EquatorMix Cruise Report
R/V Roger Revelle, Oct. 4 to Nov. 5, 2012

J. A. Smith, Chief Scientist
Et al. (see last page for full credits)

Motivation

• Based on both modeling results and prior observations, we pursue the hypothesis that turbulent structures in an active mixed layer, combined with shear across the upper pycnocline, generate energetic Near-N Internal Waves (figure 1).

• In the tropics, the most likely candidate for this kind of NNIW generation is night-time buoyancy-driven convection combined with the Equatorial Undercurrent shear (figure 2).

• An alternative hypothesis is that shear instabilities of the undercurrent shear do both mixing and generation of NNIW that may propagate up and down from the shear zone.

Objective

The objective of this expedition is to explore the importance of interactions between the mixed-layer motions (e.g., buoyancy-driven convection) and Near-N Internal Waves (NNIW, where N is the local buoyancy frequency) to the mixing dynamics in the seasonal and diurnal mixed layer and upper pycnocline near the equator, where the influences on air-sea heat and moisture fluxes are particularly crucial.

Figure 1. Depth-Time plot of the vertical velocities $w$ associated with mixed-layer motions (upper 30m) and internal waves in the stratified lower section (30 to 70m, with the lowest 20 meters devoted to an absorbing “sponge” layer). From Polton et al. 2010.

Questions to address

1. Do high-frequency internal waves interact with mixed layer motions?
2. Do they affect entrainment and mixing in the upper pycnocline?
3. Are they related to air-sea fluxes?
4. Or are they related to undercurrent variations?
Figure 2. Mooring observations of high vertical-resolution, O(1m), and high temporal-resolution, O(10s), of (a) zonal velocity, (b) vertical shear of horizontal current, and (c) potential density in the upper central equatorial Pacific, 0° N 140° W. (From R-C Lien, personal communication 2009).

Approach

We will compare the tropical generation of NNIW with our previous temperate-latitude observations of the analogous generation by Langmuir circulation and inertial currents, using new observations taken with a combination of a High-resolution Phased Array Doppler sonar (HiPADS), the fast-profiling CTD (FCTD), and the HDSS systems (140kHz and 50kHz) aboard the R/V Revelle.

Collaborative Augmentation

To augment our data set with state of the art atmospheric and surface SST measurements, we undertook some collaboration:

- High-quality air-sea flux measurements (Ken Melville’s group), including eddy-flux wind stress and heat fluxes, lidar mapping of wind profiles, and many others.
• Local-area mapping of fluxes and SST using UAV flights from the ship (Melville & NSWCDD collaboration)

Another add-on project: a feasibility study of a new approach:
• Explore new technology to map temperature along a line up to 2 km long with a fiber optic cable, using an optical backscatter property related to the temperature of the fiber
• Trade-offs between range resolution, time resolution, and temperature resolution not well established for oceanic use prior to this expedition.

Summary of instrumentation
• Fast-CTD (T, S, and density profiles to 300m every 3 min.)
• Ship-board navigation & HDSS current profilers (50 & 140 kHz)
• Extended “met-package” (including Lidar, eddy-fluxes of heat & momentum, and more)
• Leosphere WindCube for mean wind profiles up to 400 m
• HiPADS (High-Resolution Phased Array Doppler Sonar)
• UAVs (up to 2 at once- see Ben Reineman’s Ph.D.)
• Optical-fiber “virtual T-chain”

Figure 3. R/V Roger Revelle’s track over the last 6 years, including EquatorMix 2012 (circled). The expedition plan: Load in Papeete (Oct 1-4), Tahiti; Steam 4 days from Papeete to 140°W 0°S; 12 days on station; 2 days to Nuku Hiva for UAV+Melville debark (and some OPG exchange); 2 days back to 0°S; 10 days on station; 2 days to Nuku Hiva; debark (Nov 5).
Figure 4. Matt Durham (SIO res-tech) puts the HiPADS in position by the rail.

Figure 5. HiPADS in place, ready for the transit and, later, deployment.
Figure 6. HiPADS being deployed (several days later).

Figure 7. Setting up the FCTD aft & port (under the awning). With Amy Waterhouse, Tyler Hughen, and a crew member.
Deep Mixing: Layers of mixing as deep as we can see.

Overturns Observed in the Deeper FCTD casts (~1500m)

Our main quest on this expedition to the Equator is to explore mixing mechanisms in the upper ~200m, as noted above. However, because French Polynesia is thought to be a strong internal tide generation zone, we sent the FCTD to 1500 m 8 times a day over the 1st half of EquatorMix. However, we saw little activity at semi-diurnal tidal frequencies, so over the second half we reduced this to 4 times per day so we could increase the rapid sampling of the top 300 m (every 3 minutes). In both halves, it appears that variations occur more on the 2 to 7 day time periods (and longer) than at diurnal or semidiurnals ones.

Potential Temperature

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Figure 8. Example FCTD data: the deep casts. Profiles of potential temperature and density are shown. The salinity as used was roughly de-spiked and smoothed with a 10-point filter, and so density was also smoothed with a 10-point filter. Inversions in density or temperature greater than 5 m depth were flagged in red as possible. All casts are shown. The red dots denote overturns. Note they appear at discrete depths, and all the way down to 1500 m.

The deep casts suggest “bands” of overturns (see figure 8). As we shall shortly see, these appear to be occurring at roughly the depths of a series of shear layers, suggesting (somewhat
surprisingly) that the occurrence of overturns (and hence mixing) is not much weaker at the greater depths than near the surface. Note, in particular, the well-defined discrete bands of possible overturns at depths near 900 m on the 14th, and near 500 and 650 m over the 15th to 16th of October.

50 kHz Hydrographic Doppler Sonar System

Main — Velocity — Shear — Intensity — Profiles

Figure 9. A sample of zonal and meridional shear over the upper 1000 m, from the HDSS 50 kHz system. There are shear layers that are remarkably evenly spaced all the way to the max depth seen by the 50 kHz system, 1000 m, especially in the meridional component. Alternating signs of shear are spaced about 70m apart all the way down.

One surprise (for us, at least) is that at the Equator here (140°W, in the Central-Eastern Pacific), there are fairly equally-spaced "shear layers" as far down as the shipboard sonars can see, particularly in the meridional component of velocity (for example, see figure 9). These must be Equatorially-trapped modes: if we go as little as 2 degrees off the equator, this "layer cake" of shear layers disappears. This is somewhat contrary to our "normal" experience with such vertical modes in the oceans, where things tend to get larger scale with depth as the stratification decreases: here the layers remain of uniform thickness and separation. While a similar pattern does also show up in the zonal component, that is so dominated by the Undercurrent (often exceeding 1.5 m/s) that this aspect doesn't show up quite as clearly. In any case, this brings up a new question: What sets the vertical scale of this meridional interleaving motion? Why is this particular high mode (or set of modes) excited?

Back to the Main Objective: Mixing and internal waves in the upper 300 m.

Previous expeditions have largely focused on point measurements of dissipation over the top hundred meters or so (though Jim Moum of OSU has recently done high-resolution profiles over the upper 100m or so). Here, we are exploring the mixing by examining "overturns" in the density profiles (density inversions that occur briefly as internal waves "break" or as shear instabilities occur), using our "Fast-CTD" (Conductivity, Temperature, and depth, from which density profiles can be calculated), in combination with the high-resolution 140 kHz HDSS
velocity profiling system. This FCTD can sample to 300m every 3 minutes continuously (interrupted periodically by the deep casts). The 3-minute time series of casts resolve the overturns in the 3 or 4 of the above-mentioned layers reached over that depth. Sorting out internal wave propagation in the presence of such strong shears is not trivial, so we don't yet have an answer to the posed question; nor is it clear that it is useful to try to make such a clear distinction: a mixture of internal waves and shear instabilities clearly exists.

140 kHz HDSS velocity profiles

San Nguyen (my graduate student) discovered that the 140kHz HDSS data reveal high-frequency oscillations, mainly above the undercurrent maximum with a curious discontinuity there. Shown in figure 10 is the velocity anomaly (i.e., , where is the mean profile over a couple hours).

Figure 10. Zonal velocity anomaly, showing high-frequency oscillations (~8 to 10 cph) intensified above the core (maximum) of the Equatorial Undercurrent (denoted by the black line). There is some indication of amplitude decay away from the core on both sides, but the discontinuity in amplitude across the core is striking. The phase is quite vertically uniform, and generally does not appear to shift across the discontinuity.

HiPADS imaging

In addition to the fast-CTD and 140kHz HDSS, we are trying to image directly the mixing motions over a 2-D “slice” in the top 200m using a "High resolution Phased Array Dopper Sonar" (HiPADS), a sonar that broadcasts a fan of 200 kHz sound in a thin vertical plane, and beam-forms the returns using an array of receivers, resulting in a pie-shaped measurement area covered by about 64 beams, yielding both backscatter intensity (scatterer density) and Doppler shift (radial velocity). The mixed layer and undercurrent velocity profiles are imaged beautifully, but so dominate the signal that it is hard to sift out the smaller scale motions (see figure 11). At the time of this image, the undercurrent peaks at about 1.5 m/s toward the East, near 120 m depth, while the apparent surface flow is in the other direction, of order .5 m/s to the west, due mainly to the ship’s headway, which is about .5 m/s to the right, or East. These are huge signals, but there is hope we can sort out the mixing motions. (A movie version of this time-series of 2-D measurements can be viewed at http://jerry.ucsd.edu/#EquatorMix )
Figure 11. A sample “frame” of HiPADS data. This is a 1-minute average, formed after correcting each “ping” (2 per second) for tilting and vertical motion due to surface waves. (Left) Backscatter intensity, reflecting the density of scatterers. There are more scatterers (fish, squid, plankton) above the core of the undercurrent, so the intensity is greater there. (Right) Radial velocity relative to the ship (from Doppler shift). The water at 100 m depth is moving east (right) at the same speed as the ship, so has zero Doppler shift (relative velocity). Above that, the water is moving slower than the ship or even to the west; thus, there is a blue shift for beam angles forward of vertical, and a red shift at angles aft of vertical. Below 100 m, the undercurrent moves east faster than the ship, so the reverse is true: the aft angles are blue-shifted while the forward ones are red-shifted. Below about 150 m, the Eastward flow slows to less than ship’s speed again, so there is another reversal of the radial velocity pattern.

Since San Nguyen found high-frequency oscillations in the 140 kHz data, we thought to look for it in the HiPADS data too. Instead of taking out a mean profile, in this case it’s much simpler to just take the time-difference of successive velocity frames to estimate $\frac{dU}{dT}$, acceleration (to eliminate the quasi-steady undercurrent structure). The hope is to be able to estimate the wavelength, or at least the direction of propagation.

Two example frames with $\frac{dU}{dT}$ are shown in figure 12, showing the two opposite extremes of horizontal acceleration above about 125 m depth. Again, a movie version of the time-series of these 2-D measurements can be viewed at [http://jerry.ucsd.edu/#EquatorMix](http://jerry.ucsd.edu/#EquatorMix) - look for the right and left triangles above 125 m depth to alternate between green and blue. Most people viewing the movie perceive the motion to go from right to left; i.e., westward into the undercurrent. The wavelength is too long to fit in the 200 m window of the HiPADS measurements, but we should be able to get an estimate of the phase speed. With the known (measured) period, this will reveal the wavelength as well (though perhaps the phase speed itself is of more interest).
Figure 12. Two 1-minute average frames, as in figure 11, but with $dU/dT$ shown on the right, rather than $U$ (again, radial velocities). (A) Acceleration at 11:20:23 UTC on the 19th, or 02:20 as shown in figure 10 (right above where the axis label says “[UTC-9h]”), to see the context as seen in the HDSS data. (B) The same, 3 minutes later. At this time, the nominal frequency is about 6 minutes, or 10 cph. As in figure 10, it is seen here that the reversing horizontal flow is pretty well confined above 125 m, roughly the depth of the undercurrent maximum. Also, as before, the slighter signal below this remains in phase.
Rapid sampling of the upper 250m

Another main focus of the expedition is the rapid sampling of the upper 250 to 300m, repeating profiles every 3 to 4 minutes to resolve motions right up to the buoyancy frequency. High frequency signals were mostly observed at night. Figure 13 shows enhanced rapid variability of isopycnal depths during the nighttime. 3-4 minute profiling is barely fast enough to resolve the high-frequency activity. We are only resolving 2-3 points for every high frequency cycle.

Figure 13. Depths of isopycnals. Activity of high frequency oscillations of isopycnal depths were enhanced for $t > 18.9$.

Within the upper 300 m, diurnal heating/cooling cycle is a persistent signal shown as diurnal inversions in density. The stratification is strongest across the Equatorial Undercurrent (EUC). The plot of the Brunt–Väisälä buoyancy frequency ($N$) in Figure 14 shows layers below the core of the EUC. These layers consist of low and high $N$, where layers of layers of low $N$ would grow and decay away in between layers of high $N$.

Figure 14. Brunt–Väisälä buoyancy frequency ($N$) of the top 300 m in Leg 1. Negative values denote density inversions. Deepening of the diurnal heating layer shown as near surface density inversion. Enhanced stratification (high $N$) above and below the core of EUC jet.
The UAVs carried three different science packages. The “flux” package made eddy-covariance estimates of the fluxes of momentum, latent and sensible heat, and had a laser altimeter to profile the waves. The “radiometric” package measured both upward and downward long-wave and short-wave radiation. Another “imaging” package had high-resolution visible and infra-red cameras to image wave-breaking. These packages are described in detail in Ben Reineman’s Ph.D. thesis (SIO, defended Jan. 25th, 2013). At one point both “flux” and “imaging” packages
were flown on two UAVs simultaneously, with the imaging package above the flux package, providing context, wave dissipation estimates, and a second level of radiative balance measurements. The idea is to be able to close the flux budgets from the sea surface up. These flights were the product of collaborations between the Ken Melville group and NSWCDD.

**Precision Meteorological Measurements**

Also visible in figure 14A is the met-tower, which the Melville group outfitted with state of the art instruments for additional continuous measurements of the fluxes of momentum, heat, and radiation. These will prove invaluable in our own analyses as well as theirs. This suite was kindly left on board for the second half as well, after the Melville group debarked.

**Optical Fiber “Virtual Thermistor Chain”**

Rob Pinkel (SIO, co-PI on the project) also brought a piece of new technology to test: a system that permits estimation of temperature every few meters along an optical fiber, extending out to 2 km or so.

![Figure 16](image)

*Figure 16. The optical fiber was deployed at the end of the 1st leg (so we can compare with the infra-red cameras on the UAVs), but got more intensive attention during the second leg. It is the thin line going just over Mike Goldin’s head (pink shirt) along the clouds.*

Since this is a new application of the technology, we were not sure a priori what the tradeoffs would be between resolution in time, space, and temperature. We were therefore in the position of knowing that we would learn a lot from any deployment of this gear. The fiber was deployed with a small float at the end (just shy of 2 km aft) with a temperature probe of known quality for comparison, and a GPS locator so we could estimate where the fiber lay on the surface as it was dragged behind the ship (sadly, the fiber parted and the float was lost some time around 10/27; cause not certain).
Figure 17. Temperature deviations from the mean versus range and time from the optical fiber system. The dominant slant is about 2/3 m/s, corresponding to the ship speed. Not seen in this image (but detectable in 2-D FFT analysis) are a second set of sloping lines corresponding to some 10 m/s.

Empirically, after the processing scheme Rob and San came up with, it appears the optical fiber can yield ~0.1°C relative accuracy (not absolute) with ~1 minute by 30 m time-range bins.

**Zig-Zag Transects**

For our off-Equatorial transects, Rob had this great idea: if the ship zig-zags, alternating 30° port and 30° starboard of the mean course every hour (~12nm), we can estimate both components of vorticity over larger scales from the HDSS profiles. The price is only about a 13.4% increase in distance (or transit time).
Figure 18. (Left) An example zig-zag ship track (enroute Nuku Hiva to 0°N, 140°W), and (right) the resulting vertical vorticity versus latitude and depth.

Summary

- In the end, everything worked, and worked better than expected.
- There is a vast amount of data from a wide variety of instruments, coordinated in time and space for analysis.
- Overturns occur as deep as we could see, correlated with high-mode shear layers.
- HFIW do occur, and appear to be trapped above the undercurrent core.
- Zig-zag ship tracks rock!

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Mike Goldin (SciEng)
Tyler Hughen (Tech)
Tony Aja (Tech)
San Nguyen (Senior GS)
Martha Schonau (GS)
Ruth Musgrave (GS, 1st leg only)
Amy Waterhouse (Post-doc, 1st leg only)
Roy Barkan (GS, 2nd leg only)
Magdalena Carranza (GS, 2nd leg only)

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Ben Reineman (GS)
Nick Statom (Eng)

NSWCDD:
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Res Techs
Matt Durham (Deck, etc.)
N Ben Cohen (Comp., etc.)

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Gary Curry (Bos’n)
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Amando Cortez (Marine Elec.)
Scott Myers
Hawkins
Farlow
Michael Gaylord
Andrew Juhasz
Jay Erickson (Senior Cook)
Steven Lamb (Marine Cook)