

Understanding gas migration in sediments is essential to manage contaminant transport, including for sediments contaminated with oils. This could include liquids such as coal tar, often found in waterways near former manufactured gas plants, or residual bitumen, which can be found in end pit lakes associated with the Athabasca Oil Sands. Microbial activity within these sediments can generate methane (methanogenesis), and as the gas bubbles rise through the sediment, residual oil adheres to the air-water interface of the gas bubbles, facilitating upward transport of the oil into the overlying water cap. Few studies have been published regarding the transport of oil due to ebullition, and quantitative measurements are necessary to understand this process. This research addresses this gap through laboratory experiments conducted in a 2D flow cell during which nitrogen gas was injected, as a surrogate for methane, into contaminated sand. The transport of oil within and out of the sediment (sand), and the gas channels will be observed and quantified using image processing. Figure 1 displays a processed and unprocessed image for a preliminary oil-free experiment, highlighting gas channels (blue) and gas fractures (red) in a d_{50} = 0.5 mm sand. The gas channels represent connected air-statured pore spaces. As the gas channels rise, the compressive stress in the sand reduces, which allows for bubbles to form. It is expected that oil (e.g., coal tar, bitumen) will adhere to the air-water interface and migrate upwards with the gas bubbles as they rise through the overlying water. These results will aid in quantifying oil transport mechanisms, informing future efforts to manage contaminated sediments and tailings storage infrastructure.

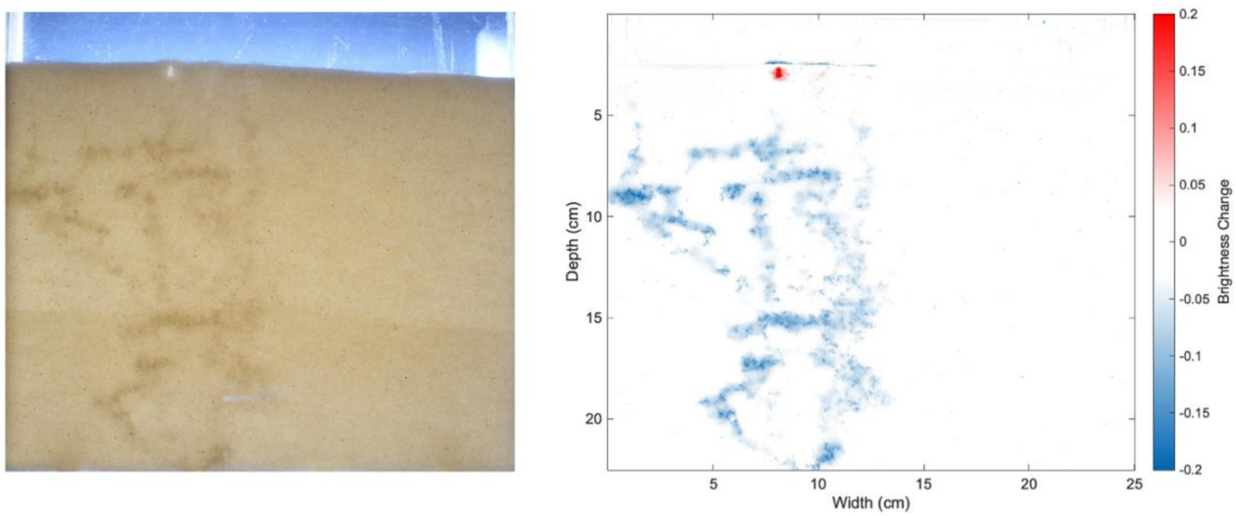

Figure 1: Gas network for an unprocessed (left) and processed (right) image taken at the same time, where positive changes in brightness represent a gas fracture and negative changes represent gas channels.

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Integrating Ecological and Hydrodynamic Modelling to Understand Nearshore Phosphorus and *Cladophora* Dynamics in Lake Ontario

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Cladophora glomerata is a filamentous green alga that has proliferated in the rocky nearshore zone of Lake Ontario since the mid-1990s, leading to extensive fouling of local beaches with decaying organic material. *Cladophora* blooms are influenced by several factors, including nutrient loading, light availability, presence of dreissenid mussels, and hydrodynamics, thus requiring a more granular approach to modelling its growth and impacts. Our analysis presents the findings from a comprehensive sensitivity and uncertainty analysis focused on the interplay among phosphorus, and three interacting modules for plankton, dreissenids, and *Cladophora*, within the nearshore zones of Lake Ontario. Based on our results, we revisited the existing parameterization and input specifications to accurately reflect the nearshore, small-scale processes within the Lake Ontario ecosystem. As the next phase of this research, we will integrate the ecological model with a hydrodynamic model to assess the influence of physical processes, including upwelling, stratification, and mixing, on nutrient transport and biological responses. This coupling will improve our ability to predict *Cladophora* dynamics under varying environmental conditions, contributing to informed management strategies for the nearshore of Lake Ontario.

A Mathematical Model of Contaminant Transport with Sorption to Sediment

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Abstract

The transport of hydrophobic contaminants in natural waters is complicated by their affinity for partitioning to phases other than water such as bubbles, sediment, or dissolved organic matter. If clean sediment is suspended in contaminated water, a contaminant may adsorb onto the surface of the particles and settle to the bottom of the domain with the sediment. Conversely, if contaminated sediment becomes resuspended in clean water, a contaminant may be introduced into the water column as it desorbs from the particles. The contaminant exists in one of two states: freely in the water, or sorbed to sediment. We model the exchange between these two states using an isothermal equilibrium condition. We then derive a mathematical model for the transport of a contaminant that undergoes reversible sorption to sediment. In the water, the contaminant concentration is governed by a scalar transport equation with an added source term to capture the exchange with the sorbed state. The transport of sediment provides a pathway through which the sorbed contaminant can be transported. The model is reduced to several limiting cases to verify its applicability. Results from early numerical simulations of the model will be presented highlighting the importance of key rate parameters. We will conclude with a discussion of our planned avenues of exploration.

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Ongoing shifts in the timing of fall overturn in Lake Simcoe due to rising fall air temperatures and decreasing wind speeds

Bridget Hart[1], Mathew Wells[1] and Lidi Shi[1]

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Abstract

North temperate lakes in North America are known to be experiencing a delayed fall overturn due to global warming and shifts in the wind patterns. Lengthened summer stratification and delayed fall overturn have an impact on species living in the lake and increase the chance of hypoxia forming in the deep water. Cold-water species, such as lake trout, are greatly affected as they must wait longer for the lake to be replenished with dissolved oxygen at depth in the fall. Using over 40 years if bi-weekly profiles of temperature in Lake Simcoe from 1980 to 2024, we investigate how changes in air temperature and wind speed contribute to cause of this delay. Through the analysis of water column stability, the historical trend showed the day of fall overturn is getting later and now occurs in October rather than September. The peak mid-summer Schmidt stability of the water column has increased by 50% since 1980. This is due to an increase in the peak mid-summer surface water temperatures, that has changed from having low values of mid-summer epilimnetic temperatures of 18oC to highs of 24oC. During the same period the maximum fall wind speeds dropped by around 30%. The delay in fall overturn could be explained by a Multi-Linear Regression that includes variability in wind-speed and fall air-temperature which had an R2 value of 0.4. For two of the recent years we have access to acoustic telemetry data, and we show how Lake Trout sit below the summer thermocline but use the whole water column during fall overturn when water temperatures drop below 12oC. We discuss how the shift in fall overturn dates then implies there will be changes in fish habitat usage and the timing of fall spawning of these important but threatened fish.

Optimized Vertical Heat Flux Estimation using Data Assimilation

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Abstract:

Vertical mixing controls the vertical distribution of heat, salt, and nutrients in lakes and oceans. Current mixing models often employ dissipation-based parameterizations to estimate the scalar fluxes, which require acoustic measurements and/or arduous parameter fitting. We developed a data-driven adjoint method to determine the optimal heat flux by minimizing error between observed temperature profile data and a simple 1D diffusion model. The method was validated against a series of synthetic datasets with diffusive and periodic fluxes and showed convergence to mean errors of $O(10^{-4}\ °C)$. In this study, we apply the method to a series of field datasets from North American lakes including microstructure profiler (SCAMP) casts of internal wave-induced shear instability, thermistor chain measurements of internal waves, and thermistor chain measurements of seasonal overturning events. We show convergence for the method across various datasets and analyze the vertical heat fluxes present. It is important to note that the method can only simulate vertical heat fluxes and thus is susceptible to higher bulk error values for field data sets with significant horizontal effects. As a result, the error for the field data applications is on the order of $O(10^{-2}\ °C)$. We evaluate diffusivities in a flux-gradient model and compare with estimates from other empirical methods. The results show that the data-driven heat flux approach is highly efficient and robust across various spatial and temporal resolutions.

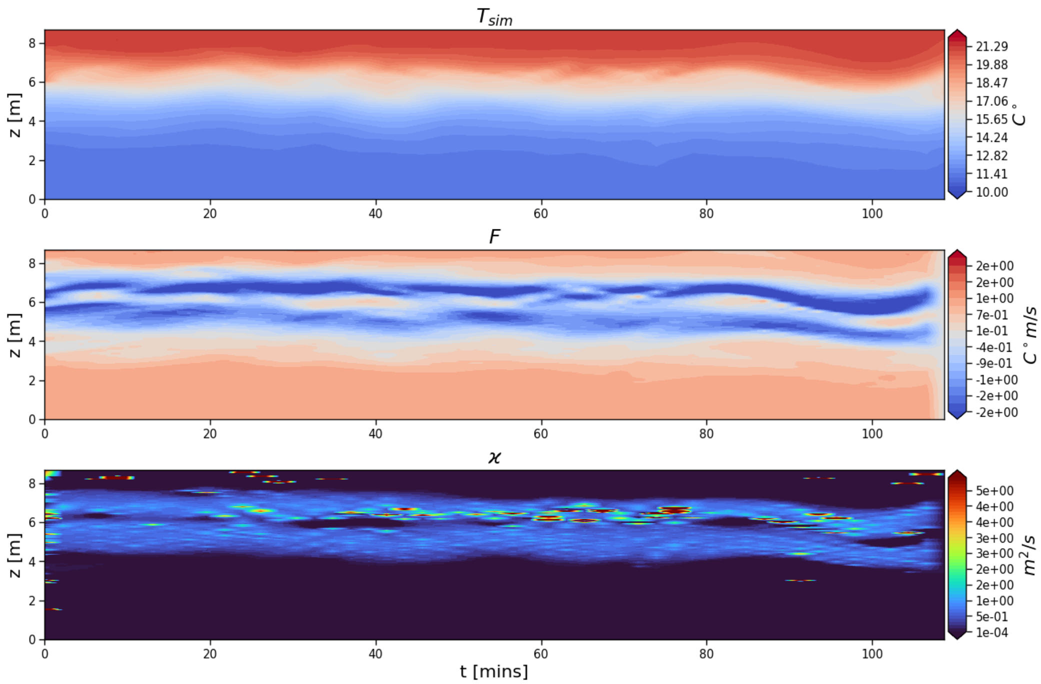

Figure 1. Simulated temperature profile T_{sim}, optimized heat flux F, and flux-gradient diffusivity κ for Lake Erie SCAMP cast data from (Bouffard et al., 2012)

References:

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Experimental investigation of bedform growth beneath periodic internal solitary waves propagating through a tidal flow

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Abstract

Internal solitary waves (ISWs) are common features of lakes and coastal oceans and have been often proposed as a mechanism for the generation of bedforms. Yet, the physical processes underlying bedform growth driven by ISWs remain poorly understood. We conducted laboratory experiments to investigate bedform generation by periodic ISWs propagating through a background tidal flow. Our experiments revealed spatially periodic resuspension 'wisps' with the passage of an ISW (Figure 1, a-c), like what was previously observed by Aghsaee et al. (2015), that coincide with increased 3D velocity fluctuations and bed stresses. We interpret these as the signature of vortices generated by the amplification of the Tollmien-Schlichting instability of the separated bottom boundary layer (BBL). We propose a feedback mechanism between the BBL instability and bed defects that leads to bedform generation. Here, the BBL instability creates spatially-periodic bed defects that act as perturbation sources, which amplify the instability and bedform growth upon passage of a subsequent ISW. The wisp spacing and bedform wavelength matched the wavelength of the most unstable mode of the BBL, as predicted by linear stability analysis. The observed morphodynamic features, and their generation, are consistent with the BBL flow beneath ISWs of depression predicted by numerical simulations (Figure 1, d-f) (Posada-Bedoya et al. 2024; Posada-Bedoya et al. 2025). Although the sediment resuspension and bedforms are driven by the ISW-induced BBL flow, they are modulated by the background tide. During an ebb tide, the BBL currents beneath the trough of an ISW of depression are reinforced by the tidal flow, increasing the local Reynolds number and correspondingly the instability growth rate.

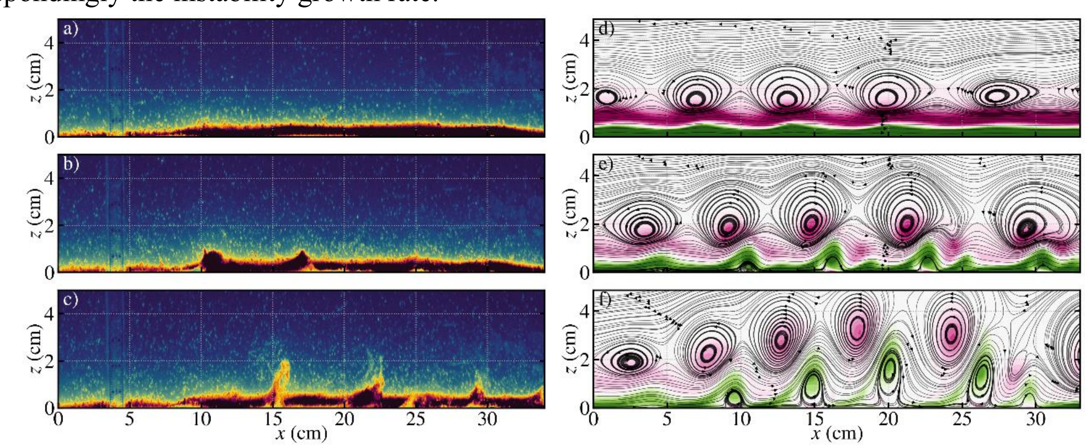

Figure 1. (a-c) False colour snapshots of the near-bed sediment resuspension upon the first ISW passage. (d-f) Snapshots of streamlines (black lines) and vorticity field (filled contours) simulated by Posada-Bedoya et al. (2024) for their case B4 (Re_{ISW}~300). Pink and green vorticity contours indicate positive and negative values.

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Modeling the Impact of Physical Processes on Lake Erie Walleye Egg Survival and Recruitment

B. Kuyumcu[1*], L. Boegman[1], S. Shan[1,2], W. Shi[1], Y. Zhao[3] and J. Ackerman[4]

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[3] Aquatic Research and Monitoring Section, Ontario Ministry of Natural Resources and Forestry Lake Erie Fishery Station, Wheatley, ON, Canada
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Abstract

Physical processes such as waves and currents may have significant impacts on fish recruitment. For example, mortality may result from egg abrasion during bed-stress events and from currents transporting eggs/larvae to unsuitable substrates/habitats. In this study, we computationally model these impacts for Lake Erie Walleye (*Sander vitreus*), which support a billion-dollar fishery. Our objective is to relate, Walleye recruitment to mortality from storms occurring during the spring incubation period [1]. We simulated water currents, temperatures, significant wave heights and periods, and applied this data to determine bed-stress, egg resuspension, temperature-dependent spawning, egg growth and the incubation period. We defined a mortality rate and threshold from published observations of egg counts before and after a storm event [2], where each bed-stress event with a shear velocity > 0.52 m/s resulting in 55% egg mortality. Egg resuspension and transport to unsuitable substrates was not modelled due to high mortality from abrasion during resuspension [2,3]. Preliminary results indicate that wave-induced bed-shear is a significant factor influencing recruitment, as wave height ranges were adversely correlated with age-2 walleye abundance. Future research will combine tracking of hatched larvae [4] with a growth model to assess whether the anticipated match-mismatch between first-feeding larvae and zooplankton explains observed variations in recruitment.

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Predicting near-bed hypoxia via stratification in a large polymictic basin—a machine learning approach

Yulong Kuai, Shuqi Lin, Mathew Wells

Polymictic lakes are not always mixed, and they often experience periods of weak stratification. Pigeon Bay, which is in northwestern basin of Lake Erie, is an example of a large polymictic basin that experiences frequent interchange of mixing and stratification. Such interchange of mixing and stratification is associated with the fluctuation of dissolved oxygen near the lakebed, and on many occasions, hypoxia can occur simultaneously with the development of strong stratification with vertical temperature difference > 2°C due to the advection of hypolimnetic water from the central basin of Lake Erie. Frequent hypoxic events can affect coagulation processes of water treatment plants, and in Pigeon Bay, there is an important near-shore municipal water intake, which supplies drinkable water to ~66,800 residents and to the second largest greenhouse cluster in the world; therefore, it is crucial to understand the correlation between the stratification and hypoxia in Pigeon Bay. To better predict the development of hypoxia, we used a machine learning (ML) model, Gradient Boost Regressor (GBR), to predict hypoxic events near the lakebed via stratification. We used high-frequency water temperature and dissolved oxygen data from three sampling sites in Pigeon Bay from 2021 to 2024 to train the model and simulate the dissolved oxygen near the lakebed. The ML approach showed promising results, which can be used for building an early warning system of fluctuation of dissolved oxygen near the lakebed for the municipal water intake.

Modelling Winter Thermal Stratification of Morphologically Diverse Lakes in Algonquin Park, Canada Through Meteorology

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Abstract

With hundreds of dimictic lakes across Canada undergoing seasonal ice cover, understanding the thermal dynamics and mixing processes within these ecosystems is essential for predicting their responses to climate change. This research investigates the thermal structure and mixing dynamics of small, interconnected, morphologically diverse lakes in Algonquin Park, Ontario. The study aims to analyze the influence of wind speed and air temperature on winter stratification using a 1D hydrodynamic model (Flake) and the Monin-Obukhov length scale to reveal a strong connection between these meteorological factors and winter thermal structure. Furthermore, the research focuses on identifying the meteorological conditions that lead to cryomictic and cryostratified regimes. Traditionally, lakes in winter were thought to always undergo inverse stratification. However, recent research highlights the importance of distinguishing between cryomictic and cryostratified regimes, which exhibit different dynamics and mixing processes. Cryomictic lakes experience mixing beneath ice, resulting in well-mixed water columns similar to the bi-annual turnover events in dimictic lakes. In contrast, cryostratified lakes undergo traditional inverse stratification, with colder, denser water residing at the surface leading to conditions such as anoxia. By using predictions of lake responses to winter conditions, this study provides insights that can inform the management of aquatic ecosystems as they face the challenges imposed by a changing climate.

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Numerical investigation of sediment resuspension beneath internal solitary waves

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Abstract

We investigate sediment resuspension beneath periodic internal solitary waves of depression ($Re_{ISW} = 300$) using two-dimensional numerical simulations. At this Reynolds number, the boundary layer beneath the rear shoulder of the wave is susceptible to a convective instability. The repeated interaction of the instability with successive waves amplifies the instability to finite amplitude [1], and we hypothesize that these interactions may enhance sediment resuspension.

To test this hypothesis, we simulate suspended sediment concentration using an advection-diffusion equation that incorporates a particle settling term. Sediment pickup at the bottom boundary is parameterized as a diffusive flux, following the approach developed experimentally by Garcia & Parker [2] and applied numerically in Olsthoorn & Stastna [3]. We identify two regimes of sediment dynamics. In the first regime, the leading wave induces bed shear, mobilizing a thin layer of sediment. With successive wave passes, the sediment layer grows to an equilibrium height determined by the balance between particle settling and diffusion. In the second regime, the amplification of the convective instability during repeated wave passes leads to enhanced sediment transport from the near-bed region into the free stream due to the convective instability. The division between these two regimes defines a critical threshold for sediment resuspension, expressed in terms of bulk wave parameters and sediment properties.

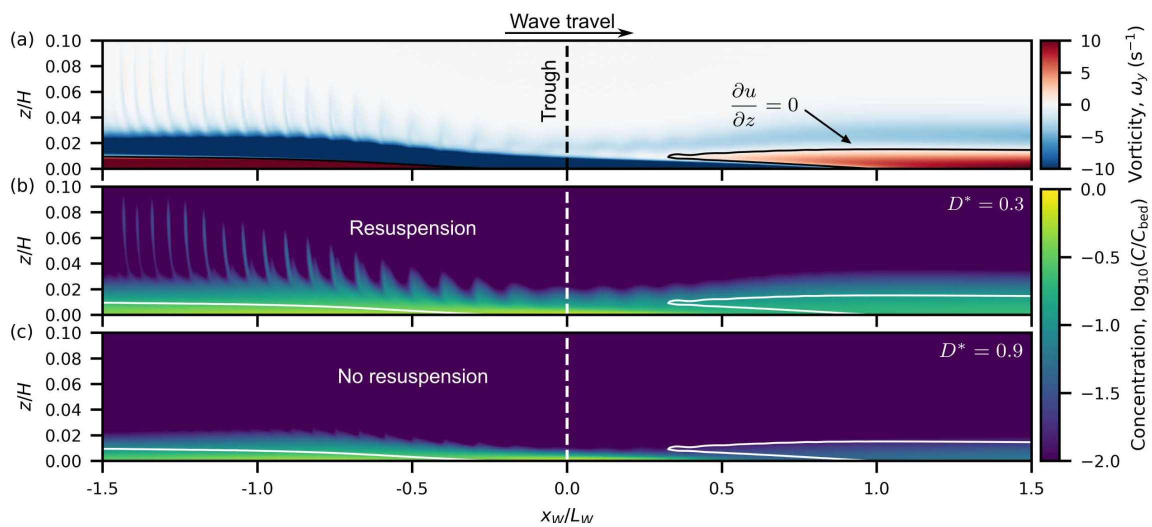

Figure 1. Near-bed region illustrating variations in (a) vorticity and (b, c) sediment concentration for dimensionless grain sizes $D^* = 0.3$ and 0.9. The wave propagates from left to right, and the wave trough is centered at $x_w/L_w = 0$.

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Climate-Induced Changes in Nearshore Circulation Patterns in Lake Ontario: Insights from Fine-Scale 3D Hydrodynamic Modeling

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Abstract

Recent shifts in wind and temperature patterns in the Great Lakes region suggest that climate change may be subtly but significantly altering nearshore hydrodynamics. This study explores circulation changes in Lake Ontario using a high-resolution, three-dimensional hydrodynamic model (MIKE 3 FM) calibrated with extensive field data collected in 2013 and 2018. The model resolves key lake-scale and nearshore processes, including upwelling and downwelling, internal Kelvin waves, and near-inertial oscillations.

Model results show that upwelling events on the northern shore, driven by southwesterly winds, have increased in frequency and intensity compared to historical baselines. These upwelling events often initiate coastally trapped Kelvin waves, which propagate cyclonically and intensify cross-shore exchange. Compared with earlier studies assuming stable, anticyclonic nearshore flow, our findings indicate a shift toward cyclonic circulation during the stratified season, particularly in urbanized regions such as the Golden Horseshoe.

To test the sensitivity of these dynamics to climate variables, we simulated four scenarios with increased wind speed, air temperature, humidity, and precipitation. Results demonstrate that higher wind energy promotes stronger and more frequent upwelling events, while elevated air temperatures deepen and stabilize stratification, delaying or suppressing weaker events. Together, these changes may amplify horizontal mixing, influencing nutrient delivery and the ecological balance in the littoral zone.

This work demonstrates how integrated modeling and observation frameworks can detect climate-driven changes in lake hydrodynamics with high spatial and temporal resolution. The findings have implications for nearshore water quality, ecosystem management, and the design of adaptive monitoring programs under changing climate conditions.

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Lake ice quality influences winter thermal stability and biogeochemistry: a case study of two southern Ontario lakes

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Freshwater ecosystems in the Northern Hemisphere are experiencing changing cryospheric conditions owing to global climate change, with shorter periods of lake ice cover and altered ice quality (ratio of white ice to black ice). Despite increasing recognition of the importance of winter to aquatic organisms and ecosystem function, many fundamental questions about winter limnology remain poorly understood. One understudied factor is the impact of ice quality, an important determinant of biogeochemistry and thermal structure of lakes under ice. To address this knowledge gap, we measured under-ice conditions over multiple winters in two lakes in southern Ontario, Lake Simcoe and Paint Lake, with contrasting ice quality, lake morphology, and land cover characteristics, but similar climates. We acquired high-frequency measurements of physicochemical parameters and weekly measurements of ice quality, chlorophyll, and water quality over two very different winters. Ice cover on Lake Simcoe consisted of up to 37 cm of predominately black ice, while Paint Lake was covered by up to 42 cm of ice with up to 70% white ice. Lake Simcoe and the deeper basin of Paint Lake were both inversely thermally stratified through the winter. However, Paint Lake had warmer under-ice temperatures and lower dissolved oxygen concentrations throughout the water column, particularly at greater depths and when snow cover was present. Meanwhile, a shallow embayment of Paint Lake was strongly stratified throughout the winter, with higher concentrations of dissolved ions (primarily Na & Cl), warm (up to 6 ºC in the hypolimnion), and nearly anoxic water near the sediments. These observations suggest that ice quality, lake morphology, and landscape characteristics are important drivers of the under-ice environment in seasonally frozen lakes, and suggest the potential for carry-over effects on productivity and physicochemical conditions in the spring.

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The role of changing winters on ice quality and light transmission in two southern Ontario lakes

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Abstract

Ice quality (the ratio of black and white ice) plays a pivotal role both for ice safety and under-ice aquatic ecosystems. While the processes leading to the development of black and white ice are clear, the evolution of ice cover during changing winters remains underappreciated from both a safety and ecosystem perspective. We conducted weekly winter sampling of two lakes in southern Ontario subject to similar hydroclimates but with differing morphologies and catchments during the ice-covered winters of 2024 and 2025. Kempenfelt Bay within Lake Simcoe, is a large (722 km^2) and deep (42 m) embayment with a substantial fetch (~14.5 km) and urbanized watershed. In contrast, Paint Lake is a smaller (1.5 km^2), shallower (21 m) lake with a heavily forested watershed. The two winters (2024 and 2025) studied had distinct climates that influenced the ice quality. In Kempenfelt Bay, a cold winter (2025) led to a doubling of black ice thickness compared to the milder winter (2024). Despite the distinct differences in temperature and snow cover between the two years, white ice remained low. In contrast, during the mild winter, Paint Lake's maximal ice thickness was 25 cm and the ice column was composed primarily of white ice (up to 70%) throughout the winter. In the colder winter, the ice was 38 cm thick, but the percentage of the ice column comprising white ice ranged from 7-64% depending on the sampling location and date. The interaction between the two seasons climates, variability in snowfall, and ice quality led to deeper light penetration in the water column during the mild winter. In response to light transmission, peak chlorophyll-a concentration was located deeper in the water column in the milder winter but was consistently located near the ice-water interface during the colder winter with thicker, more consistent snow cover. We also observed that peak chlorophyll-a responded rapidly to diminished light conditions by moving closer to the ice-water interface. Our observations illustrate that the ice-covered period has dynamic interactions between ice quality, snow cover, and light that result in primary producers that respond rapidly to changing winter conditions. Furthermore, contrasting winters strongly impact ice quality, leading to starkly different under-ice conditions that are further mediated by morphological and catchment characteristics.

Rapid lake ice structure changes across Swedish lakes puts public ice safety at risk

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Lakes are rapidly losing ice under global warming, but little is known about ice structure changes. Ice structure is a key regulator of ice stability and influences ecosystem processes, hydrology, and public safety.

Here, we present spatial and temporal variations in ice structure across 21 Swedish lakes, spanning 55 to 69 °N and over five decades. We discuss regional differences in ice quality where the fastest changes occurred in southern Sweden. The stable clear ice layer was particularly sensitive to warming, showing a rapid decline (2.3 cm decade^{-1}). The number of days when temperatures exceeded the freezing point during the ice cover period was identified as a strong driver for how ice was structured. The proportion of white ice versus clear ice showed four distinct patterns. In 67% of the cases studied, white ice thickness either increased, or white ice thickness decreased slower than the loss of clear ice. This resulted in thinner ice sheets where with ice became more dominant and with it, a high albedo. Such high albedo ice sheets potentially limit light transfer to the ecosystem below. Furthermore, the high proportion of white ice greatly reduces lake ice safety due to the lower bearing strength of white ice compared to clear ice. This study illustrates the variability in ice responses across a latitudinal gradient and the complexity of discerning lake ice safety and ice quality across multiple lakes.

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Exploratory Data Analysis of Winter Stratification in Lake Superior

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Abstract

Between 2005–2021, moorings were deployed by University of Minnesota Duluth's Large Lake Observatory in various locations across Lake Superior, with some deployments being nearly continuous over the whole time period. Data collection included thermistor output across the depth of each location, providing a wealth of information about temperature trends across the lake, spatially and temporally. This data was made freely available through DRUM (Data Repository for University of Minnesota). During winter, Lake Superior stratifies from an autumn well-mixed period, with colder, less-dense 0°C water on top, and warmer, denser 4°C water near the lakebed. Characterizing this stratification is the subject of study, using exploratory data methods to establish relationships between the onset, development, and extent of winter stratification. Empirical orthogonal functions (EOFs) provide a view into the complexity of the data, revealing that most of the data can be explained by just a few modes. The continuous wavelet transform (CWT) gives insight on what timescales stratification develops. Wavelet coherence can additionally be used to compare CWT outputs and show how air temperatures might affect surface temperatures or how shallow layers might drive the evolution of thermocline layers, and how this relationship shifts as the winter progresses. An example of this is shown below, with the left half showing the CWT on near-surface water temperature as compared to air temperature, and the right half showing wavelet coherence and its phase difference when the signals are coherent.

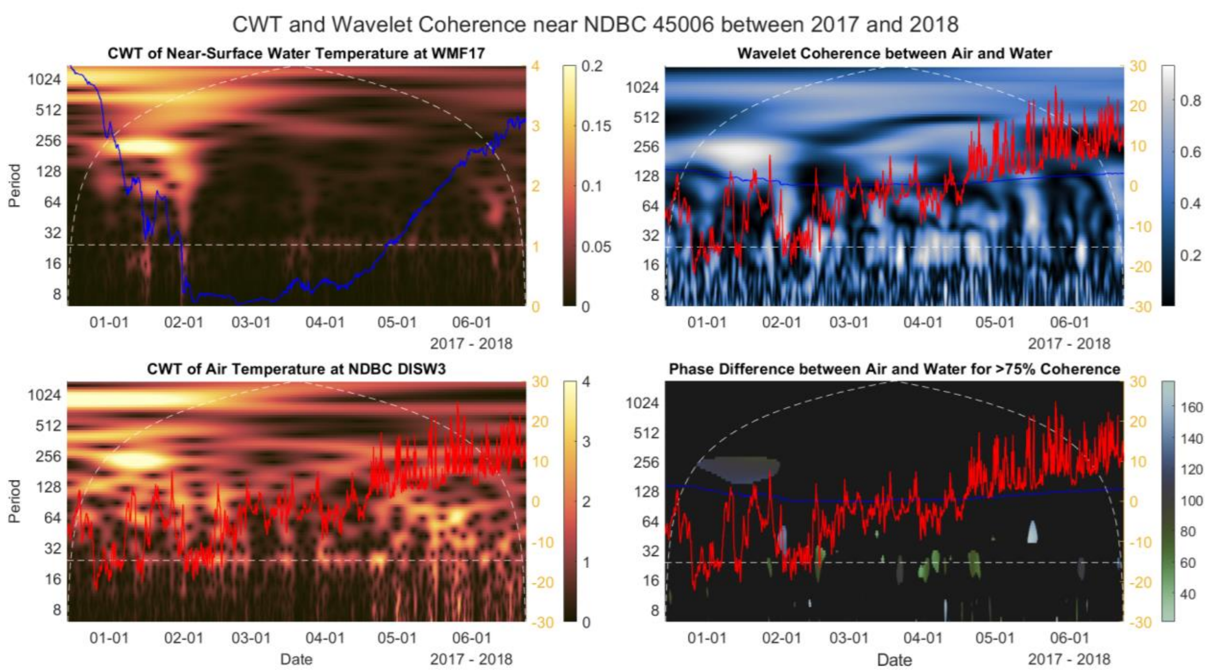

Figure 1. CWT on mooring WMF17 at 10 meters below sea level and NDBC station DISW3 with temperature profile overlaid. Station and mooring are about 90km apart. High degree of coherence in January, which may impact the onset of stratification, with no corresponding coherence in May as temperatures increase.

Inhibition of spring turnover in a brackish lake subject to ice cover

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Situated at 57°1′N, 111°37′W in Alberta, Canada, Syncrude Canada Ltd.'s Base Mine Lake (BML) is the first full-scale demonstration of an end pit lake in the oil sands industry. Formed through backfilling of fluid fine tailings into a previously mined-out pit, followed by capping with a water layer, BML has been monitored since its commissioning in 2012.

Recent studies have shown that the presence of low levels of salinity can have dramatic effects on the circulation of lakes subject to ice-cover. The exclusion of salt from ice as it forms can result in a relatively fresh surface layer immediately after ice melt. The density contrast between the ice-melt and the more saline water beneath it can be sufficient to hinder, or even prevent, turnover, thereby inhibiting the replenishment of oxygen at depth.

In this study, we investigate the inhibition and dynamics of turnover in the brackish BML, with a salinity of 2 ppt. We analyse field observations from the spring and summer of 2016 and 2017, and combine these with the results of the one-dimensional General Lake Model (GLM), to assess changes in the evolution of salinity and temperature stratification. Results suggest that while significant mixing occurs after ice-off, that turnover is ultimately incomplete in spring. Additionally, the dynamics at BML, are influenced by the expression of saline pore water from the settling of the underlying tailings, by hydrocarbon sheens on the water surface, and by two-dimensional processes, particularly upwelling. These findings highlight the limitations of using a one-dimensional model to represent this system.

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On the Velocities of Convective Sediment Fingers in a Salt-Induced Vertical Density Stratification

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Abstract:

When a river flows into the ocean, a vertical density stratification arises due to differences in temperature, salt concentration and sediment concentration. The observed settling velocity of sediment in those situations have been reported to be over an order of magnitude larger than the Stokes settling velocity, which is the theoretical settling velocity of the individual particles it constitutes of. One possible explanation for this observation is the process of convective sedimentation. Using a set of laboratory experiment we explore how the velocity of this process depends on the sediment concentration and particle size, with the goal of developing a scaling relationship that bridges the gap from laboratory to field scales. The density stratification is achieved by placing a layer of fresh water above a layer of salt water with a salinity roughly equal to that of most oceans. It is found that the sediment sinks in finger-like shapes at velocities significantly larger than the Stokes settling velocity. The velocity of the convective sediment fingers V_f is found to scale with the reduced gravity g', which depends on the sediment load, and Stokes settling velocity V_s. The experimentally found scaling of $V_f = 0.9\ (g')^{0.37\pm0.4}(V_s)^{0.45}$, with g' in m/s^2 and V_s in m/s is compared to previous proposed scalings found in literature. A new convective finger velocity scaling is put forward, the so-called `Willis and Deardorff velocity', which predicts $V_f = 0.6\ (g'V_sH)^{1/3}$. The scaling is consistent with experimental results for, but the dependence on the height of the domain H was not investigated in the current work. The Willis and Deardorff velocity predicts observed field behaviour most accurately out of three investigated theoretical finger velocities from literature.

Can you determine the lake bathymetry from patterns in the ice melt?

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Abstract

Although many lakes experience seasonal ice cover, winter limnology remains significantly less studied than its summer counterpart. This study investigates how lake bathymetry influences basin-scale circulation and associated ice melt rates during late winter. Modelling a lake with an idealized bathymetry (a truncated cone), we simulated convection-driven mixing under ice in response to atmospheric warming. In the absence of Coriolis forces, results showed that bathymetry affects under-ice circulation patterns and leaves a detectable imprint on the spatial distribution of ice melt. As Coriolis effects were introduced and intensified, an anticyclonic (clockwise) gyre developed, increasingly inhibiting lateral heat transport from density-driven currents. A transition in circulation regime was observed around a Rossby number of approximately 0.15, beyond which the melt pattern reversed—showing enhanced melting near the lake margins due to heat entrapment. These findings were further supported by simulations using real bathymetric data from Base Mine Lake, a pit lake in northeastern Alberta. Despite differences between the idealized and real-world scenarios, the observed ice melt patterns in the lake aligned closely with the non-rotational model results.

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Dynamics of Arctic Mixed-Layer Deepening

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Abstract

The first hundred meters of depth in the Arctic Ocean contain enough heat to melt the entire sea ice cover, but this heat remains trapped due to the strong salinity stratification beneath the mixed layer. Sufficient surface forcing from air-ice-ocean interactions and buoyancy fluxes produced from sea ice growth can deepen the mixed layer and entrain the underlying heat upwards, thereby ablating sea ice or inhibiting its growth (Figure 1). Earth's rotation complicates this by requiring the deepening process to adjust to rotational effects after half an inertial period, $t_f/2$ ($\approx$ 6 hours in the Arctic), resulting in two phases of deepening for a constant surface forcing: early deepening ($t < t_f/2$) and late deepening ($t > t_f/2$). In addition, turbulent motions in the mixed layer can undulate its base, radiating energy into the interior ocean through internal waves. This energy contributes to background mixing rates and, consequently, to the entrainment of stored ocean heat. Previous studies agree on the rate of mixed-layer deepening for early deepening, but disagree for late deepening. Furthermore, no study to date has investigated the difference in the internal wave field for both phases of deepening. As the Arctic Ocean continues to evolve due to climate change, it is critical we understand the dynamics of mixed-layer deepening in a polar context to predict the fate of the stored ocean heat and consequently the future state of the Arctic sea ice cover.

Using an ocean model (Large Eddy simulation) coupled to a sea ice model in free drift, we find that the rate of late deepening is fundamentally different from early deepening. We show using analytical arguments that the different rate is a direct consequence of the temporal convergence of energy input into the mixed layer. Both deepening phases produce two different internal wave fields with early deepening's being stronger due to a more efficient transfer of internal wave energy into the interior. Late deepening's internal wave field sees significant time dependence with in-phase inertial oscillations between the sea ice and ocean, which enhance internal wave energy fluxes into the interior.

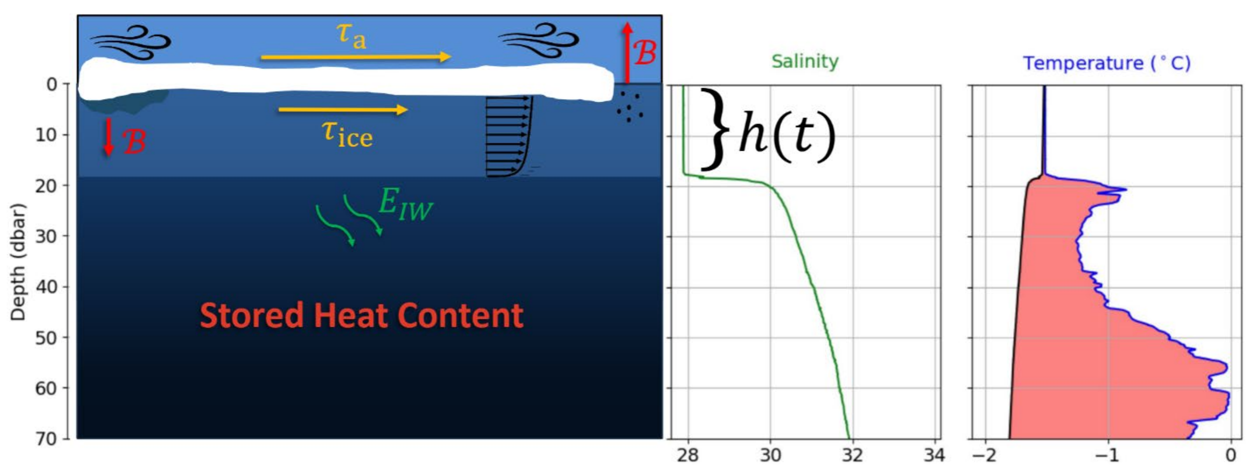

Figure 1. The ice-ocean boundary layer with a salinity and temperature profile taken from 145.646°W and 79.353°N on 26/09/2023 from WHOI's TOP8. The atmosphere imparts a momentum flux τ_a into the sea ice, which induces a momentum flux τ_{ice} into the ocean. The sea ice can also produce buoyancy fluxes $\mathcal{B}$ which can enhance or delay mixed-layer deepening. A portion of energy E_{IW} in the mixed layer of depth $h(t)$ can be radiated into the interior through internal waves. The red shaded area represents the heat available for melting sea ice.

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