

# Measurement of vertical oxygen flux in lakes from microstructure casts

Nader Nakhaei<sup>1</sup>, Leon Boegman<sup>1</sup> and Damien Bouffard<sup>2</sup>

1-Environmental Fluid Dynamics Laboratory,  
Department of Civil Engineering, Queen's University, Kingston, ON, Canada  
[nader.nakhaei@queensu](mailto:nader.nakhaei@queensu)

2- Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair,  
Ecole Polytechnique Federale de Lausanne, Switzerland

## Abstract

Vertical flux of oxygen in lakes can play an important role in regulating the severity of hypoxia. Direct measurement of oxygen flux has remained hard due to lack of sufficient data. In this research, we focus on measuring vertical oxygen flux in a small hypoxic Canadian Shield lake using Fick's Law  $F = -K_z dDO/dz$ , where  $K_z$  is the vertical turbulent diffusivity and  $DO(z)$  the vertical concentration of dissolved oxygen. To compute oxygen flux, a fast-response temperature and optical oxygen logger was attached to a temperature microstructure profiler and casts were obtained throughout the summer stratification period. The profiles were synchronized by aligning the temperature channels from the two instruments. To solve Fick's Law,  $K_z$  was obtained from the microstructure data using a buoyancy Reynolds number parameterization and  $dDO/dz$  was obtained from the oxygen logger. The results show negligible oxygen flux through the thermocline ( $\sim 3 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$ ) during the summer stratification period, in comparison to the oxygen sinks in the hypolimnion (sediment oxygen demand and respiration).

## 1 Introduction

In recent decades, increased nutrient loads and climate-induced warming has been exacerbating bottom-water hypoxia in global water resources (e.g., Diaz and Rosenberg 2008) and threatening cold-water fish species. Hypoxia results from a combination of primary production, sediment oxygen demand (SOD) and insufficient vertical mixing (Boehrer and Schultze 2008). The associated changes in hypolimnetic dissolved oxygen (DO) are complex and involve coupling between hydrodynamic and biogeochemical processes (e.g., Bouffard et al 2014). The sources and sinks of DO in the hypolimnion can be divided into four main categories: (a) horizontal advection, (b) vertical flux through the oxycline, (c) SOD, and (d) hypolimnetic oxygen demand (HOD), which is the sum of photosynthesis and respiration. Typically, (b)  $\ll$  (c) + (d) leading to DO depletion in the hypolimnion (e.g., Bouffard et al 2013). However, the vertical flux can be significant during mixing events (Bouffard et al 2014) and has never been measured through the water column of a stratified hypoxic lake. Direct measurement of vertical oxygen flux remains difficult: eddy correlation ( $F = \langle DO'w' \rangle$ ) may be applied at discrete depths (e.g., Krelig et al 2012) or flux profiles may be obtained by analogy to Fick's Law  $F = -K_z dDO/dz$ ,

where  $K_z$  is the vertical turbulent diffusivity and  $DO(z)$  is the vertical concentration of dissolved oxygen. Sufficient data to apply Fick's Law is typically lacking. For example, Rao et al. (2008) and Bouffard et al. (2013) computed vertical oxygen fluxes in Lake Erie using Richardson number-based turbulent diffusivities and bulk epilimnion and hypolimnion oxygen concentrations. Their data sets came from moorings separated by up to 100 m that recorded mean flows and concentrations. Edwards et al. (2005) used temperature gradient microstructure data to estimate the seasonal basin-average turbulent diffusivity in Lake Erie, using a constant mixing efficiency and DO data from spatially independent CTD casts. Given these deficient approaches, there is a need for improved computation of oxygen flux, where both  $K_z$  and  $dDO/dz$  are measured at high vertical resolution co-incidentally during each instrument cast. For example, Rovelli et al. (2016) recently calculated vertical oxygen fluxes in the North Sea watercolumn from co-incident temperature and oxygen microstructure data. The objective of the present research is to determine the vertical oxygen flux in a small Canadian Shield lake by applying Fick's Law to co-incident temperature microstructure and high-resolution oxygen profile data.

## 2 Methods

Eagle Lake (Figure 1-a) is a small inland lake located in Central Frontenac Township, eastern Ontario, Canada. Recently, Eagle Lake has experienced shoreline development pressure from cottages and commercial properties (Eagle Lake Property Owners' Association 2011) and increased thermal stratification from climate warming (Nelligan et al 2016). As a result, in late summer, when the lake is stratified, the hypolimnion becomes hypoxic which threatens the deep-water lake trout population.

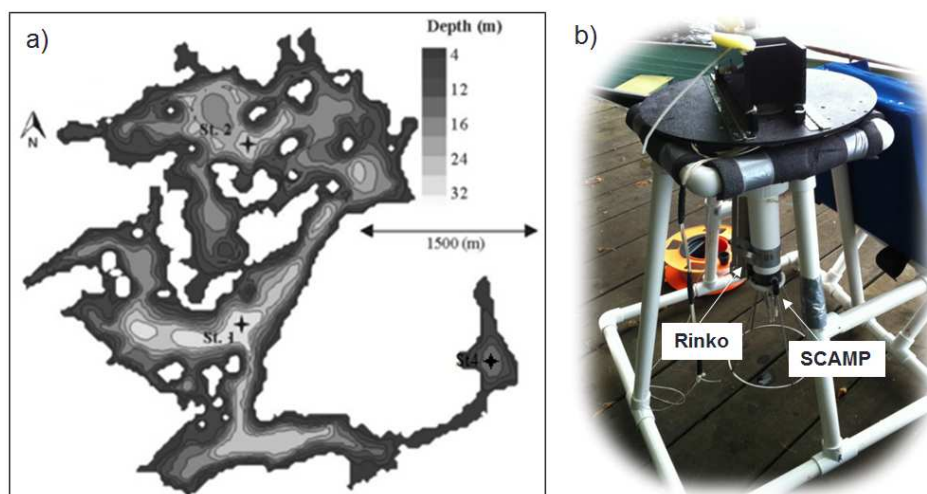


Figure 1: a) The bathymetry of Eagle Lake showing the locations of the measurement stations; b) the SCAMP microstructure profiler and attached RINKO temperature and oxygen logger. Note the additional floats added to the top of the SCAMP drag plate to compensate for the weight of the RINKO.

To compute oxygen flux, a temperature and optical oxygen logger (RINKO; 1 Hz sampling; < 1 sec 90% response time) was attached using hose clamps (Figure 1-b) to a temperature microstructure profiler (SCAMP; 100 Hz sampling). The SCAMP profiled at  $0.1 \text{ ms}^{-1}$  resulting in temperature and oxygen measurements every 1 mm and 10 cm, respectively. Vertical oxygen flux was computed from Fick's Law (above), where the turbulent diffusivity was calculated following Bouffard and Boegman (2013) according to the buoyancy Reynolds number ( $Re_b = \varepsilon/\nu N^2$ ), with turbulent dissipation following Ruddick et al (2000). The eddy diffusivity code was modified to use the molecular diffusivity of oxygen ( $2 \times 10^{-9} \text{ m}^2\text{s}^{-1}$ ). The vertical oxygen gradient ( $dDO/dz$ ) was obtained directly from the RINKO data using the depth channel from the SCAMP. To match the SCAMP and RINKO signals, temperature timeseries data were aligned through temporal adjustment of the respective temperature timeseries. To characterize the seasonal changes in oxygen flux, SCAMP+RINKO casts were collected at two stations in July and September and three stations in October during 2011 (Figure 1, Table 1).

Table 1: Depth at each station (Figure 1) and the number of valid casts with SCAMP and RINKO profiles.

Station	Depth (m)	Number of casts (2011)		
		July 5	September 8	October 6
1	30	3	3	2
2	25	4	3	4
4	12	-	-	2

### 3 Results

Figure 2 shows the calculated dissipation, turbulent diffusivity and the oxygen flux along with observed temperature (from SCAMP) and DO (from RINKO) profiles for all of the casts and stations. Since the fieldwork was during daylight, the typical photosynthetic peak in DO at the base of the upper mixed layer was observed during the summer casts (July and September). The DO profiles, along with the resulting fluxes show down-gradient fluxes, consistent with the Fickian diffusion model (Figure 2). In all casts, the diffusivities are molecular through the

thermocline region, where the strong thermal stratification and lack of significant hydrodynamic forcing inhibits mixing (e.g., wind, internal waves and/or billows; e.g., Bouffard et al 2014). When the stratification weakens in October, the thickness of the water column with molecular diffusivity decreases (from around 10 m to almost 2 m at Station 1 and from around 8 m to 3 m at Station 2) and the diffusivity through the thermocline region increases by up to one order of magnitude (Figure 2). High diffusivities (from  $10^{-5}$  to  $10^{-3} \text{ m}^2\text{s}^{-1}$ ) are also evident in the epilimnion, because of the wind stress and mixed water column. As the thermocline deepens in fall, the mixing deepens as well, and as a result there is more flux through the epilimnion.

In order to better understand vertical mixing of oxygen in Eagle Lake, we used the average DO profile at each station during each sampling campaign to calculate the fluxes throughout the different regions of the watercolumn. These include the photosynthetic peak at the base of the mixed layer, the oxycline and the hypoxic concentration boundary layer above the sediment, where there are higher oxygen gradients in the watercolumn (Figure 3). The related eddy diffusivities have been averaged over the gradient regions shown and the DO fluxes have been calculated by applying the Fick's Law along the gradient (considering the DO concentration of the first and the last point of each line). There are upward fluxes of DO in July and September (green lines in Figure 3) from the photosynthetic peak in the range  $2.88 \times 10^{-4}$  to  $7.3 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$ , except for Station 2 in July ( $5.5 \times 10^{-2} \text{ gm}^{-2}\text{d}^{-1}$ ) when both the eddy diffusivity and oxygen gradient are higher (Figure 3). The downward fluxes through the oxycline (red lines in Figure 3) are in a same range in all of the observations at Station 1 and Station 2 ( $2.7 \times 10^{-4}$  to  $4.62 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$ ). However, the downward flux at the shallowest station (Station 4) is higher ( $9.04 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$ ) where the oxycline lies directly above the sediments, likely increasing both diffusive mixing and the oxygen gradient into the sediments.

Unlike the epilimnion, the hypolimnion is not well mixed in DO (Station 1 and 2) and there is a near-bed decrease in DO, leading to a concentration boundary layer of hypoxic water from the SOD. This hypolimnetic hypoxic boundary layer is visible from the start of the sharp oxygen gradient above the bed (black lines in Figure 3). In July, the thickness of the hypoxic concentration boundary layer (Figure 3) is ~3 m at Station 1, located at the deepest point of the lake (~30 m), but is not observed at the shallower Station 2 (~25 m).

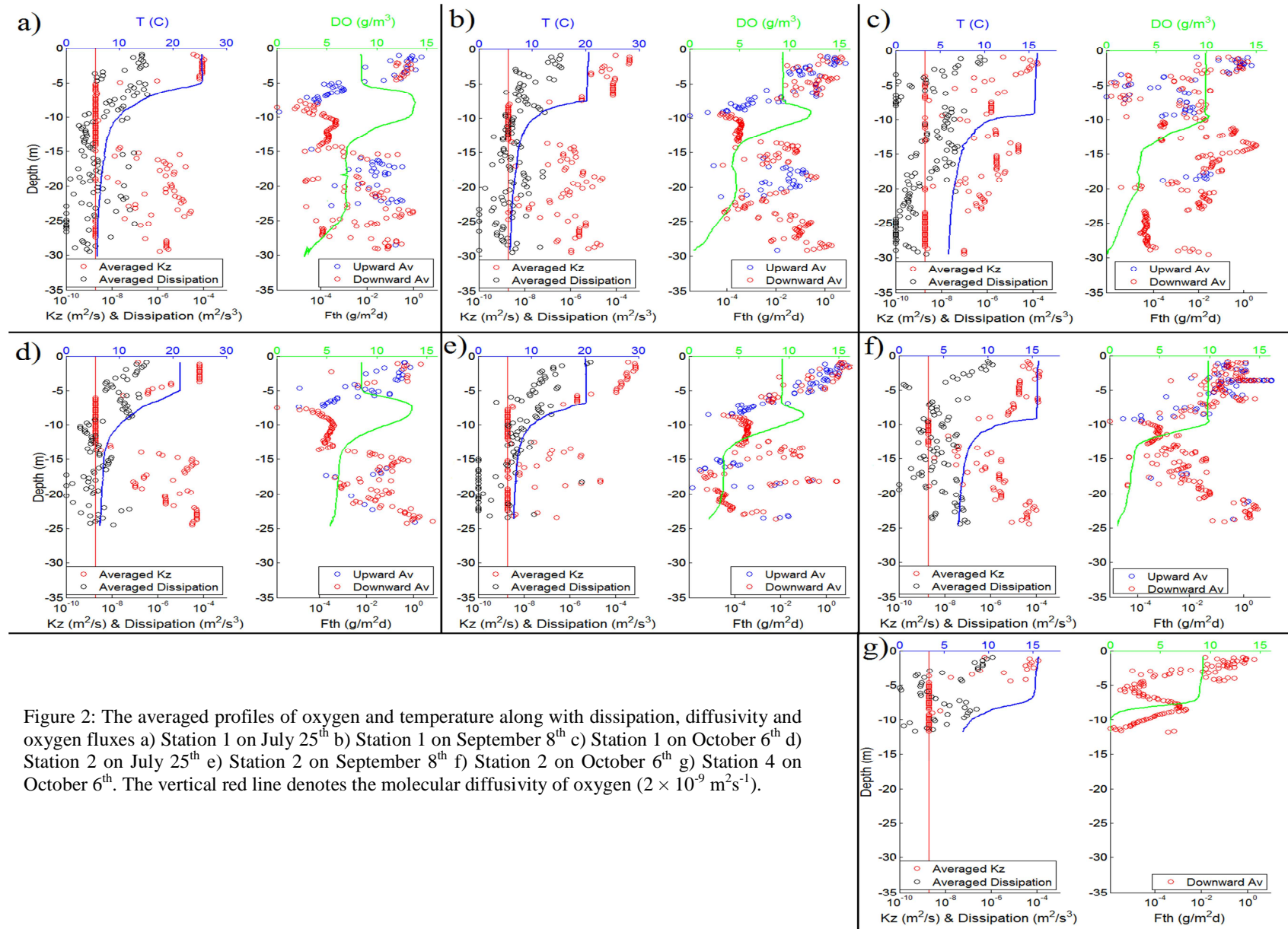


Figure 2: The averaged profiles of oxygen and temperature along with dissipation, diffusivity and oxygen fluxes a) Station 1 on July 25<sup>th</sup> b) Station 1 on September 8<sup>th</sup> c) Station 1 on October 6<sup>th</sup> d) Station 2 on July 25<sup>th</sup> e) Station 2 on September 8<sup>th</sup> f) Station 2 on October 6<sup>th</sup> g) Station 4 on October 6<sup>th</sup>. The vertical red line denotes the molecular diffusivity of oxygen ( $2 \times 10^{-9} \text{ m}^2 \text{ s}^{-1}$ ).

This suggests horizontal advection of higher DO water masses, from the main watercolumn toward the sediments at the lake perimeter, may be occurring. However, the continued oxygen flux deficit in the hypolimnion and decrease in hypolimnion volume (due to thermocline deepening), cause the thickness of the hypoxic concentration boundary layer to increase to ~5 m in September and ~7 m in October, and thus be evident at the shallower Station 2 during these months. The bottom hypolimnetic fluxes at Station 1 ( $2.3 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$  in July,  $9.5 \times 10^{-3} \text{ gm}^{-2}\text{d}^{-1}$  in September and  $8.3 \times 10^{-3} \text{ gm}^{-2}\text{d}^{-1}$  in October) and Station 2 ( $9.04 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$  in September and  $3.6 \times 10^{-2} \text{ gm}^{-2}\text{d}^{-1}$  in October), show an increasing trend as hypoxia worsens through the summer and prior to fall turnover. In general, the downward oxygen flux from oxycline into the main hypolimnion is up to an order of magnitude smaller than the flux from the hypolimnion into the near-bed concentration boundary layer indicating that the hypolimnion DO is depleting during summer until turnover.

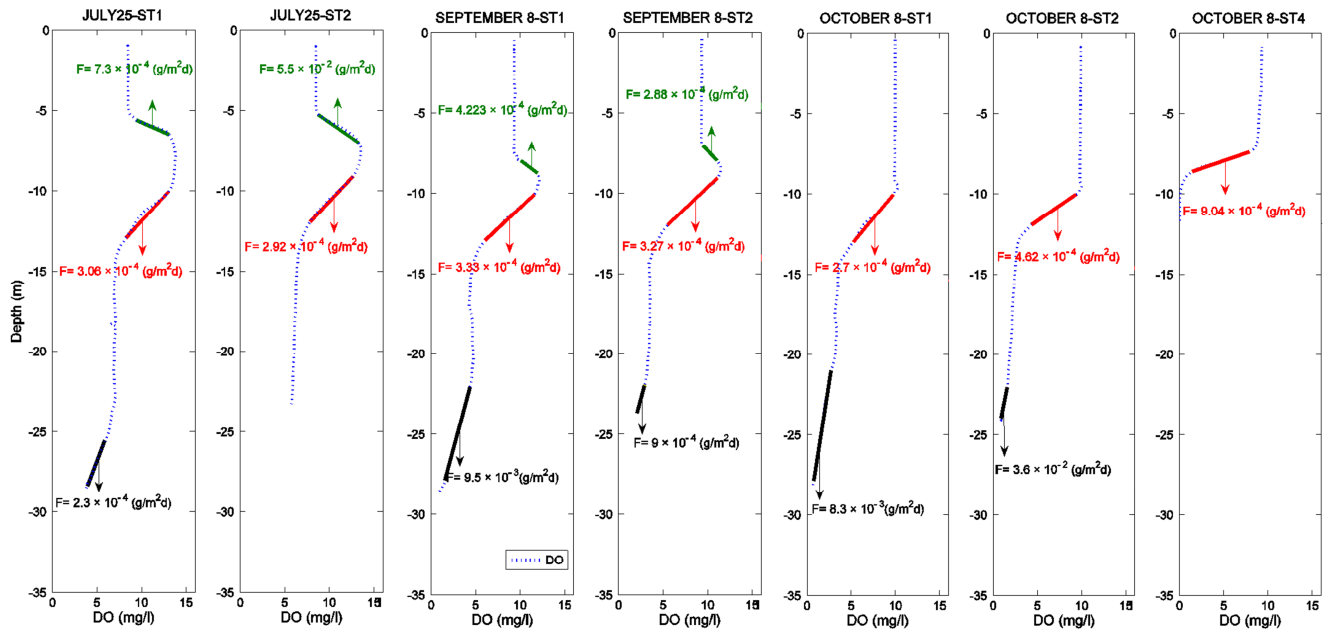


Figure 3: Calculated fluxes of DO through the water column along with the averaged oxygen profile.

## 4 Discussion

As discussed above, the eddy diffusivity, and as a result the DO fluxes between regions of the watercolumn are important for the overall DO budget. Edwards' et al. (2005) calculated diffusivities ranged from  $10^{-9}$  to  $10^{-3} \text{ m}^2\text{s}^{-1}$  in Lake Erie, which are similar to our estimates. Krelig et al. (2012) used point eddy correlation observations and calculated the total downward

flux at discrete depths of Lake Scharmutzelsee. The total downward flux at the oxycline was  $\sim 7.8 \times 10^{-3} \text{ gm}^{-2}\text{d}^{-1}$ , which is around one order of magnitude more than what we see in Eagle Lake, but is still negligible in comparison with the other terms of the oxygen budget. Nakhaei et al. (2014) found that the sinks of hypolimnetic oxygen in smaller lakes (HOD and SOD), are significantly larger than indirect estimates of vertical flux during summer stratification. Typical values of HOD and SOD were  $0.054 \text{ gm}^{-3}\text{d}^{-2}$  and  $0.62 \text{ gm}^{-2}\text{d}^{-2}$ , respectively. Our calculated hypolimnetic DO flux (black line in Figure 3) ranged from  $2.3 \times 10^{-4}$  to  $3.6 \times 10^{-2} \text{ gm}^{-2}\text{d}^{-1}$ , which is smaller than the HOD and SOD of Nakhaei et al. (2014), quantifying the significant supply deficit relative to the DO demand in the near-bed hypoxic concentration boundary layer. Similarly, Bouffard et al. (2013) found the average flux through the thermocline of Lake Erie to be around  $0.14 \text{ gm}^{-2}\text{d}^{-1}$ , larger than the flux for the relatively quiescent Eagle Lake, but an order of magnitude smaller than the SOD in the lake. Roveli et al. (2016) computed the downward flux from the oxycline in the North Sea to be  $0.8 \text{ gm}^{-2}\text{d}^{-1}$ , again significantly higher in this energetic system than our values for Eagle Lake.

## 5 Conclusions

In conclusion, High diffusivities (up to  $10^{-3} \text{ m}^2\text{s}^{-1}$ ) and as a result high oxygen fluxes (up to  $10 \text{ gm}^{-2}\text{d}^{-1}$ ) were observed in the epilimnion of Eagle Lake. Downward oxygen fluxes through the thermocline ranged from  $2.7 \times 10^{-4}$  to  $9.04 \times 10^{-4} \text{ gm}^{-2}\text{d}^{-1}$ , which are small due to the molecular diffusivities in this region. The small measured vertical thermocline fluxes in comparison to estimates of oxygen sinks from the HOD and SOD, quantifies that vertical thermocline oxygen flux is negligible in small Canadian Shield lakes. Given these fluxes, we postulate that development of a near-bed hypoxic concentration boundary layer during summer is inevitable in small lakes that are sufficiently deep to maintain a hypolimnion.

## Acknowledgements

We thank I. Dardick, R. Valipour, R. Boegman and J. Axlerad for help with the field measurements. S. MacIntyre provided SCAMP processing code. The SCAMP was purchased with funds from the Canada Foundation for Innovation. This research was supported by NSERC and the Ontario Graduate Scholarship program.

## References

Boehrer, B., & Schultze, M. (2008). Stratification of lakes. *Reviews of Geophysics*, 46(2).

- Bouffard, D., & Boegman, L. (2013). A diapycnal diffusivity model for stratified environmental flows. *Dynamics of Atmospheres and Oceans*, 61, 14-34.
- Bouffard, D., Boegman, L., Ackerman, J. D., Valipour, R., & Rao, Y. R. (2014). Near-inertial wave driven dissolved oxygen transfer through the thermocline of a large lake. *Journal of Great Lakes Research*, 40(2), 300-307.
- Bouffard, D., Ackerman, J.D., and Boegman, L. (2013). Factors affecting the development and dynamics of hypoxia in a shallow large stratified lake: Hourly to seasonal patterns. *Water Resour. Res.* 49: 14 pp
- Diaz, R. J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. *science*, 321(5891), 926-929.
- Edwards, W. J., Conroy, J. D., & Culver, D. A. (2005). Hypolimnetic oxygen depletion dynamics in the central basin of Lake Erie. *Journal of Great Lakes Research*, 31, 262-271.
- Eagle Lake Property Owners' Association (ELPOA). (2011). State of the Lake Report Eagle Lake. Township of Central Frontenac - County of Frontenac, Parham, ON. ISBN 978-0-9736518-4-3. 91 pp.
- Kreling, J., Bravidor, J., McGinnis, D. F., Koschorreck, M., & Lorke, A. (2014). Physical controls of oxygen fluxes at pelagic and benthic oxyclines in a lake. *Limnology and Oceanography*, 59(5), 1637-1650.
- Nakhaei, N. Boegman, L & Bouffard, D. (2014) Modelling sediment oxygen demand in stratified lakes. *Presented at IAGLR's Annual Conference on Great Lakes Research*, May 2014, McMaster University, Hamilton, ON, Canada.
- Nelligan, C. Jeziorski, A., Rühland, K. M., Paterson, A. M., & Smol, J.P. (in press) Managing lake trout lakes in a warming world: a paleolimnological assessment of nutrients and lake production at three Ontario sites, *Journal of Lakes and reservoirs management*.
- Osborn, T. R. (1980). Estimates of the local rate of vertical diffusion from dissipation measurements. *Journal of Physical Oceanography*, 10(1), 83-89.
- Rao, Y. R., Hawley, N., Charlton, M. N., & Schertzer, W. M. (2008). Physical processes and hypoxia in the central basin of Lake Erie. *Limnology and oceanography*, 53(5), 2007.
- Rovelli, L., Dengler, M., Schmidt, M., Sommer, S., Linke, P., & McGinnis, D. F. (2016). Thermocline mixing and vertical oxygen fluxes in the stratified central North Sea. *Biogeosciences*, 13(5), 1609.
- Ruddick, B., Anis, A., & Thompson, K. (2000). Maximum likelihood spectral fitting: The Batchelor spectrum. *Journal of Atmospheric and Oceanic Technology*, 17(11), 1541-1555.