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

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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.

OBJECTIVES

Our primary scientific objective is 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 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 will 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.

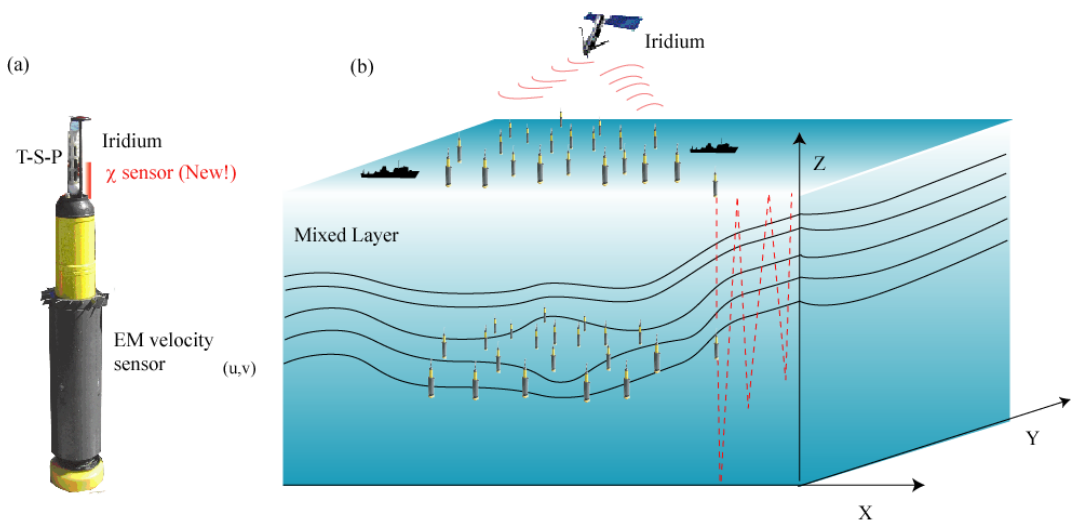

Fig. 1: (a) EM-APEX float with the proposed χ sensor. (b) Proposed experimental plan of a spatial array of 20-microstructure EM-APEX floats (χ-EM-APEX floats). N.B. The χ sensor will be mounted so as to be out of the wake produced by the Iridium antenna, which will be tilted to the side in the so-called "Mai Tai" mounting.

WORK COMPLETED

- Participated in LatMix meeting in Portland, OR on January 10-12, 2012.
- Presented initial observations at Ocean Sciences Conference in Salt Lake City, UT February 20-24, 2012
- Participated in LatMix meeting at Woods Hole on June 19-21, 2012.
- 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-lagragian 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.
- Used chi data to test consistency relations for internal waves: PE/KHE and CCW/CW spectra.

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 V, T, S, and P and b) 10 that also measured chi, the ratio of temperature gradient and square of vertical mean T gradient. 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 the 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.

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 third setting was slightly up-current (north) 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.

Results:

To ensure quality of processing and reliability of measurements, several steps have been taken. All velocity measurements were removed if the Verr 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 2 cm/s (Fig. 2). 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).

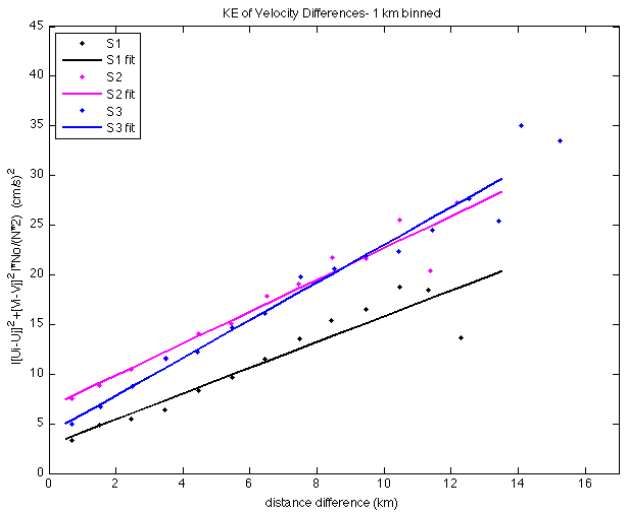

Fig. 2: Structure function, the square of WKB adjusted velocity differences vs. profiler separation, with all floats for the three settings

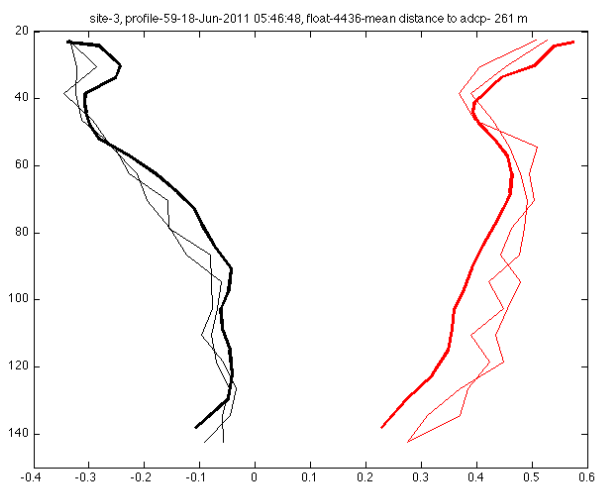

Fig. 3: Comparison of profile 59 of float 4436 with ADCP(thin line) Endeavor example for setting 3.

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. To accomplish this task, the expanded version of the formula for Π was used (Kunze, 1993), which includes background, linear and non-linear contributions: planetary vorticity, relative vorticity, vortex stretching, twisting, and two isopycnal tilting terms resulting in horizontal contributions to Π.

The background planetary vorticity was computed by spatially and temporally averaging the buoyancy frequency and Coriolis frequency. Relative vorticity was calculated using a linear regression to all the available floats following Okubo and Ebbesmeyer, 1975. Vortex stretching was calculated by finding the array mean deviation from the background N^2 profile. The twisting term is a product of the relative vorticity and the vortex stretching / f.

Since the computations are on isopycnal coordinates, the last two tilting terms are non-vertical by the sine of the isopycnal slope. It was determined that for all three settings the maximum gradient across the entire array was on the order of 5 m for 500 meters ~ .01, which is small enough to neglect the last two terms. Additionally, when looking at the depth-averaged Π, in order for these terms to be important, the isopycnal slope must be large and coherent throughout all depths, which was not the case during the 3 experiments.

Estimates of perturbations in Ertel's potential vorticity, dΠ, have been computed for the three sites using this methodology. Perturbations averaged over each time series in Π were ~ 0.05*fN^2, 0.25*fN^2, and -0.25*fN^2 for settings 1 and 2, respectively (Fig. 4).

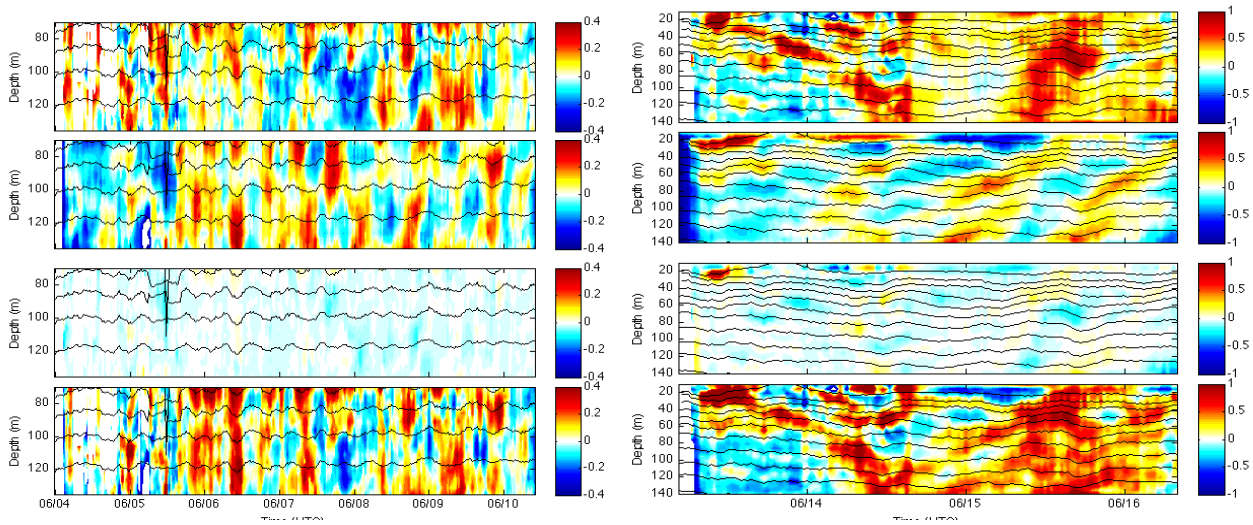

Fig. 4: RV, VS, Twisting and PV for settings 1 and 2.

The profiles exhibit a close correspondence to linear internal waves. It can be shown in the consistency relations for such waves. Figure 5 shows the comparison for ccw vs. cw energy and the ratio of PE to HKE.

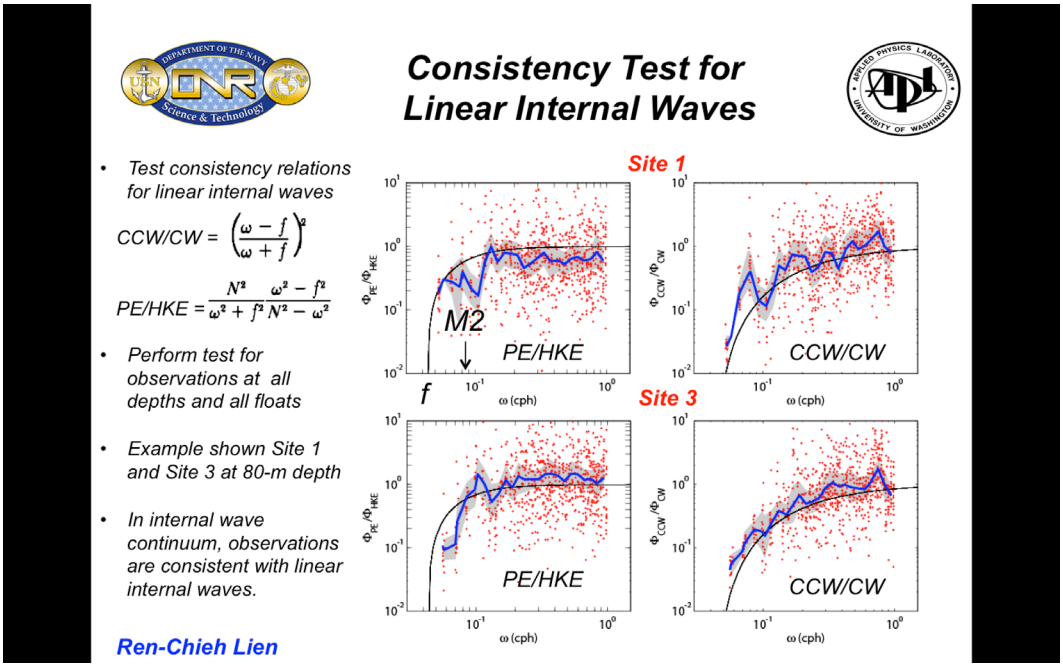

Fig. 5: Consistency tests for linear internal waves for Setting 1 and Setting 3. The black line is the theoretical expectations and the blue line is the band-averaged values of the individual values (red dots)

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.

REFERENCES

Kunze, E., and Sanford, T. B., 1993,Â Submesoscale Dynamics near a Seamount. Part I: Measurements of Ertel Vorticity,Â American Meterological Society.

Okubo, A., and Ebbesmeyer, C. C., 1976,Â Determination of vorticity, divergence, and deformation rates from analysis of drogue observations,Â Deep-Sea Research, v. 23, pp.349-352.

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 intend to deploy 5 HPIES (Horizontal electric field, pressure and IES) surrounding R-C Lien's surface moorings NE of Luzon Is., probably close to 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 will be deployed in the NEC as it approaches the Philippine Island and bifurcates into the Kuroshio Current going N. and Mindanao Current flowing S.