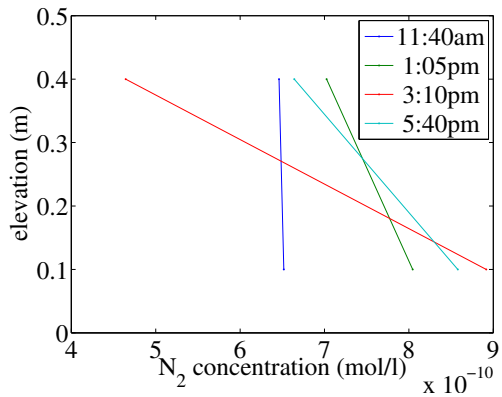
Nutrient mixing in a submerged surfzone

Stephen M. Henderson
John Harrison
Bridget Deemer

Nutrient Pollution

Lakebed pollution removal (denitrification)



Removal of NO_3^- pollution

⇒ creation of N_2 in bed

⇒ Elevation near-bed N_2

Turbulent diffusivity (Henderson)

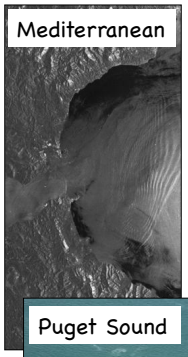
$$\text{Chemical flux} = -D\frac{\partial C}{\partial z}$$

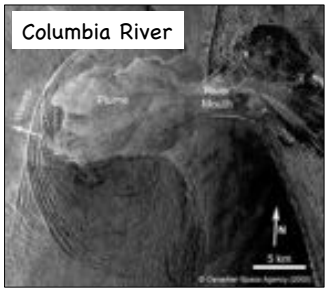
Vertical gradient in concentration (Harrison and Deemer)

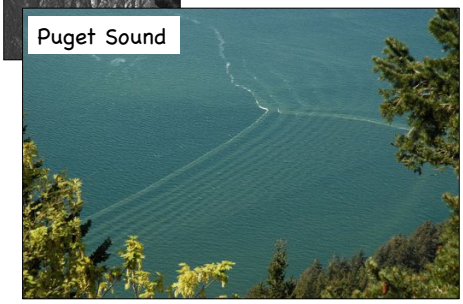
Outline

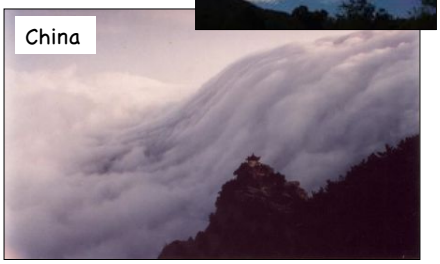
1. Description of internal waves
2. Influence of waves on nearbed mixing
3. Influence of waves on lakewide tansport

Examples of internal waves

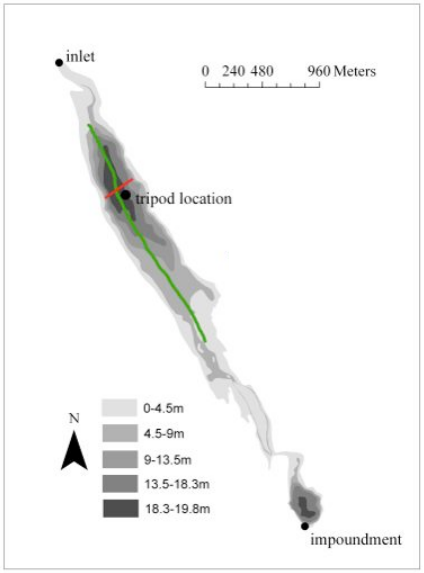




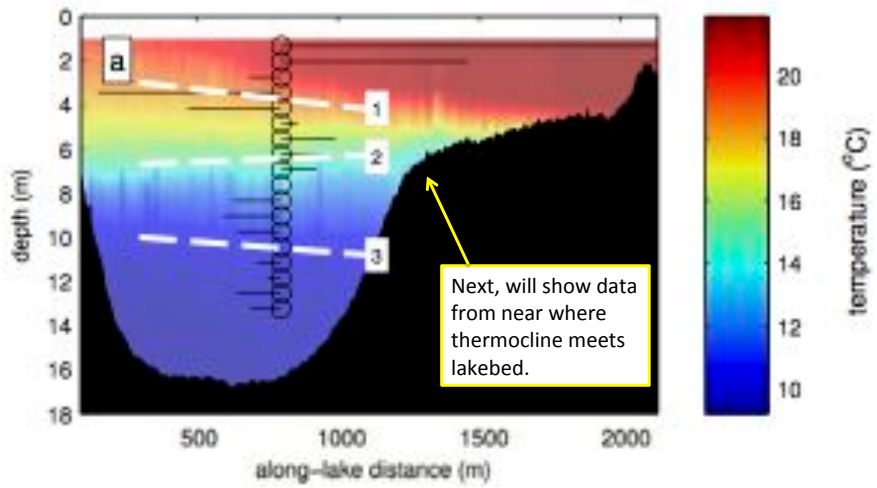




Lacamas Lake

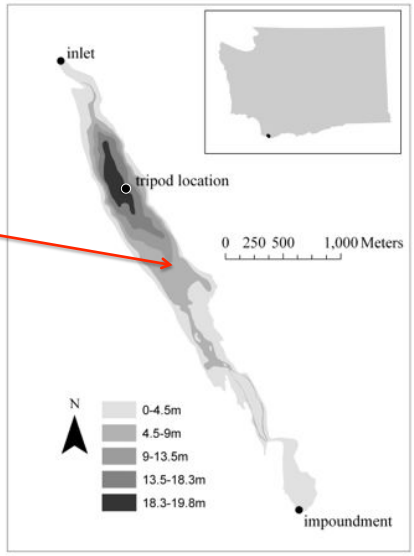


Internal waves visible as tilted temperature contours

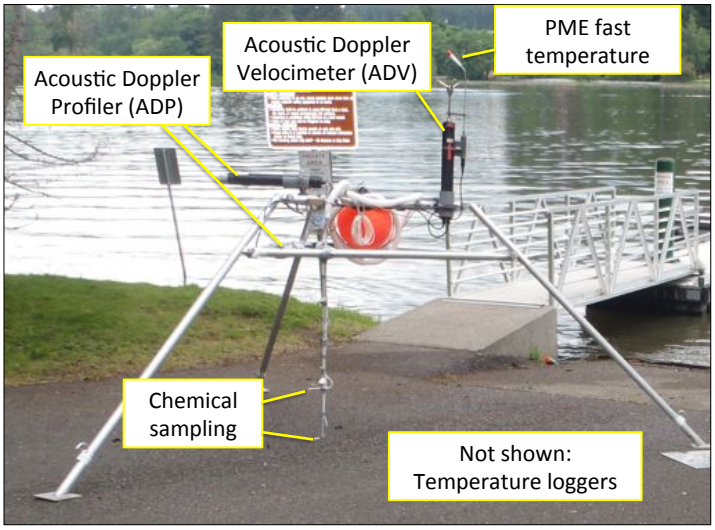


Full-depth velocity profiles

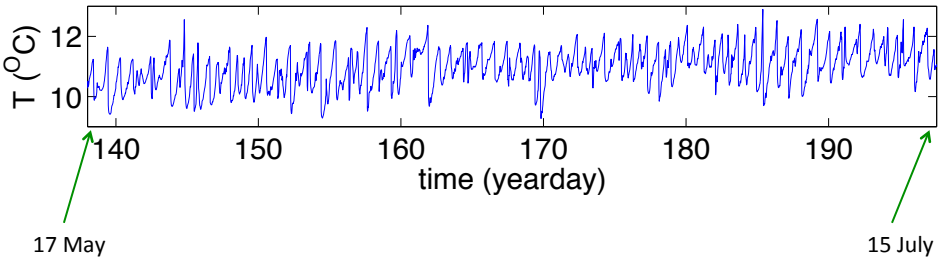
Tripod deployed where thermocline meets bed



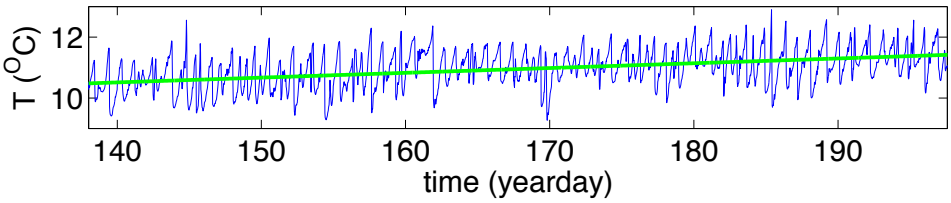
Tripods deployed on Lakebed



Temperature fluctuates owing to internal waves

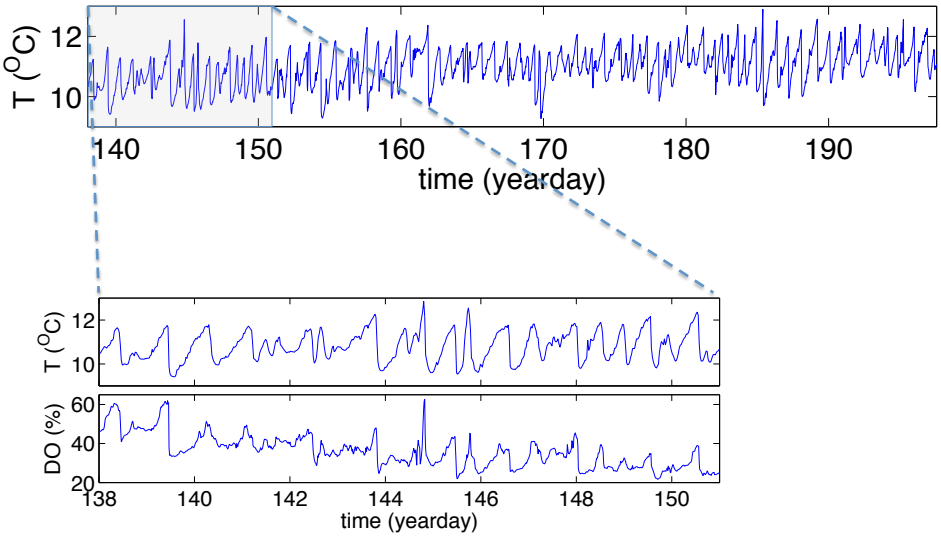


Temperature fluctuates owing to internal waves

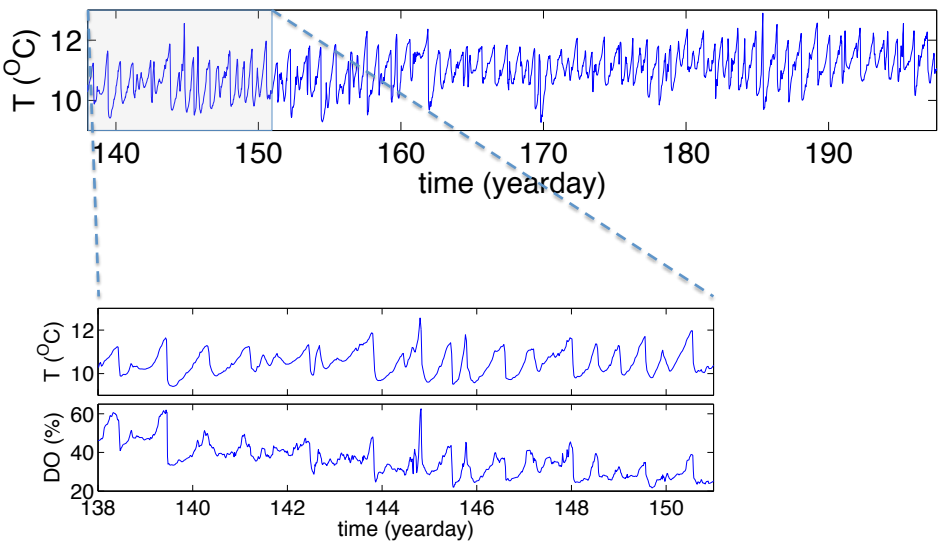


- Lake warms 1°C in 60 days.
- Waves propagate upslope at about 0.04 m/s.

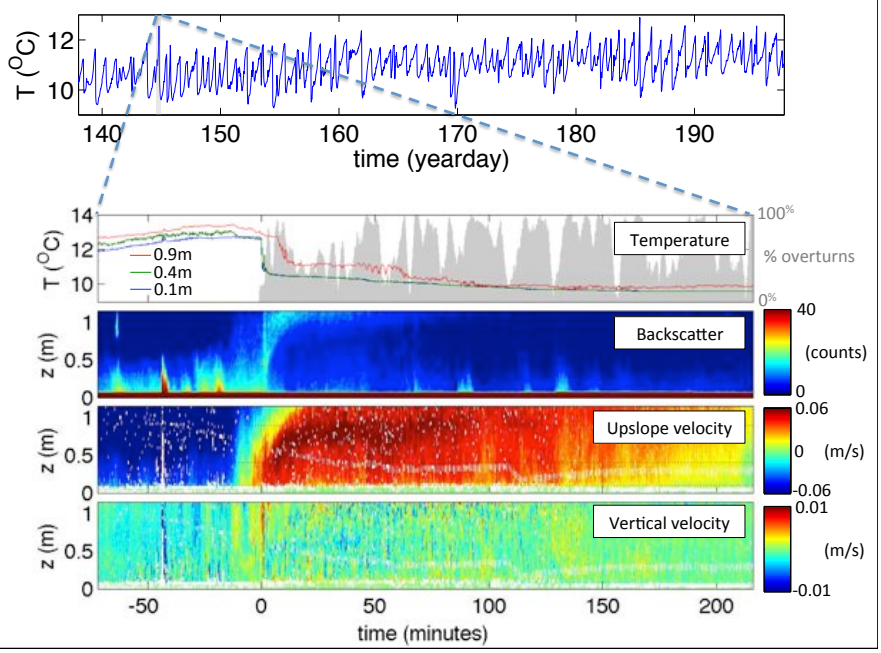
Dissolved oxygen fluctuates owing to internal waves



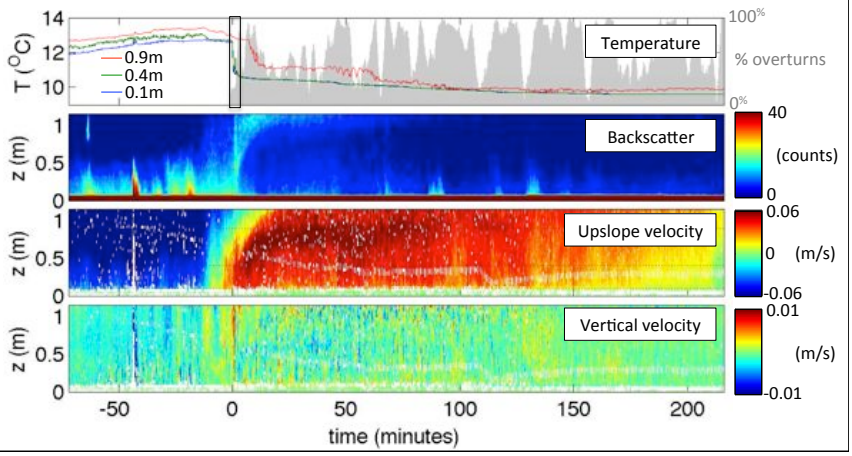
Internal bores



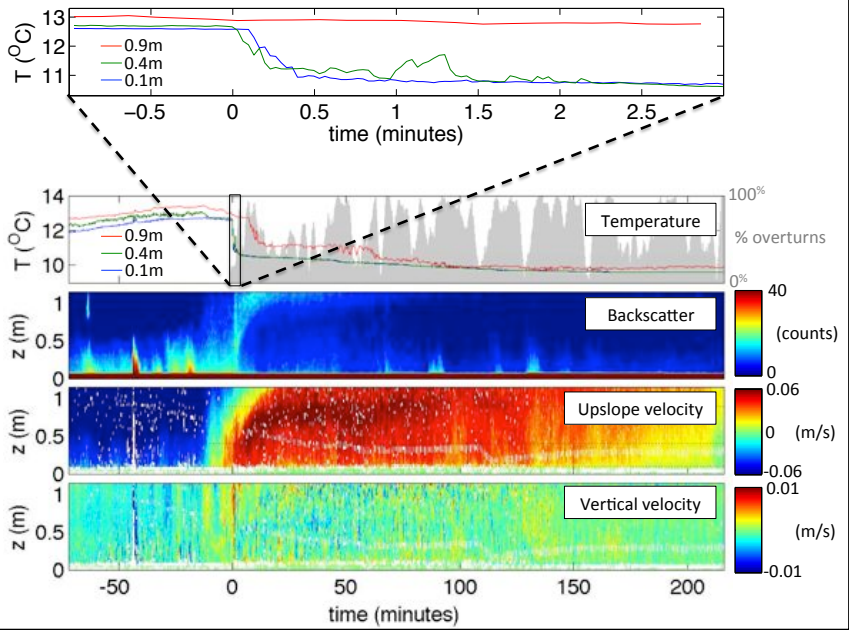
Internal bores



Internal bores

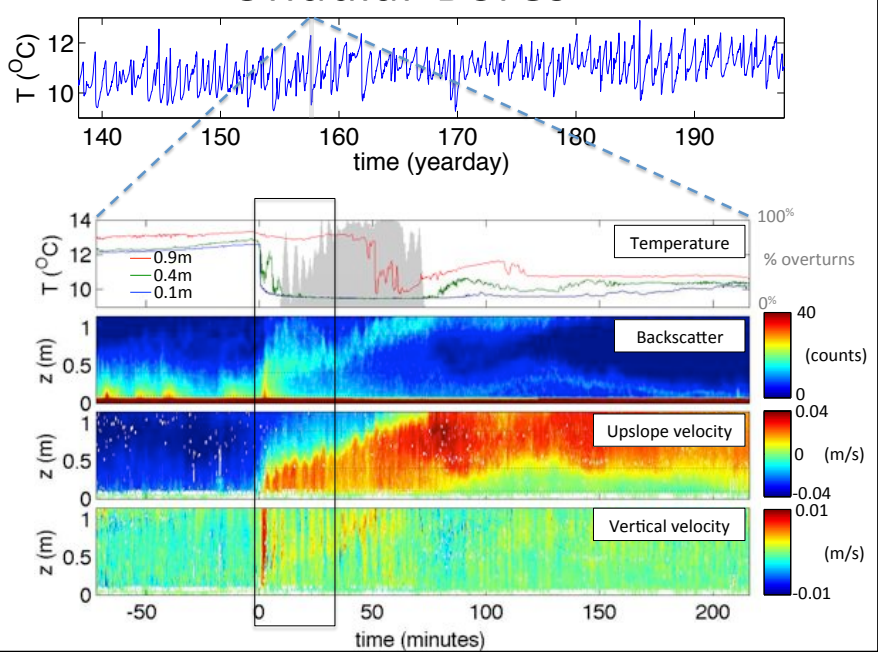


Overturning

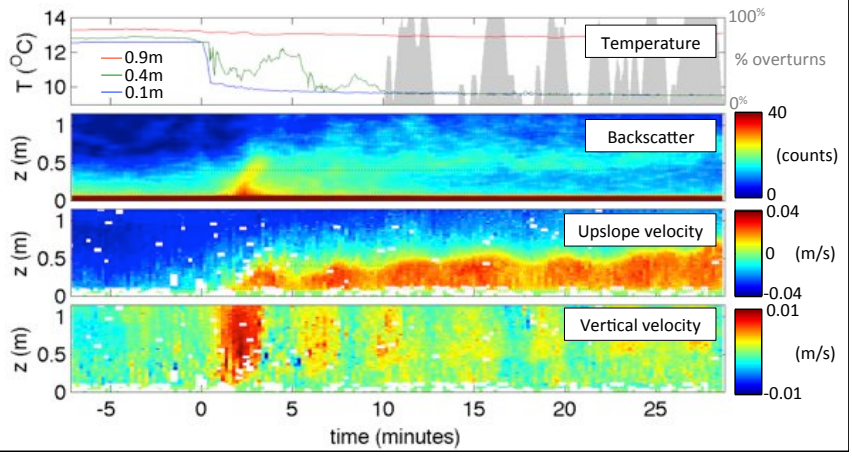


Breaking

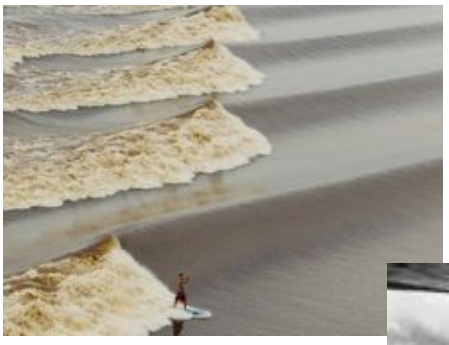
Undular Bores

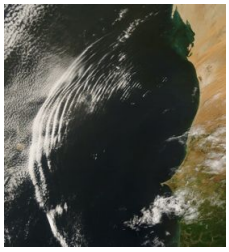


Undular Bores



Other examples of undular bores



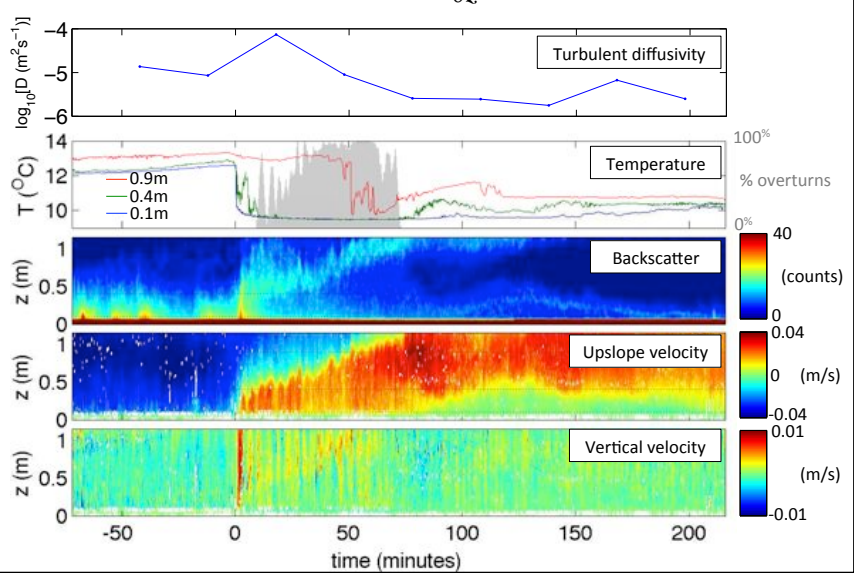


Outline

1. Description of internal waves
2. Influence of waves on nearbed mixing
3. Influence of waves on lakewide tansport

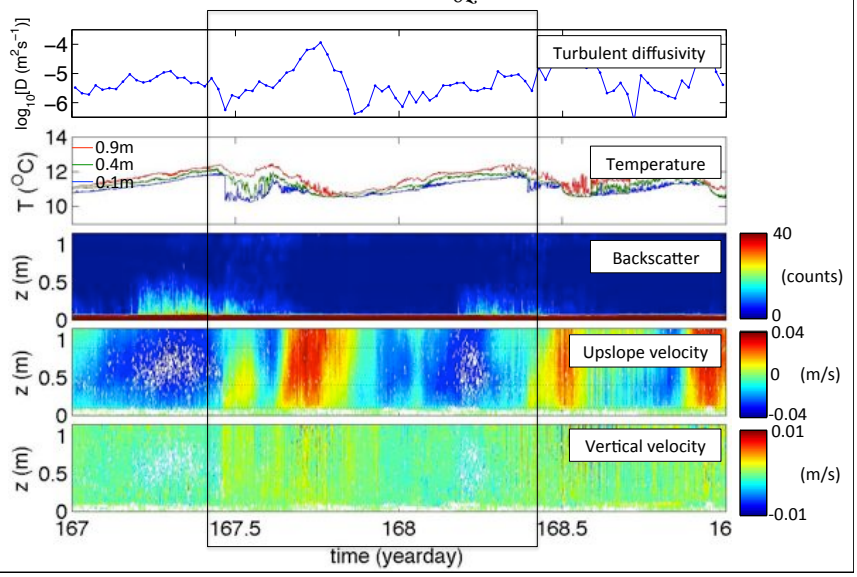
Mixing varies owing to internal waves

$$\text{Chemical flux} = -D\frac{\partial C}{\partial z}$$

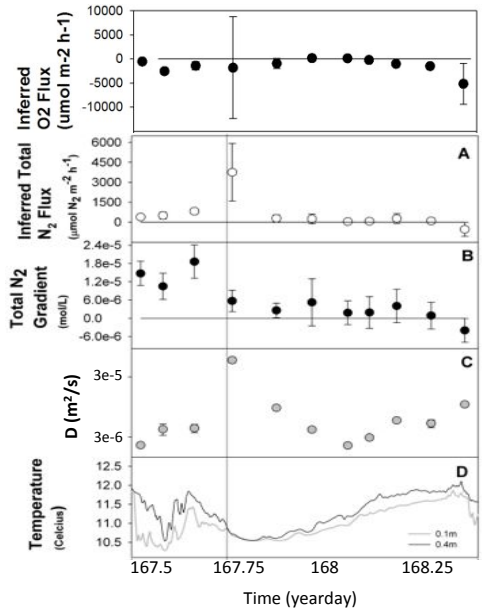


Mixing varies owing to internal waves

$$\text{Chemical flux} = -D\frac{\partial C}{\partial z}$$



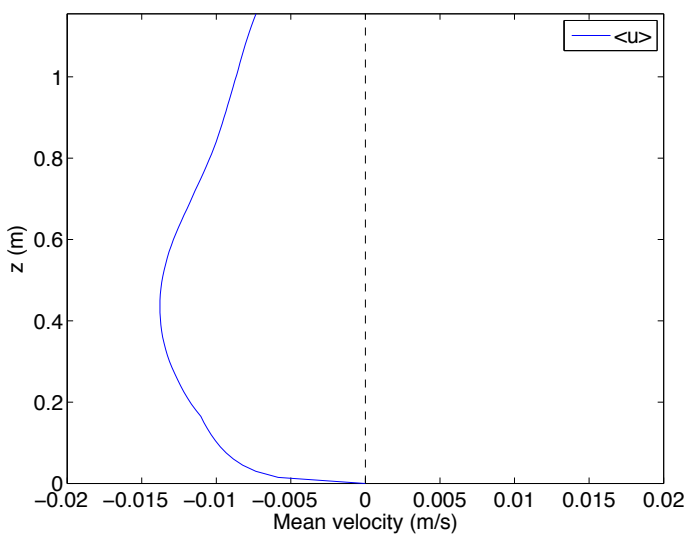
Chemical fluxes



Outline

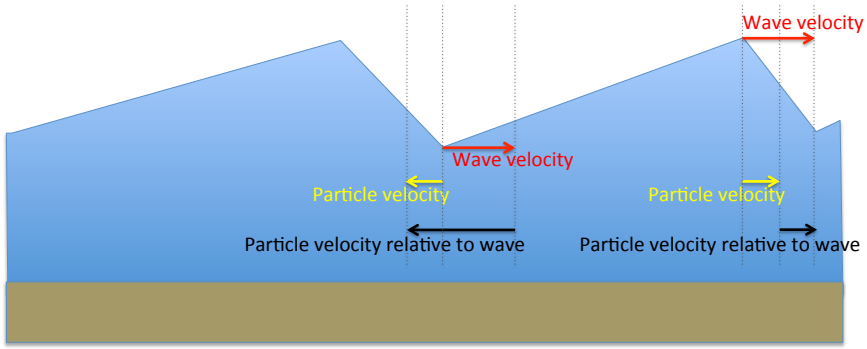
1. Description of internal waves
2. Influence of waves on nearbed mixing
3. Influence of waves on lakewide tansport

Eulerian mean currents flow downslope



- Should carry warm water downslope, but rapid warming not observed – why?

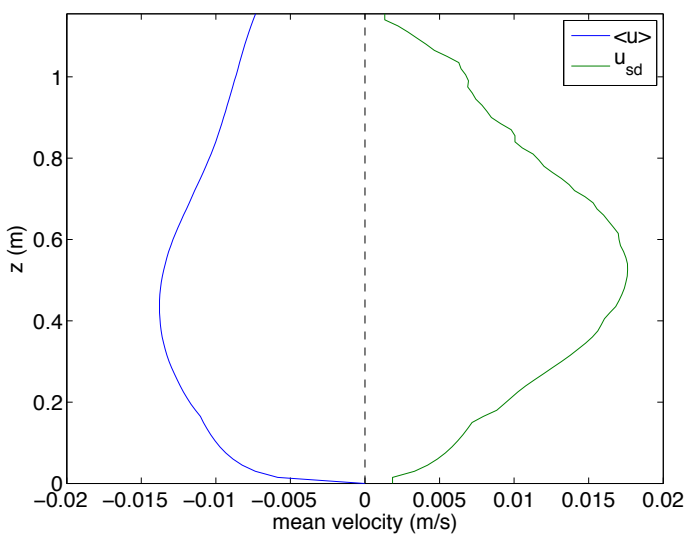
Stokes drift



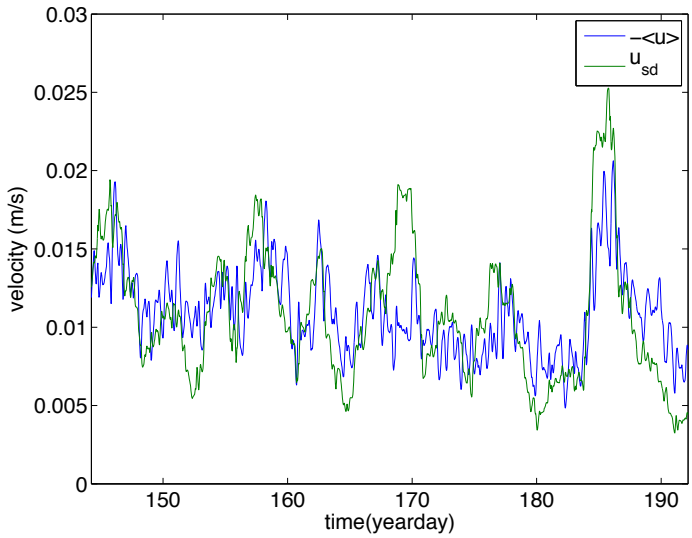
- Particles spend more time moving upslope under wave crests than downslope under troughs.
- Resulting velocity correction called Stokes drift:

  mean u for particle = u_{sd} + <u>
- If wave propagates steadily at known speed, can calculate u_{sd}.

Stokes drift cancels Eulerian mean flow



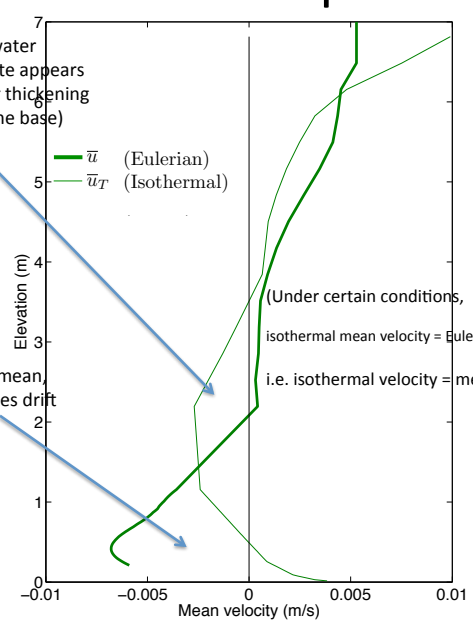
Slow variability of u_{sd} and <u> correlated



Mass transport

Intermediate temperature water transported to deep lake (rate appears sufficient to explain summer thickening and deepening of thermocline base)

Particle transport < Eulerian mean, Owing to cancelation by Stokes drift



(Under certain conditions,

isothermal mean velocity = Eulerian mean velocity + Stokes drift,

i.e. isothermal velocity = mean velocity of water particles.)

Summary

1. Internal waves pitch forward near lakebed, sometimes “breaking” or forming undular bores.
2. Mixing rates vary by orders of magnitude through wave cycle.
3. Chemical fluxes estimated from turbulence measurements and near-bed chemical gradients appear sensible (more work required).
4. Upslope Stokes drift from waves appears to roughly cancel Eulerian downslope flow.
5. Net transport of intermediate temperature water away from internal surfzone appears to make significant contribution to mixing/deepening lakewide stratification (more work required).

Ongoing work

- Major lake deployments during 2014-2017.
- Flow through mangroves in New Zealand and Mekong.
- Analysis of surfzone eddies data.