Intense High-Frequency Internal Waves Within a Deep Gravity Current Outflow

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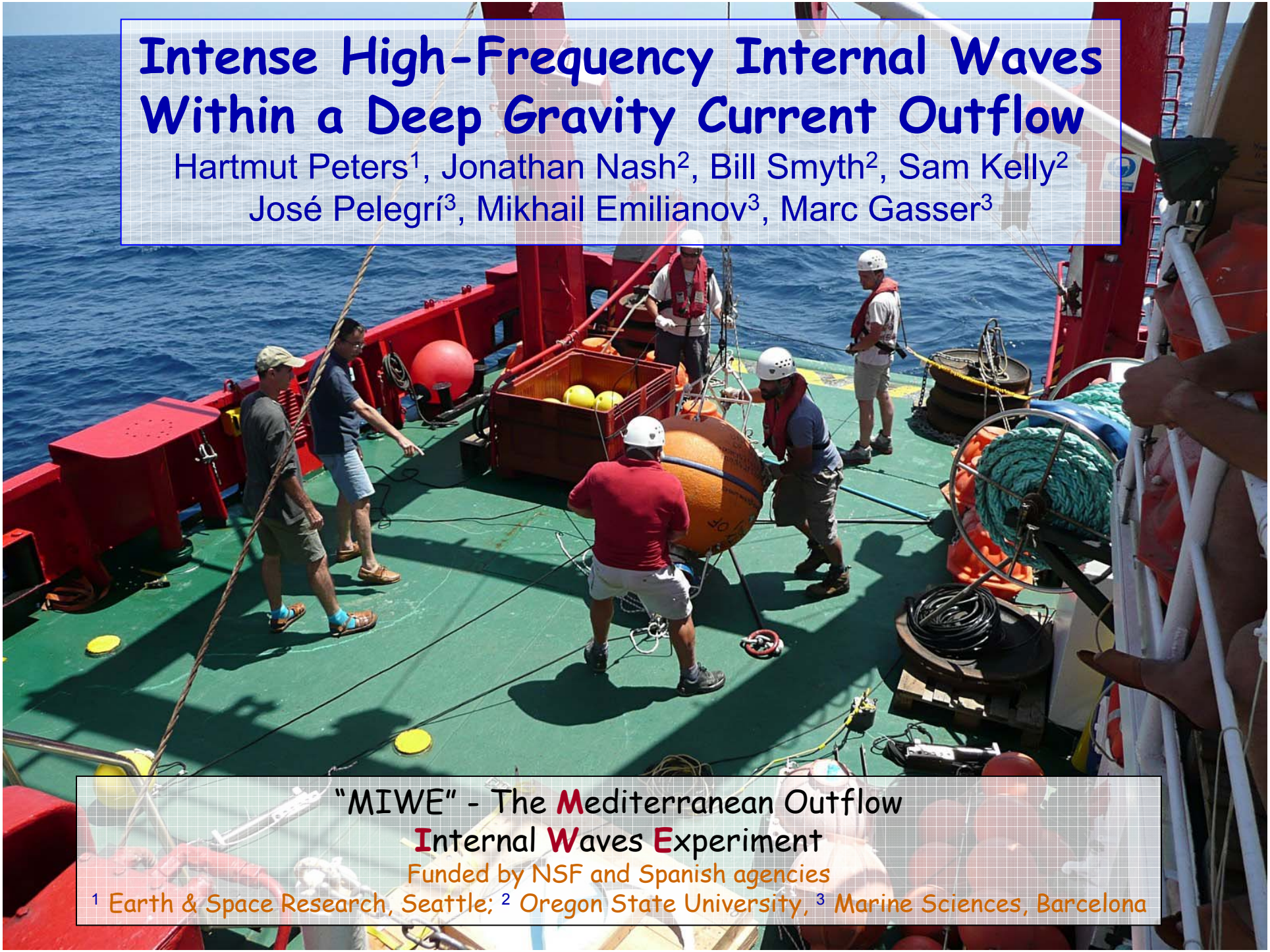

"MIWE" - The **M**editerranean Outflow
Internal **W**aves **E**xperiment

Funded by NSF and Spanish agencies

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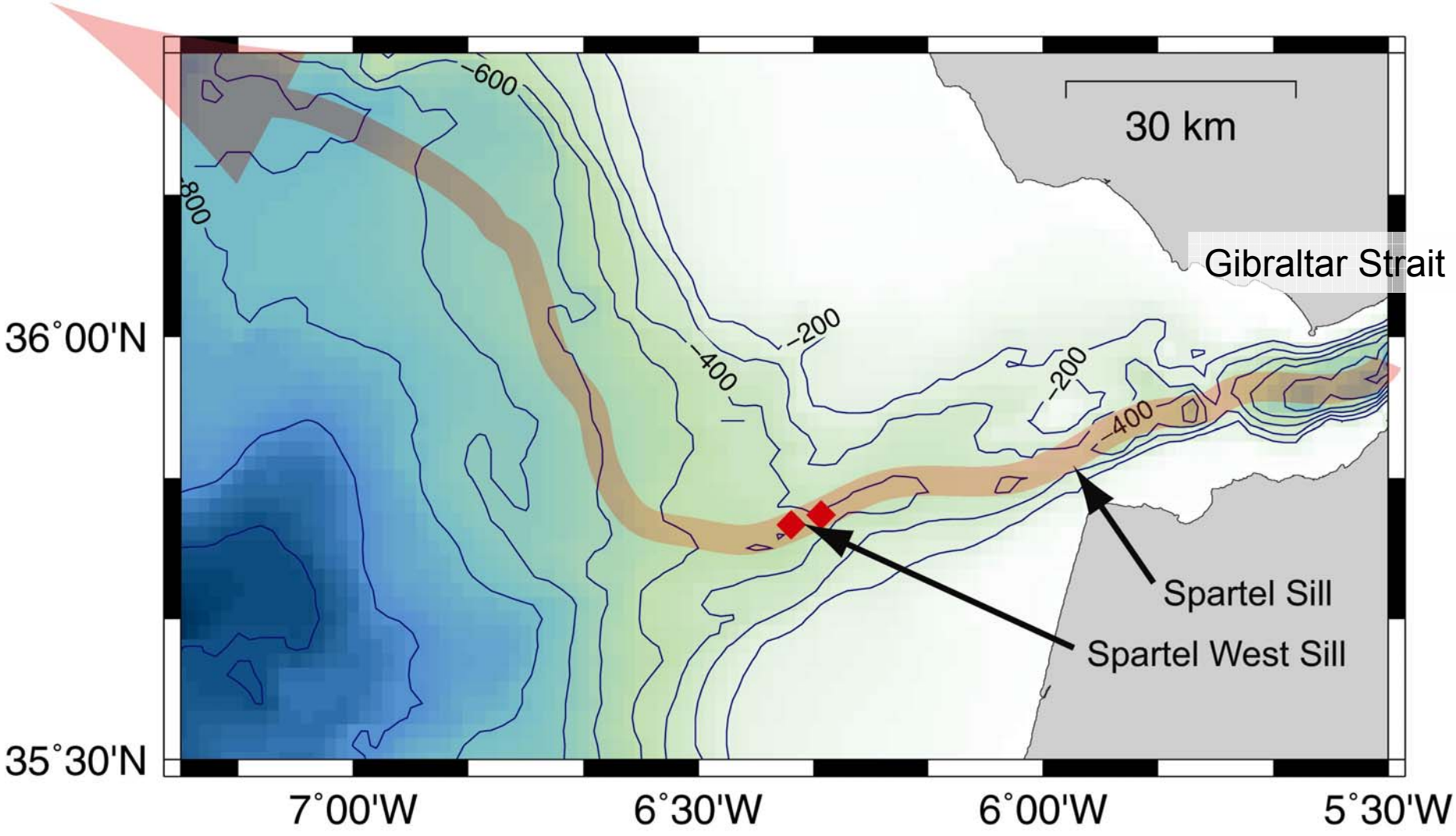
The Setting in the outflow from the Mediterranean



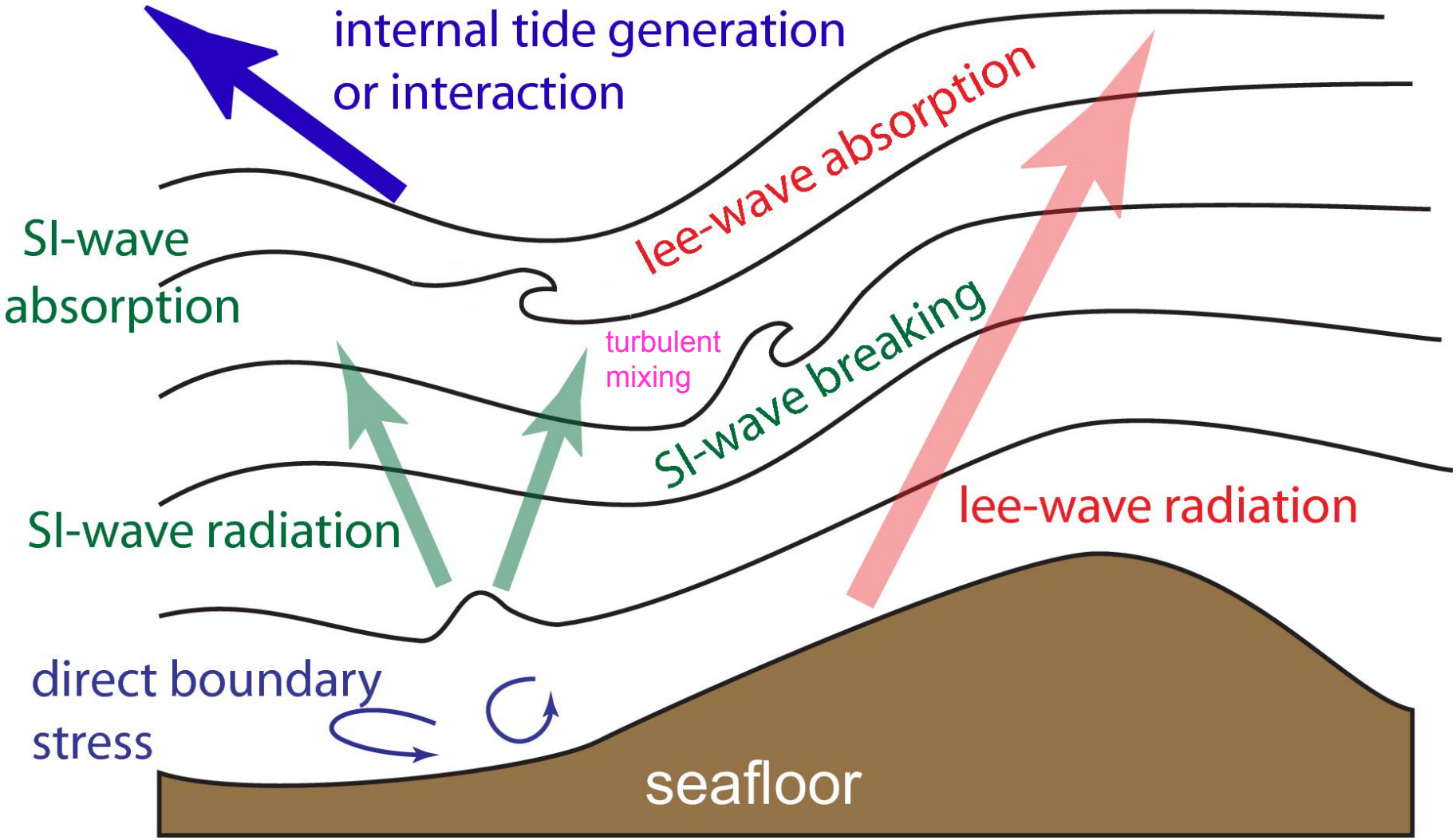
Motivation: why internal waves?
- Equatorial Undercurrent
- Baringer & Price, 1988 Gulf of Cadiz Experiment

EUC: large amplitude, high-frequency internal waves
- modulate turbulent mixing,
- produce large vertical momentum fluxes

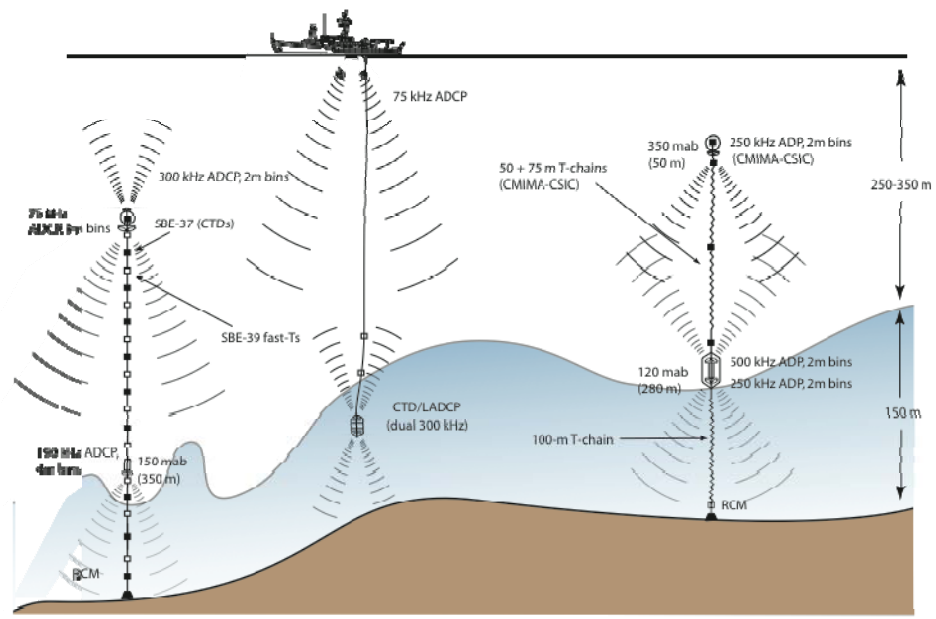
B&P found that – in our study area – the gravity current lost more momentum than the sum of bottom stress and interfacial (entrainment) stress could account for.

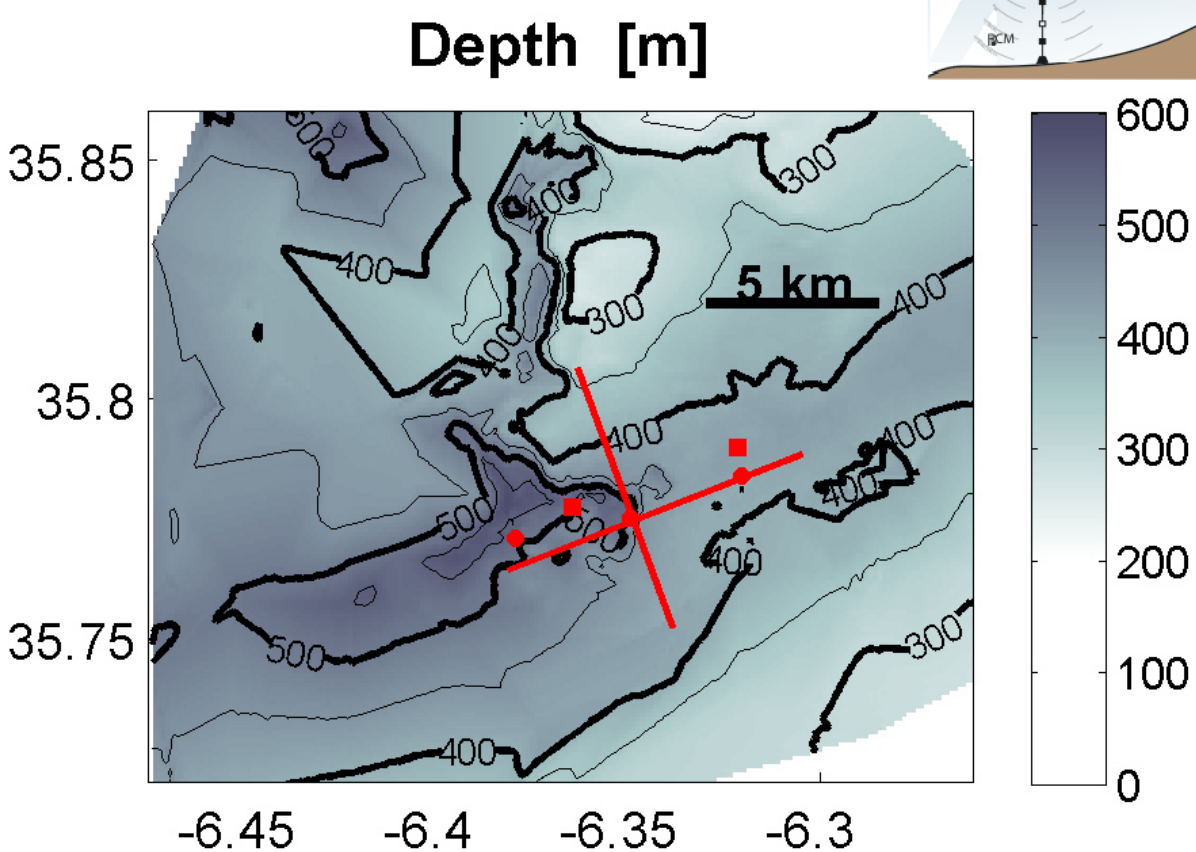
Our hypothesis: internal wave-driven momentum fluxes make up the missing term in B&P's momentum balance.

The processes we envisioned

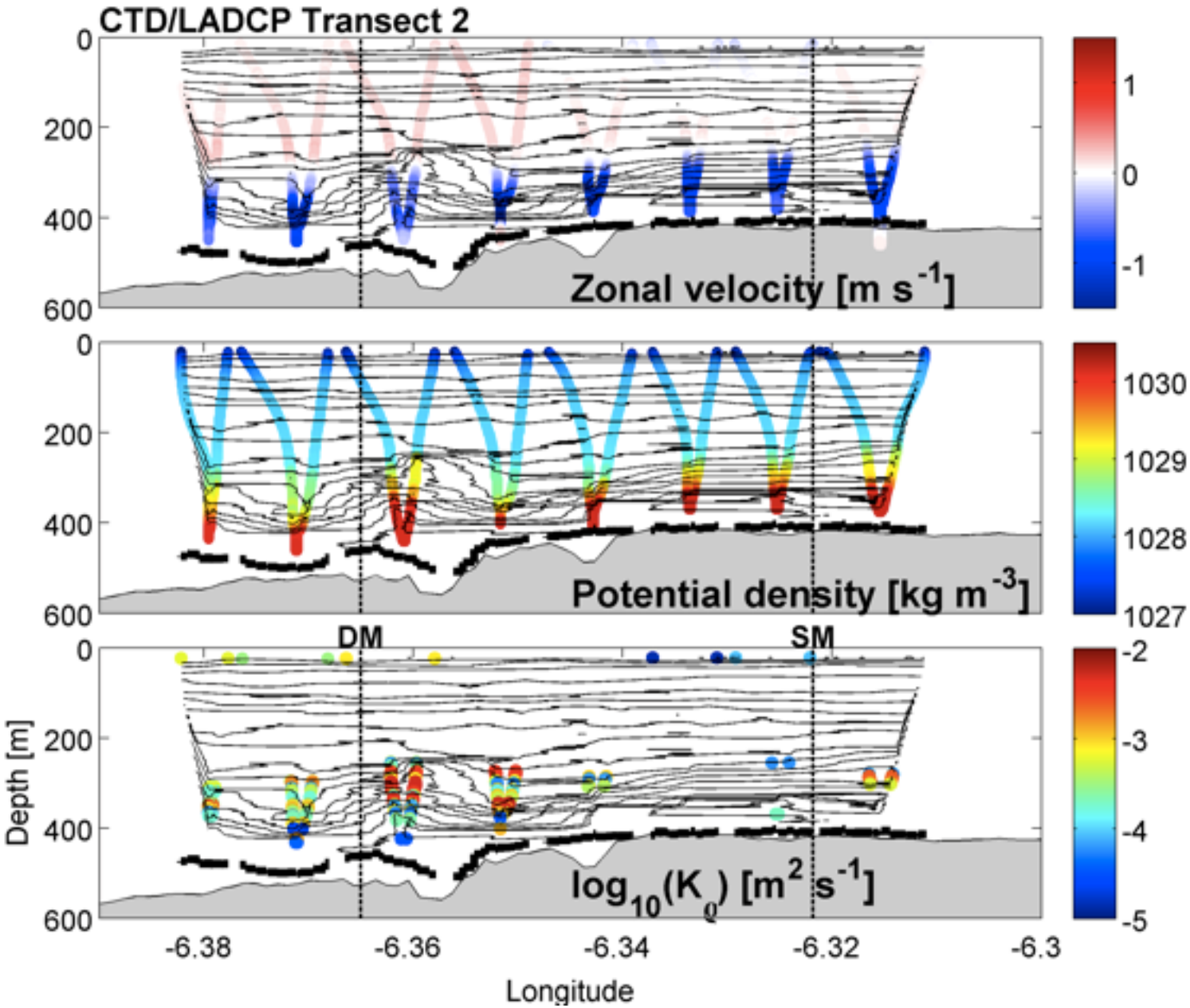


Local topography, observations

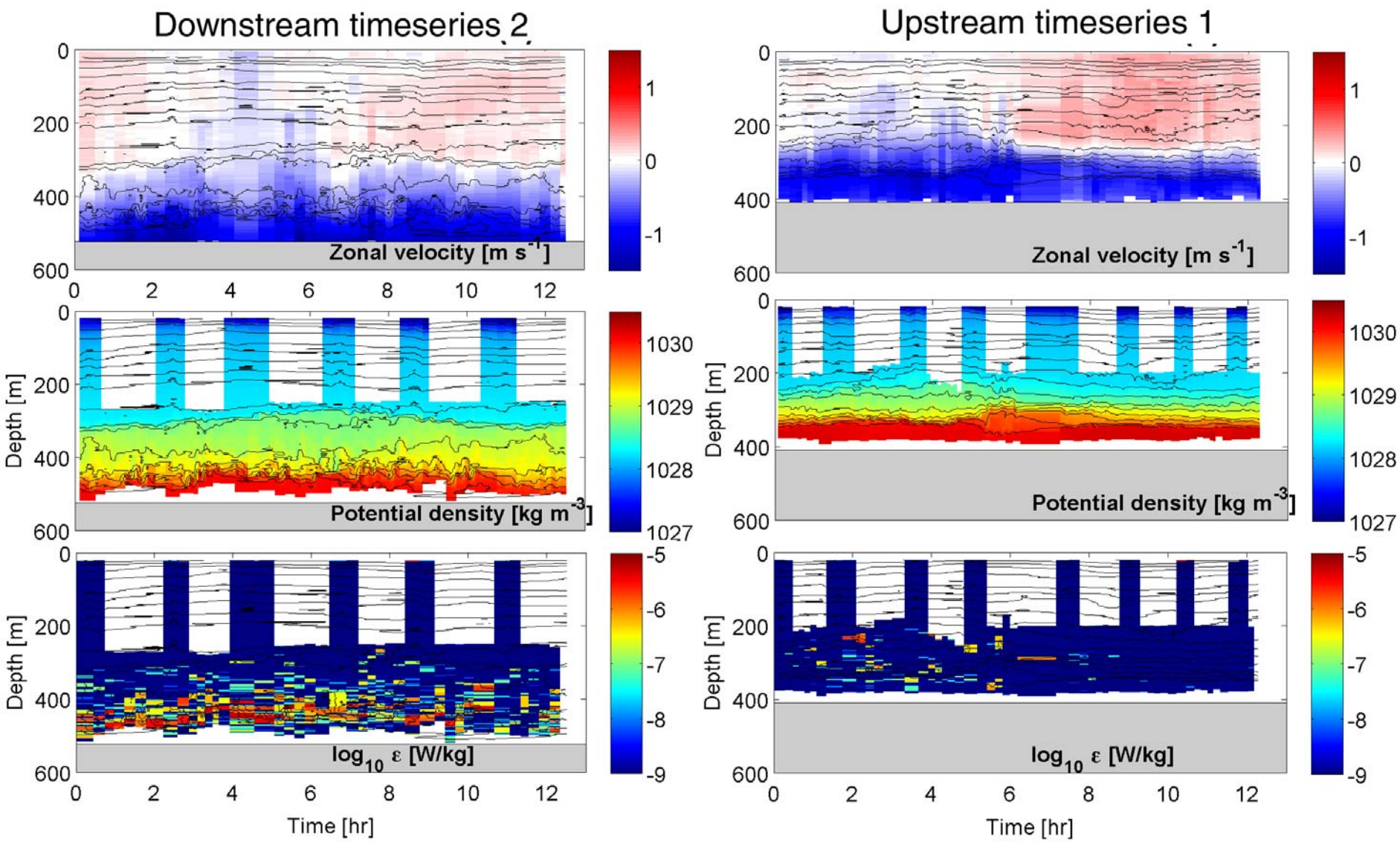




A typical along-axis transect

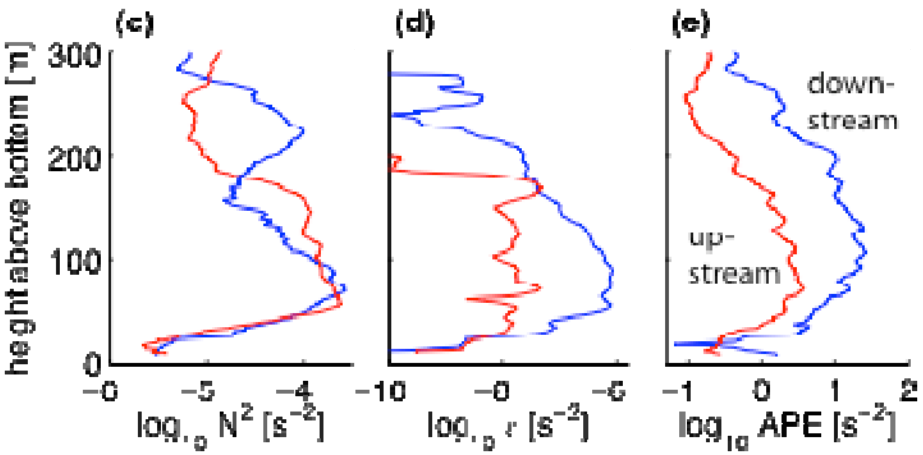


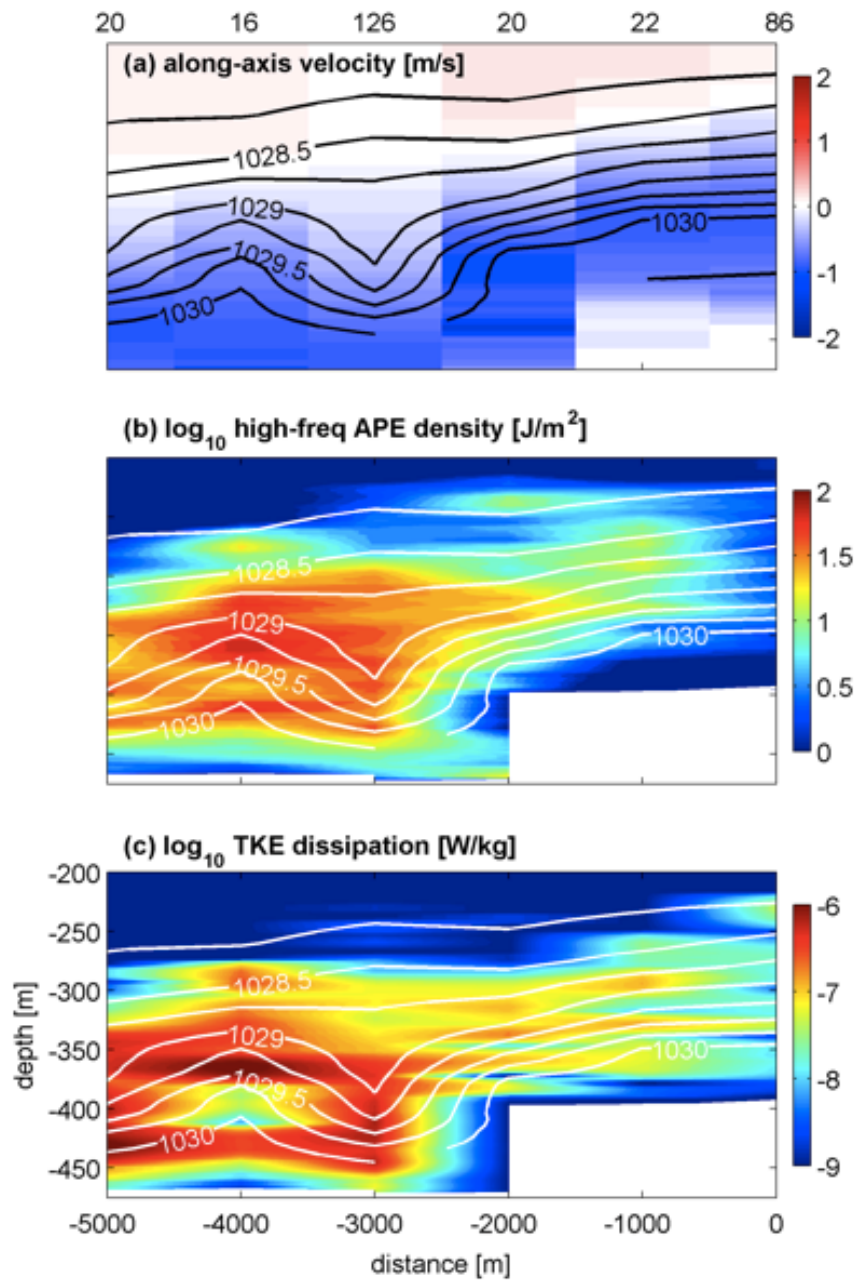
Contrast downstream and upstream timeseries



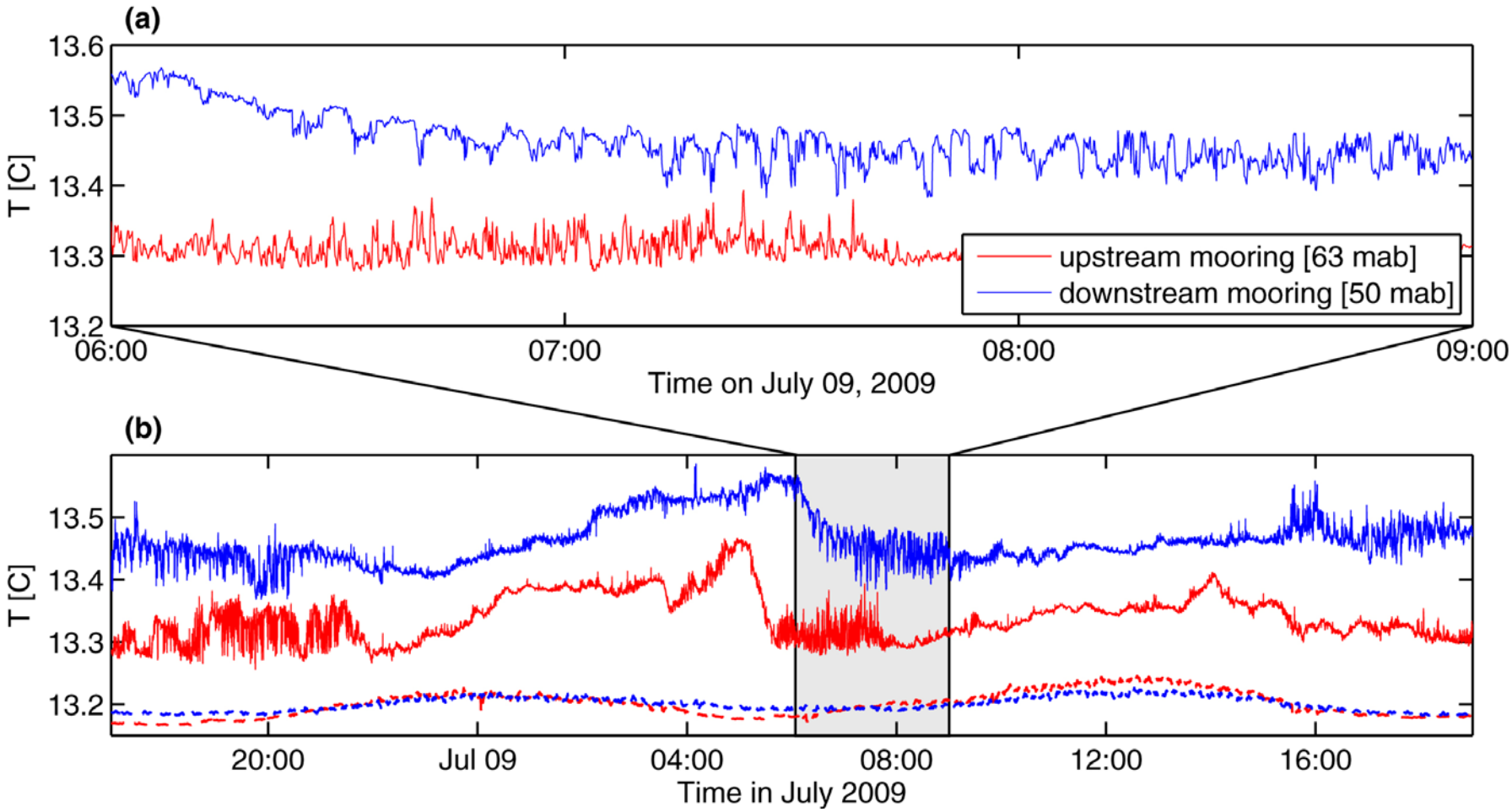
Average along-axis structure

- High-frequency APE occurs down-stream of “crest”
- Dissipation and APE co-located
- Hypothesize the variability results from a combination of lee waves, shear instability…





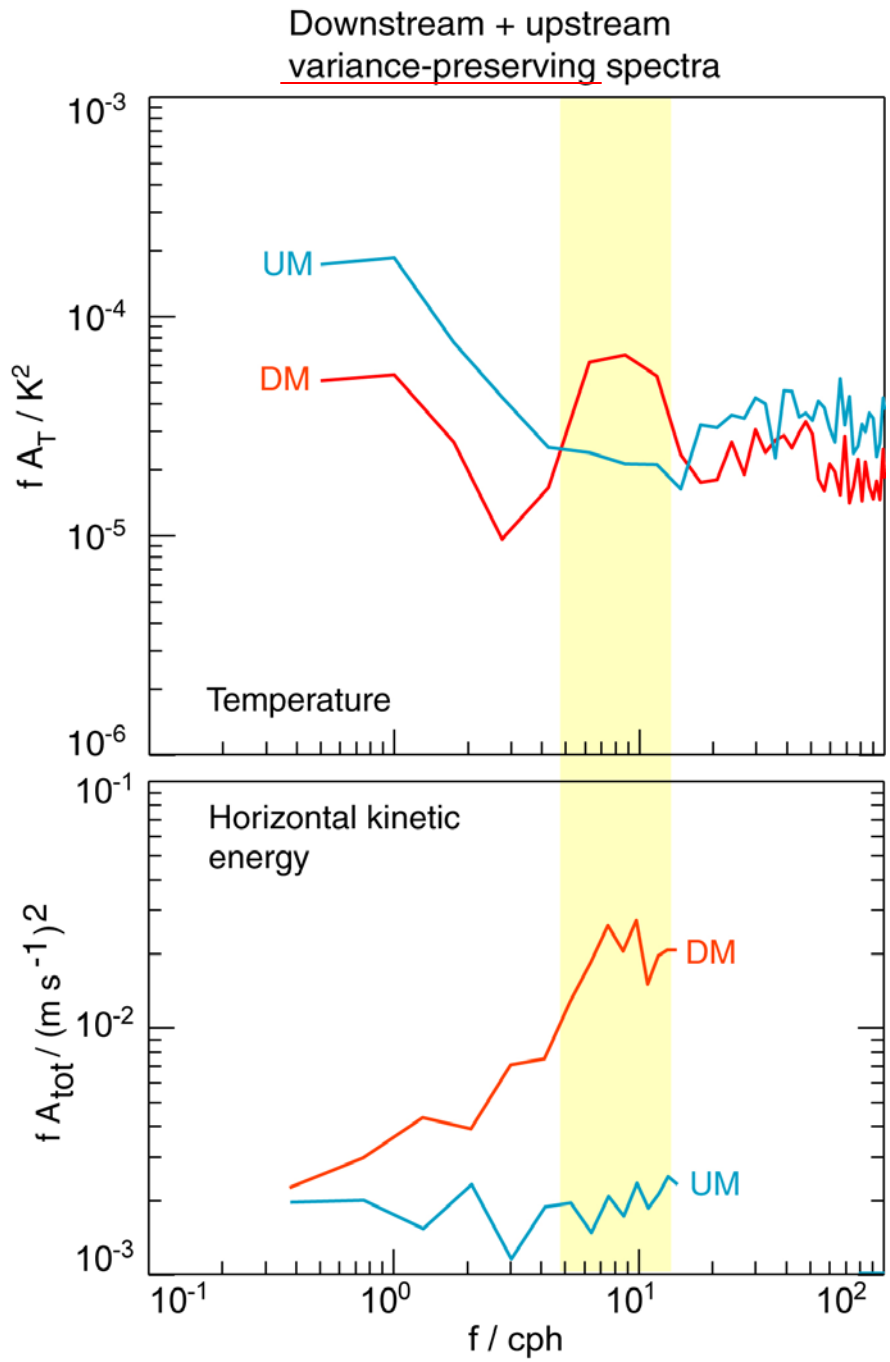
Fluctuations in near-bottom moored T (50-65 mab)



Downstream & upstream velocity and temperature spectra (1)

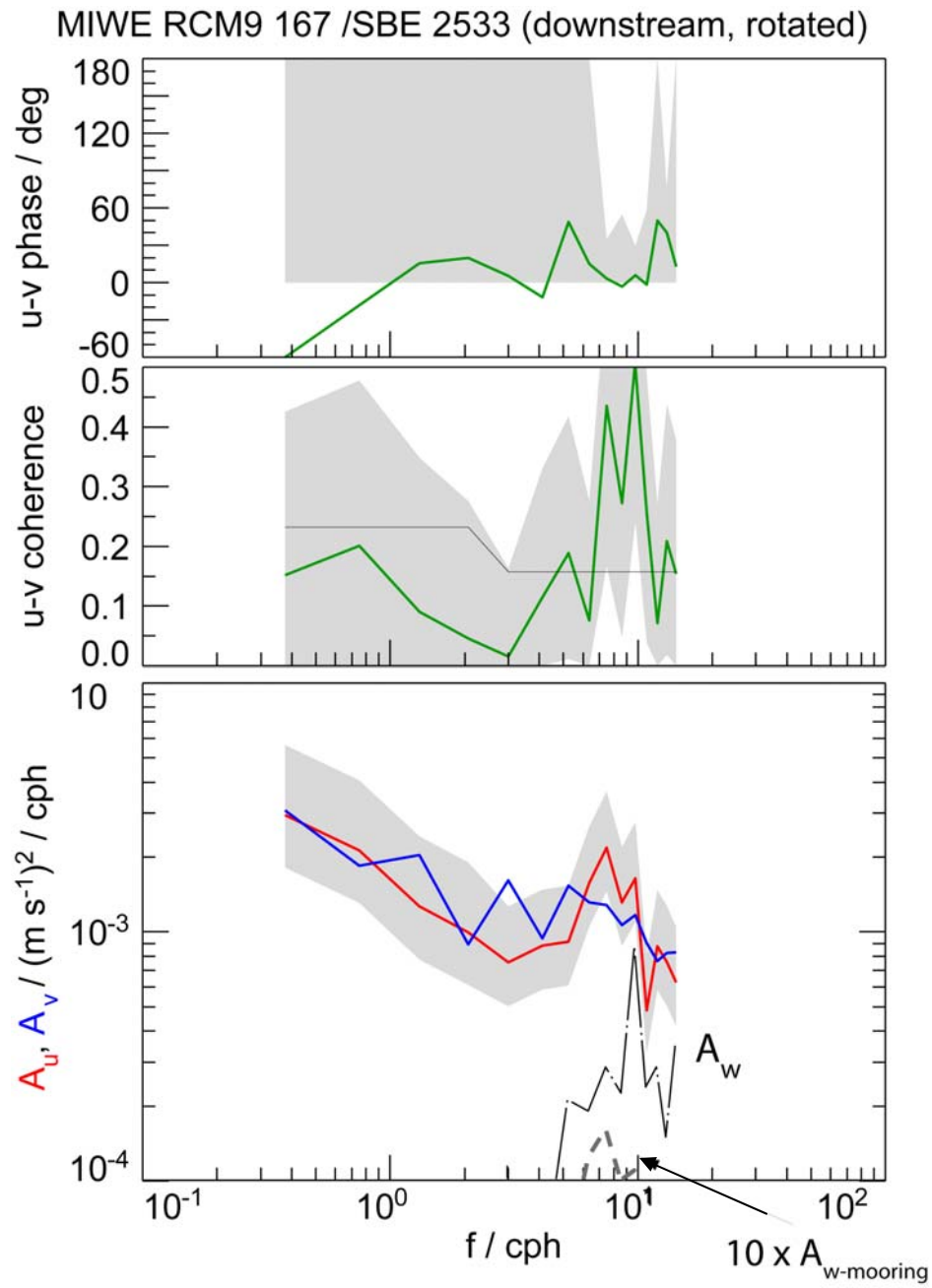
Downstream has high-frequency peak with high variance in T and V at ~5-12 cph.

Upstream has much less horizontal kinetic energy than downstream.



Downstream & upstream velocity and temperature spectra (2)

Downstream high-frequency peak:
- *u* and *v* correlated
- phase ~0
- rotary components ~ equal
  (not shown)
- → linear polarization ~±10°-30° from mean flow direction (*u*)



Can we compute *u'w'* from point *u* and *T* ?

Estimate zeta as:

$$T'/\frac{d\overline{T}}{dz}$$

and then compute

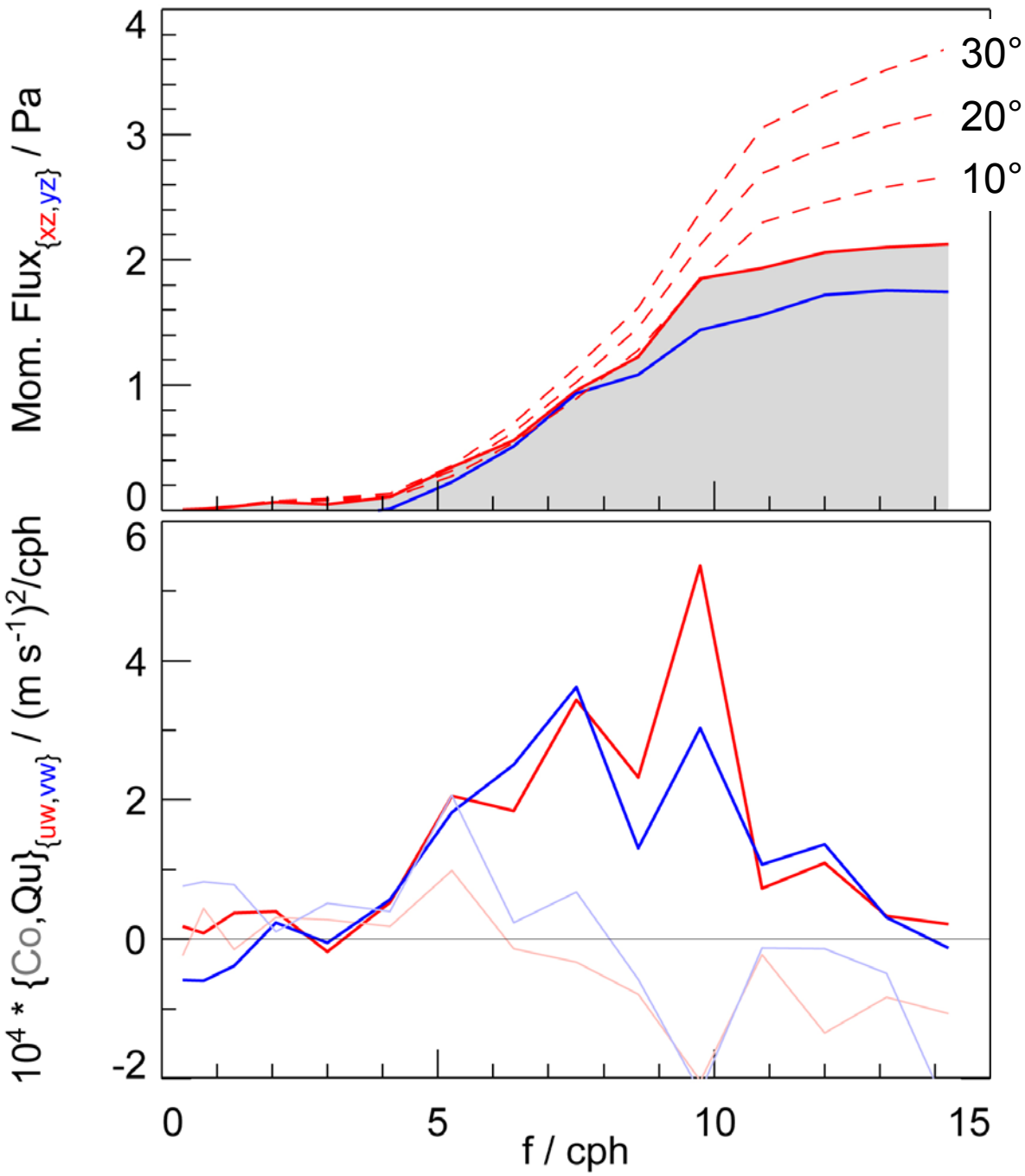
$$w \quad \frac{d}{dt}$$

and <*u'w'*> and <*v'w'*> in the cross-spectral domain

Caveats:

- What is *dT/dz* ?
- Mooring motion contaminates *T'* → *w'*, *u'*, *v'*
- *w'* contaminates u', v' because of instrument tilt

Vertical momentum flux by HF waves: large, O(1 Pa)



We can estimate the contamination
(i) of u' and v' due to w' and instrument tilt and,
(ii) at least in part by mooring motion.

(i) is demonstrated in the graph by the dashed lines for tilts of 10°-30°.

(ii) O(10-20%)…

Linear stability analysis: work in progress

Three classes of linear modes:

(1) Fastest-propagating hydrostatic waves

→ hydraulic control?

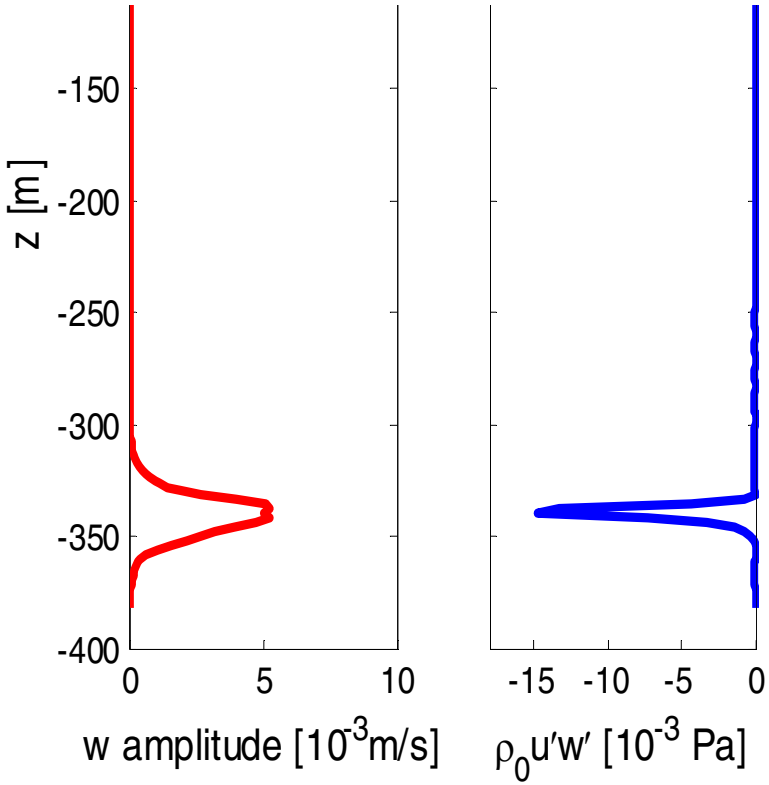
(2) Small-scale shear instabilities

→ vertical momentum flux with amplitudes from observations – roughly comparable to fluxes from downstream mooring

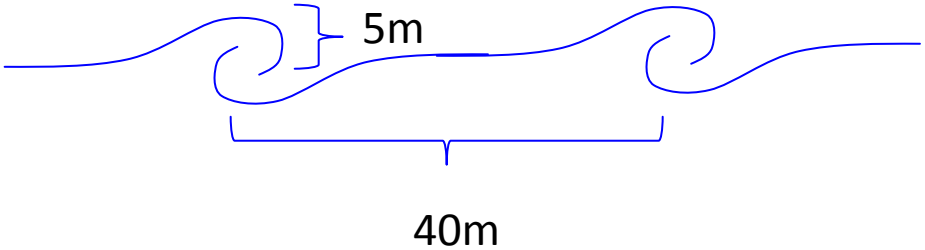
(3) Kilometer-scale lee waves

→ as seen in streamwise transects? Also transport momentum.

Estimating the momentum flux: smallscale shear instabilities



- u', w' normalized to give maximum vertical displacement = 1m.
- For other displacements h:
  multiply u' and w' by h,
  or u'w' by h^2.
- Here we assume h=5m,
  so stress ~ -0.015Pa x5^2 = -0.4Pa



Conclusions

At the Spartel West Sill in 400-500 m depth in the Med Outflow:

- Strong, O(1) tidal modulation of
  (i) the gravity current outflow,
  (ii) available potential energy related to super-tidal processes,
  (iii) turbulent mixing.
  → Rethink previous momentum/mixing analyses? (e.g. Baringer & Price)
  …and time-invariant numerical models w/o tides?
- Strong spatial modulation of outflow, APE and mixing at the sill / constriction.
  The current velocity increases on the steeper downhill slope;
  APE and dissipation increase by 1-2 orders of magnitude.
  → Importance of complex, smallscale variations in sea floor topography.
- High-frequency internal waves generate large, O(1 Pa) vertical momentum flux.
  The estimated flux magnitude has a large uncertainty margin.
  We do not know if the flux leaves the gravity current (such as to affect the integral momentum balance).
- Linear stability analysis of the flow:
  Three modes of instabilities; continuing analysis RE hydraulic control, vertical momentum flux