PhilEx Profiling Measurements of Internal Waves and Mixing Processes

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LONG-TERM GOALS

This project aims to increase our understanding of internal wave processes in straits and archipelagos, including the generation and propagation of internal tides at sills and constrictions, topographic modification of near-inertial motions, and the relative roles of local and remote forcing. These processes influence mixing and momentum transport, and their accurate representation in numerical models is necessary to simulate flow and property distributions in complex regions. An eventual goal is the improvement of such models.

OBJECTIVES

- To obtain high-resolution measurements of temperature, salinity, and velocity finestructure in the little-studied straits and basins of the Philippine Archipelago for the purposes of characterizing the spatial and temporal variability of internal tides and near-inertial internal waves, as well as other flow-driven mixing processes.
- To provide in-situ data for testing of numerical models of tides and circulation through the archipelago.
- To demonstrate the capabilities of profiling floats for remote surveying of constricted regions over long periods of time with limited ship access.
- To test the ability of EM-APEX floats to perform in a region of low vertical magnetic field strength (the magnetic equator).
- To understand the climatology of internal waves in the diurnal, semidiurnal, and inertial bands, including forcing mechanisms, topographic effects, and dependence on mean flow and stratification.

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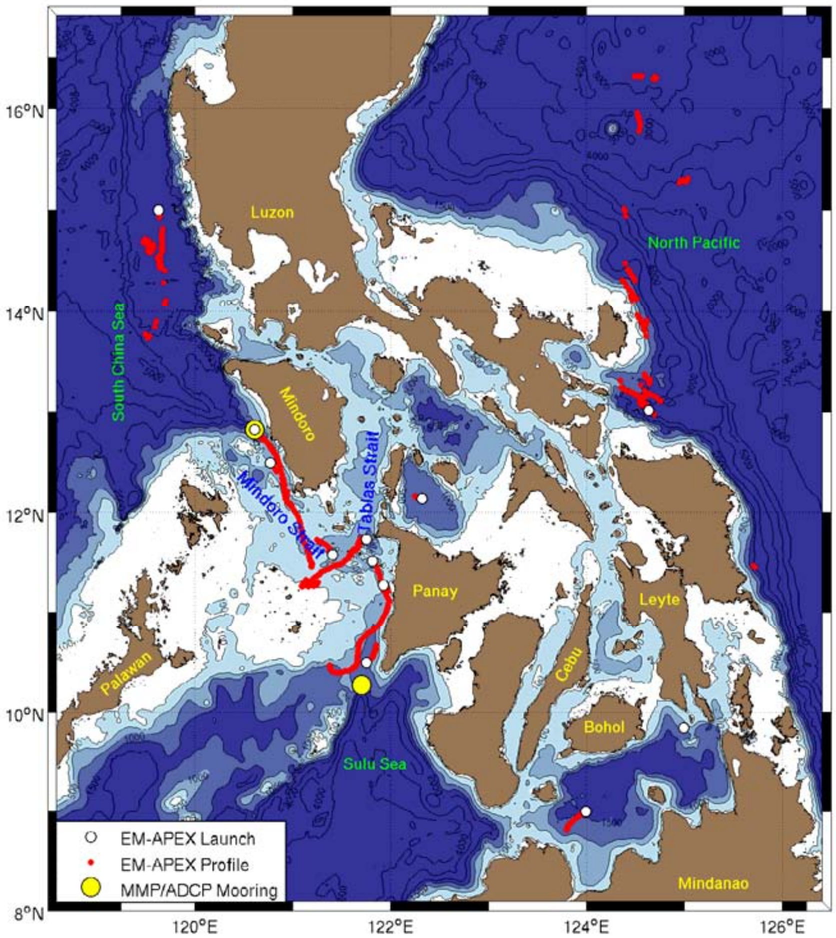

Figure 1: Locations of profiling moorings (yellow circles) and EM-APEX measurements (red dots) in the Philippine Archipelago. Mooring MP1 is at the northern (South China Sea) end of Mindoro Strait, and MP2 is at the southern (Sulu Sea) end. Shading indicates water deeper than 100m, 200m, 500m, and 1500m.

- To evaluate the importance of the different types of internal waves in the Philippines for mixing and momentum transport.
- To use this information to guide improvements in sub-gridscale parameterizations, leading to improved predictions of oceanic properties and air-sea fluxes.

APPROACH

This work is a part of a multi-investigator Departmental Research Initiative (DRI) on the "Dynamics of Archipelago Sea Straits." After choosing the Philippines Archipelago as the location for the field experiment (Figure 1), the DRI was given the title "PhilEx." The two components of PhilEx described in this report are (1) a set of EM-APEX profiling float velocity and CTD measurements distributed throughout the archipelago and spanning the multiple research cruises, and (2) two profiling moorings at the north and south ends of the Mindoro–Panay strait complex.

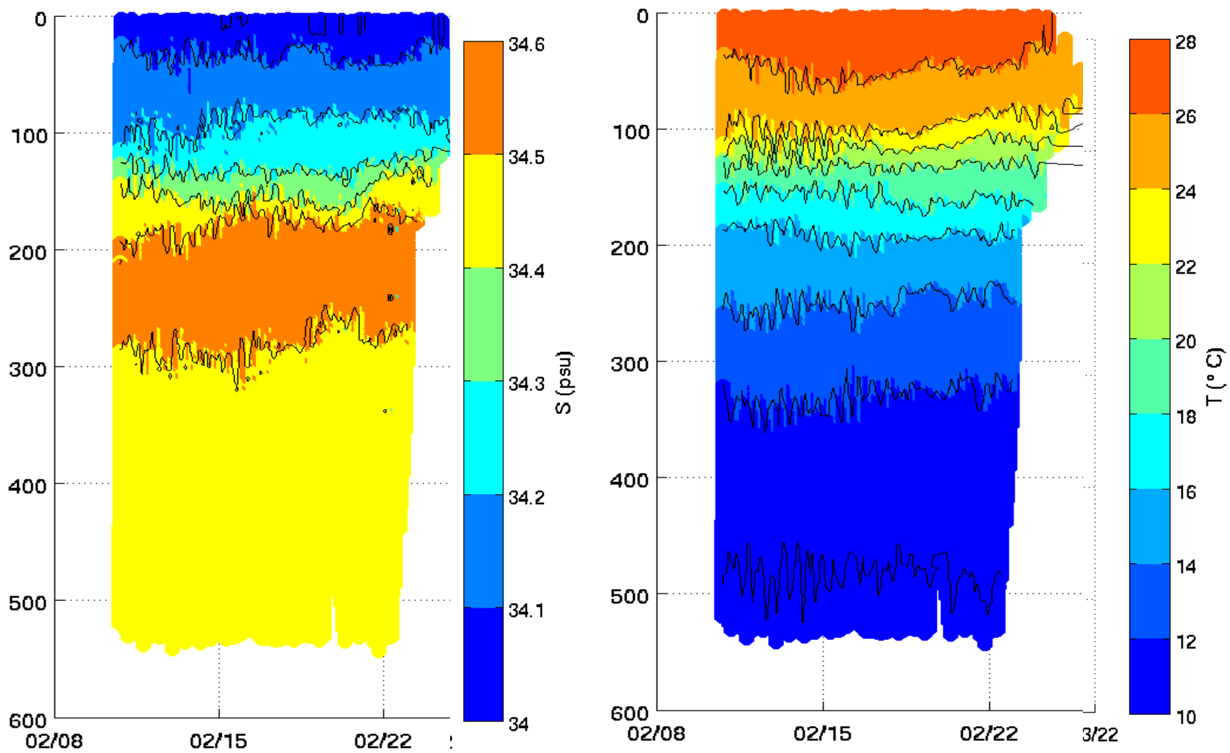

Figure 2: S and T profiles from EM-APEX 3305 in the "mixing bowl" region (the junction of Tablas and Mindoro Straits). Strong semidiurnal tidal variability is evident in the isopleths during the spring tide in the earlier part of the 2-week record.

The EM-APEX floats are a variant on the standard Argo-type profiling float with an electromagnetic velocity sensor that relies on the horizontal motion of the instrument through the vertical component of the geomagnetic field. During most of the PhilEx work, these floats made continuous round-trip profiles between the surface and 500m depth every 3 hours. A principal justification for this was to resolve the semidiurnal tide, which is significant in parts of the archipelago. One disadvantage of the velocity measurement is that the signal-to-noise ratio drops as it approaches the magnetic equator, which runs through Mindanao, the southern island of the Philippines. Though most of the measurements were made at least 3° north of the magnetic equator, and none closer than 1°, the low signal is clearly an issue. In addition, the low signal increases the vulnerability to external sources of electric currents, which can appear as spurious velocity signals in the water. In a number of EM-APEX profiles, an ionospheric current known as the "equatorial electrojet" appears to be influencing the near-surface measurements during the day.

The moorings were deployed for a period of just over 2 months and included wire-crawling McLane Moored Profilers (MMP) and acoustic Doppler current profilers (ADCP) to extend the range and to increase the temporal resolution of the mid water column MMP measurements. One mooring (MP1) was placed in 1800m of water on the

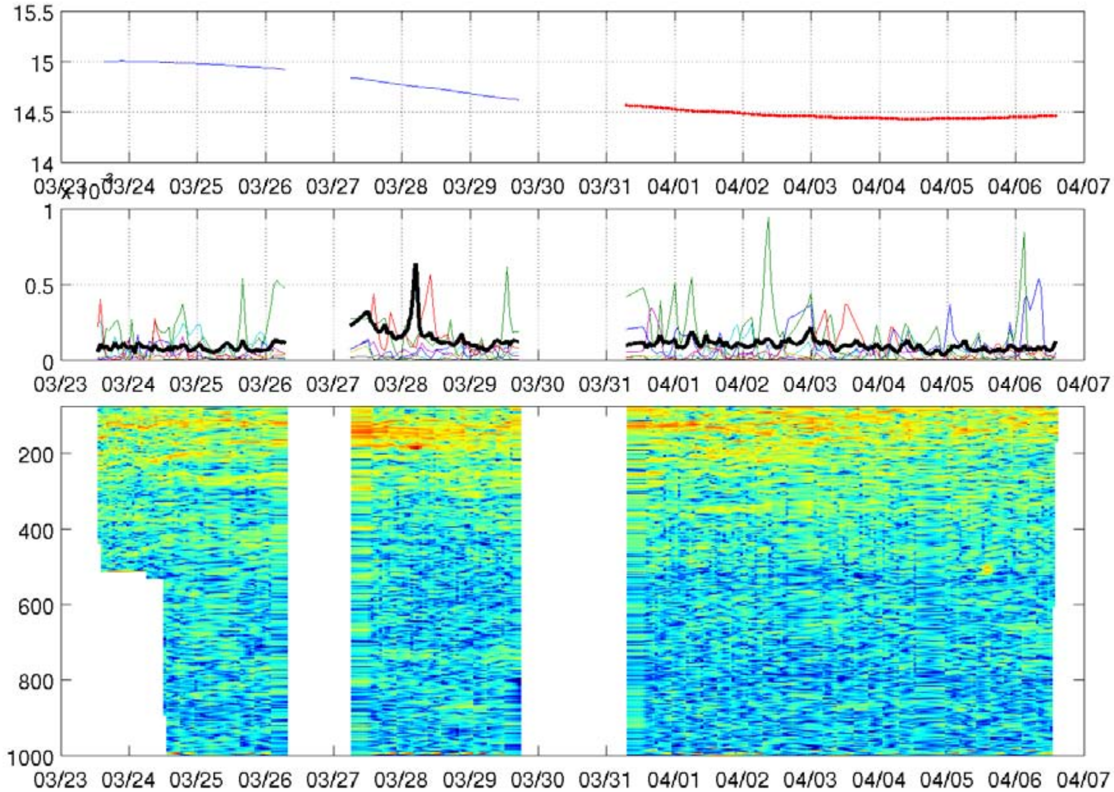

Figure 3: EM-APEX shear measurements west of Luzon near the diurnal critical latitude sampled by Alford (2008). The upper panel shows the float latitude during 3 sampling bursts. The middle panel shows shear timeseries at particular depths, along with the 100-200m average (black bold line). The lower panel shows the depth vs. time record of scalar shear $(du/dz)^2 + (dv/dz)^2$ between 100m and 1000m. The largest shear values occur in a specific event north of the critical latitude of 14.5 N, but the overall background shear level does appear to be elevated when close to the critical latitude.

South China Sea end of Mindoro Strait (i.e., northwest of the northern sill). This mooring included 2 MMPs, upward and downward-looking 300 KHz ADCPs at 100m and 1750m depth, and downward-looking 75 KHz ADCP at 100m. The other mooring (MP2), placed in 1500m of water on the Sulu Sea end of Panay Strait (i.e., south of the southern sill), held one MMP and two ADCPs (upward-looking 300 KHz and downward-looking 75 KHz at 100m). Together these positions were chosen to characterize both the generation and radiation of internal waves within the combined strait and the internal wave climate and external influence of the adjacent basins.

WORK COMPLETED

The mooring deployment ended in March 2008, so much of the activities this FY centered on data analysis, along with some quality control and post-processing operations as they became necessary. First-stage analysis of the mooring records has included the construction of band-passed current records in 3 frequency bands: 0.4, 1, and 2 cycles per day, representing the inertial frequency and diurnal and semidiurnal tides. Additional

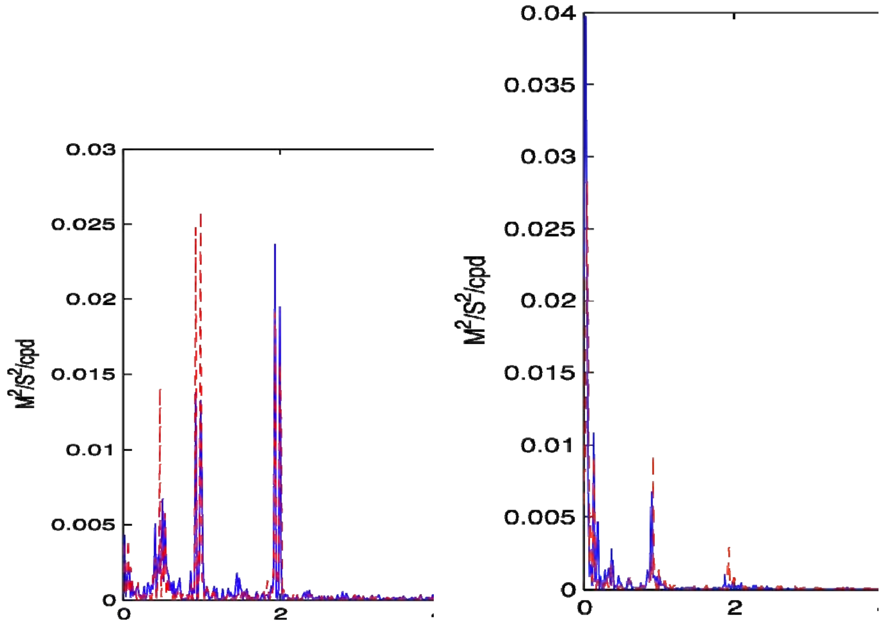

Figure 4: Frequency spectra from MP1 (left) and MP2 (right) velocities at 500m depth. In general, MP1 (on the South China Sea side) shows larger spectral peaks at the inertial, diurnal, and semidiurnal frequencies, including double tidal peaks (M2/S2 and O1/K1).

steps included the computation of kinetic energy vs. depth, separation of the band-passed signals into clockwise and counter-clockwise rotating components (in both depth and time), and tidal harmonic analysis.

Quality control issues included accounting for a conductivity sensor failure on one of the MMPs by using a T–S relation derived from the "good" portion of the record, and adjusting velocity sensor calibrations when an amplitude offset between the two MMPs on mooring MP1 became apparent.

Additionally, EM-APEX deployments continued through the end of FY09 as part of the second intensive operations period (IOP) of the experiment. One float was launched in the triple-junction, or "mixing bowl" region between the Mindoro, Tablas, and Panay Straits (Fig.2). Another was launched off the west coast of Luzon—a location studied by Alford (2008) the previous year—during a final transit across the South China Sea (Fig.3). The latter location was chosen for the purposes of investigating a critical latitude for parametric subharmonic instability (PSI) of the O1 diurnal tide.

RESULTS

The principal findings to date include the following:

- Diurnal and semidiurnal internal tide signals are evident in the EM-APEX isopycnal displacements (Figure 2), but velocity cycles are contaminated by spurious daytime electric currents—likely related to ionospheric processes.

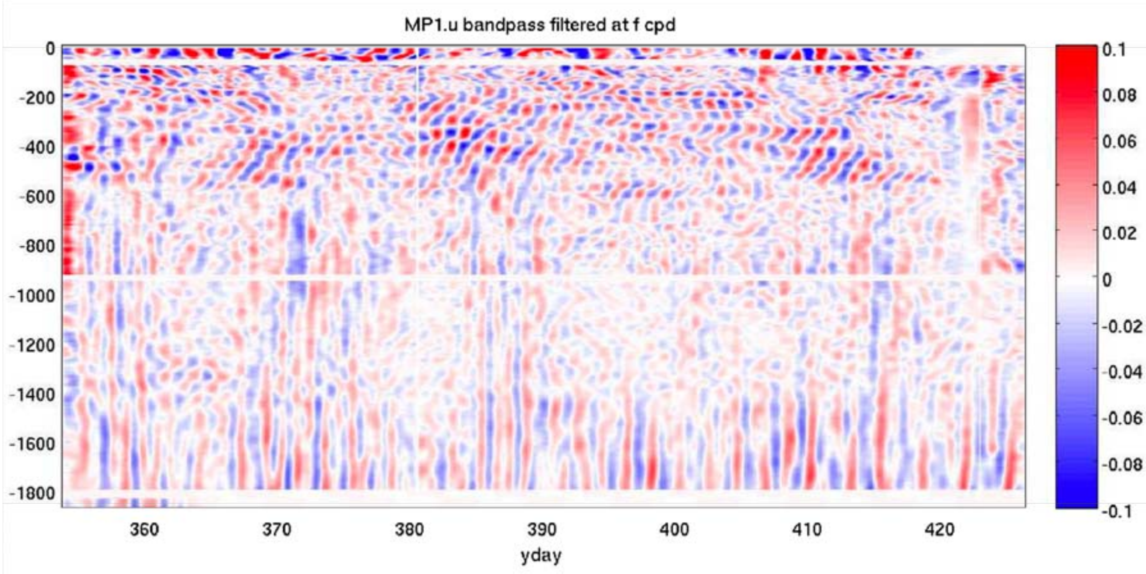

Figure 5: Near-inertial band-passed velocity from MP1. Downward-propagating (upward phase tilt with time) wave packets are present as deep as 600m, with some evidence of upward-propagation shown by the "checkerboard" patterns at certain depths and times. Between 1400m and 1800m (close to the bottom) near-inertial energy is also elevated, but shows little sign of phase propagation at these depths.

- Shear levels near the O1 tide critical latitude are somewhat elevated (Figure 3), but not to the extent observed by Alford (2008).
- Barotropic tides estimated from both moorings compare well to predictions from the TPXO7.2 model.
- Tidal energy levels on the South China Sea side of Mindoro Strait (MP1) are significantly larger than on the Sulu Sea side (MP2), while low-frequency (mesoscale) variability is larger at MP2 (Figures 4 and 8).
- Much of the near-inertial variance is in the form of downward-propagating wave packets (Figure 6), though a fair amount of upward-propagating energy is also present (Figure 7).
- Bottom-intensified near-inertial energy at MP1 shows little vertical phase propagation (though is mainly in the counter-clockwise portion of the rotary spectra) and appears to be the result of a canyon-trapped mode (Figures 5 and 7).
- All 3 bands show significant low-frequency modulation. This is clearly a fortnightly spring–neap cycle in the internal tide bands, but with substantial phase shift between the diurnal and semidiurnal cycles. The near-inertial modulation is likely due to wind variability but could also be related to breakdown of the diurnal tide through PSI.

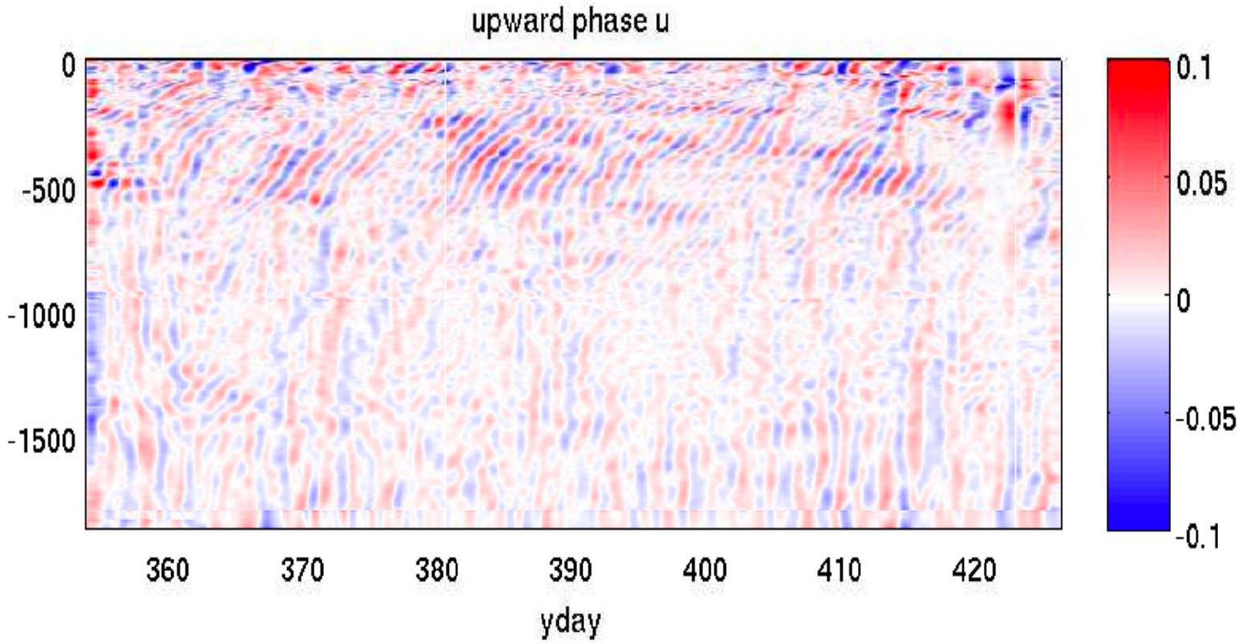

Figure 6: A reconstruction of the clockwise-rotating portion of the rotary spectra with depth. The downward propagating packets in the upper ocean show up more clearly without the checkerboarding. The deep near-inertial energy is only weakly present.

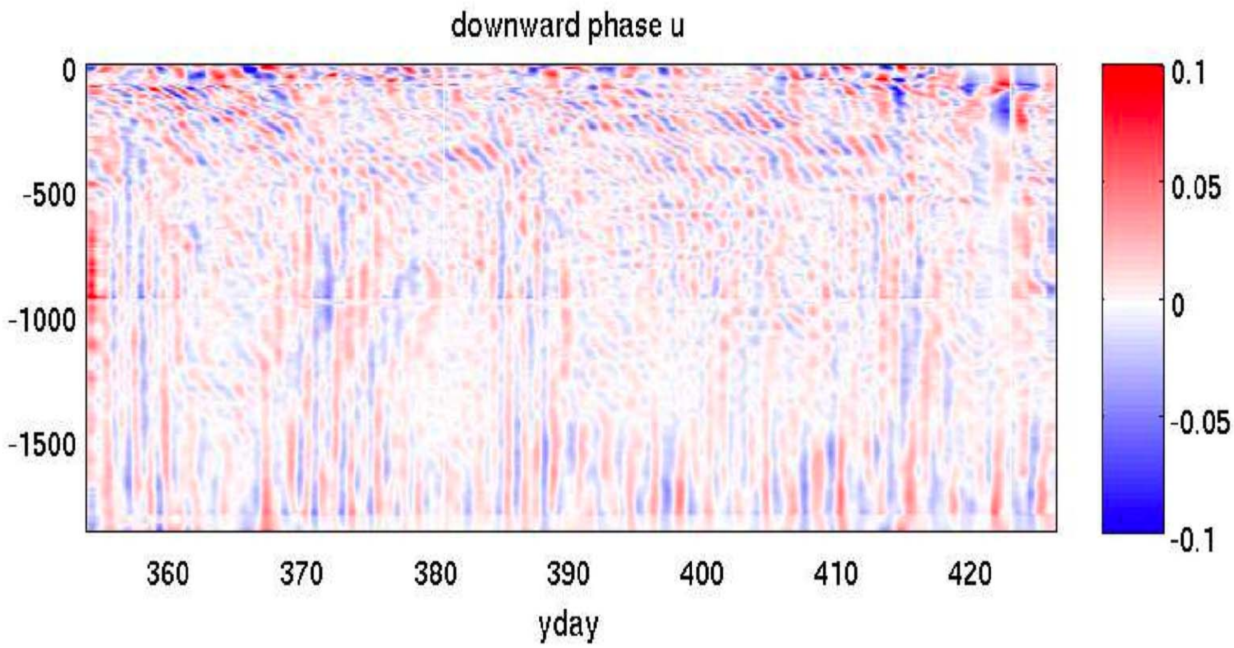

Figure 7: Counter-clockwise rotating portion of the spectra. Upward-propagating waves are present in places, as is the deep near-inertial energy.

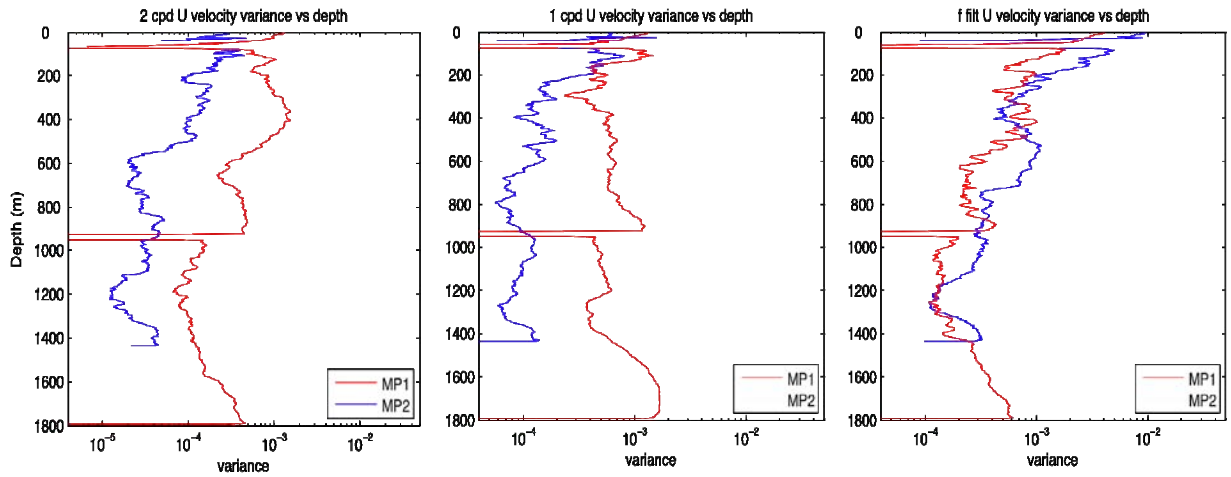

Figure 8: Velocity variance profiles in 3 bands. The diurnal and semidiurnal tidal bands have higher energy at MP1, consistent with the stronger tides in the South China Sea than in the Sulu Sea.

IMPACT/APPLICATIONS

This work represents the first measurements of the internal wave field in the Philippines and will form the basis of our understanding of internal wave processes there, including interactions with topography and implications for mixing of tracers and momentum. Both the wavefield and the topographic interactions are not well-represented in numerical models, resulting in a great degree of uncertainty over appropriate mixing coefficients or parameterizations. Our measurements will permit validation of existing parameterizations as well as aid in the development of new parameterizations.

RELATED PROJECTS

This work is part of the ONR “Dynamics of Archipelago Straits” Departmental Research Initiative (subsequently labeled the Philippines Experiment, or PhilEx) and has been carried out in close collaboration with the other investigators in that project. Scientific discussions among the full group of PIs have been very helpful in defining the physical processes, scientific questions, and geographic locations for study.

Specifically, the mooring deployment and recovery took place on two of the cruises in the first Philippines field season (2007-2008), and EM-APEX float deployments and recoveries were carried out on all 6 of the DRI research cruises, through cooperation and sharing arrangements with each of the chief scientists Arnold Gordon, Pierre Flament and Craig Lee, as well as with assistance from Philippine scientists Cesar Villanoy and Laura David.

Pre-deployment planning and data analysis and interpretation have been conducted with continued attention to the modeling efforts conducted as part of the DRI, including groups from NRL Stennis running the global HYCOM (Hurlburt, Metzger), regional NCOM EAS (Reidlinger), tidal ADCIRC (Blaine, Jarosz) and high-resolution MITgcm (Gallacher), as well as teams at other institutions running COAMPS (Pullen, May), ROMS (Arango, Curchitser, Levin, Han) and HOPS (Lermuseaux).

PUBLICATIONS

Alford, M.H., 2008: Observations of parametric subharmonic instability of the diurnal internal tide in the South China Sea. *Geophys. Res. Lett.*, **35**, L15602, doi:10.1029/2008GL034720.