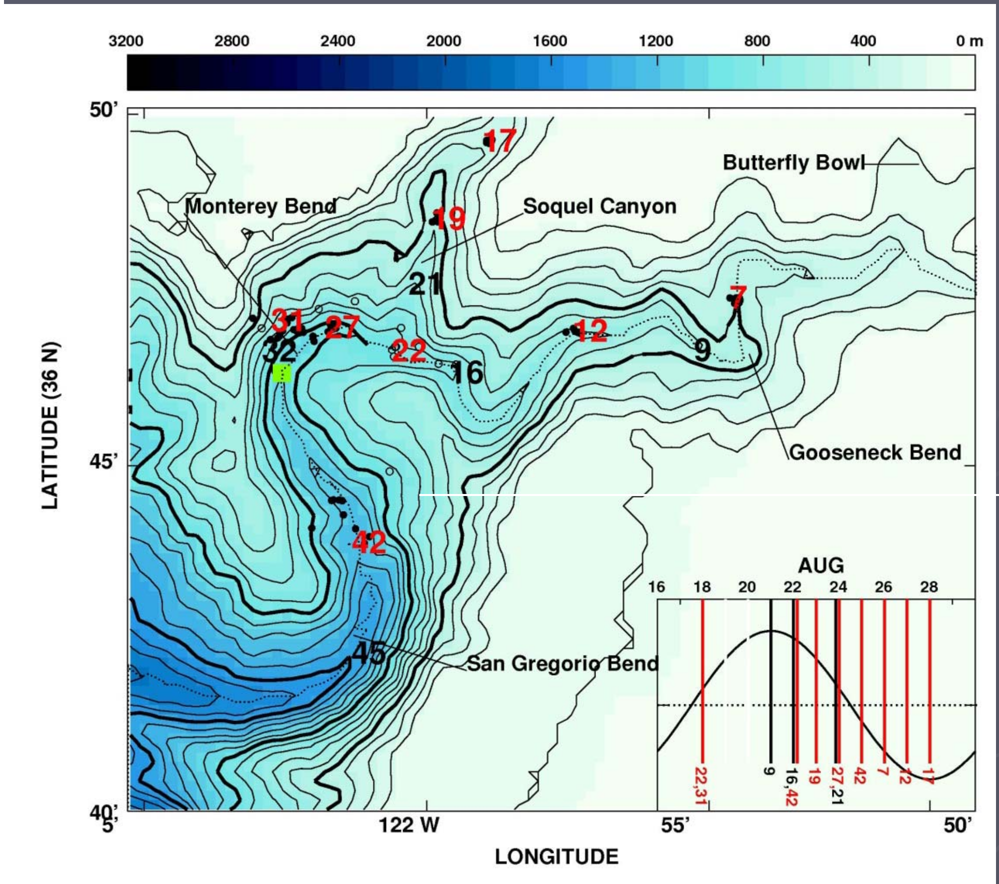
Turbulent Mixing and Exchange With Interior Waters on Sloping Boundaries

Eric Kunze, APL-U of Washington, Erika McPhee-Shaw, Katie Morrice, Moss Landing;
James Girton, Samantha Brody, APL-U Washington.

- fine- and microstructure profile time-series along the axis of Monterey Canyon during 18-30 AUG 2008 (spring tide 21 AUG) address (i) turbulence above a sloping bottoms, (ii) near-bottom mixing efficiency γ and (iii) exchange with the interior.
- previous work (Petruncio *et al*. 1998; Kunze *et al*. 2002; Carter and Gregg 2002) revealed upcanyon semidiurnal internal tide energy-fluxes with flux-convergence consistent with elevated near-bottom turbulent dissipation rates ε along the axis.
- as found on other slopes, stratified turbulent layers are an order of magnitude thicker than well-mixed bottom boundary layers.
- upslope flow convergences driven by nonuniform mixing drive exchange with the interior.

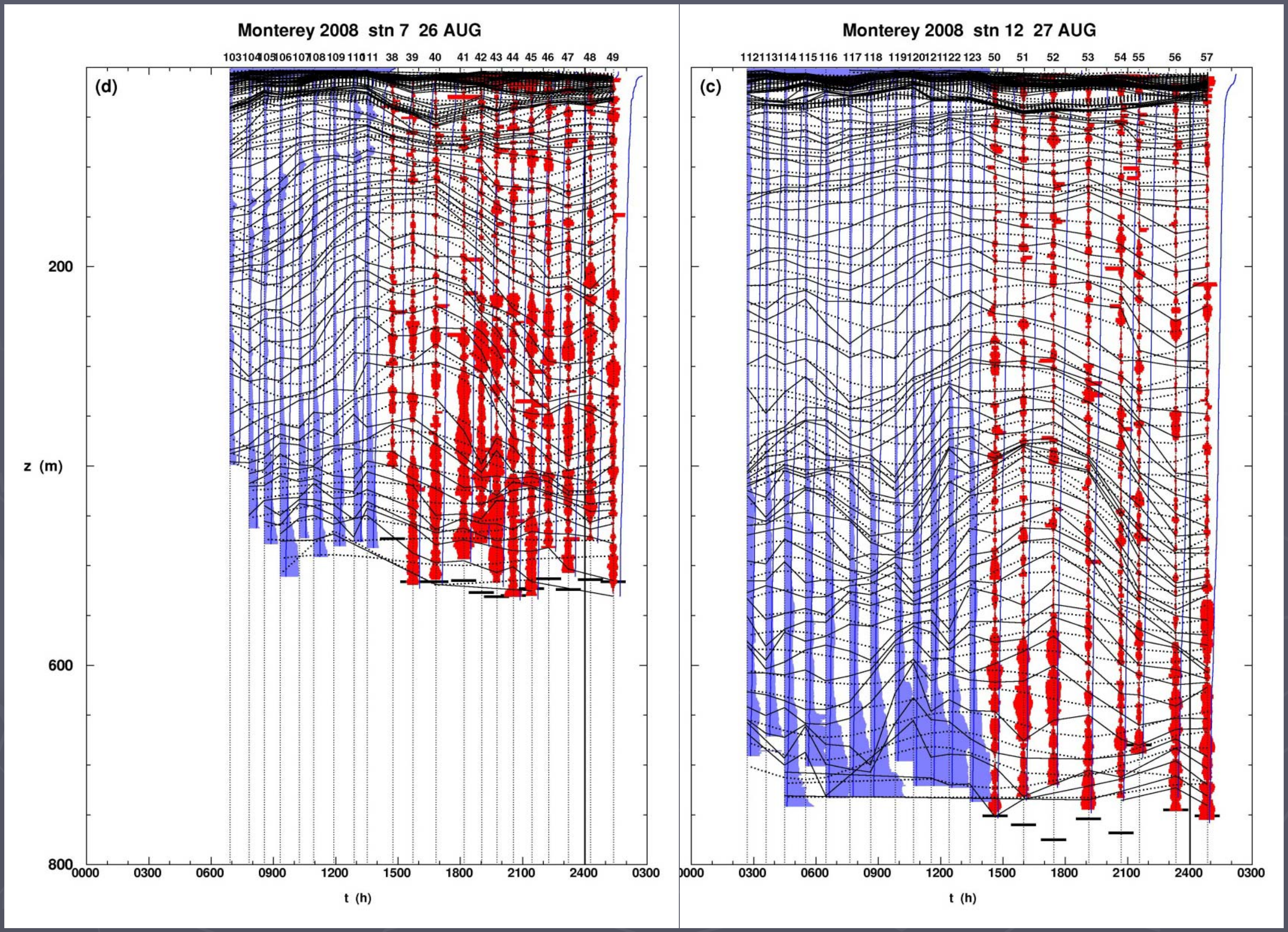
Kunze *et al*. (*JPO* submitted)

Sampling



- seven stations with 12-h of CTD/LADCP/OBS finescale profiling plus 12-h of CTD and microstructure profiling and microstructure profiles (red); five 12-h CTD-only stations (black) along the axes of Monterey and Soquel Canyons in water depths of 370-1200 m.
- sampled within 30 ± 60 m of bottom.
- 1200-m station (42) sampled over 3 different days.

Shallow Monterey (500 & 700 m)

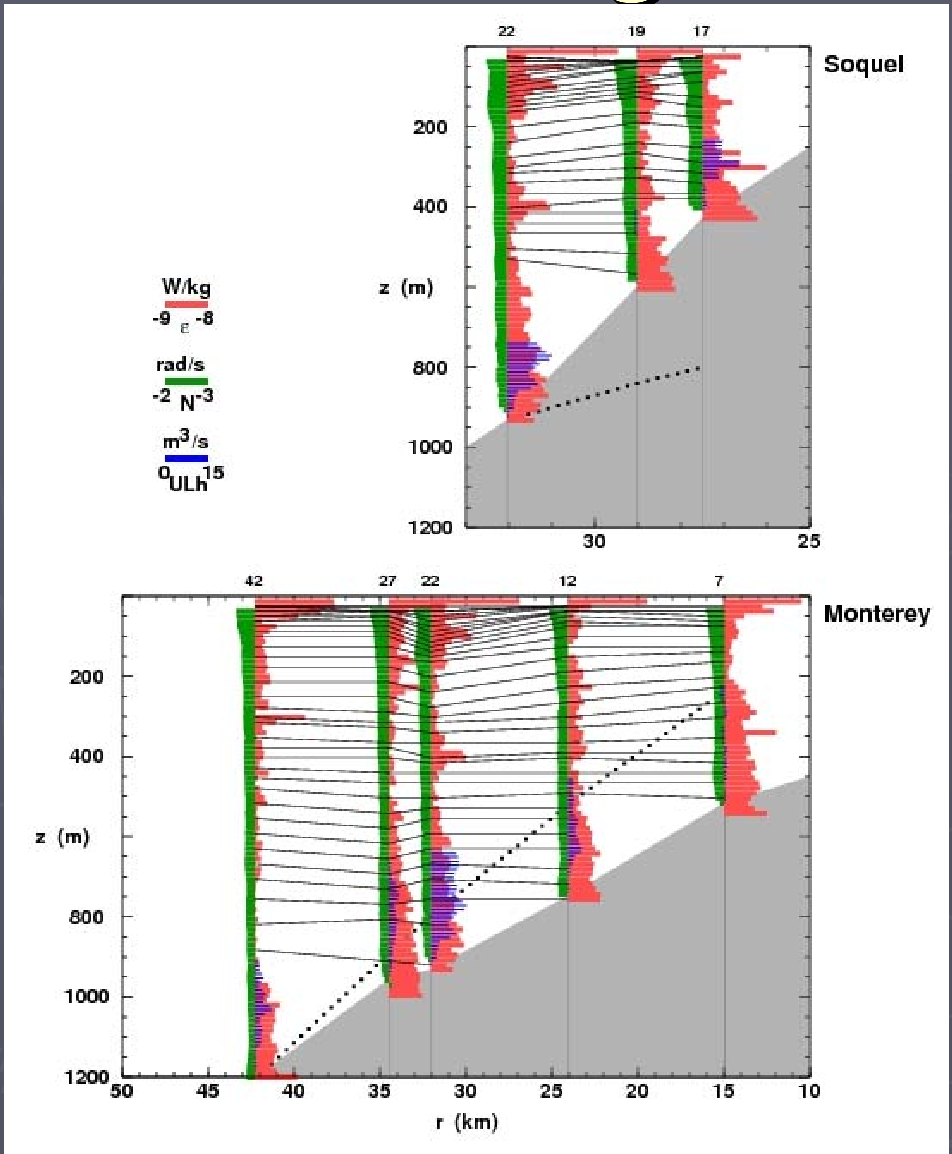


semidiurnal isopycnal displacements

elevated turbulence well into stratified water column!

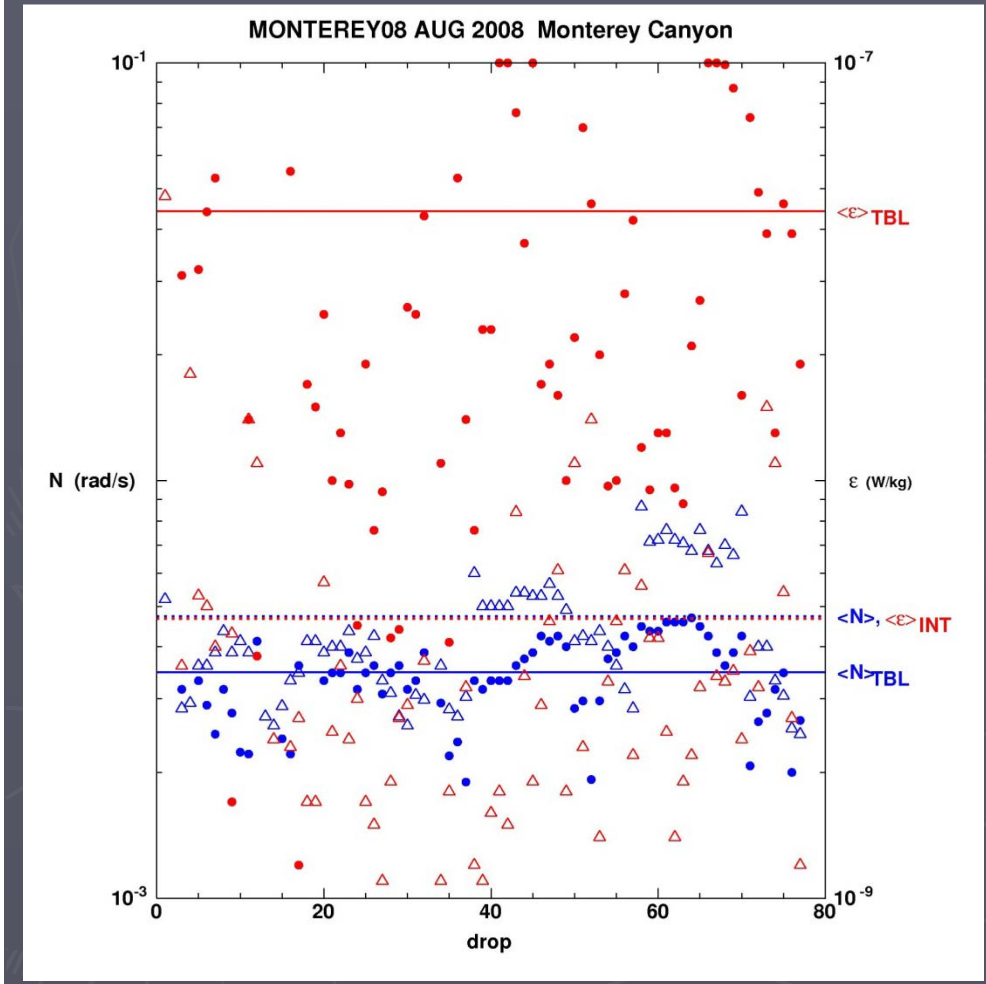
elevated backscatter

Along-Axes Sections



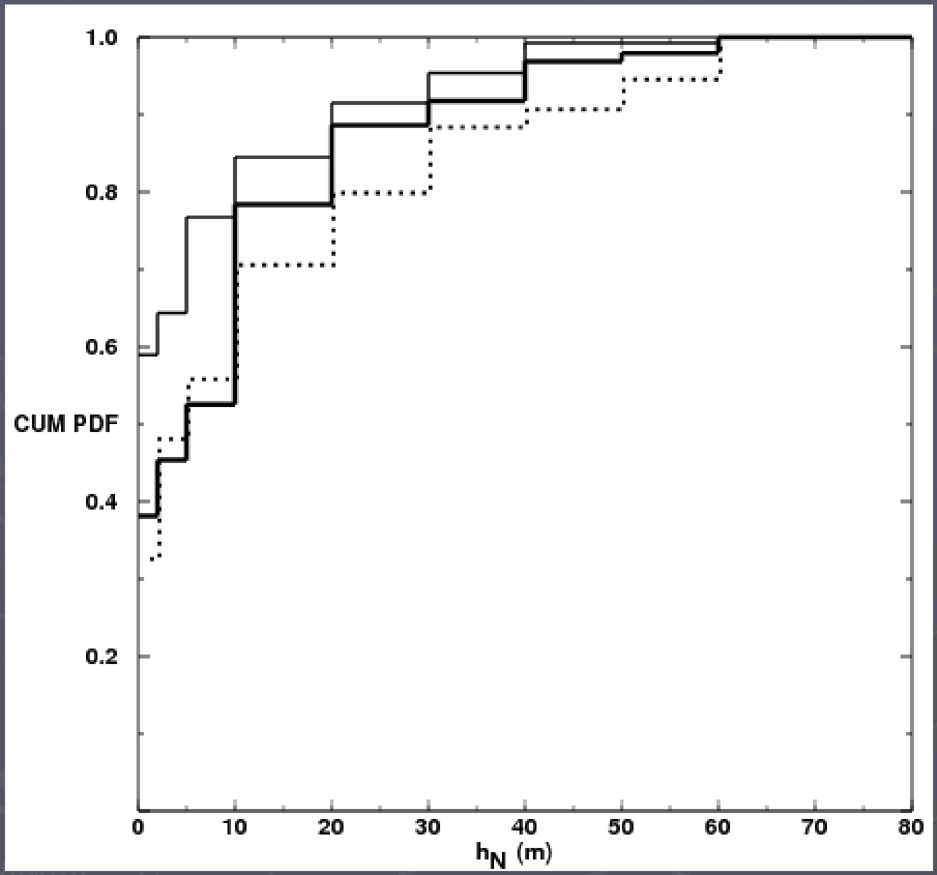
- average dissipation rates ε, buoyancy frequencies *N* and inferred upaxis transports *U*.
- turbulent layer 200-300 m thick (h_ε) as deep as 1200 m on canyon axis with $\varepsilon = 10^{-8}$-10^{-7} W/kg.

Stratified Turbulent Layer (STL)



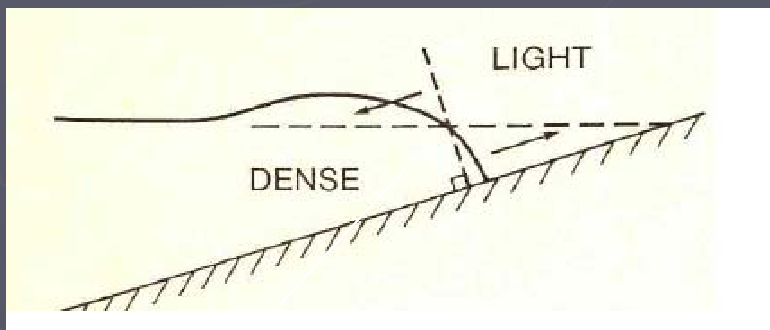
- 200-mab (solid circles) average dissipation rate ε and buoyancy frequency *N*; 300-400 mab (open triangles).
- *N* nearly identical in stratified turbulent layer as immediately above (3.5/4.5).
- above STL, $\varepsilon = 4 \times 10^{-9}$ W/kg,
- in STL, $\varepsilon = 4 \times 10^{-8}$ W/kg
- ($K = 16 \times 10^{-4}$ m²/s, $L_O < 5$ m).

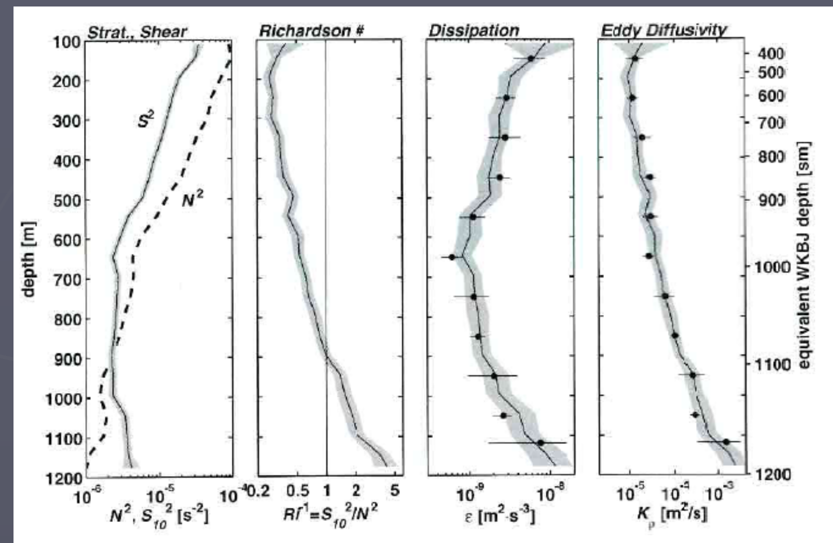
Bottom Boundary Mixed-Layer Thickness h_N



- 50% (90%) well-mixed bottom boundary layer thicknesses h_N less than 5 (30) m (based on $N < 10^{-3}$ rad/s), an order of magnitude thinner than the stratified turbulent layer thickness h_ε.

Mixing Efficiency





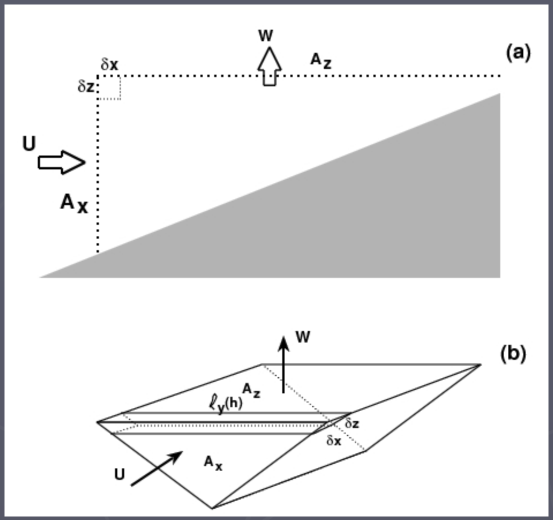
- Garrett (1990) Garrett (1991), Garrett *et al*. (1993) and Garrett (2001) argued that mixing on slopes inefficient because BBL well-mixed.

- in canyons, continental slopes (Nash *et al.* 2004, 2007), seamounts (Toole *et al* 1997) and ridges, stratified turbulent layers are often much thicker than well-mixed boundary layers ($h_\varepsilon >> h_N$) so *no* reason for low mixing efficiency. This will hold where flow/topography interactions produce unstable internal waves, but not weak interactions.

Energetics

- ΔAPE to mix bottom 200-300 m
  $= N^2 h_\varepsilon^3/12 = 10\text{-}30$ J m kg^{-1}.
- time to mix $t = \Delta\mathrm{APE}/(\gamma\varepsilon h_\varepsilon)$ = 2-5 months for mixing efficiency $\gamma = 0.2$, implying the need for restratification processes to maintain stratification.

Buoyancy Conservation 1



- Steady buoyancy conservation

$\partial[(UB + \langle u'b' \rangle)\ell_y]/\partial x + \partial[(WB + \langle w'b' \rangle)\ell_y]/\partial z = 0,$

where ℓ_y is the canyon width.

Buoyancy Conservation 2

- reduce to a 1-D vertical advection/flux-divergence balance taking canyon hypsometry ℓ_y into account (Stigebrandt and Aure 1989; McDougall 1989)

  $$W N^2 \ell_y = -\,\partial(\ell_y \langle w'b' \rangle)/\partial z$$

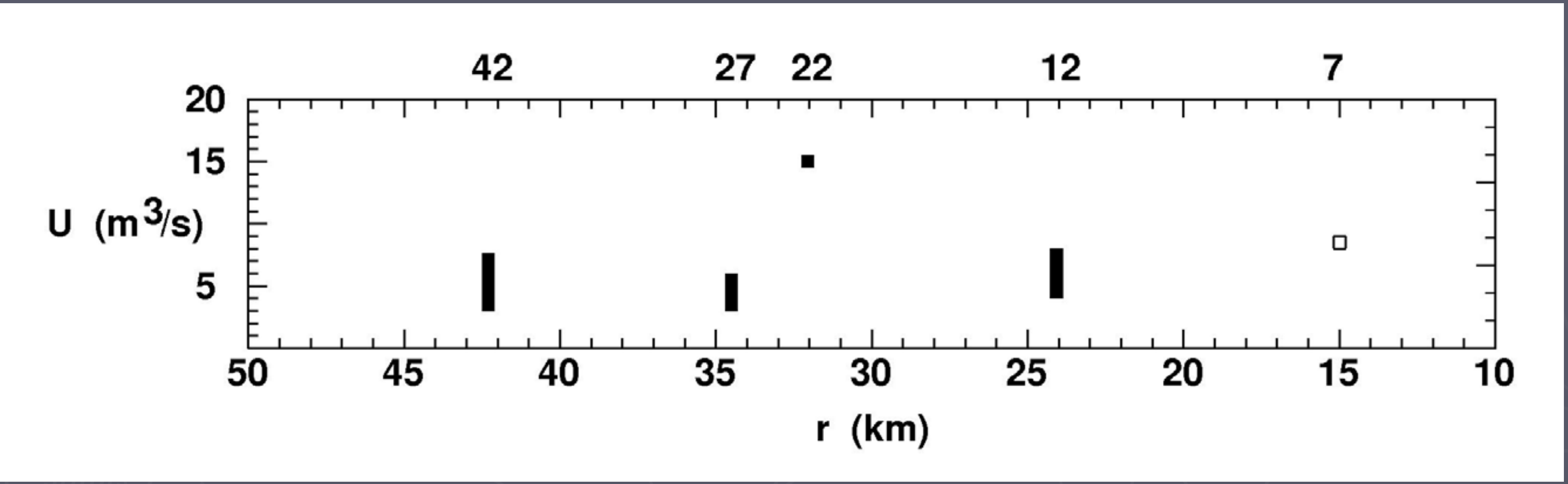
  by neglecting (i) mean upcanyon advective buoyancy-flux because mean isopycnals flat and (ii) perturbation upcanyon buoyancy-flux divergence (i.e., bolus exchange between turbulent layer and interior) without justification.

Substituting $\langle w'b' \rangle = -\gamma\langle\varepsilon\rangle$ (Osborn 1980) and canyon width $\ell_y = 4h$ where $h = z - z_b$ is height above canyon axis bottom

→ $W = (\gamma\langle\varepsilon\rangle)/(N^2 h)$ and $U = (\gamma\langle\varepsilon\rangle)/(N^2 h s)$

to satisfy the bottom boundary condition of no normal flow.

Upcanyon Transports

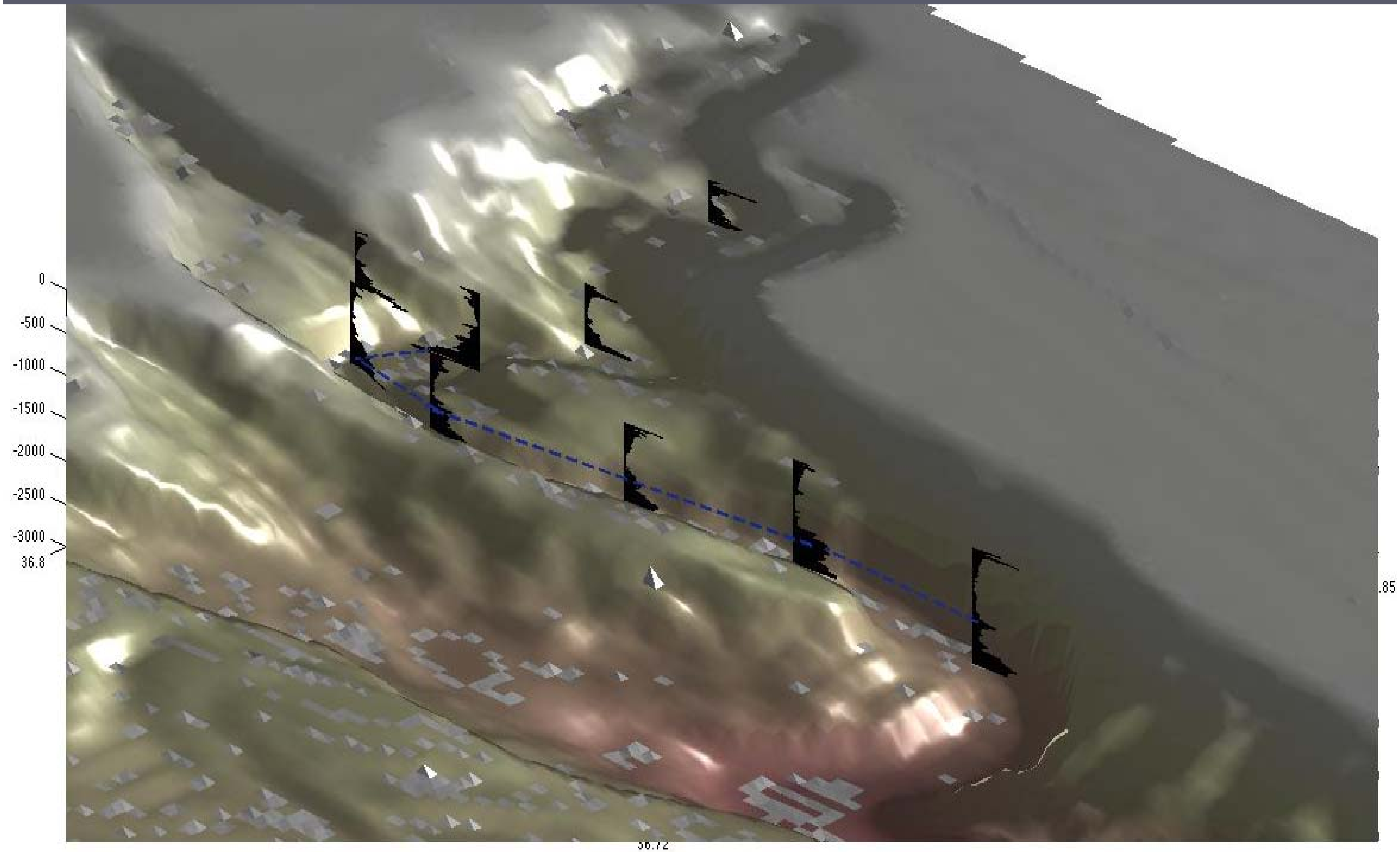


- to satisfy no mean flow through bottom, upcanyon flow *U = W/s* where thalweg slope *s* = 0.04.

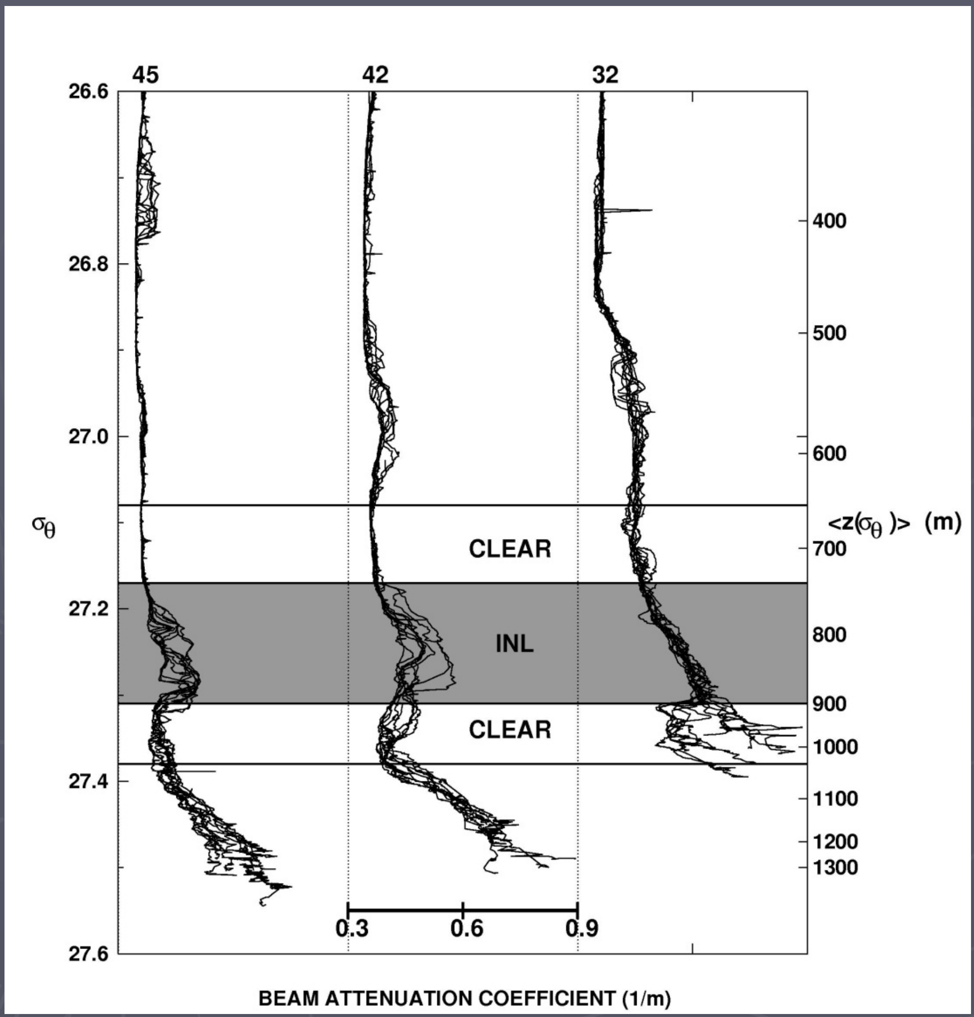
→ upcanyon transport $\int_U \sim 4\gamma\langle\varepsilon\rangle h_z h_1/(s\langle N^2\rangle) \sim$ 3-15 m^3/s
inferred upcanyon transports NOT uniform (Fig.).

- divergences and convergences around station 22 (*r* = 32 km) imply exchange between the stratified turbulent layer and interior.

Intermediate Nepheloid Layers

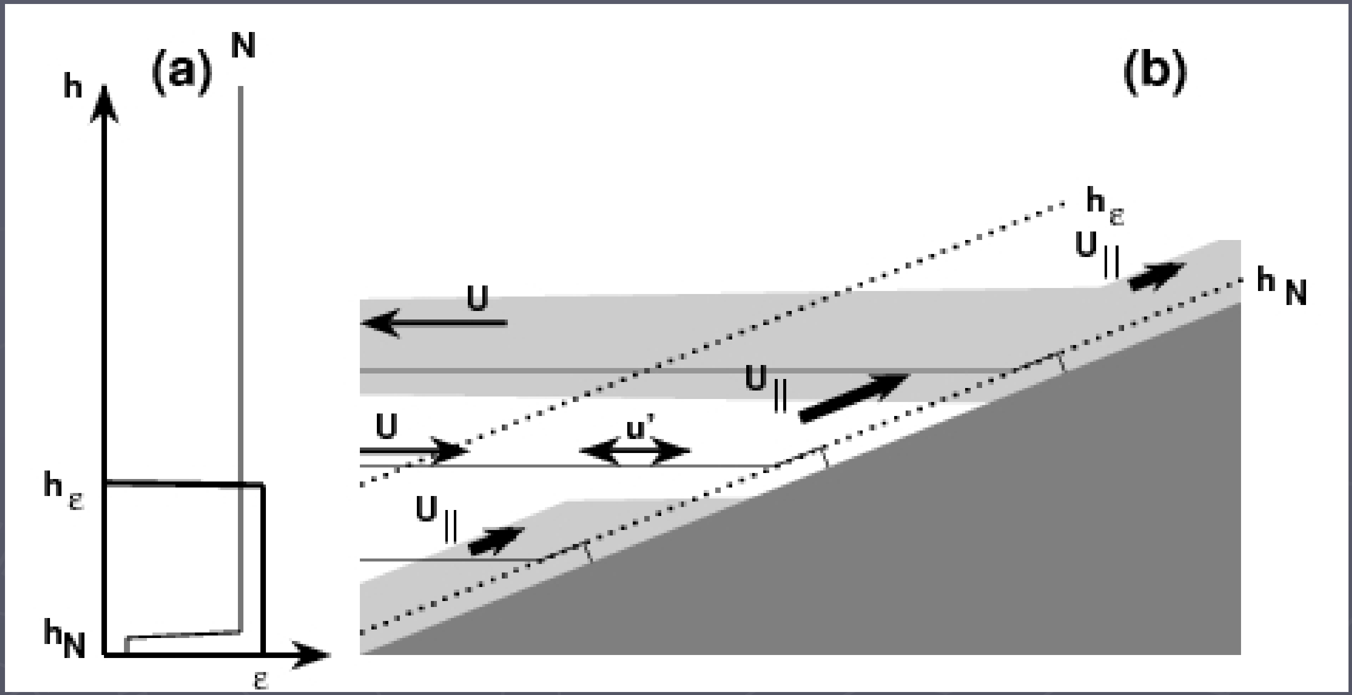


Intermediate Nepheloid Layers



- comparison of the coarse turbulence-driven predictions of the depths of turbid vs. clear water with observed INLs downcanyon.

Summary Cartoon



- stratified turbulent layer h_ε an order of magnitude thicker than well-mixed BBL h_N (a) and upslope flow convergence $U_{||}$ will drive 2-D flow U or u' and exchange with interior (b), invalidating 1-D balance.

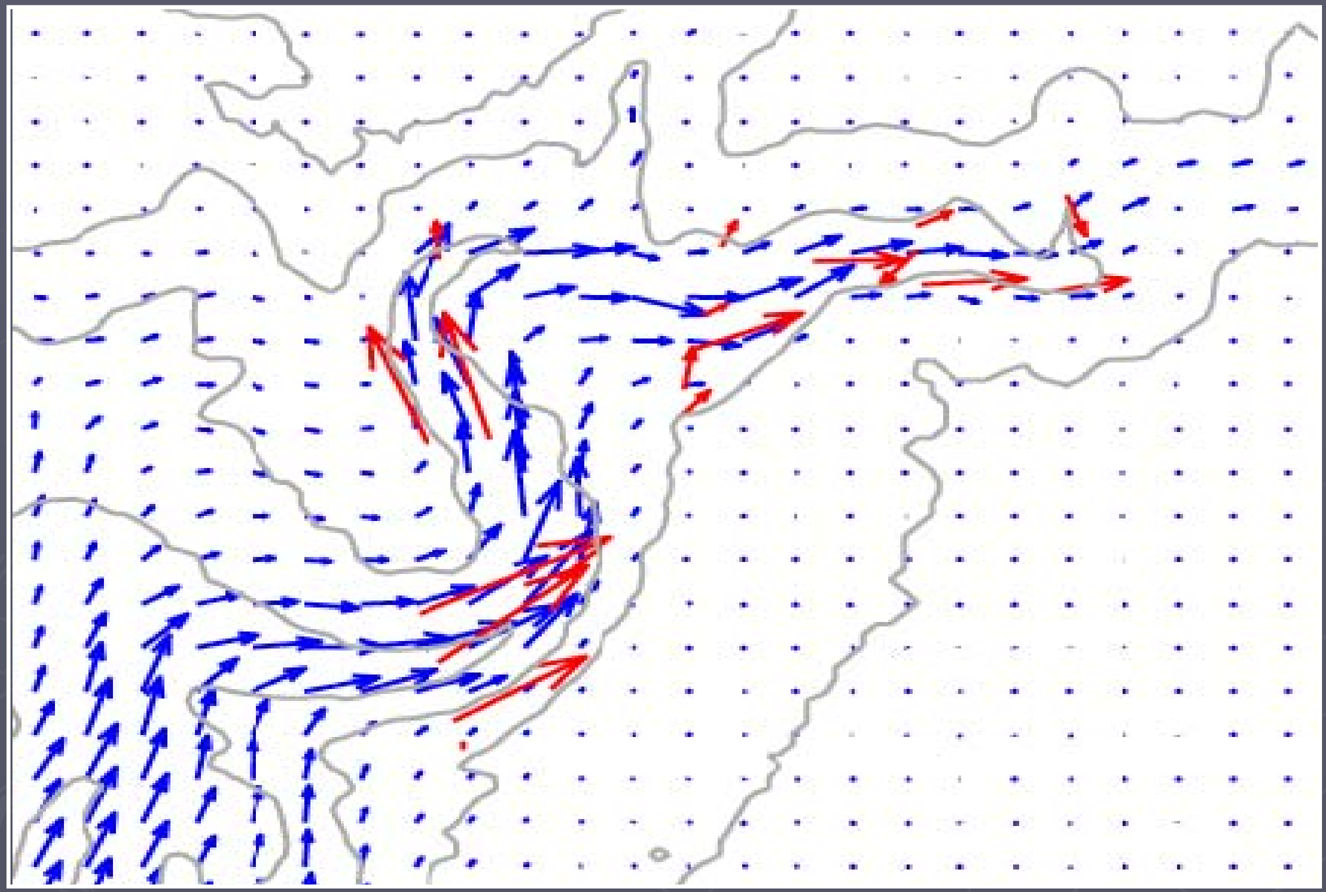
Conclusions

- 200-300 m thick turbulent stratified layers with $\langle\varepsilon\rangle = 4 \times 10^{-8}$ W/kg and diffusivities $K = 16 \times 10^{-4}$ m^2/s at 300-1200-m water depth along thalweg.
- mixing efficiencies should be high because well-mixed bottom boundary layers only 0-30 m thick ($h_N \sim 0.1 h_\varepsilon$), as commonly observed on slopes.
- timescale to mix the stratified turbulent layer ~2-5 months.
- inferred turbulence-driven upcanyon flow $U_{||}$ ranges from 50 m day^{-1} (0.05 cm s^{-1}) at h = 30 mab to 10 m day^{-1} at top of stratified turbulent layer (h_ε = 300 mab)
- globally, canyons may contribute 2-3 times as much diapycnal mixing as basin-average $K = 0.1 \times 10^{-4}$ m^2 s^{-1} in the ocean interior.
- inferred turbulence-driven upcanyon divergences and convergences consistent with observed depths of clear water and intermediate nepheloid layers, respectively.
- internal wave, turbulence and exchange dynamics on slopes *cannot* be described by 1-D models.

Future Work

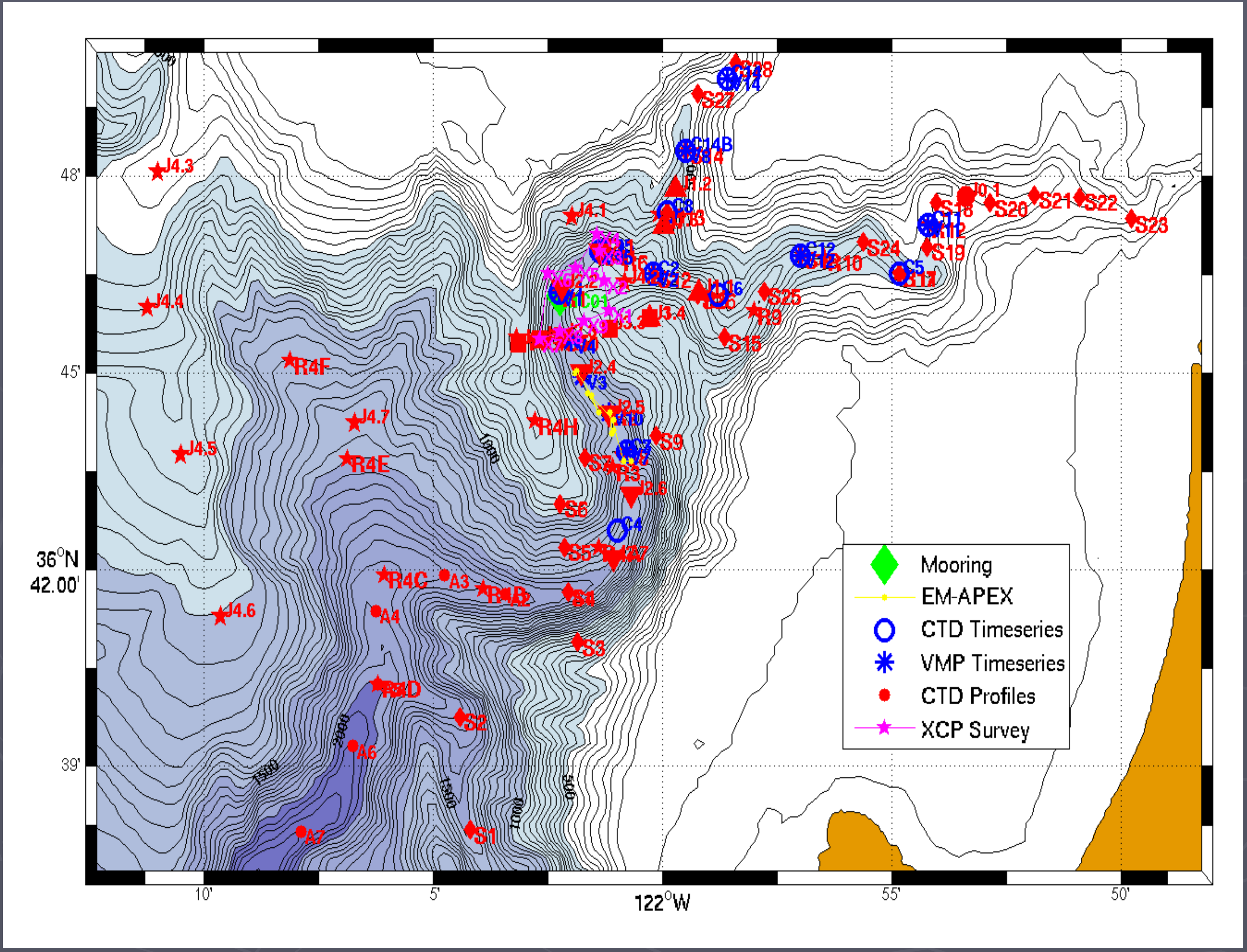
- our measurements only allowed quantification of one term in the steady buoyancy conservation with others not measurable by conventional means.

Internal Semidiurnal Energy-Fluxes



comparison of model (Jachec *et al.* 2006; Carter 2010) and observed (Kunze *et al.* 2002) vertically-integrated semidiurnal internal wave energy-fluxes.

Sampling Map



Soquel (Spring 370 & 600 m)