Contribution of high and low frequency internal waves to boundary turbulence in a lake

Danielle Wain[1] and Chris Rehmann[1]

[1]Affiliation not available

November 22, 2022

Abstract

The interior of lakes is often quiescent and most of the mixing in a lake occurs at the sloping boundaries, where wind-induced internal waves create turbulence (which leads to mixing) through interactions with the lakebed. To predict the occurrence and strength of turbulence in terms of meteorological forcing and stratification, we investigated the dependence of internal wave type, and their contribution to turbulence on the slope, on the Lake number, which compares the stabilizing tendency of stratification to the destabilizing tendency of the wind. Three thermistor chains and a meteorological station were deployed in West Okoboji Lake (length ~ 9 km, max. depth ~ 40 m) for two weeks. A wavelet analysis was conducted to determine time periods when different wave frequencies were excited, with particular focus on the first vertical mode seiche, the critical frequency with respect to the stratification and slope, and high frequency waves in the band of 1-10 times the buoyancy frequency. We measured the velocities in the bottom boundary layer (BBL) with a high resolution acoustic current profiler (2 MHz Nortek HR Aquadopp) and then computed the turbulent dissipation rate using the structure function method, which uses the spatial correlations of velocity along a beam to estimate the dissipation. This generated a two week time series of turbulent dissipation rate in the BBL which was then compared to the wavelet amplitudes. During the deployment, a strong daily wind forced near constant internal wave activity. The theoretical period of the first vertical mode seiche was ~17 hours, but the diurnal wind forcing interfered with free oscillation of this mode. Although not an obvious natural frequency of the lake, waves of the critical frequency (which had a period of ~11 hours) were activated throughout the measurement period. High-frequency waves were observed in the thermistor chain near the slope at the lowest Lake number wind events. The turbulence observed on the boundary was highest during these events, implying that the low frequency seiching was less important than higher frequency motions in driving turbulence on the slope.

Go see my student's talks!
EP43A-03 Evaluating Algal-Driven Shifts in Coastal Sediment-Water Oxygen Dynamics, **Rebecca Ellis,** Thursday, February 15, 2018, 02:30 PM-02:45 PM Oregon Convention Center - E143-E144
EP51A-02 Phytoplankton response to convective turbulent mixing: a mesocosm experiment, **Russell Arnott,** Friday, February 16, 2018, 08:15 AM-08:30 AM Oregon Convention Center - E141-E142

Contribution of high and low frequency internal waves to boundary turbulence in a lake

UNIVERSITY OF BATH

Danielle Wain[1] and Chris Rehmann[2]

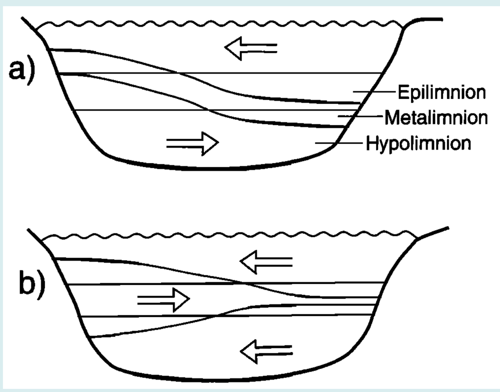
[1]Department of Architecture & Civil Engineering, University of Bath, UK; [2]Department of Civil, Construction, and Environmental Engineering, Iowa State University, USA

PO14B-2184

Introduction

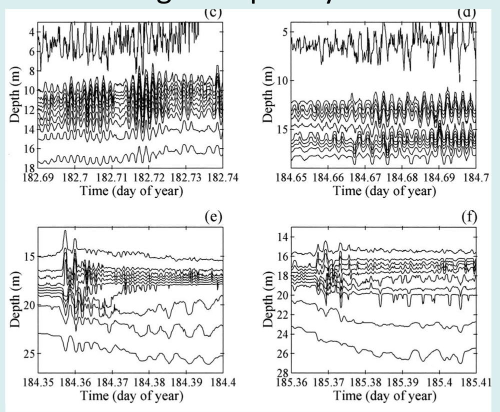
Internal waves in lakes generally originate from wind stresses on the surface, which drive basin scale seiches (most commonly vertical mode 1 and 2 waves) which can then degenerate into high frequency waves.

Low Frequency Seiches



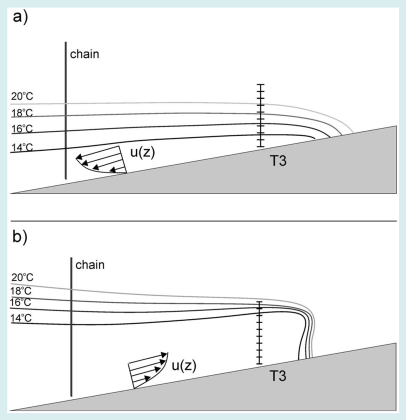
Gloor et al. (2000)

High Frequency Waves



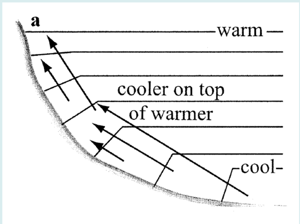
Boegman et al. (2005)

Seiching Currents
Turbulent Bores

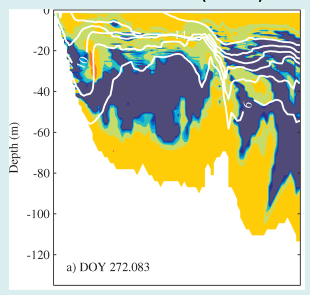


Cossu and Wells (2013)

Shear Induced Convection



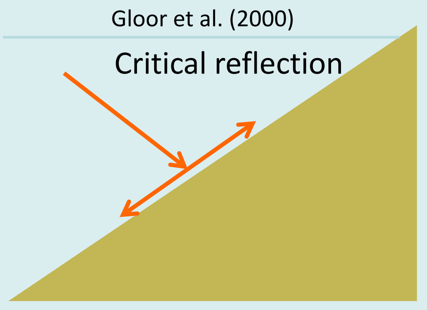
Lorke et al. (2005)



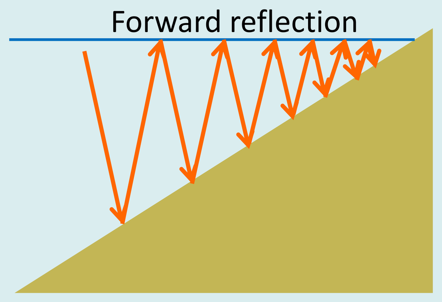
Dorostkar et al. (2013)

Internal Hydraulic Jumps

Critical reflection

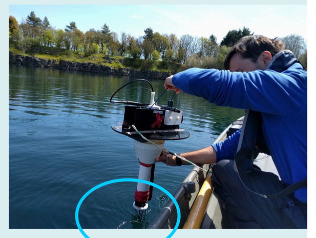


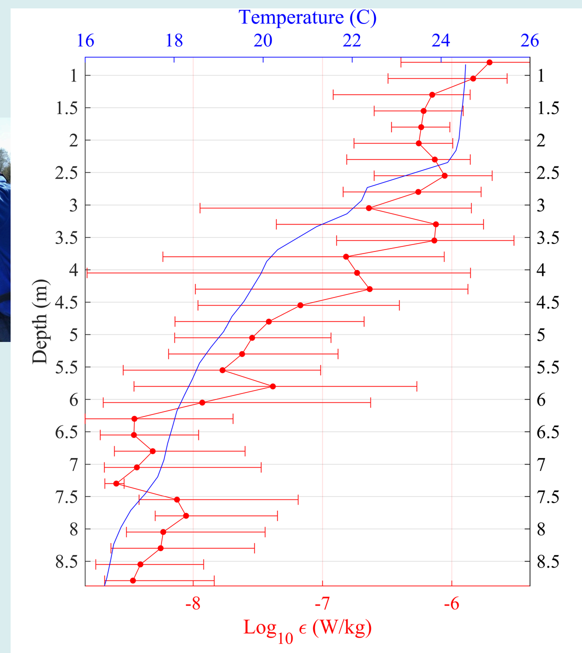
Forward reflection



When these low and high frequency waves interact with the sloping boundary of lakes, a variety of mechanisms can then lead to turbulence and mixing, including friction from seiching currents, turbulent bores in different phases of the seiche, shear-induced convection, internal hydraulics, and critical reflection and forward upslope reflection of wave energy.

Typically, turbulence is measured with microstructure profilers. While profiles give us good spatial resolution of turbulence, profiles are only a snapshot in time. Moored acoustic instruments provide a time series to better diagnose turbulence generating processes.

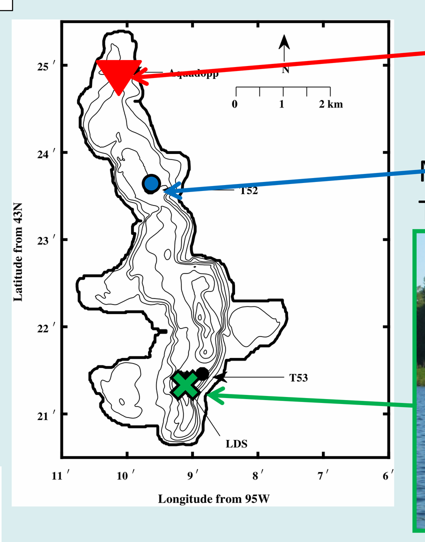




OBJECTIVE: Utilize advances in measuring turbulence using acoustic methods to determine which processes are dominant in creating boundary turbulence in lakes.

Methods

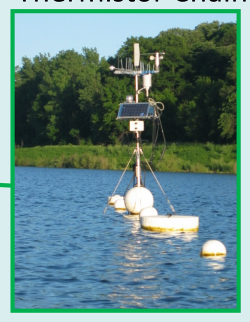
WEST OKOBOJI LAKE



Surface Area = 15.6 km²
Mean Depth = 12 m
Max Depth = 41 m

Pulse Coherent ADCP

Met Station/ Thermistor Chain



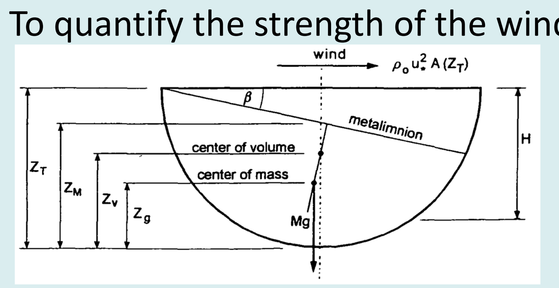
Thermistor Chain

Met Station/Thermistor Chain

- Moored in 30 m water depth
- Measures wind speed and direction (2.5 m above water), solar and net radiation, relative humidity, air temperature
- Thermistor chain with nodes every 1m
- All sensors sampled every 15 s

Stratification and Wind

To quantify the strength of the wind:



Lake number:

$$L_N = \frac{gS_t(1 - z_T/z_S)}{\rho_s u_*^2 A_s^{3/2}(1 - z_V/z_S)}$$

Stability

Wind Stresses

Internal Waves

- Stratification is evolving over short time scales
- Power spectra not ideal for non stationary signal
- Use wavelet analysis to determine evolution of frequencies of interest

Pulse Coherent Aquadopp

- In the thermocline (9m) on shallow slope (0.5°)
- 2 MHz HR Aquadopp
- Along-beam in 4 cm bins
- 1024 samples at 8 Hz every 10 minutes
- Upward looking, range ~1.5 above bed

Structure Function Method for turbulence, following Wiles et al. (2006)

Second order structure function:

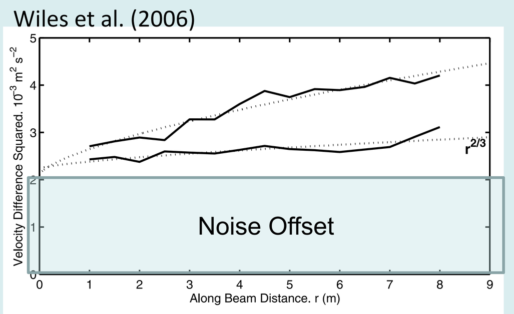
$$D(z,r) = \overline{(v'(z) - v'(z+r))^2}$$

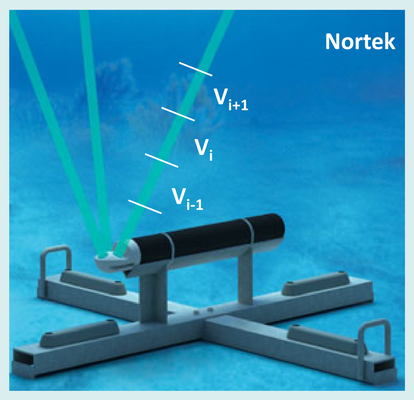
D is related to dissipation rate:

$$\varepsilon(z) = \frac{(D(z,r) - N(z))^{3/2}}{C_v^3 r}$$

Constant = 2.1

Wiles et al. (2006)

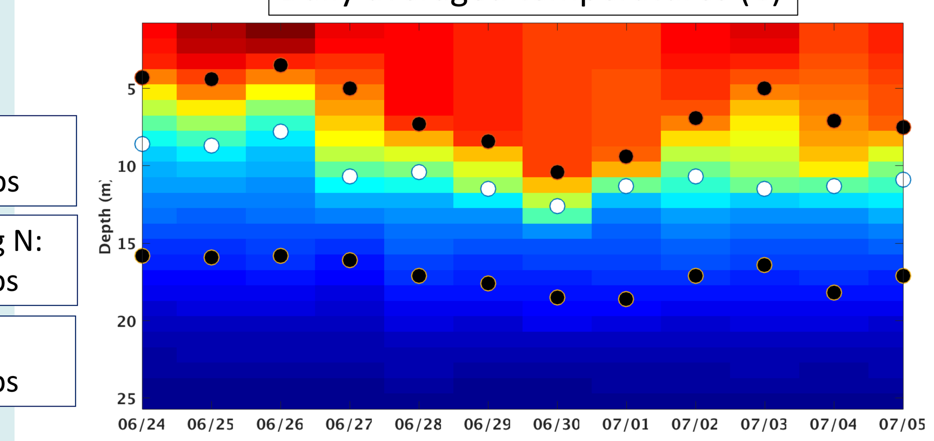




Challenges for lakes:
Low Energy
Small Ozmidov Scales

Results and Discussion

Daily averaged temperatures (C)

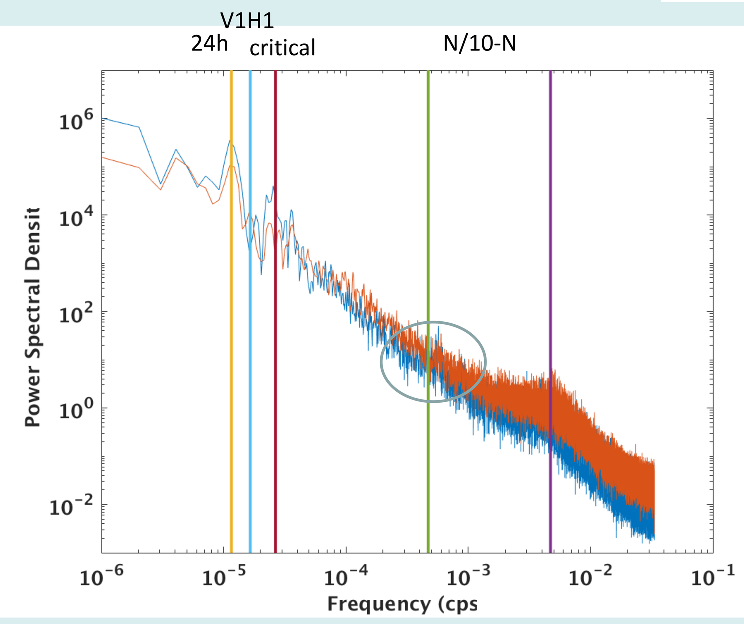


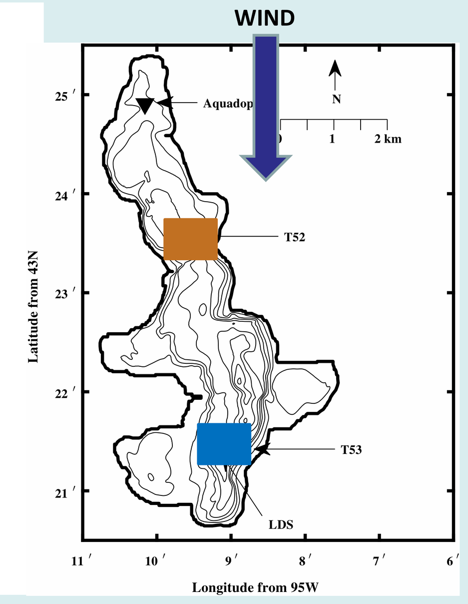
Thermocline depth computed as position of maximum amplitude of 1st vertical mode

Metalimnion boundaries computed as positions of maximum amplitude of 2nd vertical mode

Mean stratification and key frequencies evolve over the measurement period.

N in the metalimnion: $4.7 \times 10^{-3} - 5.7 \times 10^{-3}$ cps	
Critical frequency using N: $2.4 \times 10^{-5} - 2.9 \times 10^{-5}$ cps	
V1H1 frequency: $1.5 \times 10^{-5} - 1.8 \times 10^{-5}$ cps	



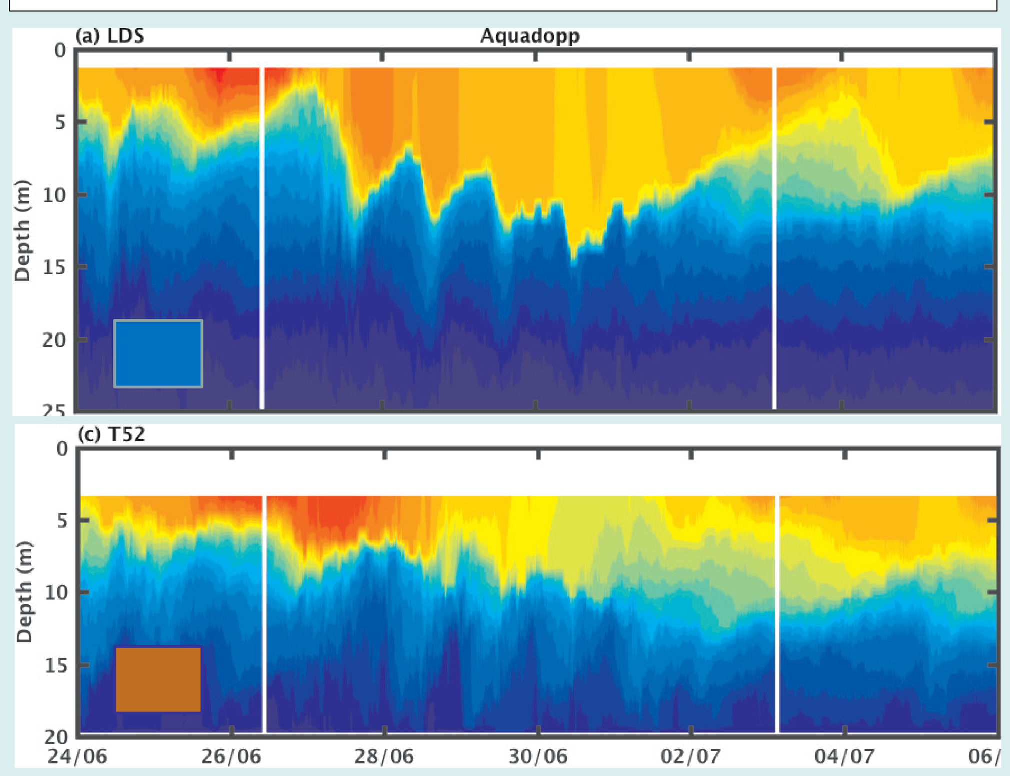


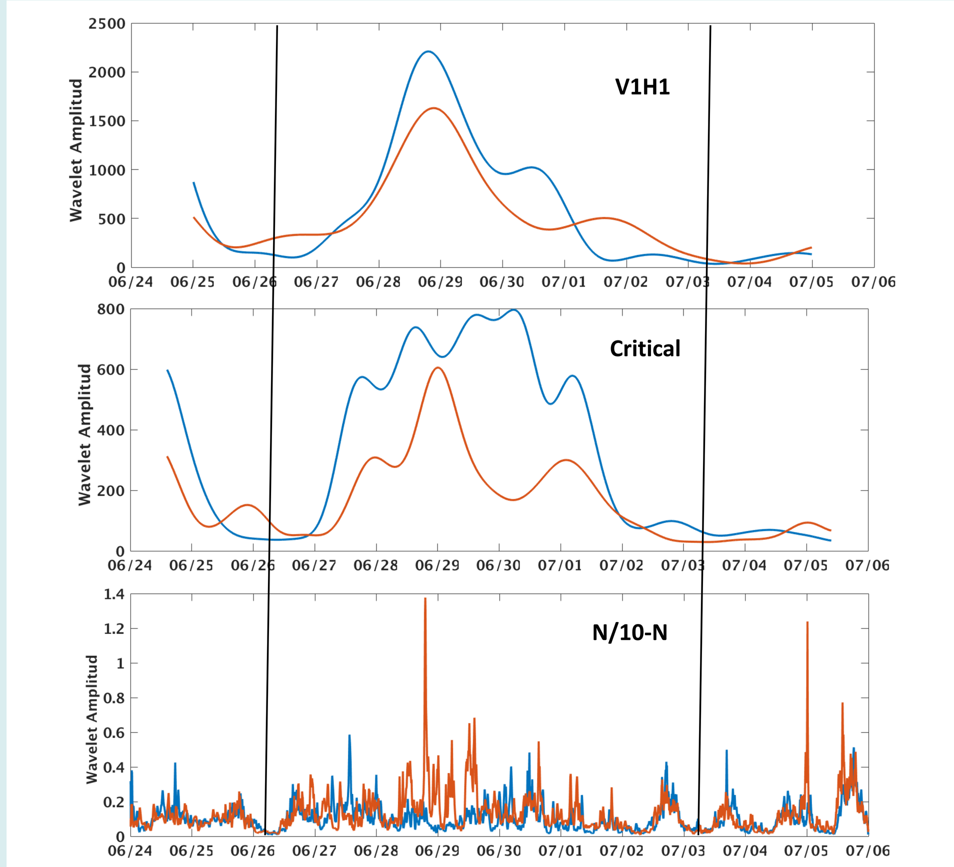
Average thermocline power spectrum of whole time series reveals strong daily forcing, which masks V1H1 frequency.

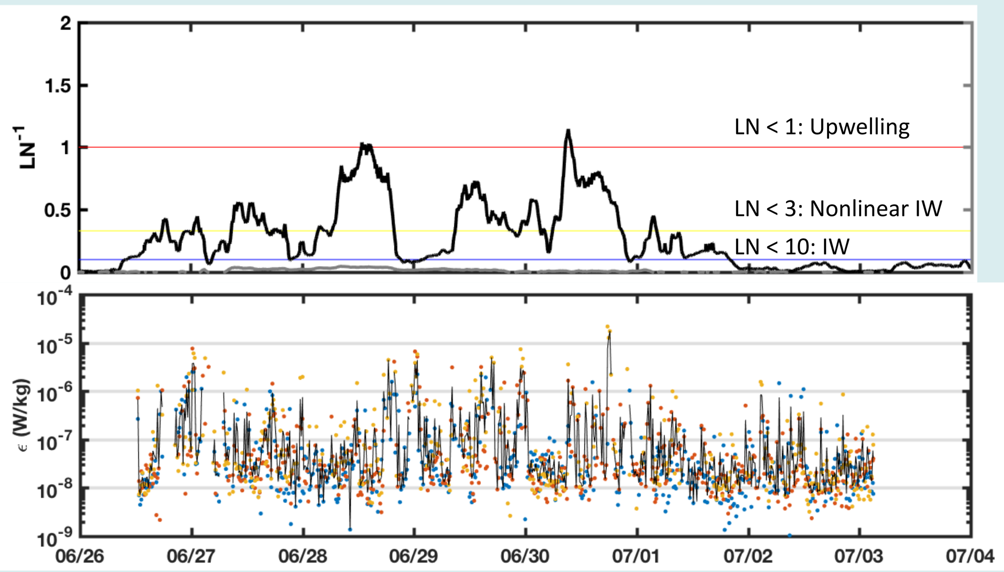
There is a peak in the critical frequency at the LDS, but this does not appear in the spectrum at T52.

There is a bump in the spectrum near N/10 in T52, indicating a shift in dominant frequencies across the lake.

Wavelet analysis shows temporal variation in frequency excitement.







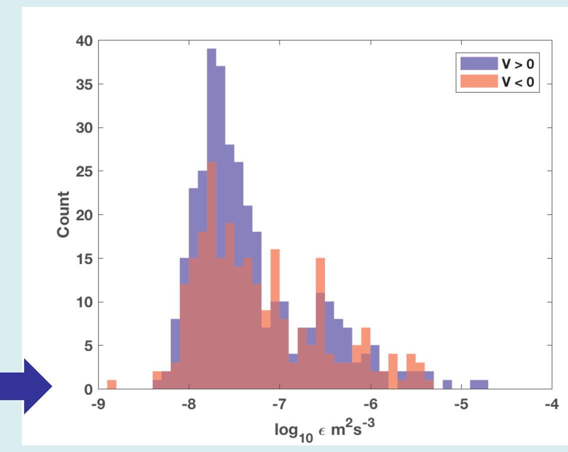
The average dissipation from the SFM over the bottom 1 m. Dots are estimates from individual beams

The highest dissipation rates correspond to the wind relaxing after strong wind events.

Double peak event corresponding with oscillations in mean velocity.

All frequencies show a peak where the turbulence peaks on the 29th.

There is a peak at the critical frequency corresponding to the peak on the 30th.



Asymmetry in turbulence if velocity is up or downslope. Mean velocity is very close to 0 – no net upslope flow. More turbulent events when velocity is upslope, but averages the same. Is slope so small that it is close to flat bottom?

Summary

- Boundary turbulence processes in lakes are wind-driven and thus inherently intermittent.
- Other methods besides profiling are needed to capture the turbulent events that will drive most mixing in small and medium sized lakes.
- In WOL, the wind excites a broadband spectrum of internal waves, which can generate turbulence through several mechanisms, with both low frequency and high frequency waves present when there is high turbulence on the slope
- Need to properly look at three thermistor chains to characterize transfer of energy through scales

Literature cited

Cossu, R., and M. G. Wells (2013), The interaction of large amplitude internal seiches with a shallow sloping lakebed: observations of benthic turbulence in Lake Simcoe, Ontario, Canada,PloS One,8(3), e57,444.
Dorostkar A., Boegman L. (2013). Internal hydraulic jumps in a long narrow lake. Limnology and Oceanography. 58 (1), p153-172.
Gloor, M., A. Wüest, and D. M. Imboden (2000), Dynamics of mixed bottom boundary layers and its implications for diapycnal transport in a stratified, natural water basin,J. Geophys. Res.,105(C4), 8629–8646.
Lorke, A., F. Peeters, and A. Wüest (2005), Shear-induced convective mixing in bottom boundary layers on slopes,Limnol. Oceanogr.,50(5), 1612–1619.
Wiles PJ, Rippeth TP, Simpson JH, Hendricks PJ (2006) A novel tech- nique for measuring the rate of turbulent dissipation in the marine environment. Geophys Res Lett

Acknowledgments

We thank the Iowa Lakeside Lab for providing support during fieldwork at West Okoboji Lake. The authors also thank Mike Kohn and Josh Scanlon for help with the experiments. We also acknowledge support from the Division of Ocean Sciences of the National Science Foundation under grant 06-47253 awarded to CRR.

Further information

For more information, contact Danielle Wain at d.j.wain@bath.ac.uk.