Quantify Lateral Dispersion and Turbulent Mixing by Spatial Array of χ-EM-APEX Floats

Thomas B. Sanford
Applied Physics Laboratory and School of Oceanography
University of Washington
1013 NE 40th Street
Seattle, Washington 98105
Phone: (206) 543-1365 fax: (206) 543-6785 email: sanford@apl.washington.edu

Ren-Chieh Lien
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, Washington 98105
Phone: (206) 685-1079 fax: (206) 543-6785 email: lien@apl.washington.edu

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LONG-TERM GOALS

Our long-term scientific goals are to understand the dynamics and identify mechanisms of small-scale processes—i.e., internal tides, inertial waves, nonlinear internal waves, vortical modes, and turbulence mixing—in the ocean and thereby help develop improved parameterizations of mixing for ocean models. Mixing within the stratified ocean is a particular focus as the complex interplay of internal waves from a variety of sources and turbulence makes this a current locus of uncertainty. Our focus is on observing processes that lead to lateral mixing of water properties. The exploitation of autonomous platforms is a long-term goal.

OBJECTIVES

Our primary scientific objective is to use an innovative swarm of autonomous profilers to improve our understanding and parameterization schemes of small- to submeso-scale oceanic processes. Dispersion due to lateral processes with vertical and horizontal shears could enhance turbulent mixing. Both internal waves and vortical motions exist at vertical scales smaller than order of 10 m and horizontal scales smaller than few km. They have distinct kinematics and dynamics. Internal waves propagate and may carry energy to remote regions before they break and dissipate via turbulent processes, whereas vortical motions do not propagate and are often long lived. Separation of these two motions is necessary to improve parameterization schemes.

APPROACH

We operated an array of EM-APEX floats, manufactured by Teledyne Webb Research Corp, with some modifications by our group. In particular, 10 floats were modified to operate with dual, high-frequency-response thermistors. These were used to determine ocean turbulence levels on the upward traverses of the floats.

Our approach was to measure the internal wave background, shear vector, vorticity vector, and turbulent mixing using a "swarm" of EM-APEX profiling floats that profile simultaneously through the surface mixed layer and upper seasonal pycnocline every hour (Fig. 1). These 3-D observations of turbulence, instability, and small-scale processes are vital to understanding the dynamics of the coupling between the diapycnal mixing and oceanic lateral processes. Our primary purposes are to quantify the time evolution of the complete horizontal and vertical structures of turbulence mixing and shear instability including thermal diffusion rate χ, vertical shear S, stratification N, shear instability gradient Richardson number Ri, Ertel's potential vorticity Π, and effective horizontal eddy diffusivity k_h on isopycnal surfaces from shear dispersion, and to quantify effects of internal waves and vortical modes on horizontal dispersion and diapycnal mixing.

WORK COMPLETED

- Participated in LatMix meeting at Stanford in January 2013.
- Quality control and submission of data to LatMix server.
- Adjusted EM-APEX relative velocity to absolute velocity using GPS fixes for every surfacing of the floats. Compared the processed absolute velocities to nearby ADCP shipboard data for quality assurance.
- Computed quasi-Lagrangian quantities, such as relative vorticity, horizontal divergence, vortex stretching and potential vorticity, projected onto isopycnal surfaces for three deployments.
- Developed algorithm using Kelvin's circulation and a linear regression to find horizontal gradients in higher order computed quantities, specifically PV.
- Computed vortex stretching to compare with relative vorticity.
- Tested consistency relations for linear internal waves: PE/KHE and CCW/CW spectra.
- Presented results at the ONR Peer Review in Chicago in September 2013.

Experiment Recap:

Our cruise on the R/V *Endeavor*, 1-21 June 2011, involved 3 EM-APEX deployments imbedded within the 3-ship LatMix experiment. Two varieties of float were used: a) 11 standard floats that measure U, V, T, S, and P and b) 10 that also measured χ, the thermal variance diffusion rate. The floats were programmed to rise to the surface at the same time. In addition to Slocum gliders and Lagrangian floats, for each setting, 3- ship ADCP, S, T, P, and dye concentration surveys were conducted to observe:

i) Large scale (15 x 15 km radiator pattern), 18-hour background field on the *R/V Oceanus*.
ii) 10 km, 4-hour butterfly following dye on *R/V Endeavor*.
iii) Dye following to track the advection and mixing of the dye patches on *R/V Cape Hatteras*.

The first region was dubbed the "Big Nothing" based on minimal upper ocean property gradients. 21 EM-APEX floats were deployed in 3 concentric circles of radii 0.5, 1 and 2 km late on 3 June and evolved until 10 June, with some floats rearranged in the middle of the time series to reduce ellipticity of the arrangement. On 7 June, the array was carried into a more dynamic region with increasing southwest velocity, which caused the array to reshape into an ellipse with a NW-SE dominant axis [seems strange. Southwest velocity causes NW-SE ellipse?].

The second region (30 km north of setting 1) was surveyed and chosen based on its large property gradients. On 13 June, 19 floats were deployed in the same concentric circle orientation near the dye release. The initial location was in a stagnation point, which the floats stayed in for about 24 hours before being transported to the northeast, with strong south-east/north-west gradients. The other assets were moved northward immediately, causing an increasing separation between the EM-APEX float array and most other instruments. The strong strain necessitated recovery and repositioning of some floats to maintain a circular form. Despite this, for most of this experiment and setting 3, the float orientation was elongated in the northeast/southwest direction, with aspect ratio near 5 to 1. The floats were recovered on 17 June.

The third setting was slightly down stream of the evolving dye injections in anticipation of being overtaken and measuring similar ocean properties from 17 June through 20 June. Again, the high strain caused an elongation of the floats, though adding 2 floats halfway through this deployment helped maintain circularity of the array.

The summary of observations is:

- Innovative new use of multiple, autonomous vertical profilers to collect simultaneous profiles of U, V, T, S and χ in the upper ocean on horizontal scales of 10 m to 10 km
- Obstacle avoidance system developed and installed on each R/V's bridge informed watch of the locations of various platforms on the surface
- 21 EM-APEX floats, including 10 with χ sensors, deployed in 3 settings with a single profiler lost
- 9274 vertical profiles obtained from surface to 100 m or deeper. 99.9% had CTD profiles. 90.1% yielded velocity profiles.
- 2056 profiles also observed fast temperature gradient observations for χ (and ε). 1792 or 87.7% yielded good data.

RESULTS

To ensure quality of processing and reliability of measurements, several steps have been taken. All velocity measurements were removed if the Verr (i.e., velocity uncertainty) of the fit to the voltage was above 1 cm/s. Depth-averaged, array-averaged estimated velocities from surface GPS position fixes were computed to adjust the measured relative velocity to absolute velocity profiles. Consistency between simultaneous, near-by floats was examined by plotting the relationship between the square (kinetic energy) of the depth-averaged velocity differences and the float separation distance. This gives an estimate of the inherent instrument noise of about 1-2 cm/s (Fig. 2). The squares of the velocity differences are adjusted according to WKB scales. That is, the higher N in the upper ocean results in higher variances. The factor N_0/N (N_0 is 1 cph) adjusts for this effect. As an independent comparison, the individual velocity profiles were compared with the ADCP measurements for the same depth range in close proximity (under 200 m separation) (Fig. 3).

A main interest of the LatMix overall experiment was to observe the formation and interplay of isopycnal and diapycnal mixing events on submesoscales. Specifically, understanding the mechanisms for increased mixing and the energy cascade on small scales have their roots in observed deviations from the internal wave energy spectrum, which some propose can be attributed to small scale vortical motions. The EM-APEX profiling array is suited well to look at the vertical, horizontal and temporal structure of the internal wave field and possible vortical motions on scales from 0.1 – 10 km in the frequency range f to N. Primarily, by computing Ertel's potential vorticity, Π, any deviations from the background over time should indicate other sources of energy besides internal waves. Ertel's PV is

$$\Pi = (\boldsymbol{f} + \boldsymbol{\nabla} \times \boldsymbol{U}) \cdot \boldsymbol{\nabla}(z - \eta)$$

The formula for Π (Kunze and Sanford, 1993) includes background, linear and non-linear contributions: planetary vorticity, relative vorticity, linear vortex stretching, and nonlinear vortex stretching, tilting and twisting.

The background planetary vorticity was computed as the spatially and temporally averaged Coriolis frequency. Relative vorticity was calculated using a linear regression to all the available floats following Okubo and Ebbesmeyer (1975). *The nonlinear component* is negligible compared to the linear terms. The linear PV is simply:

$$PV = f + RV - VS.$$

The floats were deployed in the configurations depicted in Fig. 4. The array gradually became distorted with unequal major and minor axes.

An example of the RV and VS terms for Site 1 is shown in Fig 5. The vortex stretching term has negative sign to show more clearly the compensating nature of the terms. There is considerable mirror imaging of RV and –VS. In the absence of background vorticity, internal waves possess no PV. However, if there is ambient vorticity in the background, the observations may exhibit PV through the interactions of ambient flow and the internal waves.

Spectra of the velocity and density fluctuation conform to GM expectations in spectral form and within a factor of two of GM energy level. Figure 6 shows the spectra from Site 1 and 3. Site 1 has lower energy overall with increased spectral energy density near f and Nyquist frequency (0.5 cph). Site 3 has more energy density near f.

The Chi sensors produced results that show some spatial variations, which may appear also in the turbulence observations from other investigators. The computations of χ, ε, and κ_z are shown for Site 1 in Fig, 7.

The preliminary conclusions for RV and VS are:

- EM-APEX float array is a powerful tool in assessing the motion and water properties on small scales: 20 floats, simultaneous profiles

- For site 1, there is a distinct background internal wave field, shown in the compensation of relative vorticity and vortex stretching.
- Anomalous potential vorticity is present in site 1 with magnitudes around 0.3 f This could be due to advection of PV across the field, but still needs to be resolved.
- For site 2, there is a movement through a salinity front, which shows high anomalous PV values on the order of 0.5 f. For the period, thermal wind balance is maintained across the front

The internal wave preliminary conclusions are

- Background internal wave energy in the continuum varies from 0.5 GM at sites 1 and 2 to ~0.9 GM at site 3.
- χ-EM-APEX floats capture the major portion of the temperature gradient spectrum and provide quality estimates of χ, κ_z, and ε.
- κ_z decreases by more than 3 decades in the upper 40 m, implying the potential strong interplay between vertical diffusion and isopycnal diffusion and dispersion.
- Turbulence is the weakest at site 1, and the strongest at site 3 in the upper 40 m, and the strongest at site 2 below 40-m depth.

IMPACT/APPLICATION

The use of autonomous vehicles operating in a coordinated way is able to separate temporal and spatial variability. In contrast, observations at a single site consist of fluctuations caused by both time and space dependencies. The use of a swarm of UUVs, all programmed to operate in unison, is now possible and surely will provide much more information than obtained by the more traditional methods. During this field study, over 8,000 CTD and velocity profiles were obtained in three experiments.

TRANSITIONS

The EM-APEX float resulted from a SBIR contract from ONR to Webb Research. This instrument has already begun to have an impact on a variety of experiments. The recent ONR DRI projects that the PI has been involved in have EM-APEX components. Other investigators have purchased and used these floats, such as James Girton, Eric Kunze, Mike Gregg and Helen Phillips (U. Tasmania). I understand that NAVO will be purchasing some.

RELATED PROJECTS

Process Study of Oceanic Responses to Typhoons using Arrays of EM-APEX Floats and Moorings (N00014-08-1-0560) as a part of the ITOP DRI. Fourteen EM-APEX floats were air-deployed into two W. Pacific typhoons. *T. Fanapi* was a category 1 tropical cyclone. Seven floats were deployed about a day in front of *Fanapi* in mid-September 2010. Similarly, 7 floats were deployed in front of Super Typhoon Megi in mid-October. All floats survived the deployment and reported profiles. We are studying the characteristics and dynamics of the oceanic response to and recovery from tropical cyclones in the western Pacific Ocean

Studies of the Origins of the Kuroshio and Mindanao Currents with EM-APEX Floats and HPIES (N00014-10-1-0468). This is a component of the Origins of the Kuroshio and Mindanao Currents DRI. We deployed 5 HPIES (Horizontal electric field, pressure and IES) surrounding R-C Lien's surface moorings NE of Luzon Is., south of the Balintang Channel. The purpose of the HPIES is to determine barotropic velocity from the electric field and baroclinic velocity from PIES in a triangle around a mooring. The total water column measurements nicely compliment those from the moorings. In addition, EM-APEX floats were deployed in the NEC as it approaches the Philippine Island and bifurcates into the Kuroshio Current going N. and Mindanao Current flowing S.

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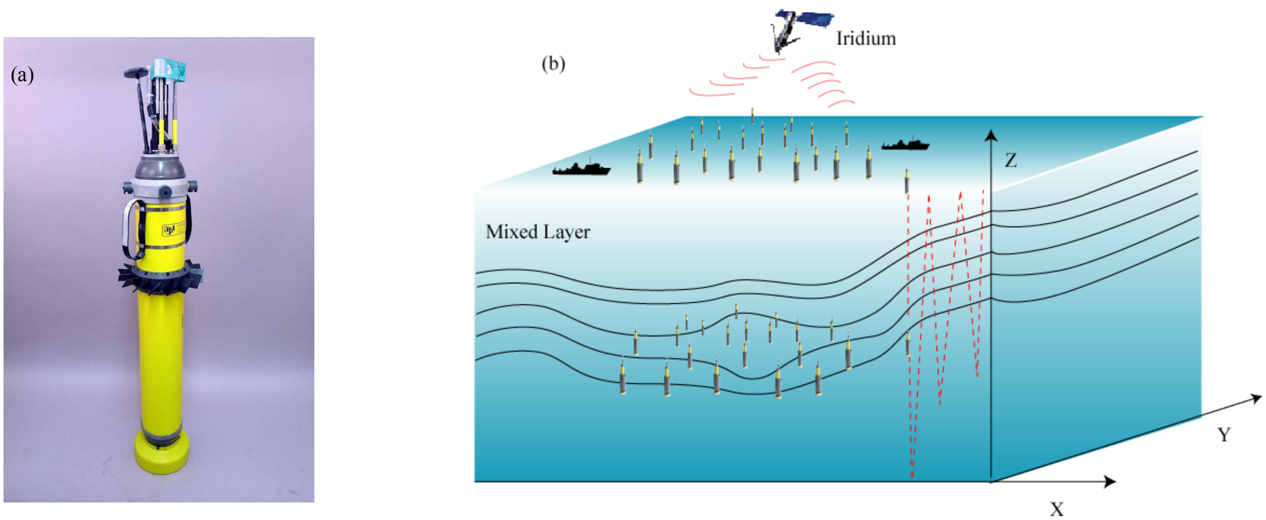

Fig. 1: (a) EM-APEX float with dual χ sensors. (b) Schematic of a spatial array of 10-microstructure EM-APEX floats (χ-EM-APEX floats) and 10 regular EM-APEX floats. N.B. The χ sensors were mounted so as to be out of the wake produced by the Iridium antenna, which will be tilted to the side in the so-called "Mai Tai" mounting.

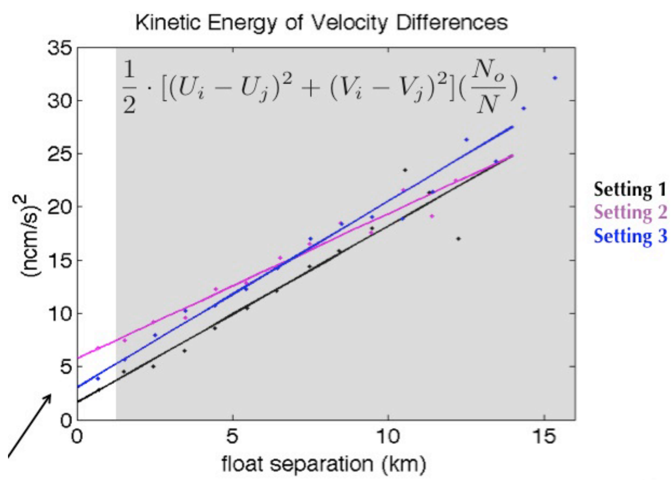

Fig. 2: Velocity structure function, the square of WKB adjusted velocity differences vs. profiler separation, with all floats for the three settings. Intercept (arrow in figure) corresponds to 1-2 cm/s uncertainty.

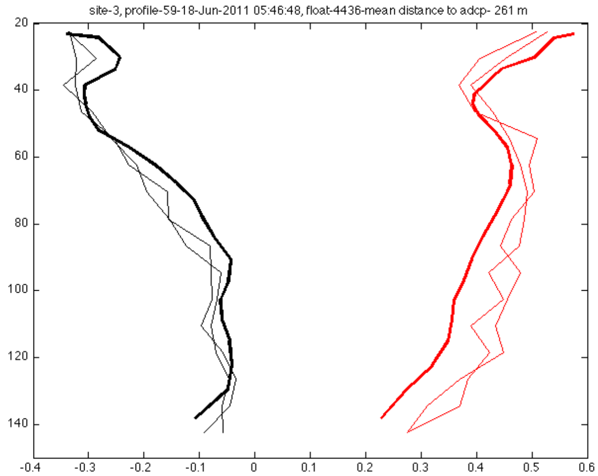

Fig. 3: Comparison of profile 59 of float 4436 with ADCP (thin line) from Endeavor example for setting 3. Missing x label and y label.

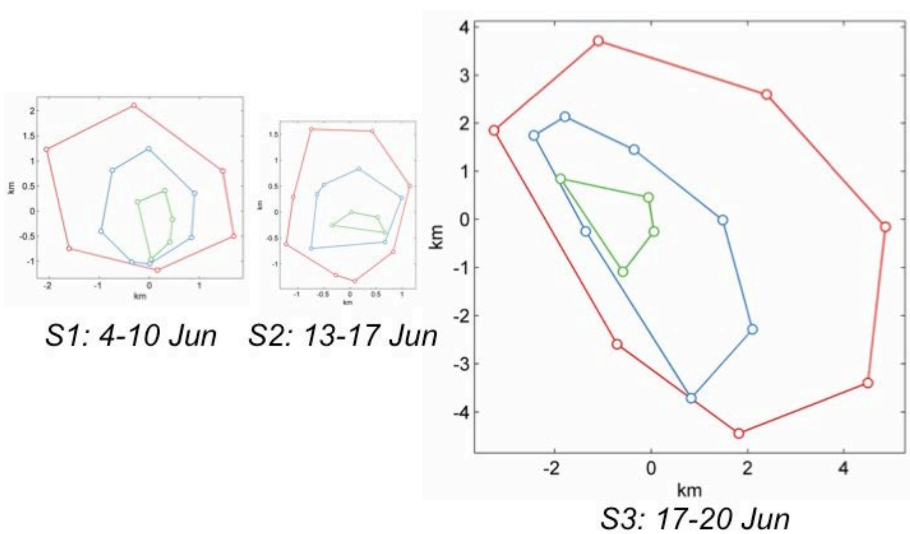

Fig. 4: Initial float deployment configurations. Because of the ambient currents and time necessary to slowly steam around the intended pattern, the resultant configuration was not of concentric circles.

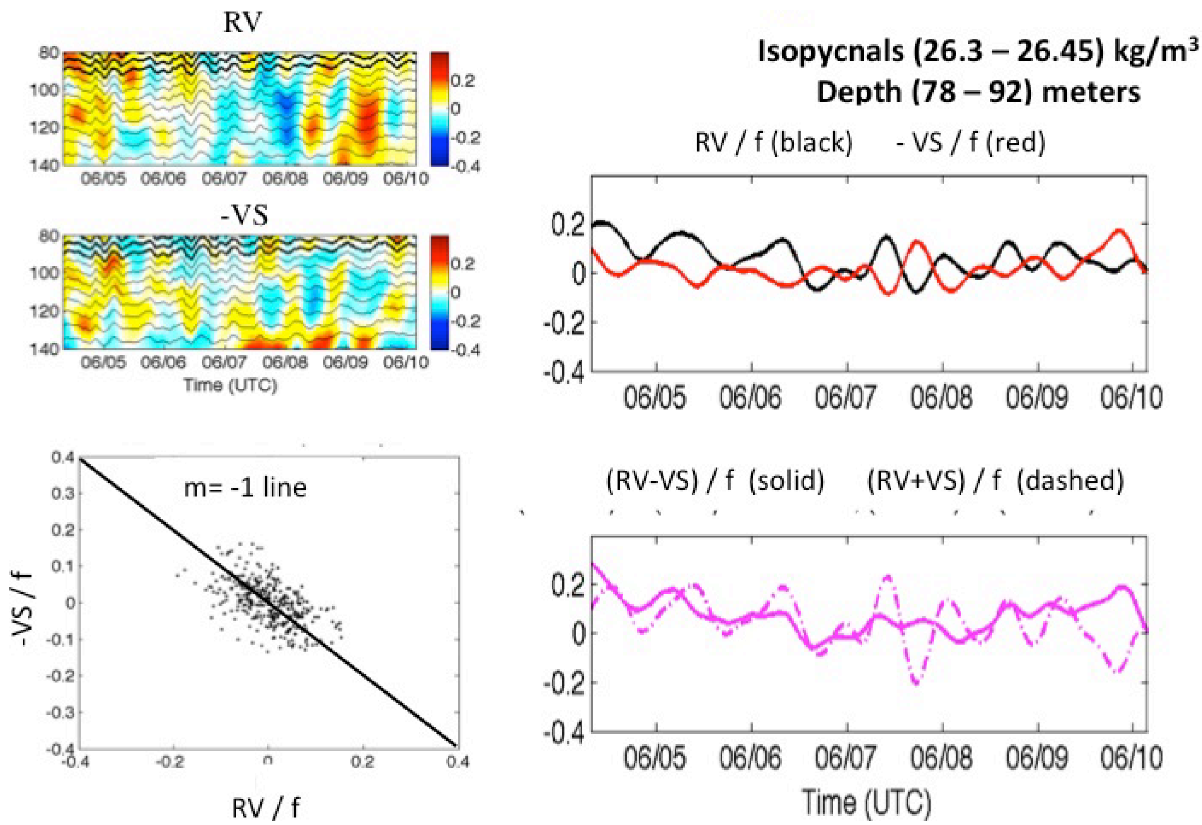

Fig. 5: RV and VS at Site 1 between isopycnals 26.3 and 26.45 kg m^{-3}. The compensating behavior of VS and RS indicates that much of the variability is caused by internal waves. However, there is a PV trend to the background linear PV in the early portion of the record.

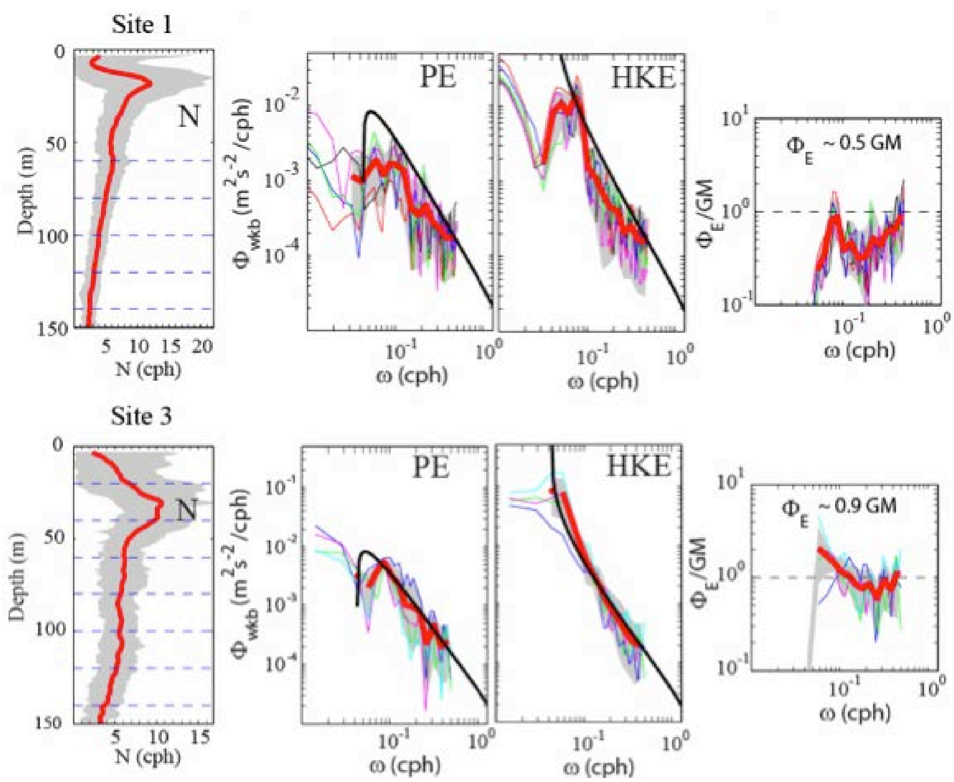

Fig. 6: Vertical profiles of buoyancy frequency (left column), averaged WKB-scaled spectra of potential energy and horizontal kinetic energy (middle two columns), and the ratio of observed total energy spectra to the GM model (right column) at Site 1 (top row) and Site 3 (bottom row). Horizontal vertical dashed lines in the left two panels mark the depths where spectra are computed. In the two middle columns, thick red curves are depth averaged WKB scaled spectra, and thick black curves are GM model spectra. In the right column, the thick red curves are averaged ratio of observed energy spectra to that of GM model.

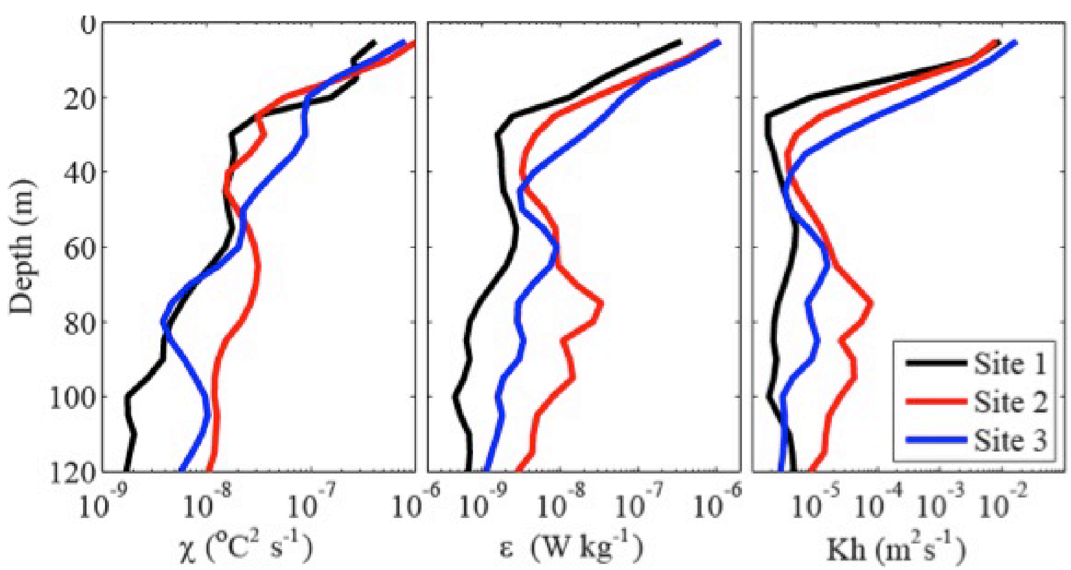

Fig. 7: Vertical profiles of averaged χ, ε, and κ_z of the three sites. N.B. the sharp gradients above 40 m.