Internal wave dissipation and mean flows in a sloping, stratified lakebed boundary layer

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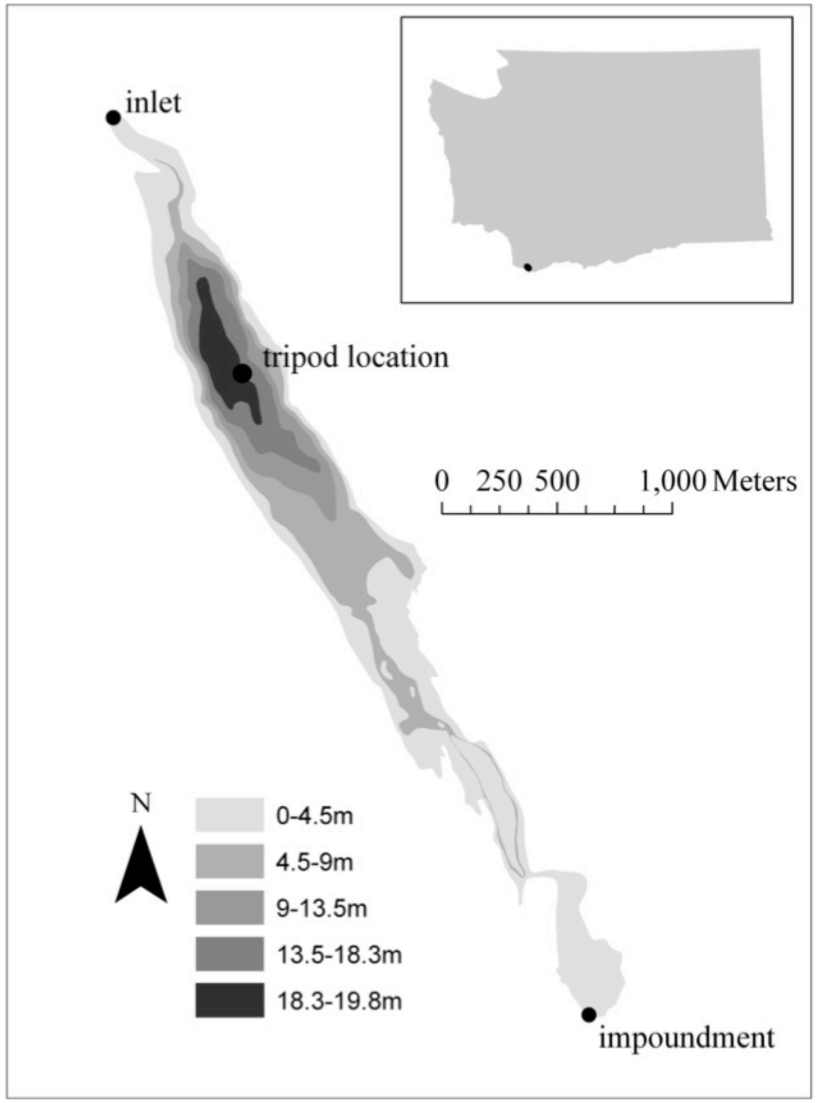
John Harrison
Bridget Deemer

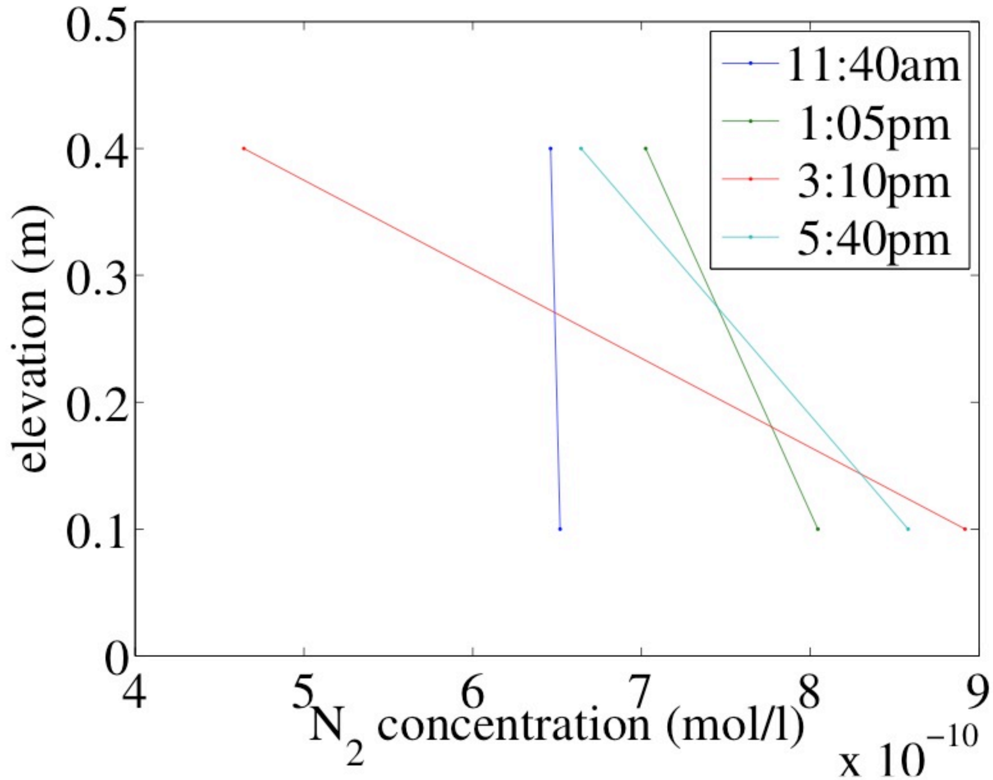
Observations in Lacamas Lake, WA



"Hypereutrophic"

Motivation: Nutrient Pollution (NO_3^-)

Estimating pollution removal (denitrification)



Removal of NO_3^- pollution

⇒ creation of N_2 in bed

⇒ Elevation near-bed N_2

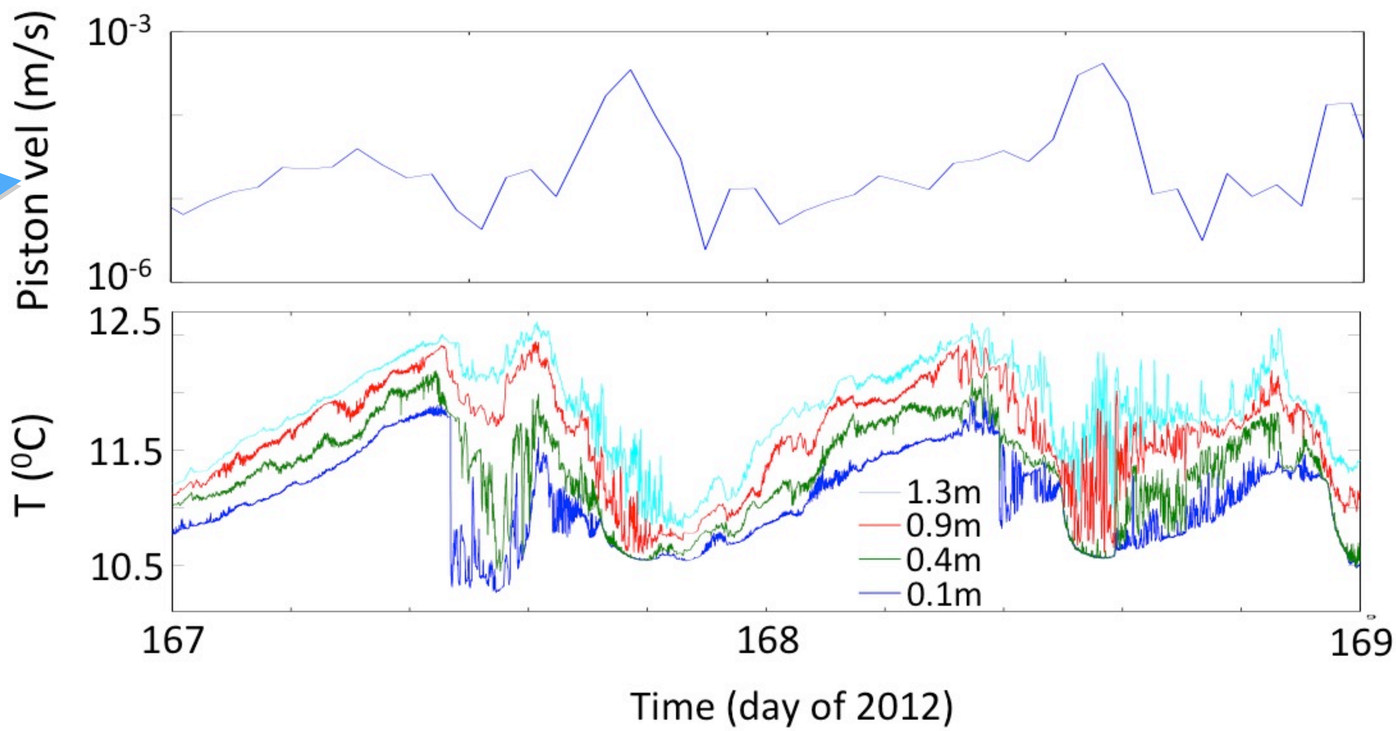
Turbulent diffusivity (Henderson)

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

Vertical gradient in concentration (Harrison and Deemer)

Fluctuations in turbulent mixing

Layer-integrated measure of diffusivity



Big variations in near-bed mixing resulting from periodic stratification resulting from internal waves

Outline

1. Instrumentation
2. Lakewide internal waves
3. Boundary layer, deep lake
4. Boundary layer, thermocline
5. Summary/discussion of periodic stratification

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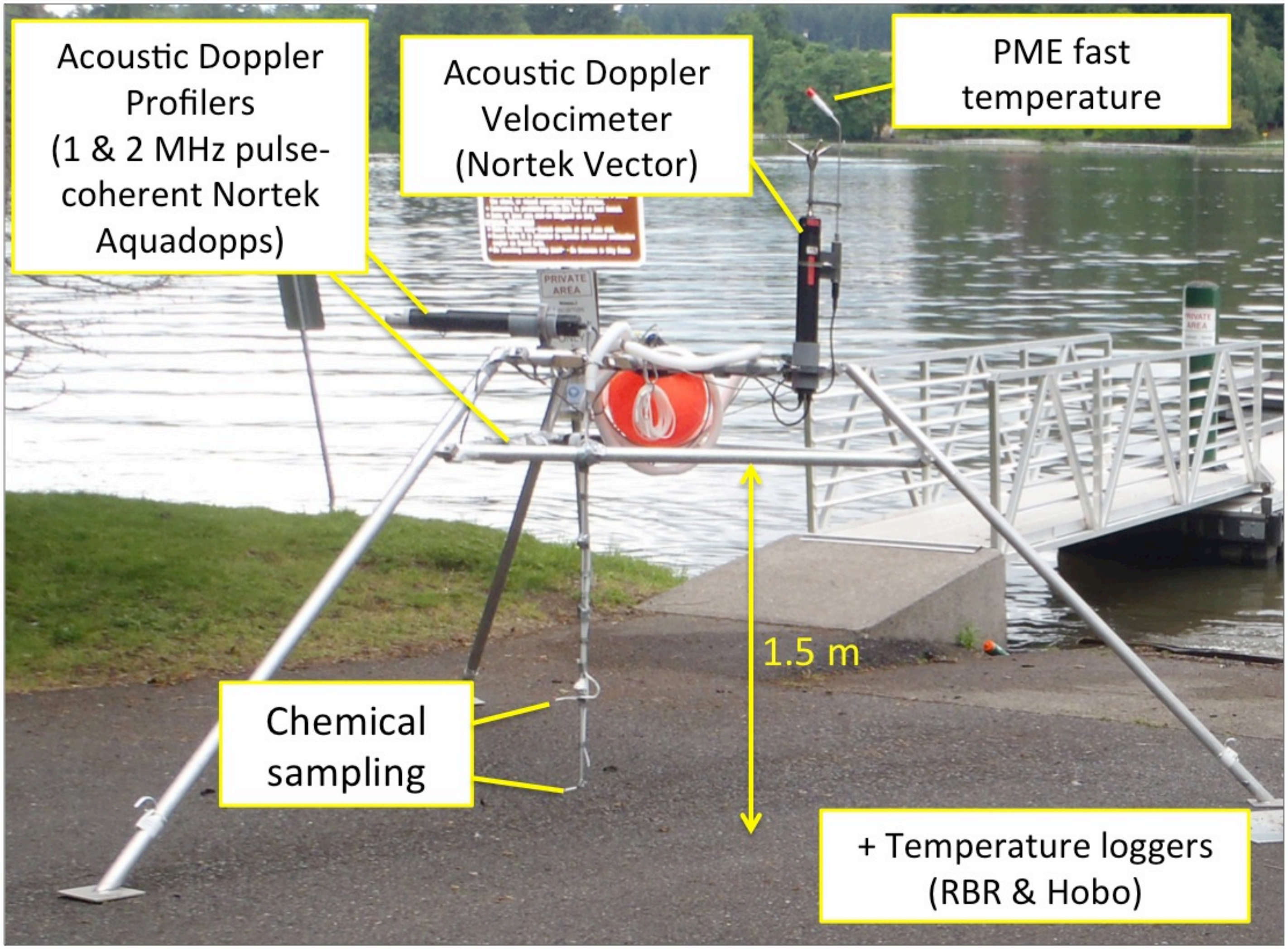
Tripods deployed on Lakebed



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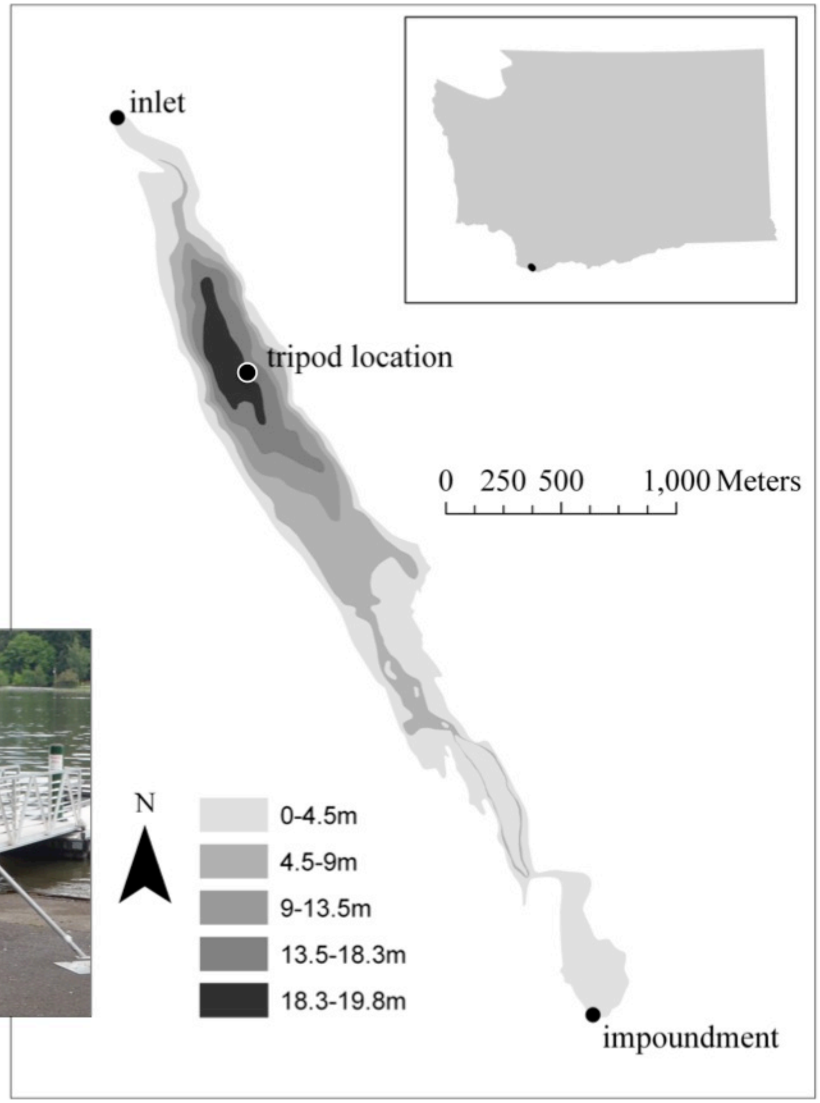
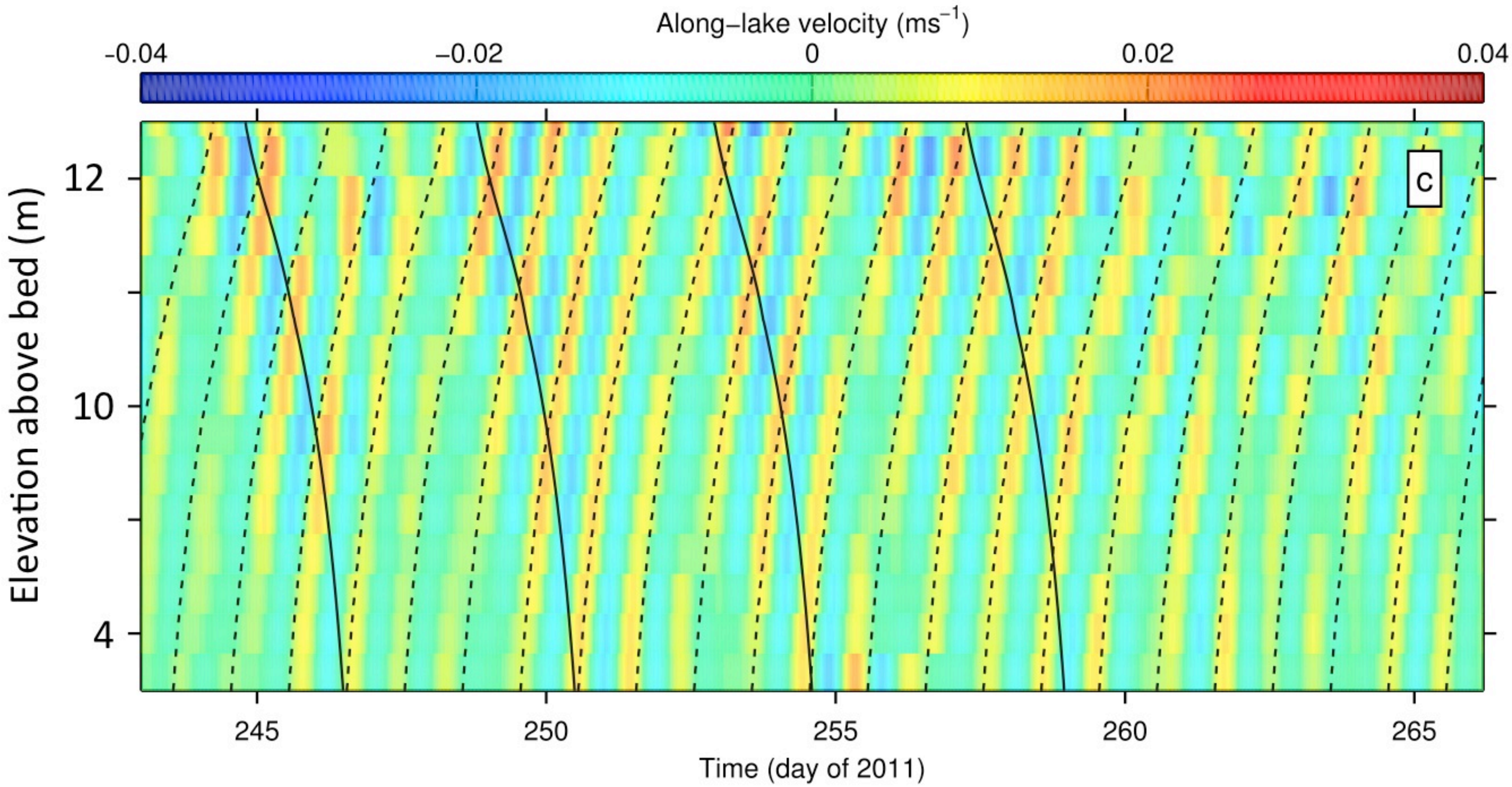
Full-depth velocity profiles

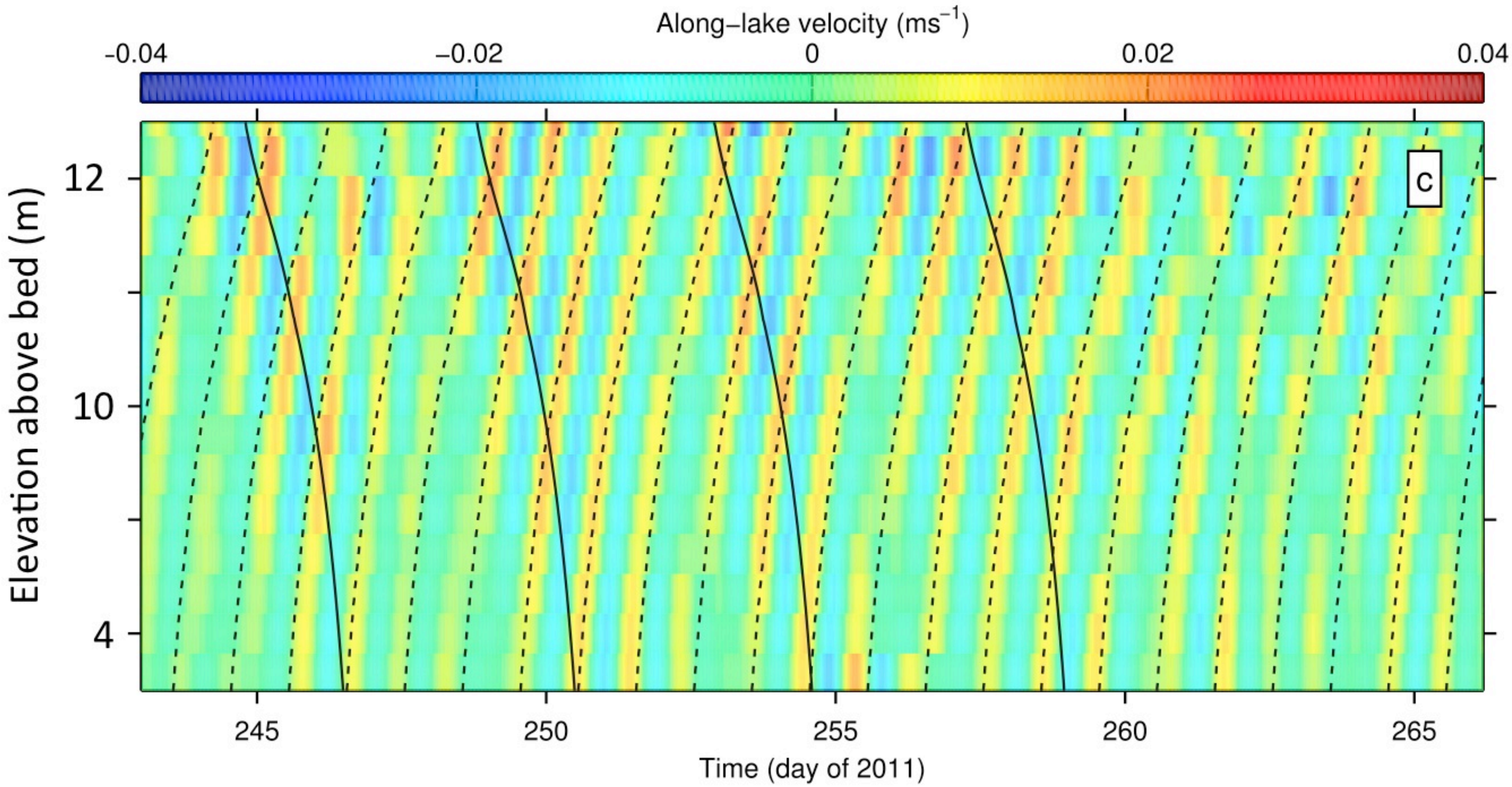
Acoustic Doppler Profiler (ADP)



Diurnal waves, upward phase propagation



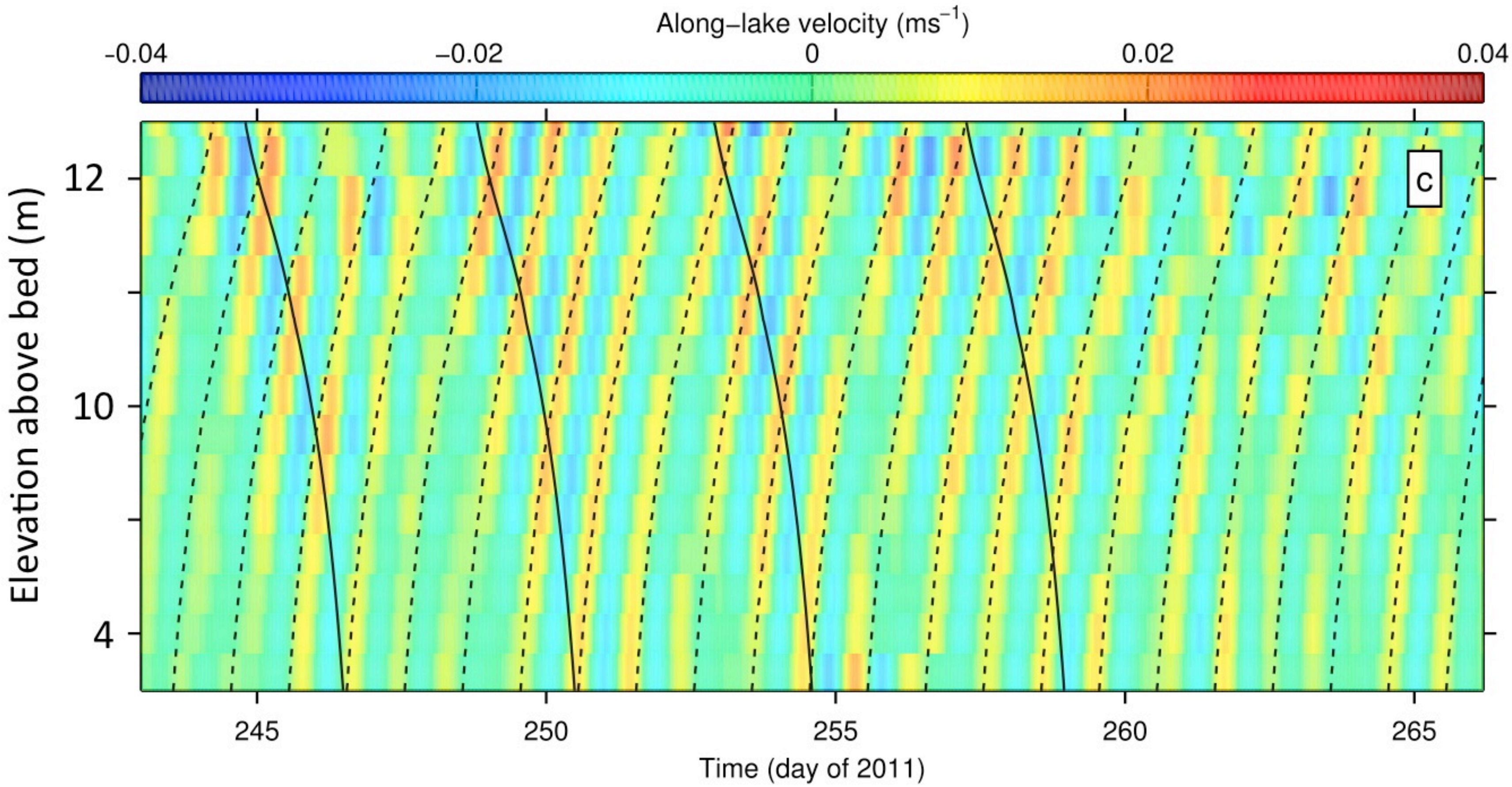
Diurnal waves, upward phase propagation



- - - - Theoretical internal wave propagation.

wave speed → $c_z = 2\pi\sigma^2\lambda_x/\overline{N}$, $\overline{N} = [-(g/\overline{\rho})\partial\overline{\rho}/\partial z]^{1/2}$, σ=frequency, ρ=density

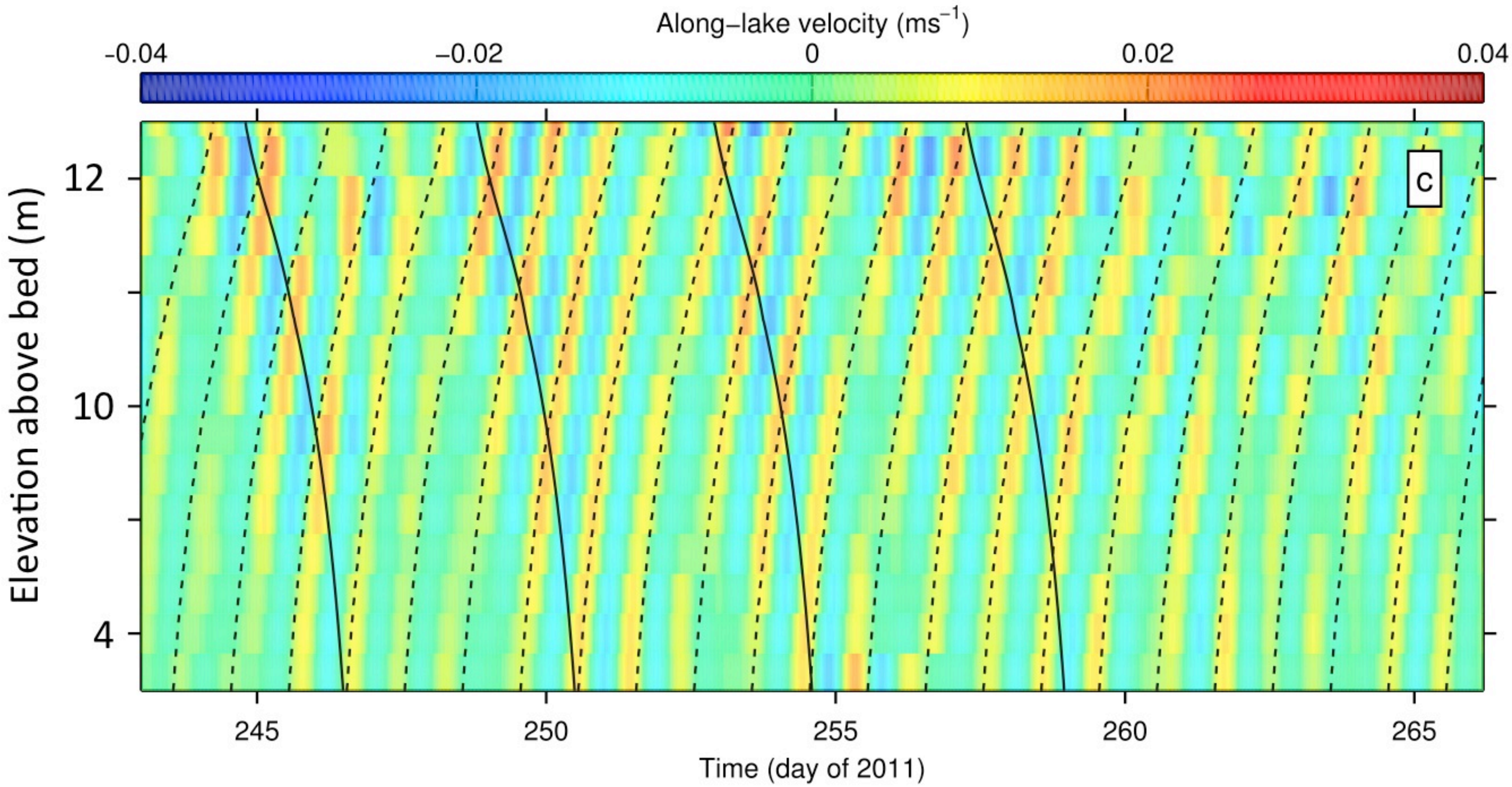
Diurnal waves, upward phase propagation



- - - - Theoretical internal wave propagation.

Fitted horizontal wavelength (λ_x=3000 m) about twice lake length.

Diurnal waves, upward phase propagation

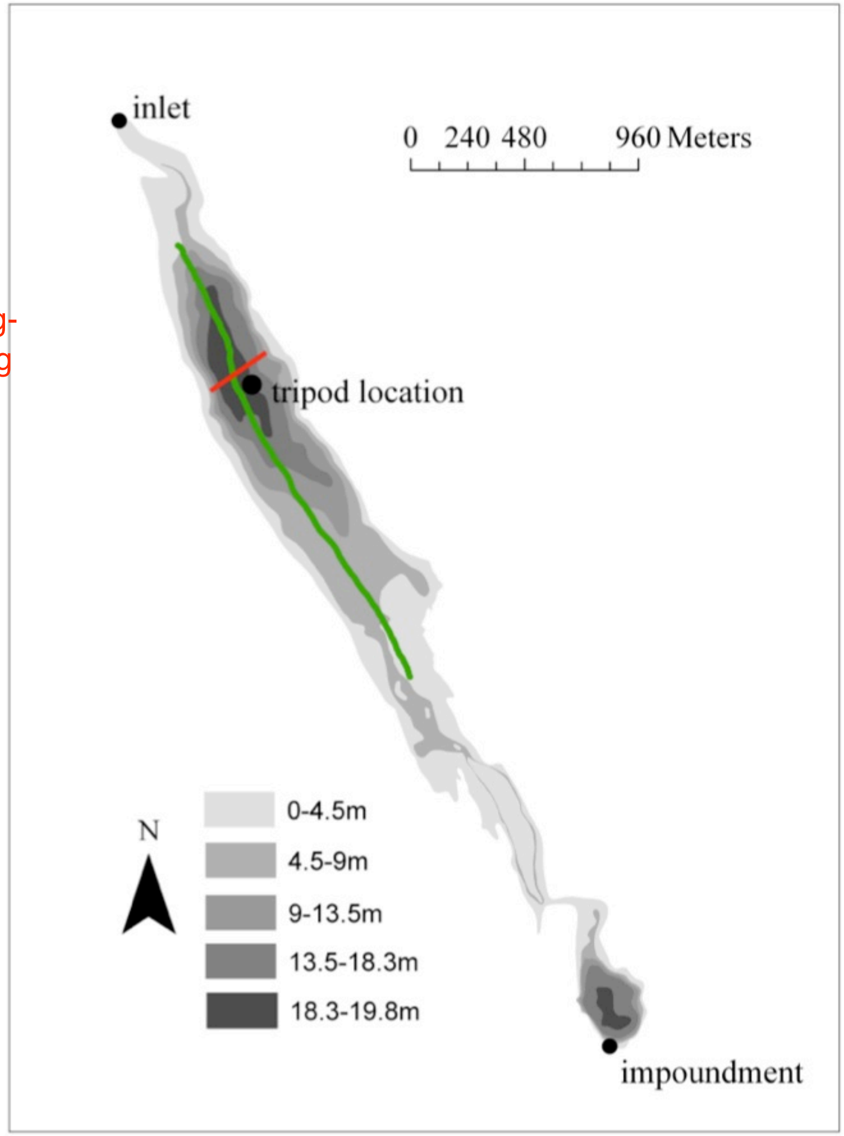


- - - - Theoretical internal wave propagation.

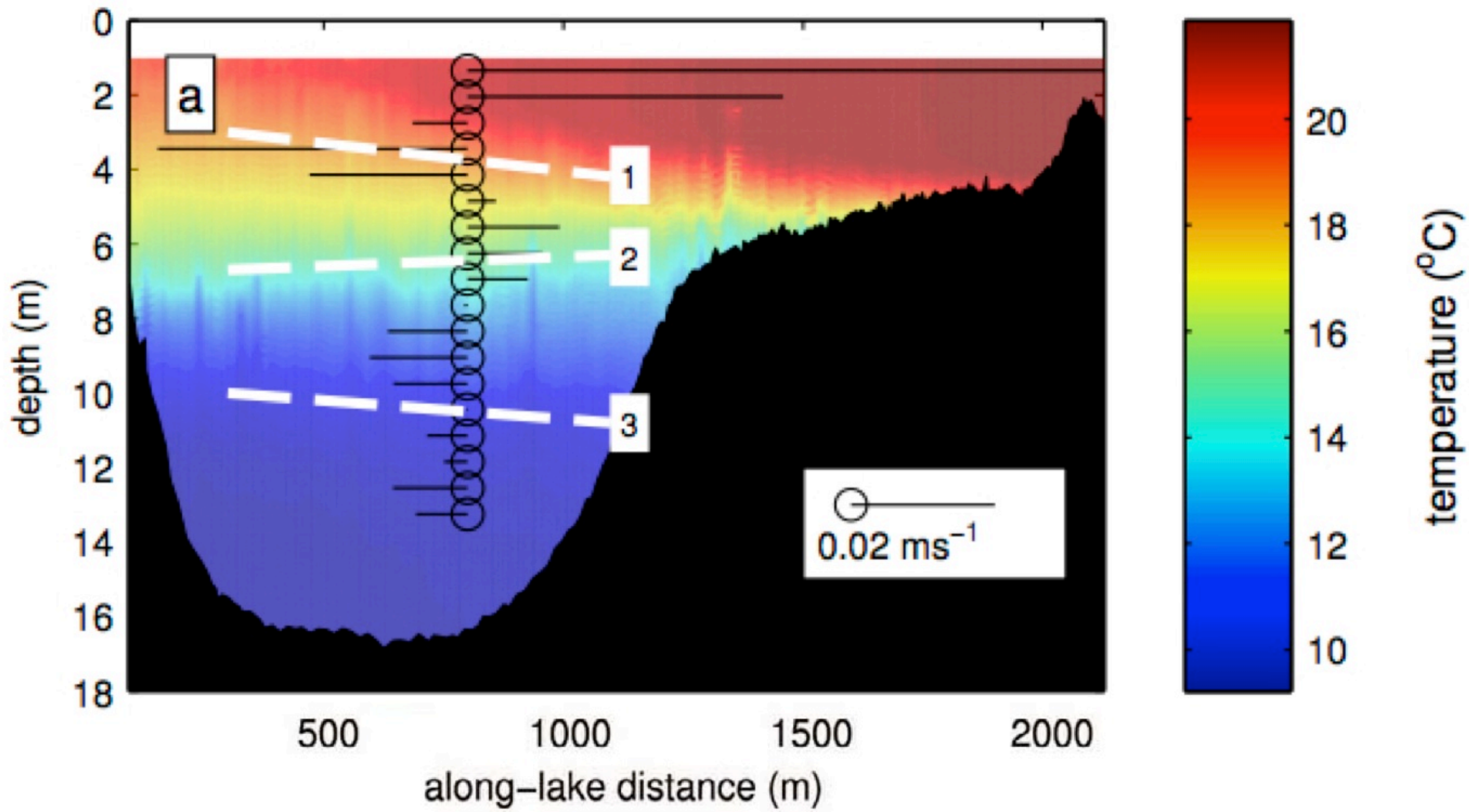
——— Theoretical energy propagation.

Temperature Profiles

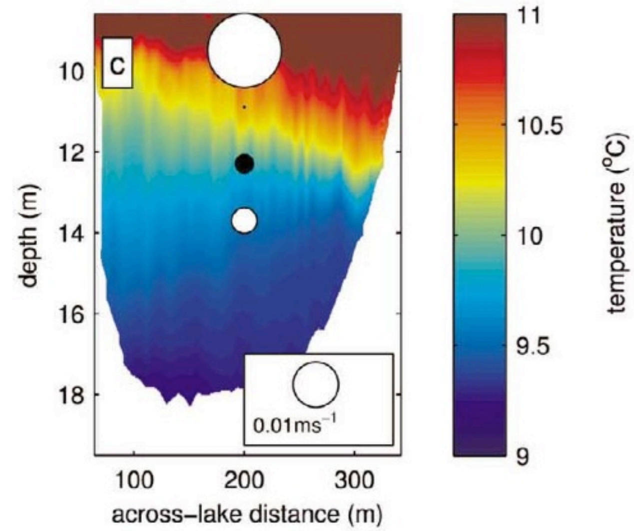
temperature transects measured along- and across-lake by repeatedly lowering and raising CTD from underway boat



Along-lake: long wavelength

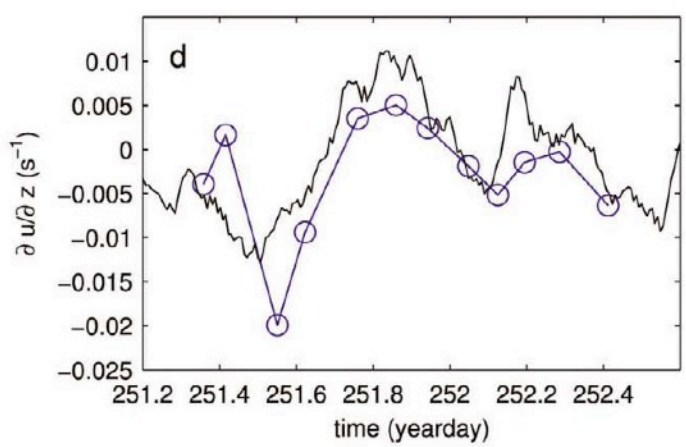


Across-lake: geostrophy



White circle: velocity into page
Black circle: out of page
Radius proportional to speed

Geostrophy (thermal wind)
observed for across-lake forces
above bottom boundary layer



$$\partial u/\partial z = (\rho f)^{-1} g \partial \rho / \partial y,$$

Velocity gradient:

— Observed

–○– Inferred from thermal wind

Like seiches, the observed waves had wavelength exceeding lake length.

Unlike standard seiches, the observed waves propagated vertically.

Geophys. Res. Lett., 39, L06405, doi:10.1029/ 2011GL050534.

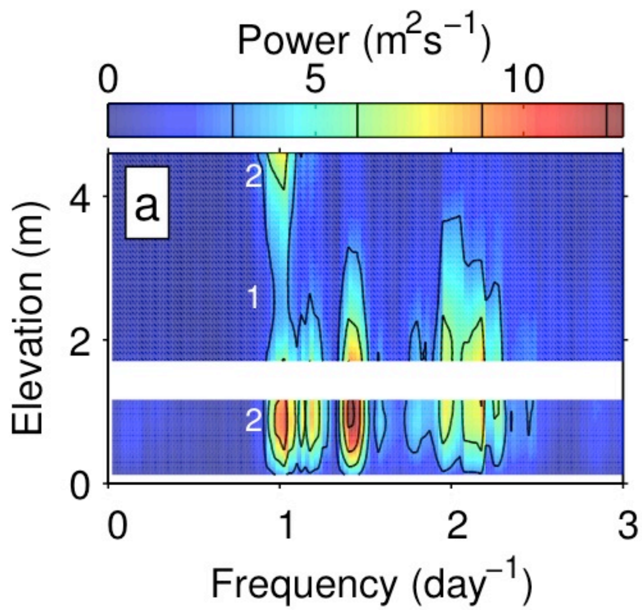
Like seiches, the observed waves had wavelength exceeding lake length.

Unlike standard seiches, the observed waves propagated vertically.

Why?

Nodal structure?

- Velocity spectra peak at elevation 1m, with second peak ~4.5m. Antinodes?



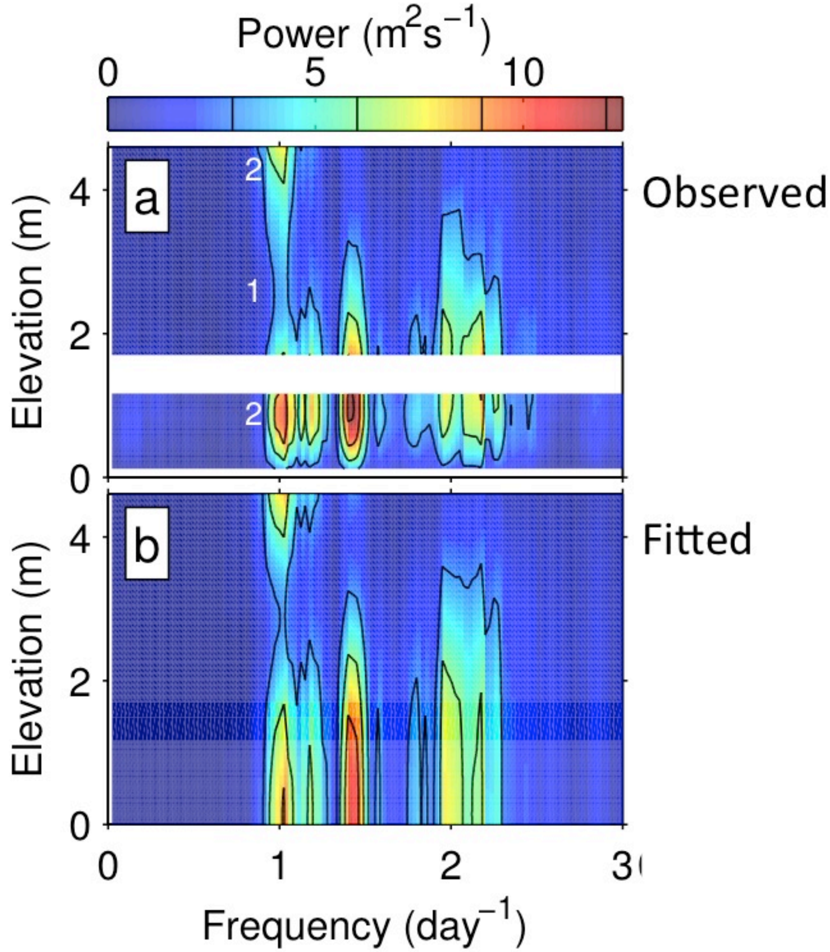
spectra measured by upward- and downward-looking ADCPs
Blanked out elevations (1.5-1.8m) span location of ADCP

Nodal structure

using theoretical internal wave propagation theory

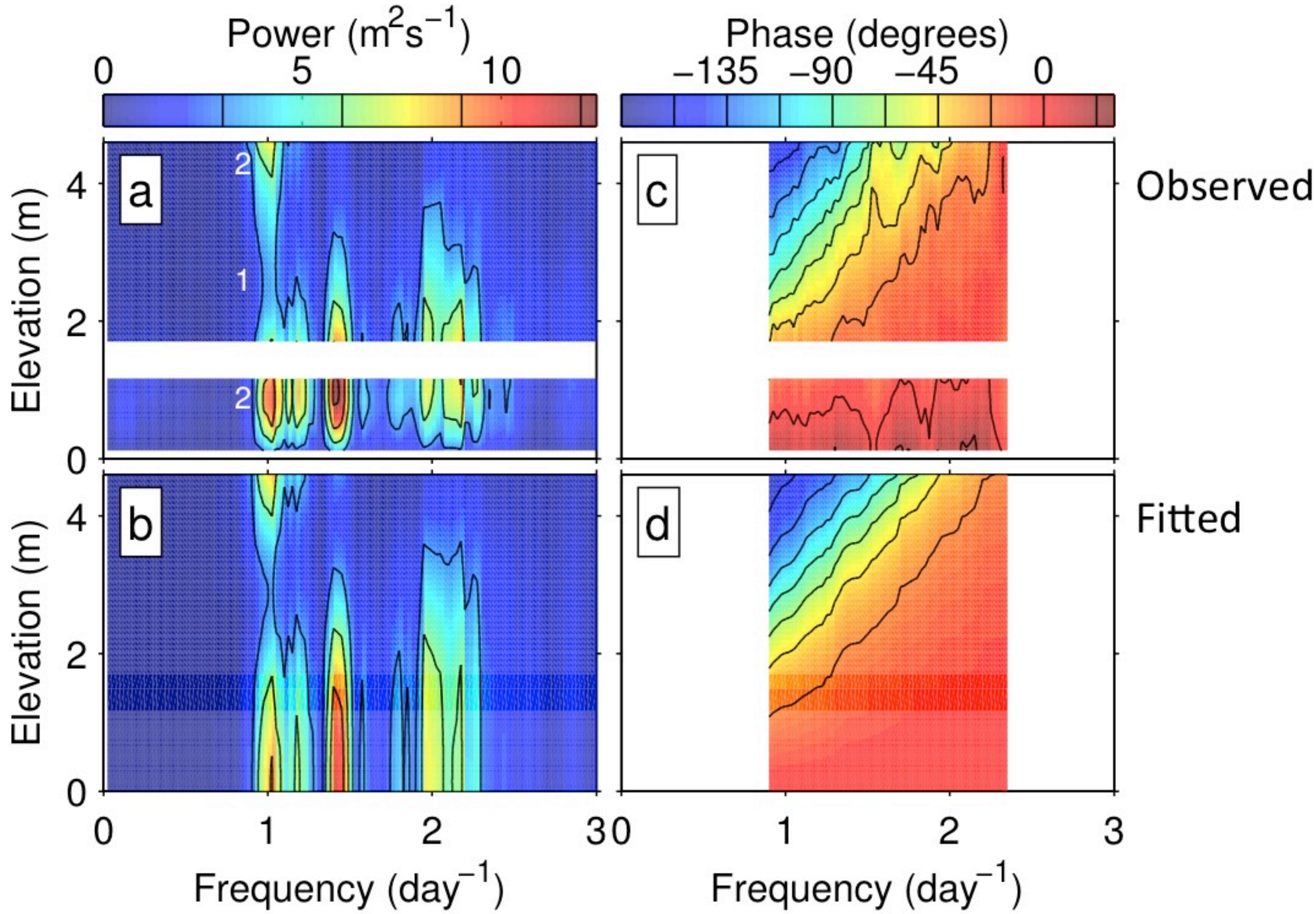
- Fitting vertically-propagating waves to observations 1.7 – 4.6 m above bed (A_{up}=R*A_{down}, wavelength = 1284 m), reproduces observed power spectra..

Note reflection coefficient R is frequency-dependent fitting parameter
- this asks what reflection coefficient best fits data



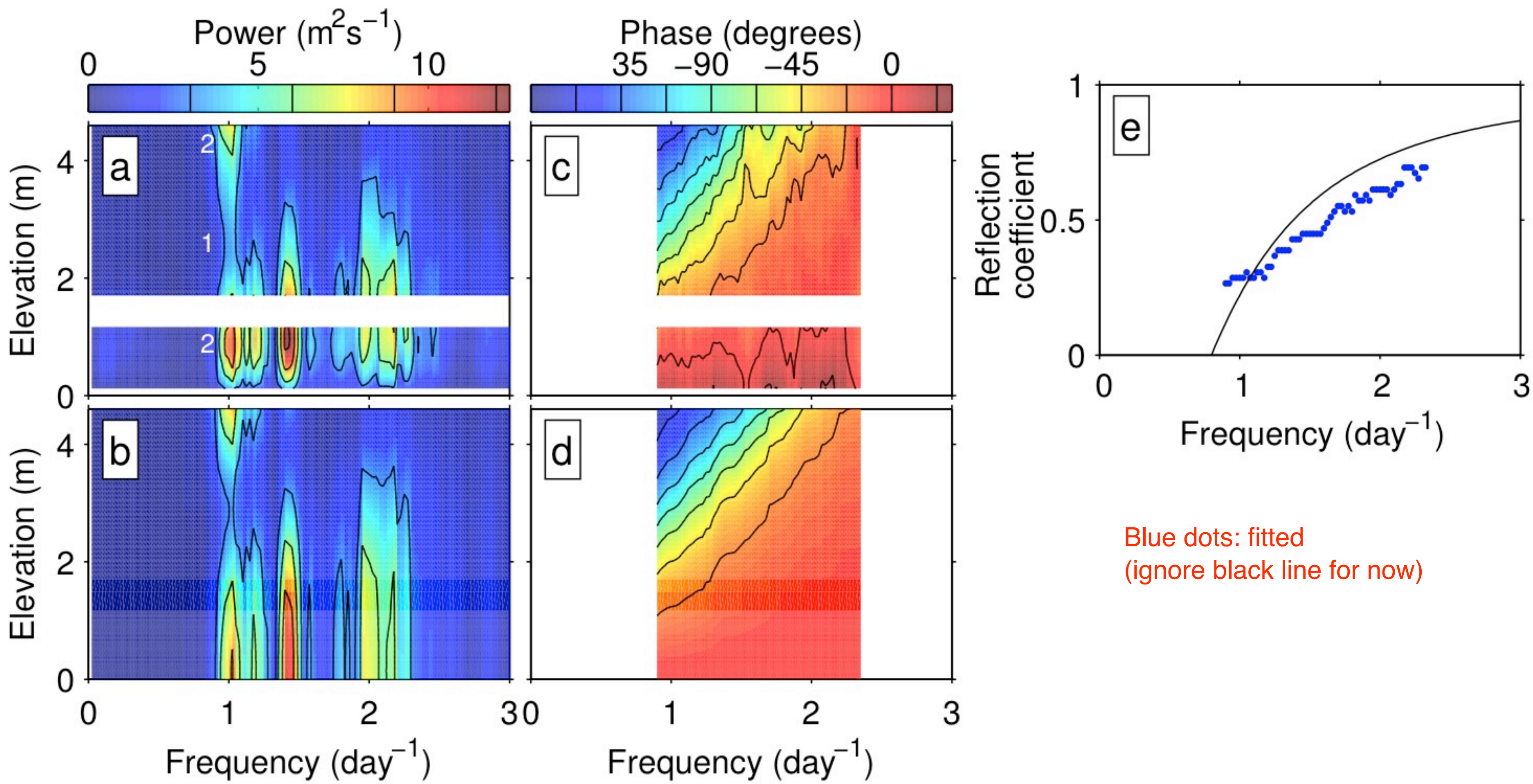
Upward phase propagation

- Upward phase propagation consistent with downward energy propagation.



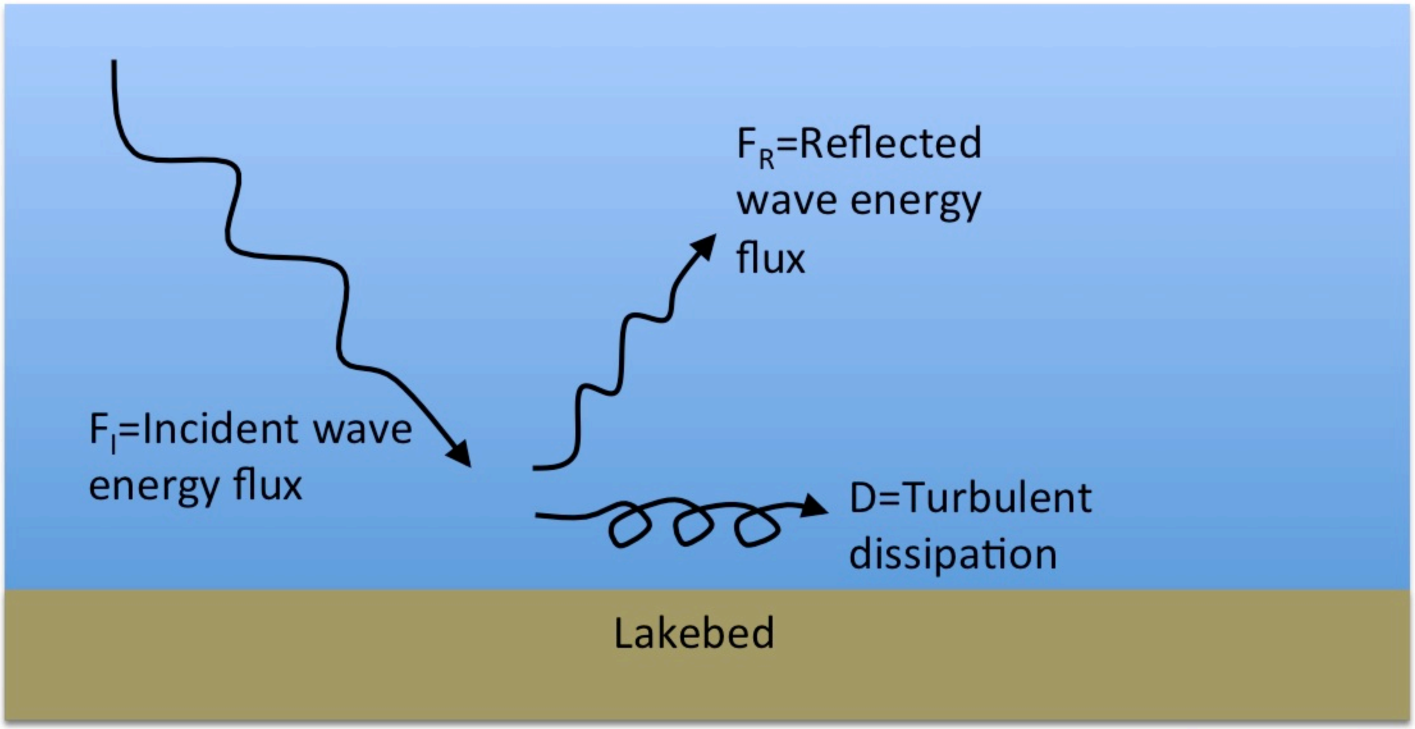
Partial reflection

Non-dissipative seiches would have R=1



Blue dots: fitted
(ignore black line for now)

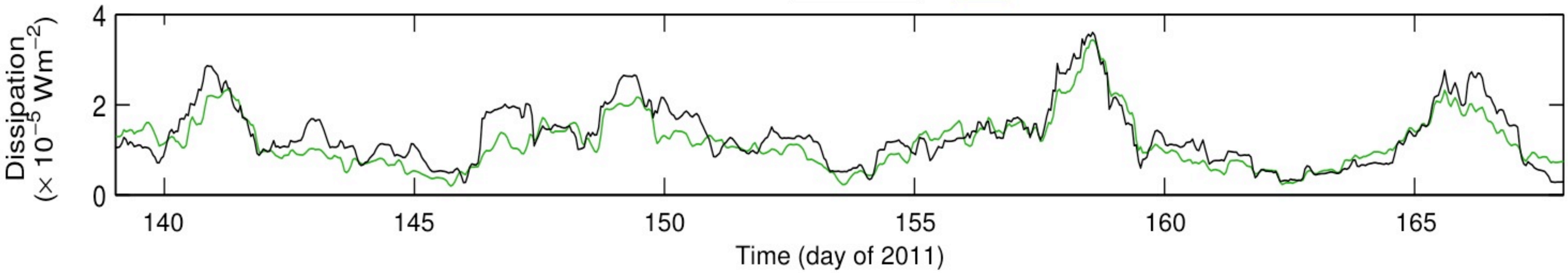
Energy balance



From hourly mean velocity, fitting waves to upward ADP measurements

$$F_I - F_R = D$$

From turbulent velocity statistics, downward ADP



Predicting Reflection

$$R = \frac{\text{Reflected amplitude}}{\text{Incident amplitude}}$$

$$R_{\text{pred}}(\sigma) = \frac{1-\alpha}{1+\alpha},$$

$$\alpha = K\frac{u_{rms}}{c}$$

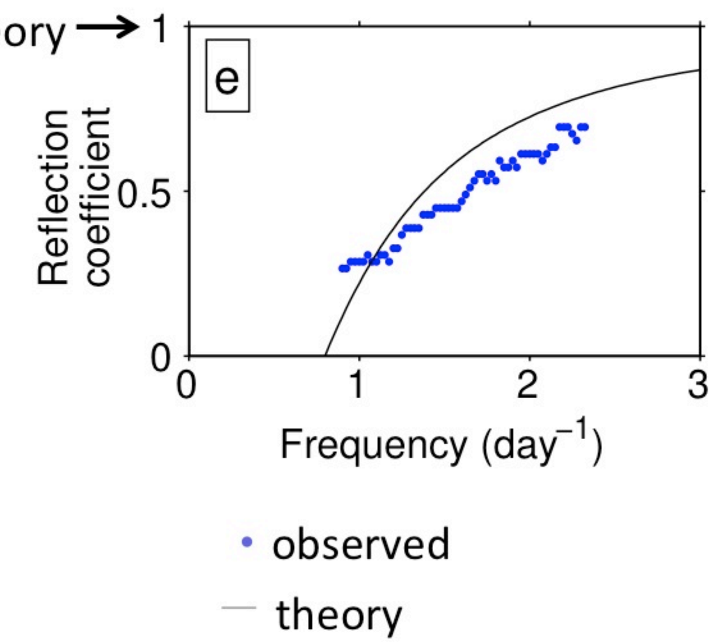
$$K = 2\left(8/\pi\right)^{1/2} C_D$$

Velocity magnitude (u_{rms})

Vertical wave speed (c)

constant (C_D)

Seiche theory → 1



- Reflection was weak because
  vertical wave speed small ($c=10^{-4}ms^{-1}$), because
  Lacamas lake is small.

- Published data indicates vertical propagation in some other small lakes.

I think this sort of vertical propagation might be widespread in small lakes
Leading-order departure from standard seiche idea.