Workshop on Physical Processes in Natural Waters

15th - 18th June 2020

PPNW 2020

Workshop on Physical Processes in Natural Waters

15th - 18th June 2020

The Workshop on Physical Processes in Natural Waters brings together specialists in physical limnology. The workshop aims to foster intensive exchange between the participants and offer sufficient space for discussions between scientific talks. Meetings are usually held annually with around 40 to 50 participants. Due to COVID-19 restrictions, it will not be possible to meet in person in 2020. The meeting planned for 2020 in Vancouver, Canada at UBC has been re-scheduled for July 26th - 30th, 2021.

Nevertheless, we felt that the platform for exchanging new ideas and findings among specialists was needed. Hence we decided to hold the PPNW 2020 workshop as a video conference in a reduced form. We will transmit live presentations via video to participants during the previously planned time span **15 - 18th June 2020.** Participation in the workshop as presenter and / or listener is **free of charge**.

The workshop is structured into blocks of presentations held live using video conference software. Each block will begin with 3 to 5 **main presentations** (15 minutes plus 15 minutes of discussion), followed by a number of **flash presentations** (6 minutes each). There will be time for **general discussion** at the end of each block. The presentations are staggered to accommodate the different time zones of participants and will start on Monday 15 June at 17:00, Tuesday 10:00, Wednesday 17:00, Thursday 17:00 (Berlin Time = UTC+2). Those who would like to participate as listeners should have received the login details for the sessions. Please contact Muhammed Shikhani (muhammed.shikhani@ufz.de) if you still need login details.

We were able to win **Colm Caulfield** of the Department of Applied Mathematics and Theoretical Physics of the University of Cambridge for a plenary talk on turbulence. His talk on Monday 15th June 10:00 (Berlin Time = UTC+2) will be on **Open questions in turbulent stratified mixing: Do we even know what we do not know?**

The program and the brief abstracts are available for download from www.ufz.de/ppnw2020.

I would like to express my thanks to those who have submitted presentations and registered as participants. I am looking forward to hearing interesting new science and fruitful discussions!

Sincerely,

Bertram Boehrer

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Helmholtz Centre for Environmental Research - UFZ
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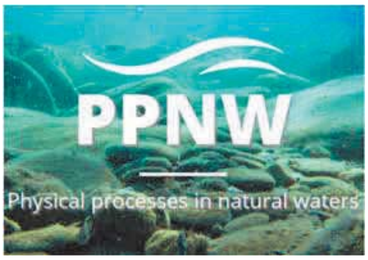
Workshop on Physical Processes in Natural Waters 2020

PPNW 2020 Programme



The presentations will be delivered live as Zoom video conferences. Please familiarize yourself with the system. We will open the session a few minutes before the start of the presentations. Colleagues (beyond the presenters), who intend to participate, are asked to indicate so by Email to Muhammed.Shikhani@ufz.de **by Wednesday 10th June 2020, that we can send the link for the sessions.**

Times are given in Berlin time, i.e. UTC+2

More information on www.ufz.de/ppnw2020 and ppnw.info

MONDAY, June 15, 2020

	16:50	Boehrer	Welcome note
Plenary	**17:00**	**Caulfield Colm**	**Open questions in turbulent stratified mixing: Do we even know what we do not know?**
	18:00	B. Fernández-Castro, C. Troy, T. Doda, H. Chmiel, C. Minaudo, H. N. Ulloa, L. Serra, O. Sepúlveda-Steiner, D. Bouffard and A. Wüest	Seasonality of the mechanical energy budget in a large lake, Lake Geneva (Switzerland-France)
BREAK			
	18:45	E. Bohórquez, L. Rovelli and A. Lorke	Near-surface turbulence generated by rain: Laboratory experience using Particular Image Velocimeter (PIV)
	19:15	Allen, S., N.K. Soontiens, M. Dunphy and D.J. Latornell	Controls on Exchange through a Tidal Mixing Hotpot at an Estuary Constriction
	19:45	Sally MacIntyre, David Bastviken, Lars Arneborg, Adam T. Crowe, Jan Karlsson, Andreas Andersson, Magnus Gålfalk , Anna Rutgerson, Eva Podgrajsek , and John Melack	Turbulence in a small boreal lake: Consequences for air-water gas exchange
	19:51	R. Schwefel, S. MacIntyre, A. Cortés, and S. Sadro	Controls on temperature and oxygen depletion in ice-covered arctic lakes
	19:57	All	Informal discussion

TUESDAY, June 16, 2020

10:00	Guseva, S., M. Aurela, A. Cortés, R. Kivi, et al.	Physical drivers of near-surface turbulence in a regulated river
10:30	Doda, T., C. Ramon, H.N. Ulloa, A. Wuest, et al.	Density currents induced by differential cooling in a small temperate lake: seasonality in their occurrence and magnitude
11:00	Boehrer B., Wentzky, V.C., M.A. Frassl, C. Mi, T. Shatwell, K. Rinke	Metalimnetic oxygen minimum and the presence of Planktothrix rebescens in the low-nutrient Rappbode reservoir
11:30	J. Jansen, B. F. Thornton, M. Wik, S. MacIntyre and P. M. Crill	Physical and biological drivers of the temperature sensitivity of lake CH4 emissions
11:36	Jia Liu, Shangbin Xiao, Zhengjian Yang, Defu Liu, Xiaojuan Guo, Liu liu, Denghua Yan, Andreas Lorke, Chenghao Wang	Spatial high-resolution investigation of dissolved CH4, CO2 and their emission fluxes in the Three Gorges Reservoir
11:42	Guo Xiaojuan, Liu Jia, Liu Defu, Yang Zhengjian, Xiao Shangbin and Andreas Lorke	High-resolution profiles reveal the Three Gorges Reservoir (TGR) backwater reduces nitrous oxide emission potential in its tributary bay
11:48	M. Ishikawa, I. Haag, J. Krumm, K. Teltscher and A. Lorke	The effect of stream shading on inflow characteristics in downstream reservoirs
11:54	All	Informal discussion

WEDNESDAY, June 17, 2020

17:00	Wells, M.	Convection above and below sediment laden instrusions in stratified lakes and the ocean
17:30	Senja Walberg, Marek Stastna, Kevin Lamb	High resolution simulations of Lake Erie over the summer season
18:00	D. Deepwell, R. Ouillon, E. Meiburg and B. Sutherland	Particle pair settling through a thin density interface

BREAK

18:45	Garcia, S.	Turbulence behaviour over reservoir sedimented non cohesive soil

19:15	Yang, B., M. Wells	Wind mixing during the restratification period in dimictic lakes determines initial winter thermal profiles under the ice: observations from a range of Northern American, European, and Asian lakes.
19:45	Adam Jiankang Yang, Edmund Tedford, Jason Olsthoorn and Gregory Lawrence	Asymmetric Holmboe instabilities in stratified shear flow
19:51	W. Zhou, J. Imberger, C. L. Marti, N. Fowkes	A New Pseudo-3D Lagrangian-Eulerian Hydrodynamic Model
19:57	Muhammed Shikhani, Tadhg N. Moore, Daniel Mercado-Bettín, María Dolores Frías, Chenxi Mi, Marc Scheibel, Eleni Teneketzi, Bertram Boehrer, Tom Shatwell, Karsten Rinke	New workflows for the integration of seasonal forecasts into reservoir operation
20:03	All	Informal discussion

THURSDAY, June 18, 2020

17:00	H. N. Ulloa, C. L. Ramón, K. B. Winters, T. Doda, A. Wüest and D. Bouffard	Buoyancy-driven modes of motion in radiatively heated rotating ice-covered waterbodieshugo.ulloa@epfl.ch
17:30	McInerney, J.B.T., A.L. Forrest and J. Largier	Resolution of internal wave sampling paths for autonomous underwater gliders
18:00	Graves, K., B. Laval and G. Lawrence	Seasonal mixing depth in a small, deep lake near the temperature of maximum density and with ice-cover

BREAK

18:45	J. Bonneau, B.E. Laval, D. Mueller, A.K. Hamilton, A.M. Friedrichs, A.L. Forrest	Winter dynamics in Milne Fiord, NU, Canada
19:15	B. Moore-Maley and S. E. Allen	Topographic influences on wind driven upwelling in a large fjord sea
19:21	Horwitz, R.M, Y. Wu, M.Z. Li and E. Devred	Mackenzie River outflow dynamics in an FVCOM model of the Arctic
19:27	Lawrence, G, Oolsthorn J.	Vancouver 2021 Introduction
19:32	Boehrer	Farewell note
19:34	All	Informal discussion

PLENARY

Open questions in turbulent stratified mixing: Do we even know what we do not know?

C. P. Caulfield[1]

[1] *BP Institute & DAMTP, University of Cambridge*
cpc12@cam.ac.uk
http://www.damtp.cam.ac.uk/person/cpc12

Abstract
Understanding how turbulence leads to the enhanced irreversible transport of heat and other scalars (such as salt and pollutants) in density-stratified fluids is a fundamental and central problem in geophysical and environmental fluid dynamics. There is a wide range of highly important applications, not least the description and parameterization of diapycnal transport in the world's oceans, a key area of uncertainty in climate modelling. Recently, due not least to the proliferation of data obtained through direct observation, numerical simulation and laboratory experimentation, there has been an explosion in research activity directed at improving community understanding, modelling and parameterization of the subtle interplay between energy conversion pathways, turbulence, and irreversible mixing in density-stratified fluids. However, as I will discuss in this talk, there are still leading order open questions and areas of profound uncertainty concerning turbulent stratified mixing. Therefore, I will present a personal perspective on some priorities for further research into this hugely complex, important and fascinating fluid dynamical challenge.

Seasonality of the mechanical energy budget in a large lake, Lake Geneva (Switzerland-France)

B. Fernández-Castro[1], C. Troy[2], T. Doda[1,3], H. Chmiel[1], C. Minaudo[1], H. N. Ulloa[1], L. Serra[1], O. Sepúlveda-Steiner[1], D. Bouffard[3] and A. Wüest[1,3]

[1] *Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair, Institute of Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*
[2] *Lyles School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA*
[3] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Surface Waters - Research and Management, Kastanienbaum, Switzerland*

Abstract

Mechanical energy (ME, potential + kinetic) is supplied to lakes at the atmosphere-lake interface in form of heat fluxes and wind stress. The interplay between these energy fluxes and the fate of kinetic energy (mixing *vs.* dissipation) once it reaches the interior of the waterbody determine the vertical stability and the magnitude of the turbulent exchange between the layers, and, hence, shape the ecosystem dynamics. Previous attempts to close the ME budget are restricted to a few case studies, which focused exclusively on the summer season. However, seasonal changes in forcing and stratification certainly modify the energy pathways. For this study we collected year-round measurements in Lake Geneva, the largest freshwater water body of Western Europe. Depth-resolved temperature, currents and turbulent kinetic energy dissipation rates were obtained with moored instruments and microstructure profiles (~400) from a newly built research platform LéXPLORE, located 600 m away from the northern shore of the lake. Preliminary results for the summer period (17 July-14 August) showed that 0.5% (22 J/m^2/d) of the wind work at 10 m height fed internal lake motions, which included a basin-wide cyclonic gyre and Kelvin as well as Poincaré waves, and stored on average 127 J/m^2. About 20% of the energy input was invested in mixing the stable density gradient (4 J/m^2/d), and the remaining ~18 J/m^2/d, lost to dissipation. These numbers indicate a decay time-scale of ME of 6 days. The mixing efficiency, close to 20%, is in agreement with previous studies. However, contrary to smaller lakes, the bulk of the energy dissipation was observed in the interior (15.5 J/m^2/d), and not in the bottom boundary layer. However, the extrapolation of this results to the basin-scale might be limited by our local sampling strategy and requires further assessment. This analysis will be extended to a full annual cycle from April 2019 to 2020. Stay connected!

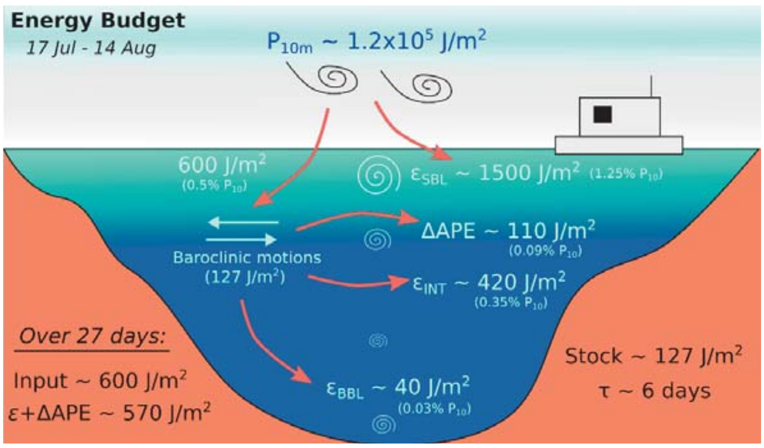


Figure **1**. Summer ME budget in Lake Geneva

1 *Corresponding author, e-mail bieito.fernandezcastro@epfl.ch*

Near-surface turbulence generated by rain: Laboratory experience using Particular Image Velocimeter (PIV)

E. Bohórquez [1,2*], L. Rovelli[2] and A. Lorke [2]

[1] *Department of Geosciences and Environment, Universidad Nacional de Colombia, Medellín, Colombia*
[2] *Institute for Environmental Sciences, University of Koblenz-Landau, Landau, Germany*

Abstract

Near surface turbulence is a hydrodynamic phenomenon, which regulates or affects several important processes such as the diffusive fluxes of greenhouse gases at the water-atmosphere interface. It can be controlled by different hydrodynamic forcings, such as wind, cooling, heating or rain. The effect of rain on near-surface turbulence has been scarcely studied. Rain-induced turbulence can be expected that to be of high relevance in the tropics, where precipitation intensity and frequency is the main aspect of seasonal weather changes. In this study we explored the influence of rain intensities from 7 - 90 mm h^{-1} on near surface turbulence and gas exchange velocities under laboratory conditions. Raindrops at terminal velocity were generated using a simple set up consisting on a 1x1 m plate of perforated Plexiglas, which was located at a height of 20 m above an aquarium (0.5 x 0.5 x 0.5 m). In a total of 14 different runs, rain intensities were varied by controlling the water level above the plate and by modifying the amount and size of the holes. For each run, rain-induced turbulence near the water surface in the aquarium was observed by particle image velocimetry, while the rain intensity was observed from water level changes. Dissipation rates of turbulent kinetic energy ranged between 10^{-10} to 10^{-7} W kg^{-1} and generally increased with rainfall intensity. Gas transfer velocities showed a well fitted linear relationship with the rainfall intensity. The vertical distribution of dissipation rates followed logarithmic profiles. Depending on rainfall intensity, enhanced energy dissipation rates were mainly restricted to the uppermost 6 cm of the water column.

Keywords
Rain-induced turbulence; Particular Image Velocimeter; Gas transfer velocities.

* *Eliana Bohórquez Bedoya, e-mail elibohorquezbed@unal.edu.co*

Controls on Exchange through a Tidal Mixing Hotpot at an Estuary Constriction

S.E. Allen[1*], N.K. Soontiens[1,2], M. Dunphy[1,2] and D.J. Latornell[1]

[1] *Department Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada*
[2] *now at Fisheries and Oceans, Canada*

Abstract

Deep estuaries are often separated from the open ocean by sills and constrictions. These constrictions are areas of intense mixing often dominating the total estuarine mixing. The amount and depth of the estuarine exchange depends sensitively on the mixing and the densities of the waters on the two sides of the mixing region. Thus, the density, nutrient concentration, oxygen saturation, and dissolved inorganic carbon content of the incoming estuarine flow depend on local tidal mixing processes and large scale buoyancy dynamics. We have investigated this process using a numerical model (SalishSeaCast) of the Salish Sea on the West Coast of North America, straddling the Canada/US border. The region receives considerable freshwater dominated by the outflow of the Fraser River. The Fraser River first flows into the deep Strait of Georgia but the freshwater must traverse the strongly tidally mixed passages through the San Juan/Gulf Islands before it reaches the Pacific Ocean (Figure One). The model correctly reproduces the deep water flow into the Strait of Georgia as evaluated against Ocean Networks Canada (ONC) four bottom-mounted, continuously recording, conductivity-temperature instruments which capture this incoming flow. Using a four-year hindcast from the model we determine the amount, depth and position of the outflow and inflow. Comparing with previous literature and through process studies with the model we show the dominance of convective mixing, the important dependence on the density of the incoming ocean water and the timing of strong along strait wind events in the Strait of Georgia relative to the tides.

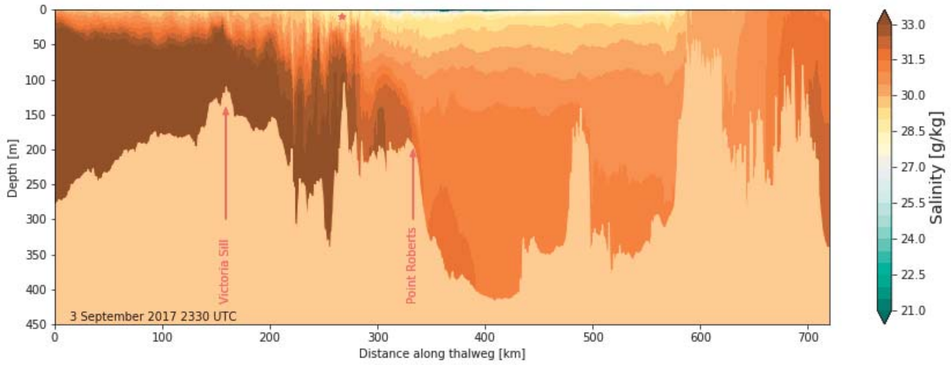


Figure One: Salinity along the thalweg of SalishSeaCast showing the stratified Strait of Georgia (between 330 and 600 km) and the mixing zone between Victoria Sill and Point Roberts (between 180 and 330 km).

[*] *Corresponding author, e-mail sallen@eoas.ubc.ca*

Turbulence in a small boreal lake: Consequences for air-water gas exchange

Sally MacIntyre[1], David Bastviken, Lars Arneborg, Adam T. Crowe, Jan Karlsson, Andreas Andersson, Magnus Gålfalk , Anna Rutgerson, Eva Podgrajsek , and John Melack

[1] *University of California at Santa Barbara, Santa Barbara, California.*

ABSTRACT
The hydrodynamics within small boreal lakes have rarely been studied, yet knowing whether the turbulence at the air-water interface and in the water column scales with metrics developed for larger water bodies is essential for computing metabolism and fluxes of climate-forcing trace gases. We instrumented a humic, 4.7 ha, boreal lake with 2 meteorological stations, 3 thermistor arrays, an infra-red (IR)camera to quantify surface divergence, obtained turbulence as dissipation rate of turbulent kinetic energy (ε) using an acoustic Doppler velocimeter and a temperature-gradient microstructure profiler, and conducted chamber measurements for short periods to obtain fluxes and gas transfer velocities (k). Near-surface ε varied from 10-8 m2 s-3 to 10-6 m2 s-3 for the 0 to 4 m s-1 winds and followed predictions from Monin-Obukhov similarity scaling. The coefficient of eddy diffusivity in the mixed layer was up to 10-3 m2 s-1 on the windiest afternoons, an order of magnitude less other afternoons, and near molecular at deeper depths. k computed from the surface renewal model using ε agreed with those from chambers and surface divergence and increased linearly with wind speed. The upper thermocline upwelled when Lake numbers (LN) dropped to values < 4 but only the base of the mixed layer upwelled when LN ~=10. Mixing was enhanced at the interface. Results extend scaling approaches developed for larger water bodies, illustrate turbulence and k are greater than expected in small wind-sheltered lakes and are sustained for ~ an hour after winds cease, and provide new equations to quantify fluxes.

Controls on temperature and oxygen depletion in ice-covered arctic lakes

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

[1] *Earth Research Institute, University of California at Santa Barbara, Santa Barbara, California.*
[2] *Marine Science Institute, University of California at Santa Barbara, Santa Barbara, California*
[3] *Department of Ecology, Evolution and Marine Biology, University of California at Santa Barbara, Santa Barbara, California.*

ABSTRACT
Controls on temperature, thermal stratification, and solute and oxygen concentrations were investigated during ~200 days of ice-cover in 5 arctic lakes over several years. Volume-weighted mean temperatures during ice-covered period (T_W), calculated from ice-on until the end of February, ranged from 1.5 to 3.1°C, depended on lake size, water temperatures in summer, and the length of the unstratified period before ice-on. Coldest T_W occurred when strong winds caused rapid heat loss before ice on. Temperature stratification and its change over time was determined by the extent of mixing prior to ice on, which determined whether the lakes of each size class were warmer or cooler, and the subsequent magnitude of heat fluxes from the sediments and through the ice. Rates of increase in specific conductance and drawdown of oxygen, products of sediment respiration, were both largest following ice-on with the largest increases near the sediments and indicative of gravity currents bringing the products of respiration to deep locations. Rates of oxygen depletion in early winter in the lakes < 11 ha were ~300 mg O_2 m^{-2} d^{-1} and were ~125 mg O_2 m^{-2} d^{-1} in a 150 ha lake. Rates did not depend on T_W and decreased over time. An anoxic layer, which developed near the sediment-water interface, was thicker for warmer T_W. The quality of organic matter did not change over winter. Predicting temperature and the extent of anoxia under the ice in other lakes requires consideration of legacy effects and hydrodynamics as they influence mass transfer limitation.

Keywords
winter limnology, hypoxia, under-ice measurements, legacy effects

Variable physical drivers of near-surface turbulence in a regulated river

S. Guseva[1], M. Aurela[2], A. Cortés[3], R. Kivi[4], E. Lotsari[5,6], S. MacIntyre[3], I. Mammarella[7], A. Ojala[8,9,10], V. Stepanenko[11,12], P. Uotila[7], A. J. A. Vähä[7], T. Vesala[7,9], M. B. Wallin[13,14] and A. Lorke[1]

[1] *Institute for Environmental Sciences, University of Koblenz-Landau, Landau, Germany*
[2] *Climate Research Programme, Finnish Meteorological Institute, Helsinki, Finland*
[3] *Earth Research Institute, University of California, Santa Barbara, California*
[4] *Space and Earth Observation Centre, Finnish Meteorological Institute, Sodankylä, Finland*
[5] *Department of Geographical and Historical Studies, University of Eastern Finland, Joensuu, Finland*
[6] *Department of Geography and Geology, University of Turku, Turku, Finland*
[7] *Institute of Atmospheric and Earth System Research (INAR)/ Physics, University of Helsinki, Helsinki, Finland*
[8] *Ecosystems and Environment Research Programme, Faculty of Biological and Environmental Sciences, University of Helsinki, Helsinki, Finland*
[9] *Institute for Atmosphere and Earth System Research/Forest Sciences, Faculty of Agriculture and Forestry, University of Helsinki, Helsinki, Finland*
[10] *Helsinki Institute of Sustainability Science (HELSUS), Faculty of Biological and Environmental Sciences University of Helsinki, Helsinki, Finland*
[11] *Laboratory for Supercomputer Modeling of Climate System Processes, Research Computing Center, Lomonosov Moscow State University, Moscow, Russia*
[12] *Department of Meteorology and Climatology, Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia*
[13] *Department of Earth Sciences: Air, Water and Landscape, Uppsala University, Uppsala, Sweden*
[14] *Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden*

Abstract

Rivers and streams are an important source of the greenhouse gases CO2 and CH4 to the atmosphere [1]. Besides dissolved gas concentration, a major controlling parameter of the gas exchange across the air-water interface is the transfer velocity (k), which is mainly driven by near-surface turbulence in the water. The commonly used surface renewal and film model describe the dependence of k on the dissipation rate of turbulent kinetic energy near the water surface [2]. While in lakes and reservoirs near-surface turbulence is mainly driven by atmospheric forcing, including wind shear, convective cooling, and surface wave-breaking, in shallow rivers and streams it is mainly generated by bottom friction. Knowledge about the main physical drivers and the resulting spatial and temporal variability of k in large rivers is rather limited. Conceptual models suggested a transition from the dominance of the flow velocity for rivers with smaller channels to wind control for estuaries and large rivers [3].

In this study, we aimed to identify the key drivers of near-surface turbulence using a comprehensive dataset from a field campaign conducted in a large regulated river (Kitinen River, 67.3665º N, 26.6230º E) in Finland. Continuous measurements of flow velocity, near-surface turbulence, and meteorological forcing were conducted throughout the ice-free season (June – September 2018). We compared observed dissipation rates against commonly applied scaling relations in terms of bulk parameters (wind speed and flow velocity) and a one-dimensional numerical turbulence model (k-ε). Our results revealed the comparable contribution of wind and bed shear to near-surface turbulence during the season. Diurnal flow regulation by an upstream dam strongly affected the temporal dynamics of near-surface turbulence. Based on our findings, we provide a mechanistic concept for the relative importance of wind forcing and river flow for near-surface turbulence as a function of flow depth.

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Density currents induced by differential cooling in a small temperate lake: seasonality in their occurrence and magnitude

T. Doda[1,2*], C. Ramón[1], H. N. Ulloa[2], A. Wüest[1,2] and D. Bouffard[1]

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

[2] *Physics of Aquatic Systems Laboratory, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland*

Abstract

The traditional cooling and mixed-layer deepening observed during calm and cold periods in lakes is modified by the presence of lateral sloping boundaries. The littoral region cools faster than the pelagic region, leading to horizontal density gradients and cross-shore transport of nearshore negatively buoyant waters, which plunge as downslope density currents called "thermal siphons" (Monismith et al. 1990). The seasonal variability of the process is unclear as thermal siphons have been observed in the field only during specific cooling events (e.g., Monismith et al. 1990; Fer et al. 2002). To characterise the seasonal effects on the occurrence and magnitude of the density currents, we collected temperature and current velocity data over one year in Lake Rotsee, a small (0.5 km^2) monomictic perialpine lake in Switzerland. Two vertical moorings, both composed of a chain of thermistors and an upward-looking Acoustic Doppler Current Profiler (ADCP), were deployed in the littoral and the pelagic regions. They measured temperature and velocity over the entire water column from spring 2019 to spring 2020, providing information on the background stratification and the occurrence of thermal siphons. Additionally, temperature profiles were collected along cross-shore transects and meteorological forcing was obtained from a weather station close to the lakeshore. Our observations reveal lateral temperature gradients on the order of 10^{-4}-10^{-3} °C/m during cooling periods. This differential cooling produces a density current with a thickness of 1-2 m, reaching velocities of around 0.03 m/s (Fig. 1). The seasonal variability of the forcing conditions, in particular the surface buoyancy flux ($B_0 \sim 10^{-9}$-10^{-7} W/kg), leads to a remarkable variability of the cross-shore transport. Thermal siphons are rarely present in spring but occur on a daily basis from mid-summer to winter. The duration of the process is also season-dependent: in summer, the flushing stops in the middle of the day whereas thermal siphons are continuously flowing in late fall. The discharge per unit width can reach ~10^3 m^2/d in fall, which corresponds to a complete flushing of the littoral region in a few hours only. These observations are complemented by numerical experiments resolving the small-scale processes (DNS) and basin-scale consequences (RANS).

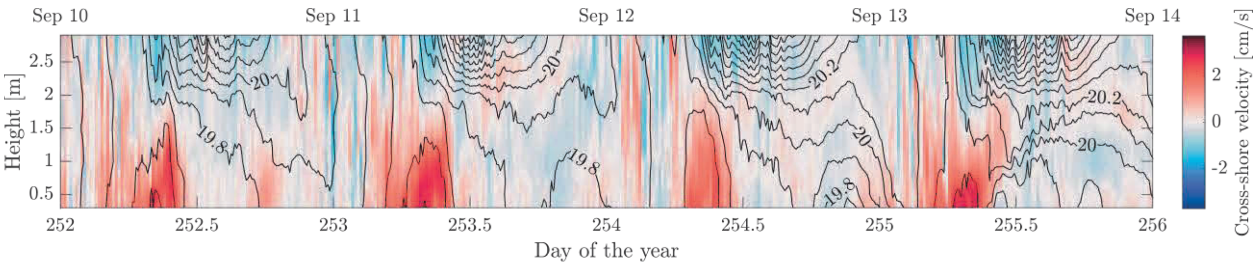

Figure 1. Cross-shore velocity and 0.1°C isotherms measured in the sloping region of Lake Rotsee, as a function of time and height above the sediment. Red (positive) values are associated to thermal siphons.

References

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

Metalimnetic oxygen minimum and the presence of *Planktothrix rubescens* in the low-nutrient Rappbode reservoir

Valerie C. Wentzky[1,2], Marieke A. Frassl[1,3], Chenxi Mi[1], Tom Shatwell[1], Karsten Rinke[1], Bertram Boehrer[1,*]

[1] *Helmholtz Centre for Environmental Research-UFZ, Brueckstrasse 3a, D-39114, Magdeburg, Germany*
[2] *State Agency for Agriculture, Environment and Rural Areas Schleswig-Holstein (LLUR),Flintbek, Germany*
[3] *Australian Rivers Institute, Griffith University, 170 Kessels Rd, Nathan, Queensland, 4111, Australia*

Abstract

Dissolved oxygen is a key player in water quality. Stratified water bodies show distinct vertical patterns of oxygen concentration, which can originate from physical, chemical or biological processes. We observed a pronounced metalimnetic oxygen minimum in the low-nutrient Rappbode Reservoir, Germany. Contrary to the situation in the hypolimnion, measurements of lateral gradients excluded the sediment contact zone from the major sources of oxygen depletion for the metalimnetic oxygen minimum. Instead, the minimum was the result of locally enhanced oxygen consumption in the open water body. A follow-up monitoring included multiple chlorophyll a fluorescence sensors with high temporal and vertical resolution to detect and document the evolution of phytoplankton. While chlorophyll fluorescence sensors with multiple channels detected a mass development of the phycoerythrin-rich cyanobacterium *Planktothrix rubescens* in the metalimnion, this species was overlooked by the commonly used single channel chlorophyll sensor. The survey indicated that the waning *P. rubescens* fluorescence was responsible for the oxygen minimum in the metalimnion. We hypothesize that pelagic processes, i.e., either oxygen use through decomposition of dead organic material originating from *P. rubescens* or *P. rubescens* extending its respiration beyond its photosynthetic activity, induced the metalimnetic oxygen minimum. The deeper understanding of the oxygen dynamics is mandatory for optimizing reservoir management.

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* *Corrwsponding author: bertram.boehrer@ufz.de*

Physical and biological drivers of the temperature sensitivity of lake CH_4 emissions

J. Jansen[1,2]*, B. F. Thornton[1,2], M. Wik[1,2], S. MacIntyre[3] and P. M. Crill[1,2]

[1] *Department of Geological Sciences,*
Stockholm University, Stockholm, Sweden
[2] *Bolin Centre for Climate Research, Stockholm, Sweden*
[3] *Marine Science Institute,*
University of California at Santa Barbara, Santa Barbara, CA, USA

ABSTRACT

Lake emissions of the climate forcing trace gas methane (CH_4) are strongly dependent on thermal energy input due to the compound effects of temperature-sensitive biogeochemical and physical processes. The temperature sensitivity of the flux varies between sites and emission pathways (ebullition and diffusion), but the reasons for this are largely unknown. For improved modeling, a mechanistic understanding of flux temperature sensitivity and its variability is required. We use a multiyear dataset (2009–2017) of ice-free CH_4 emissions from three subarctic lakes obtained with bubble traps (n = 14677) and floating chambers (n = 1306) to quantify the temperature sensitivity of the flux. Arrhenius functions closely fit measured fluxes ($R^2 \geq 0.93$). Ebullition (activation energy 1.36 eV) expressed greater temperature-sensitivity than diffusion (1.00 eV) [1]. In this talk we briefly discuss the physical processes that may contribute to this difference, such as stratification, and highlight key questions that remain.

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Keywords

Lakes; methane; temperature; proxy; ebullition; diffusion.

Spatial high-resolution investigation of dissolved CH4, CO2 and their emission fluxes in the Three Gorges Reservoir

Jia Liu [1], Shangbin Xiao [1*], Zhengjian Yang [1], Defu Liu[2], Xiaojuan Guo [1], Liu liu [3], Denghua Yan [4], Andreas Lorke[1,5], Chenghao Wang[6]

1. College of Hydraulic & Environmental Engineering,
China Three Gorges University, Yichang, China
2. College of Resources & Environment Sciences,
Hubei University of Technology, Wuhan, China
3. Department of Experimental Limnology,
Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Stechlin, Germany
4. Water Resoources Department,
China Institute of Water Resources and Hydropower Research, Beijing, China
5. Institute for Environmental Sciences,
University of Koblenz-Landau, Landau, Germany
6. Departmen of Earth System Science,
Stanford University, Stanford, CA, USA

ABSTRACT

Due to the huge spatial variability in reservoir leading to difficulties in obtaining representative data, the dissolution and emission of methane (CH_4) and carbon dioxide (CO_2) are usually not accurately obtained. Three Gorges Project, as the largest water conservancy project in the world, its greenhouse gas emissions have attracted widespread attention, but there is still a lack of high-precision investigations. To better clarify the distribution and flux of CH_4 and CO_2, we performed a high-resolution mapping survey of the dissolved concentration and flux of mainstream CH_4 and CO_2 in the Three Gorges Reservoir (TGR). The results showed that the high spatial variability of dissolved CH_4 (0.22 ± 0.16 μmol L^{-1}) and CO_2 (47.53 ± 9.92 μmol L^{-1}) concentrations is a comprehensive result of topography, human activities, dam operation and uncertainties, with areas after Wanzhou (WZ), CH_4 concentration gradually increasing and reaching the highest level at the backwater area. The fluxes of CH_4 and CO_2 also exhibited a large spatial variability, and the average diffusive flux of CH_4 and CO_2 was 0.31 ± 0.33 mmol m^{-2} d^{-1} and 30.92 ± 18.08 mmol m^{-2} d^{-1}. The backwater area was a hot spot for carbon emissions due to high dissolved concentration and high gas transfer velocity (k). High spatial variability in k was observed, and average k_{600}-CH_4 was 2.35 times higher than k_{600}-CO_2 in the area before WZ, while the ratios (k_{600}-CH_4/ k_{600}-CO_2) in areas after WZ were almost the same. Assuming a fixed k and ignoring the contribution of microbubbles may lead to seriously underestimate the flux of CH_4 and CO_2 in the TGR. The results provide new insights into the carbon distribution of the TGR, and are more conducive to the estimation of the reservoir 's greenhouse gas emissions.

Keywords

Three Gorges Reservoir; greenhouse gas emissions; dissolved methane and carbon dioxide; gas transfer velocity; microbubbles

High-resolution profiles reveal the Three Gorges Reservoir (TGR) backwater reduces nitrous oxide emission potential in its tributary bay

Guo Xiaojuan [1], Liu Jia [1], Liu Defu [1], Yang Zhengjian [1]*, Xiao Shangbin [1]* and Andreas Lorke [1, 2]

[1] *Hubei Field Observation and Scientific Research Stations for Water Ecosystem in Three Gorges Reservoir,*
China Three Gorges University, Yichang, China
[2] *Institute for Environmental Sciences,,*
University of Koblenz-Landau, Landau, Germany

ABSTRACT

Reservoirs are considered significant source of the potent greenhouse gas nitrous oxide (N_2O), but there are limited reports about N_2O in the world's largest reservoir-Three Gorges Reservoir. Thanks to a new developed fast-response automated gas equilibrator, high-resolution dissolved N_2O profiles of a typical eutrophic tributary bay in the TGR - Xiangxi Bay are reported in this study. The flux (0.4-1μmol/ (m^2*h)) and transfer velocity (9-34cm/h) of N_2O emission presented high spatial heterogeneity in the bay. Dissolved N_2O was oversaturated both in July (118%-302%) and October (106%-231%) with pronounced vertical concentration gradients. The intrusive backwater of the TGR with lower N_2O concentration occupied the most upper layer of the bay and the inflow from the tributary upstream with lower temperature carried twice higher dissolved N_2O (part of it was produced from riverbed of the bay) and slid toward the Yangtze River through the riverbed. The distribution of N_2O was primarily controlled by the seasonal hydrodynamics of the two water sources. In this sense, N_2O emission potential was reduced in the bay and controlled by the TGR backwater hydrology regime instead of the upstream water. The results yield a new insight of N_2O emission in the reservoir area and indicate appropriate reservoir operation may be an option to mitigate N_2O emission potential in the TGR by controls the bidirectional density currents.

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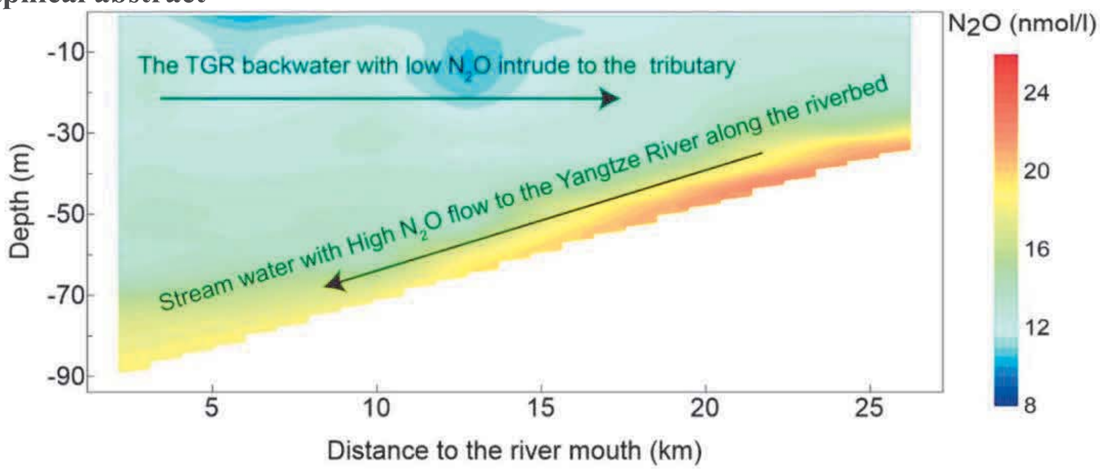
Keywords
Greenhouse Gas; Dissolved N_2O; N_2O emission; Bidirectional density currents; Three Gorges Reservoir.

Graphical abstract



The effect of stream shading on inflow characteristics in downstream reservoirs

M. Ishikawa[1]*, I. Haag[2], J. Krumm[2], K. Teltscher[2] and A. Lorke[2]

[1] *Institute for Environmental Sciences, University of Koblenz-Landau, Landau, Rhineland-Palatinate, Germany*
[2] *HYDRON GmbH, environmental and hydrological consulting, Karlsruhe, Baden-Württemberg, Germany*

ABSTRACT
With the increasing number of reservoirs for various purposes, such as power generation, water storage and flood control, there is also an increase of environmental problems in existing reservoirs concerning their water quality. Reservoir water quality is strongly affected by inflowing nutrient loads and reservoir hydrodynamics. In stratified reservoirs, inflows form density currents and the availability of nutrient loads for algae growth depends on the interplay between inflow temperature and reservoir stratification. Meanwhile, inflow temperature is affected by catchment properties, including stream shading. Stream shading by riparian vegetation is often considered in catchment management and stream restoration efforts, but its effect on inflow dynamics in downstream reservoirs has not been studied. We assessed the alteration of density currents in a small drinking water reservoir in the tropics by different degrees of stream shading within its catchment. Inflow dynamics and inflow temperature were simulated using the distributed water-balance model LARSIM-WT, which also integrates the heat-balance and water temperature of river stretches on a physical basis. Measured temperature profiles in the reservoir were compared to inflow temperature over a seasonal cycle to identify the prevailing type of density current. Inflow temperatures larger than the reservoir surface temperature were assigned as overflows, inflow temperatures lower than the bottom temperature were defined as underflows, and otherwise they were considered as interflows. In the status quo scenario, underflows were the most frequent path for inflowing water, representing 66% of the period, followed by interflows, while overflow situations were absent. In a scenario without stream shading in the catchment, average inflow temperature increased by about 1.8 °C, and the inflow dynamics changed completely. Interflows were the most frequent pathway (51%), followed by underflows (33%) and overflows (16%). With this change, we would expect a degradation of reservoir water quality, as overflows promote longer periods of anoxia with additional adverse effects, such as the increasing release of nutrients, contaminants and methane. Moreover, a larger fraction of the inflowing nutrient load would be delivered to the photic zone, being a potential trigger for algae blooms. This study revealed an important, yet unexplored aspect of catchment management for controlling reservoir water quality.

Keywords
Density currents; stream shading; water quality; reservoirs; catchment.

[1] *Corresponding author, e-mail ishikawa@uni-landau.de*

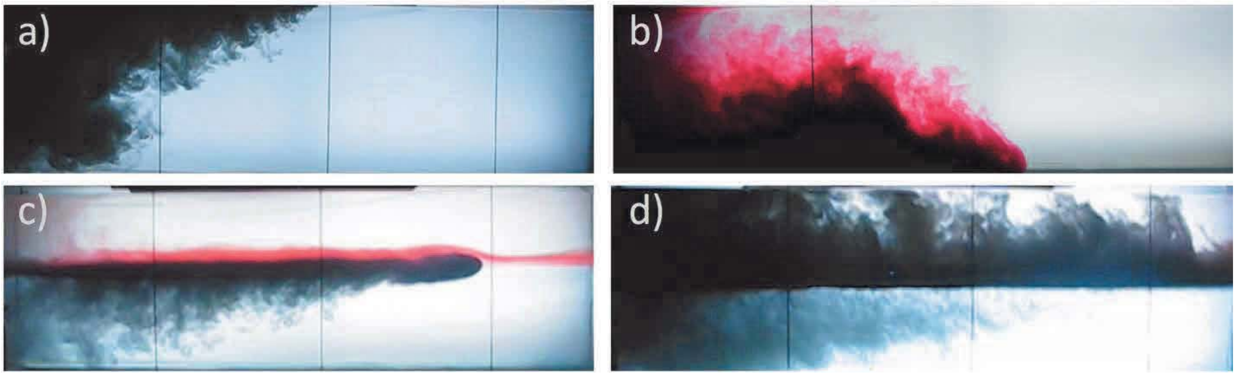
Convection above and below sediment laden intrusions in stratified lakes and the ocean.

M. Wells*[1]

[1] *Department of Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, Canada*

ABSTRACT

When a sediment laden river flows into a stratified water body, this river water could intrude as an overflow, interflow or underflow, depending upon the density contrast between the river and lake or ocean. If the river is sufficiently warm or fresh enough to compensate for the additional mass of sediment, an overflow results (a), below which there is convective sedimentation [1]. If the sediment load is sufficiently high, then an underflow initially occurs (b), from which the warm/fresh interstitial material can subsequently loft [2]. For intermediate cases, an interflow can occur. Here it is possible for both lofting and sediment driven convection to occur above and below the pycnocline (c and d). Finally, it is possible for "explosive" or very vigorous lofting to occur, which can overturn the water column stratification. These different regimes can be described in terms of two dimensionless parameters: namely $R_S = \Delta\rho_S / \Delta\rho_C$ and $R_{rho} = \Delta\rho_A / \Delta\rho_C$, where $\Delta\rho_A$ is the "freshness" density contrast between river and upper-layer, $\Delta\rho_C$ the density contrast due to sediment between the river and upper-layer, and $\Delta\rho_S$ the density contrast between upper and lower layers. Overflows occur when $R_{rho} > 1$, interflows when $R_{rho} < 1$ and $R_S + R_{rho} > 1$, and underflows when $R_{rho} + R_s < 1$. We use laboratory experiments to determine the vigour of convection in these three regimes, and to explore the water column mixing in the case of the "explosive" lofting. Possible applications of water column mixing by turbidity currents in stratified lakes will be discussed.



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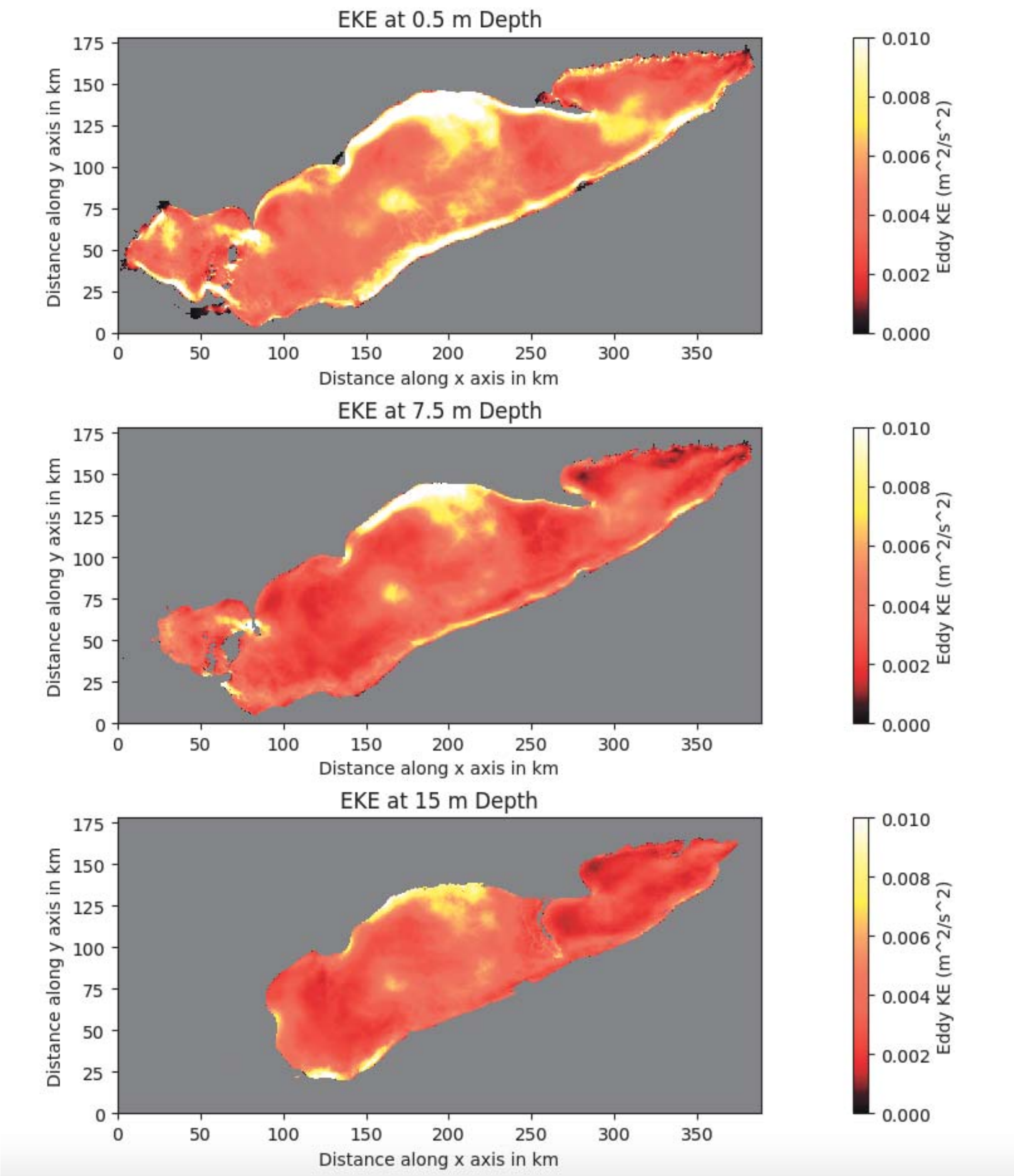
* *Corresponding author, e-mail wells@utsc.utoronto.ca*

High resolution simulations of Lake Erie over the summer season

Senja Walberg, Marek Stastna, Kevin Lamb

Lake Erie is the shallowest and southernmost of the Laurentian Great Lakes. The lake is divided into three basins with large differences in average depth, and while it has a generally elliptic shape several large features, like the Long Point peninsula, are a challenge to resolve in numerical simulations. In the summer Lake Erie exhibits a sharp pycnocline, and often a large region of hypoxia. Coupled with upwelling episodes this has led to large scale fish kills in the recent past. We report on modeling with the MIT gcm at a variety of horizontal resolutions, with 100m being the finest attempted. We outline features in the 100m grid resolution simulation, such as those evident in the plot of eddy kinetic energy at various depths below, that are not evident in coarser simulations, and discuss the manner in which inter-basin and nearshore off-shore exchange varies with model resolution.



Particle pair settling through a thin density interface

D. Deepwell[1*], R. Ouillon[2], E. Meiburg[3] and B. Sutherland[1]

[1] *Department of Physics, Faculty of Science, University of Alberta, Edmonton, Canada*
[2] *Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA*
[3] *Department of Mechanical Engineering, University of California, Santa Barbara, CA, USA*

Abstract

Particle sedimentation in the ocean primarily consists of suspended material from river outflows in the form of sand, silt, clay, and/or increasingly microplastics. As the rate of plastic production and waste continues to exponentially increase, the prevalence of microplastics entering into oceans and lakes will become dramatic. These environments are often stratified, either thermally or by salinity, which further complicates the sedimentation process. Many studies have shown either particle retention or delayed settling at these density interfaces.

A particle will settle through an interface when it is large enough, dense enough, or both. Due to the viscosity of the fluid, a particle settling through an interface will drag lighter, upper layer fluid with it into the lower layer, thereby deforming the interface. Neighbouring particles may be caught up in this descent leading to further particle entrainment. As this process continues, the collection of particles form a larger plume which enhances the particle settling rate. Experiments indicate that this is the cause for an enhanced settling rate compared to that of an individual particle.

To understand the origins of this collective problem, we analyzed the simpler behaviour of a pair of particles passing through a thin interface of miscible Newtonian fluids. This provides a framework to understand the larger collective settling of multiple particles. Direct numerical simulations were used to measure the particle paths for a wide parameter range of initial conditions, particle Reynolds numbers, and the strength of the stratification. Particles aligned vertically are more likely to aggregate as the lower particle is hindered at the interface allowing the trailing particle to effectively catch up. With a horizontal alignment, the trailing particle interacts with the deformed interface in a complex manner which can lead to particle attraction.

[*] *Corresponding author, e-mail deepwell@ualberta.ca*

Turbulence behaviour over reservoir sedimented non cohesive soil

S. García[1*]

[1] *Department of Sustainable and Civil Technologies, School of Sciences and Engineering, Monterrey Institute of Technology and Higher Education, Guadalajara, Mexico*

ABSTRACT

Turbulent flows occur in nature and all the geophysical flows. It is difficult to define the concept of turbulence, nevertheless these flows show some properties like irregularity, diffusivity, higher Reynolds numbers, vorticity fluctuations, dissipative and governed by fluid mechanics equations, these properties are given by flow not by the fluid. General and theoretical solution for turbulent flows had not obtained because equations that govern the phenomena and Navier-Stokes equations are non-linear and have chaotic characteristics.
The transport of sediments has been simulated in physical and numerical models to offer a way to understand this phenomenon and had improved the design of several hydraulic works, these studies only are used for design, but the turbulence is not part of the analysis.
In this paper Reynolds shear stress and relative turbulent intensity is analyzed for a qualitative point of view using Nakagawa and Nezu (1993) derivate equations for this parameters and data collected using an Acoustic Doppler Velocimetry for a physical bed movable model (García S. 2005). The continuity and Reynolds equations derivate from the Navier-Stokes equations can be expressed:

$$\partial U/\partial x + \partial V/\partial y = 0$$
$$U\partial U/\partial x + U\,\partial U/\partial y = g\sin\theta - \partial/\partial x(P/\rho) + \partial/\partial x\left(-\overline{u^2}\right) + \partial/\partial y(-\overline{uv}) + \nu\nabla^2 U$$
$$U\,\partial V/\partial x + V\,\partial V/\partial y = -g\cos\theta - \partial/\partial y(P/\rho) + \partial/\partial x(-\overline{uv}) + \partial/\partial y\left(-\overline{v^2}\right) + \nu\nabla^2 V$$

For a 2-D open-channel flow where V=0 and ∂/∂x=0, the turbulent structures using mean and friction velocity U* were evaluated, the results are show in figures 1 and 2.

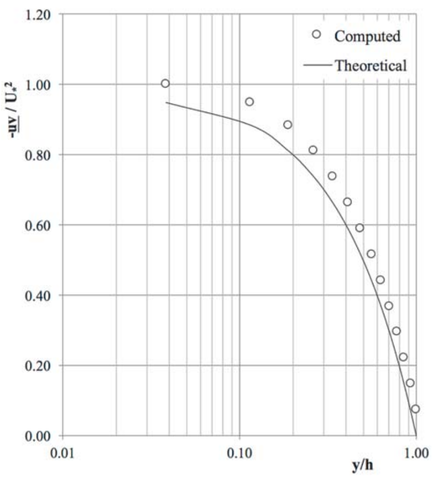


Figure 1.- Reynolds shear stress variation.

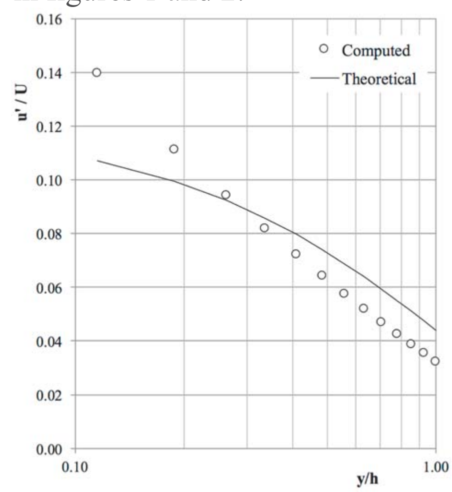


Figure 2.- Relative turbulent intensity variation.

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Keywords

Reservoir; sedimentation; turbulence; Reynolds shear stress; modelling.

* *Corresponding author, e-mail sgarcia@tec.mx*

Wind mixing during the restratification period in dimictic lakes determines initial winter thermal profiles under the ice: observations from a range of Northern American, European, and Asian lakes.

Bernard Yang [1], David Wells [1]

[1] *Department of Physical and Environmental Sciences, University of Toronto Scarborough, Toronto, Ontario, Canada*

ABSTRACT

During winter, dimictic lakes have an inverse thermal stratification, whereby temperatures are near 0°C below the ice, and deeper waters can approach 4°C. While nearly half the lakes worldwide are in the mid- to high-latitudes and freeze during winter, the strength of winter stratification in these lakes is not well understood compared to summer stratification. Water becomes less dense below 4°C, so that the subsequent cooling of a dimictic lake below this temperature is a stabilizing buoyancy flux that restratifies the water column. This means that in larger, windy lakes the whole water-column could be close to 0°C when ice forms due to stronger wind-driven mixing, whereas in smaller, calmer lakes, there will be a thin buoyant layer of cold water below the ice, above a deeper 4°C layer. We will describe the relative contribution of wind stress during the restratification period to water column temperatures before ice-on in 20 mid to high-latitude lakes over different years. We find a good trend between the depth averaged temperature and the wind stress, for lakes that vary in area between 0.5 to 82,000 km^2. Specifically, lakes that have stronger mean winds > 3 $m\ s^{-1}$ during restratification period, have depth averaged temperatures between 0-2°C, whereas those lakes with weaker winds < 3 $m\ s^{-1}$ are warmer with depth averaged temperatures between 2-4°C at the time ice forms. We discuss how differences in the initial thermal structure under the ice potentially act as important controls upon winter fish habitat usage and solar convection patterns in late winter.

Asymmetric Holmboe instabilities in stratified shear flow

Adam Jiankang Yang[1*], Edmund Tedford[1], Jason Olsthoorn[1] and Gregory Lawrence[1]

[1] *Environmental Fluid Mechanics Lab, Civil Engineering, University of British Columbia, Vancouver, BC, Canada*

Abstract

We are interested in the shear-induced instability of a statically stable fluid. Such background flows occur in many geophysically relevant situations in straits, estuaries, costal inlets and ship canals. As these instabilities grow at the interface, they contribute to the interfacial shear stress and to mixing between the layers. The most well-known shear instability is the Kelvin-Helmholtz instability (KHI), which occurs at a low Richardson number (bulk Richardson number < 0.08 based on shear layer thickness [1]) and has been studied extensively. However, the natural environment usually presents a much higher Richardson number, which results in another type of mixing mechanism-Holmboe instability. In recent years increasing attention has been paid to this more generic mixing mechanism.

Holmboe instabilities in an arrested salt wedge flow have been investigated analytically and in the laboratory. In the laboratory particle image velocimetry and laser induced fluorescence are used to obtain flow velocities and the height of the density interface. The Holmboe instability presents "one-sidedness" due to the offset between the centre of shear layer and density interface. This asymmetric Holmboe instability (Fig. 1) exhibits a roll-up structure, often associated with KHI. We focus on the spatial evolution of the asymmetric Holmboe instability. Comparisons are made with linear stability analysis considering the evolving background mean flow.

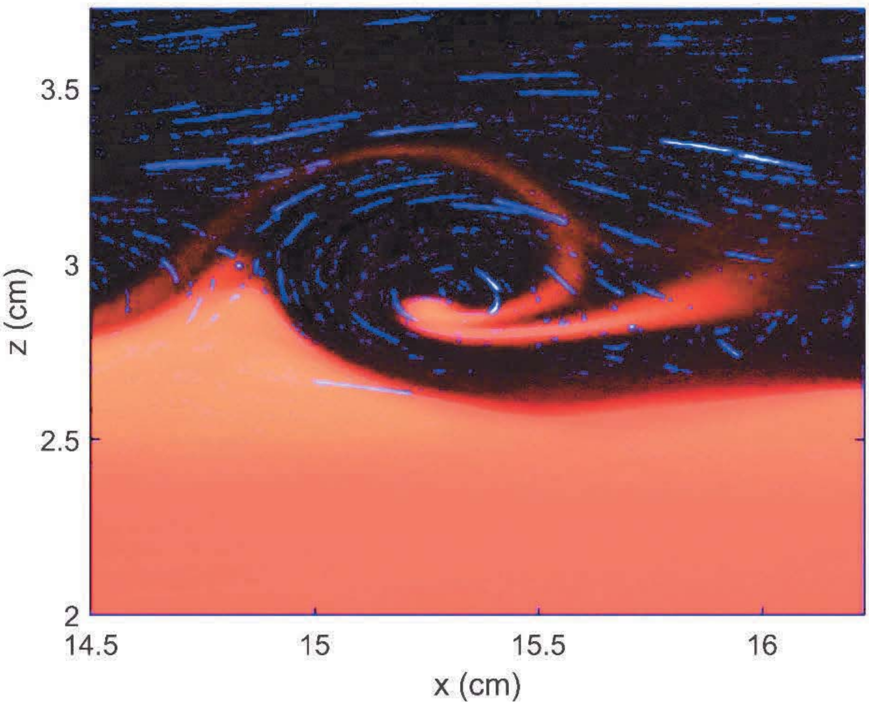

Figure. 1. Ejection of asymmetric Holmboe instability in an arrested salt-wedge flow

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

A New Pseudo-3D Lagrangian-Eulerian Hydrodynamic Model

W. Zhou[1*], J. Imberger[2], C. L. Marti[3,4], N. Fowkes[5]

[1]*Earth Research Institute, University of California Santa Barbara, Santa Barbara, CA, USA*
[2] *Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL, USA*
[3]*Department of Civil and Environmental Engineering, University of Vermont, Burlington, VT, USA*
[4]*Sustainable Engineering Group, Faculty of Science and Engineering, Curtin University, Perth, Western Australia, Australia*
[5]*Department of Mathematics and Statistics, School of Physics, Mathematics and Computing, The University of Western Australia, Perth, Western Australia, Australia*

ABSTRACT

Framework of the classic one-dimensional (1-D) Lagrangian Dynamic Reservoir Simulation Model (DYRESM) has been expanded for incorporating a horizontal water exchange algorithm to allow gravitational mass transport between adjacent sub-basins to be simulated. The yielded pseudo-three-dimensional Multi-Basin DYRESM (MB-DYRESM) first divides a lake into Eulerian sub-basins, then runs DYRESM in each sub-basin over one parent model time step and lastly activates the newly developed gravitational horizontal exchange algorithm with the calculated horizontal mass fluxes inserted into each sub-basin. The capacity of the new model was demonstrated by comparing its output both with that from a high-resolution full 3D numerical simulation and with field data. The test cases considered here included flow within two idealized two-basin rectangular domains, and the general summer circulation in Lake Argyle (Australia) in a period when an inflow event took place. MB-DYRESM performed well for situations where the main exchange driver was gravitational. It successfully reproduced the thermal structure and mass distribution of the water column in each sub-basin, indicating a reasonably well capture of the horizontal mass fluxes among sub-basins. With the Lagrangian scheme inherited from DYRESM, MB-DYRESM has removed an accumulative numerical diffusion commonly seen in many 3-D models and shown computational speed approximately 300 times faster than the 3-D model applied in this study under similar configuration. Through the combination between low demand of computational power and reasonable spatial resolution of mass flux path, MB-DYRESM has achieved the initial goal to bridge the computationally cheap but spatially coarse 1-D lake models and the spatially accurate but computationally expensive 3-D lake models. Potentially, MB-DYRESM provides a more applicable option for simulations over climatic temporal scales in deep stratified lakes where the balance between affordable computational demand and proper spatial resolution are of great concern.

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Keywords

pseudo-three-dimensional lake model; stratified lakes; flux path; gravitational exchange.

New workflows for the integration of seasonal forecasts into reservoir operation

Muhammed Shikhani[1*], Tadhg N. Moore[3], Daniel Mercado-Bettín[4,5], María Dolores Frías[6], Chenxi Mi[1], Marc Scheibel[2], Eleni Teneketzi[2], Bertram Boehrer[1], Tom Shatwell[1], Karsten Rinke[1].

[1]Department of Lake Research, Helmholtz Centre for Environmental Research, Magdeburg, Germany

[2]Department of Water resource and flood risk management, Wupperverband, Wuppertal, Germany

[3]Dundalk Institute of Technology, Dundalk, Co. Louth, Ireland

[4]Catalan Institute for Water Research (ICRA), Girona, Spain

[5]Universitat de Girona, Girona, Spain

[6]Grupo de Meteorología. Dpto. de matemáticas Aplicada y Ciencias de la computación, Universidad de Cantabria, Santander, Spain

While we are all familiar with using climate models for short term forecasts (i.e. weather forecast) or log-term projections (e.g. climate change projections until 2100), there is a so-called "prediction gap" in between on the scales of seasonal predictions. The advancements in climate modeling, especially in mid-term prediction, have meanwhile paved the way for implementing new generations of decadal and seasonal projections. Such mid-term information is essential in developing foreseeable strategies to mitigate climate change effects and improve the preparedness for extreme weather events. These services were applied to some sectors like agriculture and health, but so far they were not utilized for water management in the lake/reservoir sector.

Within the framework of the WatexR project, we applied a combination of global reanalysis ERA5 and seasonal forecasting SYSTEM5 from ECMWF on an integrated workflow of a lumped hydrological model (GR6J) coupled to a hydrodynamic lake model (GLM). This workflow was used to generate seasonal predictions (as hindcasts) of the water quality variables of the Wupper Reservoir in Germany. This workflow represents a technical solution, implemented in the software R, which represents a model chain starting from seasonal projections from different climate models over a hydrological model producing the inflow time series for the terminal lake model. Since seasonal climate projections are provided as an ensemble (25 members), the workflow also produces ensembles for stream discharges and water temperatures in the reservoir. The ERA5 data was used for both, to bias correct the climate seasonal forecasting and to provide meteorological input data for model spin-up. Despite the fact that seasonal forecasts still exhibit limited skills in climate prediction over continental Europe, the established workflow represents a new technological solution for the integration of seasonal forecasts in reservoir operation. With further improvements of model skills these techniques can contribute valuable information for smart and adaptive reservoir management practices.

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[*]Corresponding author: Muhammed Shikhani, muhammed.shikhani@ufz.de

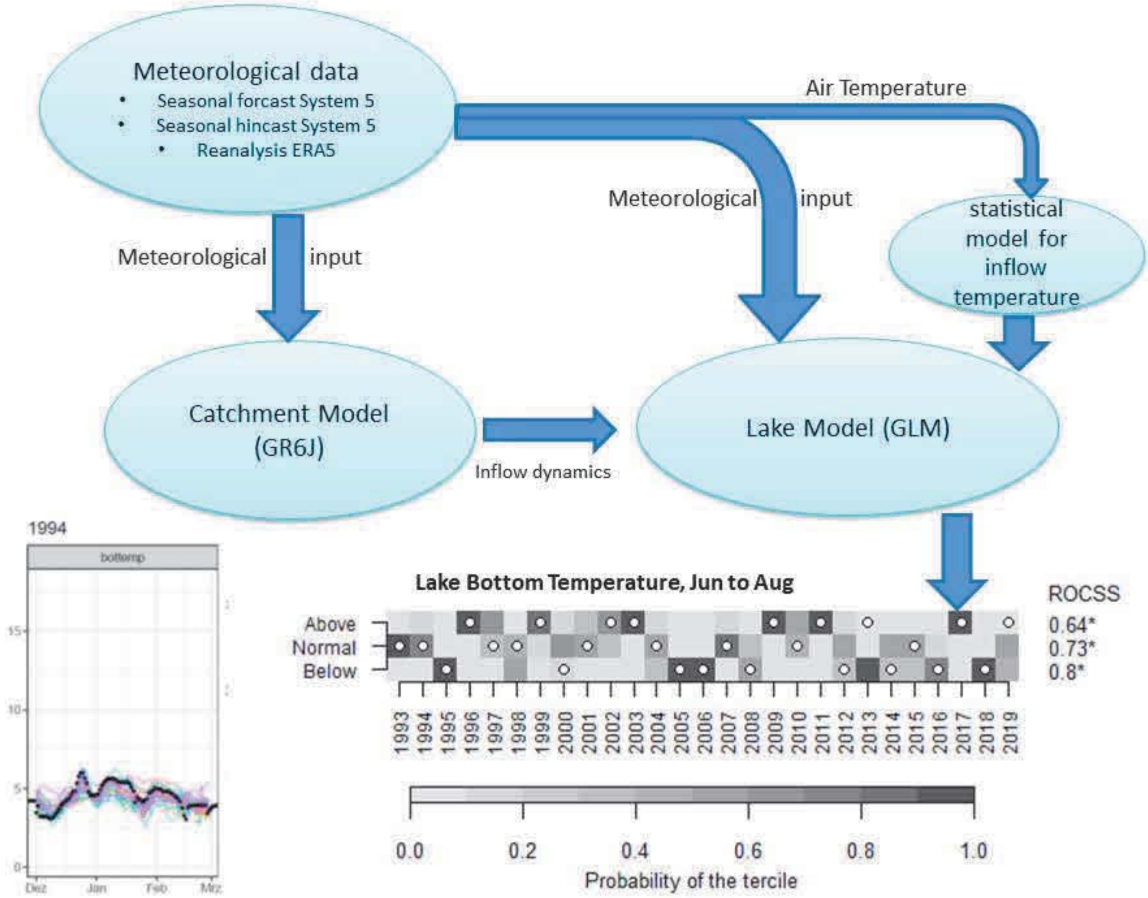

Fig. 1: The established workflow and an example of the expected results

Buoyancy-driven modes of motion in radiatively heated rotating ice-covered waterbodies

H. N. Ulloa[1*], C. L. Ramón[2], K. B. Winters[3], T. Doda[1,2], A. Wüest[1,2] and D. Bouffard[2]

1 Physics of Aquatic Systems Laboratory (APHYS)-Margaretha Kamprad Chair, EPFL, Switzerland
2 Eawag, Swiss Federal Institute of Aquatic Science and Technology, Aquatic Physics Group, Department of Surface Waters-Research and Management, Kastanienbaum, Switzerland
3 Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA

Abstract

Lake managers are facing the problem of a pervasive decline of the ice-covered period and increasing risks associated with traditional winter activities. Better predictions of ice phenology will come from better global characterisations of the under-ice heat dynamics. Although recent in-situ studies have broadened our understanding of under-ice physical processes, the impact of such processes in the water heat distribution remains partially characterised. Our goal is to provide a more in-depth picture of the physical processes controlling the heat and energy distribution in radiatively heated rotating ice-covered lakes. Bearing this in mind, we use numerical experiments to quantify the general properties of buoyancy flows resulting from the differential heating of sloping under-ice fresh waterbodies. Our results allow us to characterising (i) convective plumes length and velocity scales, (ii) downslope gravity currents, (iii) the internal wave field resulting from convection, and (iv) the rotating flows (Bouffard et al. 2016, 2019, Winters et al. 2019, Ulloa et al. 2020, Ramón et al. 2020). Our results show that the heating rate of the interior convective mixing layer (CML) depends on the fraction of the basin volume occupied by the region whose depths are shallower than the CML depth and the rotating regime of the waterbody. Whereas downslope gravity currents resulting from the differential heating of shallow waters enhance the CML heating rate, Coriolis acceleration diminishes it. Results from different modelling approaches will be discussed at the meeting.

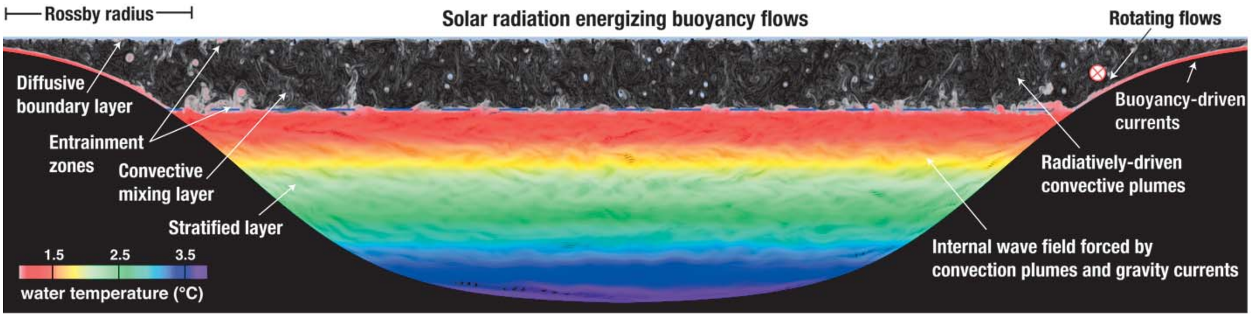

Figure**. 1.** Numerical results. Snapshot of the temperature field during day time.

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* *Corresponding author, e-mail hugo.ulloa@epfl.ch*

Resolution of internal wave sampling paths for autonomous underwater gliders

J. B.T. McInerney[1,2*], A.L. Forrest[1,2], J. Largier[3]

[1] *Civil & Environmental Engineering, University of California – Davis, Davis, CA, USA*
[2] *Tahoe Environmental Research Center, University of California – Davis, Incline Village, NV, USA*
[3] *Bodega Marine Laboratory, University of California – Davis, Bodega Bay, CA, USA*

Abstract

Internal waves occur in lakes and other large bodies of water where stratification is present. If a lake is sufficiently large, the motions of fluids within it, including internal waves, will be effected by the rotation of the earth. In this case, rotational Poincaré waves and/or Kelvin waves may be present. These long period waves can be accompanied by other high frequency smaller internal waves, some of which may be generated by the progression of the Kelvin and/or Poincaré waves themselves. The effect of the lake boundaries results in a spatially non-uniform wave-field. Collecting spatially and temporally meaningful observations of internal waves in lakes has long posed a challenge. Autonomous underwater gliders are a promising new tool for the observation of internal wave-fields. They can be equipped with a wide range of sensors that can reveal internal wave dynamics including Conductivity, Temperature and Depth (CTD) probes, turbulent microstructure probes and Acoustic Doppler Current Profilers (ADCP). There is immense flexibility in the path of the vehicle through the internal wave-field. Sustained observations can be made for tens of days allowing for repeat transects. The orientation of a glider’s transects to the dominant wavefront of the internal wave-field will dictate the spatial and temporal resolution of the data it collects. We consider a simplified wave-field and compare the relative resolution of glider transects perpendicular, parallel, and at an angle to the wavefront. We explore cases using typical internal wave parameters identified from glider and mooring data collected in Lake Geneva (Switzerland/France) and Lake Tahoe (USA), and the typical flight of a G2 Slocum glider. While transects parallel to the wave front may provide better information about the across-shore variability of the wave, the greatest coverage along the wave train is provided by flying perpendicular to the wavefront.

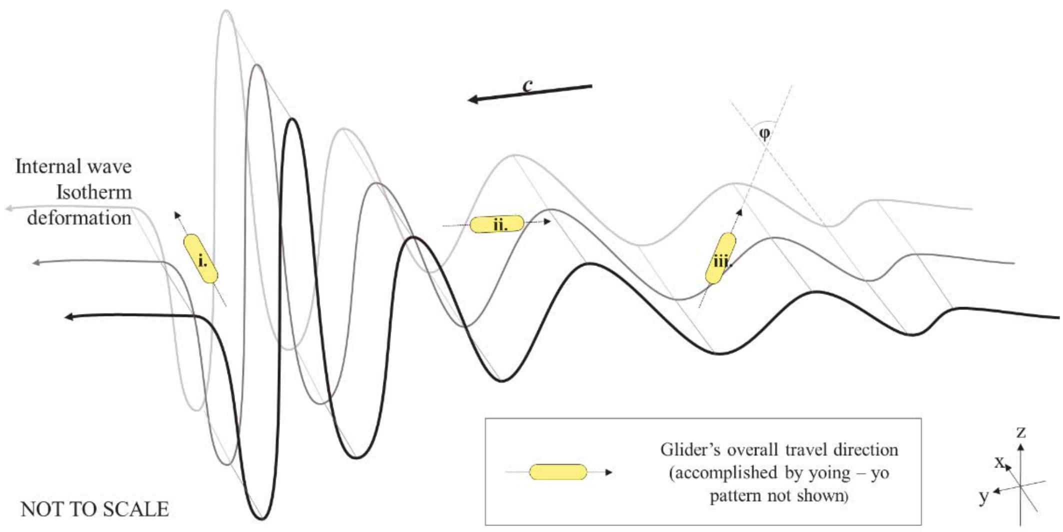


Figure 1 Simplified internal wave progression at some phase speed, c, and the path which an autonomous underwater glider may travel though it by completing it's saw-toothed yo pattern. The path may be i) parallel to the wave front, ii) perpendicular to the wavefront, or iii) at some angle, φ, to the wavefront.

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

Seasonal mixing depth in a small, deep lake near the temperature of maximum density and with ice-cover

K. Graves[1*], B. Laval[1] and G. Lawrence[1]

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

Many temperate lakes are dimictic, meaning that they turnover twice a year (in fall and spring). The breakdown of seasonal thermal stratification that leads to turnover is driven by wind stirring and/or convection due to surface buoyancy flux (B_0) from surface heat fluxes. Typically, it is assumed that at some point during turnover the entire lake homogenizes and is actively mixing. However, depending on the duration of turnover period and the depth of the lake, mixing may not reach the bottom before stable stratification sets in.

In fall, net surface cooling and wind stirring result in forced penetrative convection which deepens and cools the surface mixed layer. Once surface water is cooled below the temperature of maximum density (T_{md}), B_0 becomes stabilizing. Thus, convection ceases, and the surface mixed layer only continues to deepen if there is sufficient wind stirring to overcome the stabilizing B_0, otherwise the surface mixed layer shoals. Once ice forms, the surface mixed layer stops deepening. If the entire water column did not homogenize at T_{md}, the water column was not mixed to the bottom.

In spring, it is typically assumed snow cover comes off prior to ice-off, which allows for radiatively driven convection to establish a mixed layer beneath the ice. However, for lakes where snow remains until ice-off, solar radiation is prevented from penetrating through the ice-cover and initiating mixed layer formation. Once both snow and ice come off the lake, surface water is colder than T_{md}. Thus, surface heating and associated destabilizing B_0 drive convective mixing to establish a surface mixed layer. Wind stirring aids in the deepening of the surface mixed layer. In snowy regions, ice-off may occur close to summer solstice when solar radiation is near its maximum. This results in rapid warming of surface water to and above T_{md} such that B_0 stabilizes the water column and any further deepening only occurs if wind stirring is sufficient to overcome this stabilizing B_0. Similar to fall, if the entire water column did not homogenize at T_{md}, the water column was not mixed to the bottom.

This work will investigate the interplay between the forcings, geometry, and timing that lead to incomplete mixing in deep, temperate lakes that are near T_{md} and experience snow and ice-cover. Thermistor chain observations from Deeks Lake, B.C. will be compared to theory. These observations and analysis have implications on the understanding of how temperate lakes experience turnover and can be used to help predict what will occur when ice-seasons are altered by climate change. There are potentially many lakes that are thought to be dimictic because they experience seasonal ice-cover, but actually only mix fully on a multi-annual basis.

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

Field C

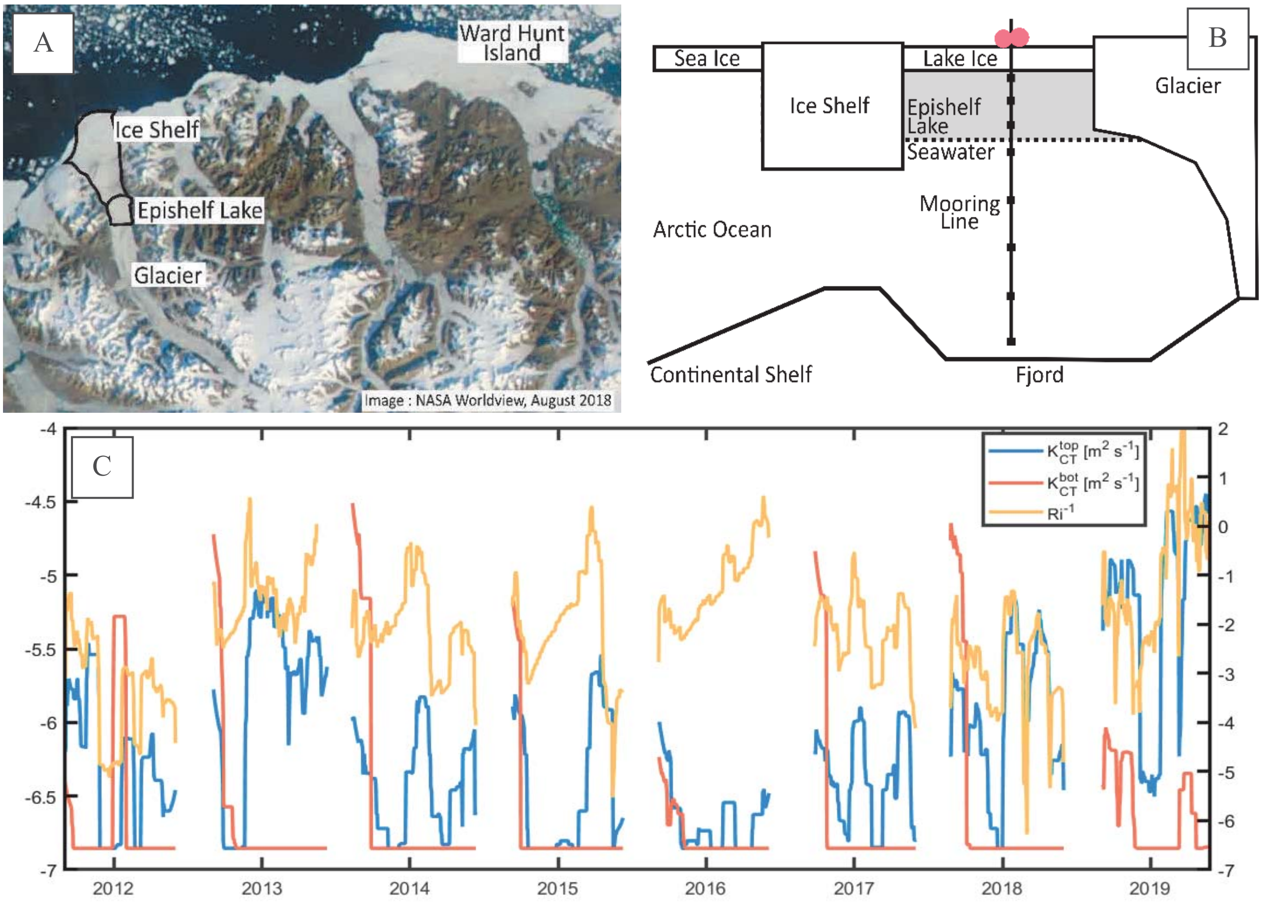
Winter dynamics in Milne Fiord, NU, Canada

J. Bonneau[1*], B.E. Laval[1], D. Mueller[2], A.K. Hamilton[3], A.M. Friedrichs[4], A.L. Forrest[4]

[1]*Department of Civil Engineering, University of British Columbia, Vancouver, BC, Canada*
[2]*Department of Geography and Environmental Studies, Carleton University, Ottawa, ON, Canada*
[3]*Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, Canada*
[4]*Civil and Environmental Engineering, University of California Davis, CA, USA*

Milne Ice Shelf (81.6°W, 82.5°N, A) is the last intact ice shelf in the Northern Hemisphere. This thick (mean ~50 m) mass of ice, situated at the mouth of Milne Fiord, restricts the flow of meltwater from the catchment to the ocean and thereby creates a perennial layer of freshwater on top of the seawater called an "epishelf lake" (B). Milne Fiord epishelf lake is the last epishelf lake in the Arctic. In order to study the epishelf lake, a mooring was deployed in May 2011 and has been continuously recording since. The temperature and conductivity measurements of the mooring line from May 2011 to July 2019 are employed in the present study. In order to tie together this extensive dataset, a one-dimensional model is used to formulate an inverse problem and the unknown parameters of the model (mixing and outflow) are determined using an iterative fitting method. The results are twofold:

1) The outflow of the epishelf lake is through a basal channel in the ice shelf. The ice shelf channel area is in ice mass equilibrium on the timescale of the study.
2) During winter, mixing is surprisingly higher in the epishelf lake (K_{CT}^{top}) than in the seawater below the halocline (K_{CT}^{bot}). Moreover, estimation of the Richardson number shows that enhanced mixing in the epishelf lake is linked to one or more geostrophic wave-like structure (eddies)(C)



* *Corresponding author, jeremie.bonneau@alumni.ubc.ca*

Topographic influences on wind driven upwelling in a large fjord sea

B. Moore-Maley* and S. E. Allen

Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, Canada

Abstract

Wind driven upwelling is common in lakes and coastal seas, and can produce rapid changes in surface temperature, nutrients, pCO_2 and dissolved oxygen. The strength of upwelling in these basins is controlled primarily by wind stress, stratification and basin scale; the competing effects of these quantities are summarized by the Wedderburn number, defined as the bulk Richardson number multiplied by the aspect ratio of isopycnal tilting[1]. For large basins where along-shore wind stress drives cross-shore Ekman divergence, the structure of upwelling depends additionally on cross-shore bottom slope because the vertical shear of the alongshore jet increases with bottom depth, changing the vertical structure of the cross-shore flux of alongshore momentum[2]. The Salish Sea is a complex network of fjords and inlets on the Canadian Pacific coast, the largest of which, the Strait of Georgia, has an along-axis wind climatology and demonstrates episodic fluctuations in surface temperature, salinity and pCO_2 following strong wind events. Here we analyse 10 years of hourly, 3-D hydrodynamic fields from the high resolution, semi-operational SalishSeaCast configuration[4] of the Nucleus for European Modelling of the Ocean (NEMO), along with 10 years of hourly, 2.5 km resolution atmospheric forcing fields from the Canadian High Resolution Deterministic Prediction System (HRDPS)[5]. Significant variability in upwelling depth and offshore pycnocline front displacement between individual upwelling events in the SalishSeaCast record are explained to first order by the Wedderburn number. However, large residuals between SalishSeaCast and the Wedderburn number prediction emerge for upwelling depth at steep bottom slopes and for offshore pycnocline displacement at gradual bottom slopes. Using a theoretical upwelling model that explicitly considers cross-shore advection[6], we attribute the upwelling depth residual to an increasingly vertical cross-shore circulation as the cross-shore slope steepens. We also attribute the offshore pycnocline displacement residual to a decreasing area displaced by shoaling isopycnals as the cross-shore slope becomes more gradual. Additionally, we propose improved predictions of upwelling depth and offshore pycnocline displacement as functions of both the Wedderburn number and the slope Burger number.

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* *Corresponding author, e-mail bmoorema@eoas.ubc.ca*

Mackenzie River outflow dynamics in an FVCOM model of the Arctic

R. M. Horwitz[1]*, Y. Wu[1], M. Z. Li[2], and E. Devred[1]

[1] *Fisheries and Oceans Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada*
[2] *Natural Resources Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada*

ABSTRACT

The Mackenzie River is a major source of fresh water to the Arctic ocean. A long history of field campaigns in the region have described the ocean's response to wind and ice forcing at several sites along the Beaufort Shelf. Episodic upwelling circulation moves fresher surface water offshore and draws saline, nutrient-rich waters onto the shelf. However, sharp bends in the coastline and isobaths near the Mackenzie delta makes the wind-driven response decidedly three dimensional. It is therefore difficult to fully characterize with spatially limited mooring data, while 9 months annual ice coverage additionally limits remotely sensed surface data. This work uses a high-resolution numerical model (FVCOM, 0.5-3km resolution on the shelf) that has been validated with observational data. In this work, we map the spatial patterns of wind- and ice-driven transport on the Canadian Beaufort Shelf in both open water and ice covered seasons, and link the export pathways of Mackenzie River water to the dynamical regimes that drive them.

* *Corresponding author, e-mail Rachel.Horwitz@dfo-mpo.gc.ca*