

## **Moored Observations of Internal Waves in Luzon Strait: 3-D Structure, Dissipation, and Evolution**

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### **LONG-TERM GOALS**

We are interested in the general problems of internal waves and ocean mixing. Knowledge of these is important for advancing the performance of operational and climate models, as well as for understanding local problems such as pollutant dispersal and biological productivity. In the specific case of NLIWs, the currents and displacements of the waves are strong enough to impact undersea operations. More generally, most of the ocean's physical and acoustic environments (and particularly in straits) is severely impacted by internal waves. The research proposed here should substantially improve both our understanding and predictive ability of linear internal tide and NLIWs in Luzon Strait and the South China Sea.

### **OBJECTIVES**

- To understand the generation mechanisms, and better predict the arrival times, of waves that ultimately become the NLIW that propagate westward into the northeastern South China Sea (SCS).
- To better understand generation and propagation of internal waves in a strongly sheared environment (the Kuroshio).
- To relate findings to the more general problem of internal waves in straits.

### **APPROACH**

The IWISE DRI (Internal Waves in Straits Directed Research Initiative) includes an impressive combination of moored, shipboard and autonomous observations, together with remote sensing and modeling studies. Though observations in other straits such as Surigao Strait in the Philippines may be undertaken, the most intensive observations in IWISE will take place in Luzon Strait (Figure 1) during summer 2011. These were preceded by a pilot experiment (just completed) to shake out equipment, refine hypotheses and determine the best location for the assets in the main experiment.

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Our contribution to the main experiment is a 7-element array of profiling moorings (strawman plan in Figure 2). These feature McLane moored profilers (MP), which repeatedly transit a standard subsurface mooring wire while measuring temperature, salinity, dissolved oxygen, turbidity and velocity. These ~hourly profiles will be augmented by much faster measurements from up and downlooking 300-KHz and 75-KHz ADCP's (for velocity) and Seabird microcats and T-loggers (temperature and salinity). Turbulence will be estimated both from density overturns measured by the profiler and by micro-temperature measurements from an OSU chi-pods (Moum/Nash) mounted on the profiler and on the wire above and below. The array will serve as a "backbone" for the rest of the observations and enable determination of the 3-D structure of the internal waves generated in the Strait.

## WORK COMPLETED

We volunteered to take the lead on the pilot experiment, which is now complete. We will now begin analyzing the data to hone intuition and hypotheses for the main experiment. Goals for our portion of pilot experiment were to 1) test techniques and the performance of our moored and shipboard equipment in a high-flow environment, 2) gain enough of an understanding of the nearfield generation physics of the waves to help us design the main experiment in May 2011, and 3) deploy an array of five of David Farmer's PIES moorings, which will assay wave generation and propagation over the upcoming winter. We accomplished all of these goals.

Three moorings (see Figure 3) were deployed for most of the cruise duration to test their performance and to contextualize the other shipboard measurements. Their locations were chosen to help assess the large-scale three dimensional patterns of internal tide generation and propagation.

During the bulk of the cruise we conducted a series of 36-hour long yo-yo CTD/lowered ADCP stations (Figure 4), interspersed with 4-12 hour microstructure time series. These stations served both to expand the spatial patterns beyond the mooring locations and to look in detail at energetic dissipative regions. The LADCP stations were grouped along two "lines," one along 20.5N, and one along a NW oriented (cross-ridge) southern line. Mid-cruise we also dedicated 36 hours to a tidally resolving spatial survey over the eastern ridge near 20.6N (Figure 3, red line), using shipboard ADCP and periodic XBT drops, which will be reported on later.

## RESULTS

Our measurements reveal an incredibly energetic and variable internal wave climate, with dramatic overturning events both in the upper water column and in large near-bottom layers. Along our southern line we completed 5 stations on a line perpendicular to the expected flux direction (from Simmons' model). The depth-integrated fluxes are in surprisingly good agreement with modeled fluxes (Fig. 3). The majority of the flux is concentrated in the upper ocean and is diurnal in character (Fig. 5), consistent with the primarily diurnal nature of the barotropic tide during most of this section (Fig. 4). At the stations nearest the beam (S4, S5) there is evidence of vertically localized diurnal motions with strong shear and strain, suggesting a diurnal "beam". Further west, there is also evidence of semidiurnal energy and flux along an M2 raypath near the western ridge along this line (Fig. 4).

Along the northern line, fluxes are to the west near the western ridge, and to the southeast near the eastern ridge (possibly due to interference of eastward radiation from the western ridge). Both stations

near the western ridge were occupied twice. At N1, the fluxes were very similar between the two occupations. At N2, significant near-inertial signals appeared to contribute during the second occupation. Discounting this second occupation of N2, agreement is again excellent between observed and modeled fluxes.

We observe strong patches of turbulence in both the upper water column and deep ocean. The strongest dissipation rates in the upper water column are associated with the beam-like features located on or near the eastern ridge along our southern line. Station S4 shows the cleanest diurnal cycle of dissipation rate, co-located with large diurnal strain. At station F1 there is also strong upper ocean dissipation with a mixed semidiurnal/diurnal periodicity.

At many stations, truly enormous overturns are observed near the bottom over steep topography, comparable to those observed by Pinkel and Klymak earlier this summer. Stations N1 and N2 show the largest near-bottom dissipations, with a clear tidal periodicity. Ongoing work will attempt to assess the fraction of the conversion going to dissipation. Preliminary indications are that it is higher than at other more "linear" locations such as the Hawaiian Ridge, supporting the notion of a dissipative resonating basin formed by the two ridges spaced by an internal tide wavelength.

One of the ongoing themes of both our observations and upcoming plans is the dramatically shifting nature of the magnitude and patterns of wave energy and associated turbulent dissipation as generation shifts from primarily diurnal to primarily semidiurnal over the course days to weeks. For example, though we observed strongly diurnal motions at S4, when we returned to a nearby station a week later (S8), the energy was largely semidiurnal and the patterns of elevated shear and dissipation had shifted location in the upper water column, perhaps to a location more appropriate for an M2 beam. Similarly, the large near-bottom dissipation at stations N1 and N2 shifted almost completely from semidiurnal to diurnal between our first and second occupation (Fig. 4) helps orient where we are in the tidal cycle). Ongoing work will use harmonic analysis to separate the semidiurnal and diurnal frequencies.

The mooring designs for the pilot were based on experience from NLIWI and finite element simulations (WHOI cable) forced with tidal velocities from Harper Simmons's model. Based on these simulations, knockdowns similar to those observed in NLIWI were expected (70 m). At MP-S, which was not in the Kuroshio, knockdowns were as predicted (70 m), and generally did not impede profiling. However, MP-N experienced greater knockdowns (150 m). While velocity from the ADCP's are still fine, the knockdowns prevented the profiler from descending the wire during the strongest periods as described above. Examination of the measured currents indicates that the intense northward flow of the Kuroshio superposed with the tidal velocities led to the greater knockdowns. Based on this, we plan to modify the design for next year's moorings that are expected to be in the Kuroshio to include a subsurface float with an uplooking long ranger ADCP near 400-500 m, and a string of temperature or temperature/conductivity instruments on a light line sampling the upper ocean, with the McLane profiler sampling below this.

Additional details are given in the cruise report, found at [http://mokuleia.apl.washington.edu/~malford/TWISE10\\_CruiseReportLR.pdf](http://mokuleia.apl.washington.edu/~malford/TWISE10_CruiseReportLR.pdf).

## **IMPACT/APPLICATIONS**

## **TRANSITIONS**

## **RELATED PROJECTS**

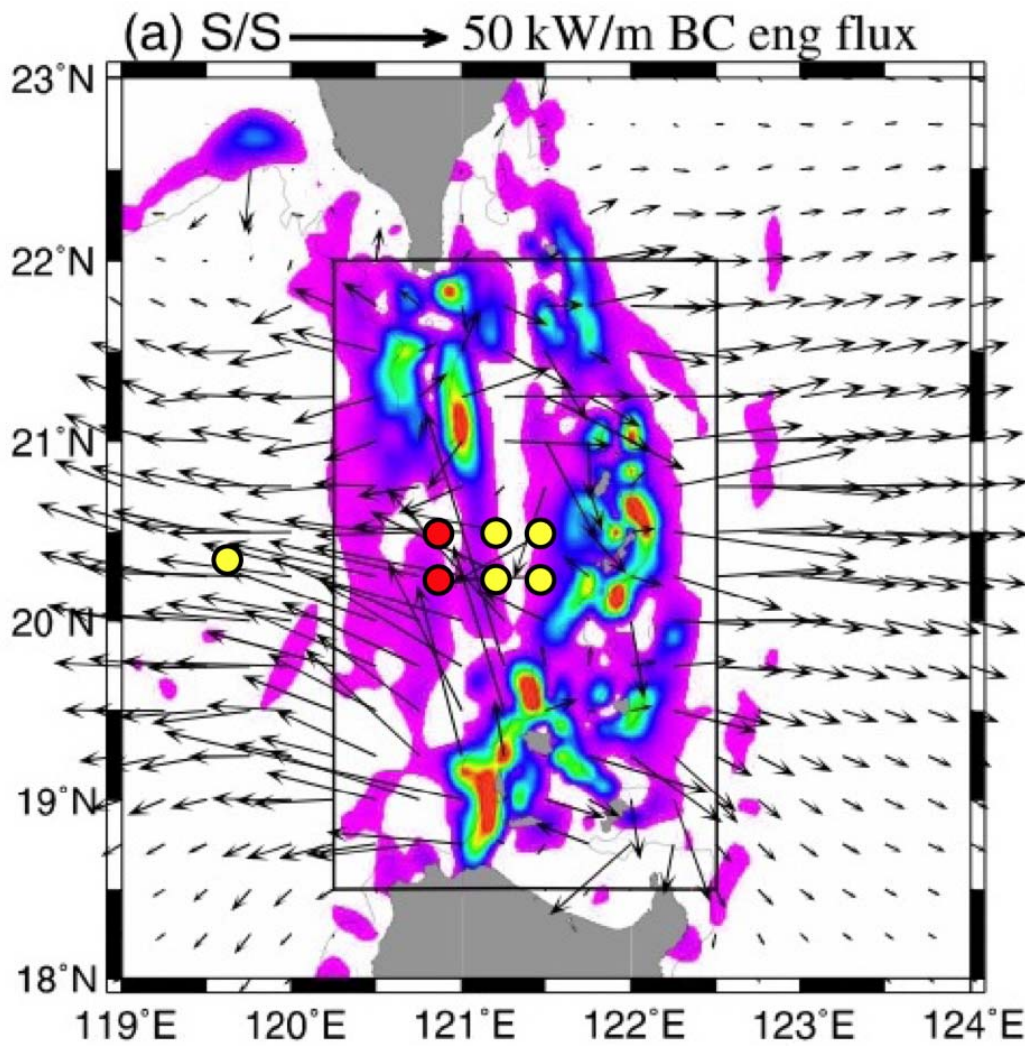
Within IWISE, we are working closely with modelers (sepecially Klymak, Simmons, and Fringer), as well as with other observational groups (Moum/Nash in developing the moored profiler chi-pod, and Nash/Moum in LADCP/CTD measurements during the pilot and main experiment).

With regard to other DRI's, the understanding of the generation process of the NLIW, which is the goal of IWISE, fills a major void in the NLIWI DRI. In addition, the measurements taken during the Typhoons measurement period will benefit that DRI.

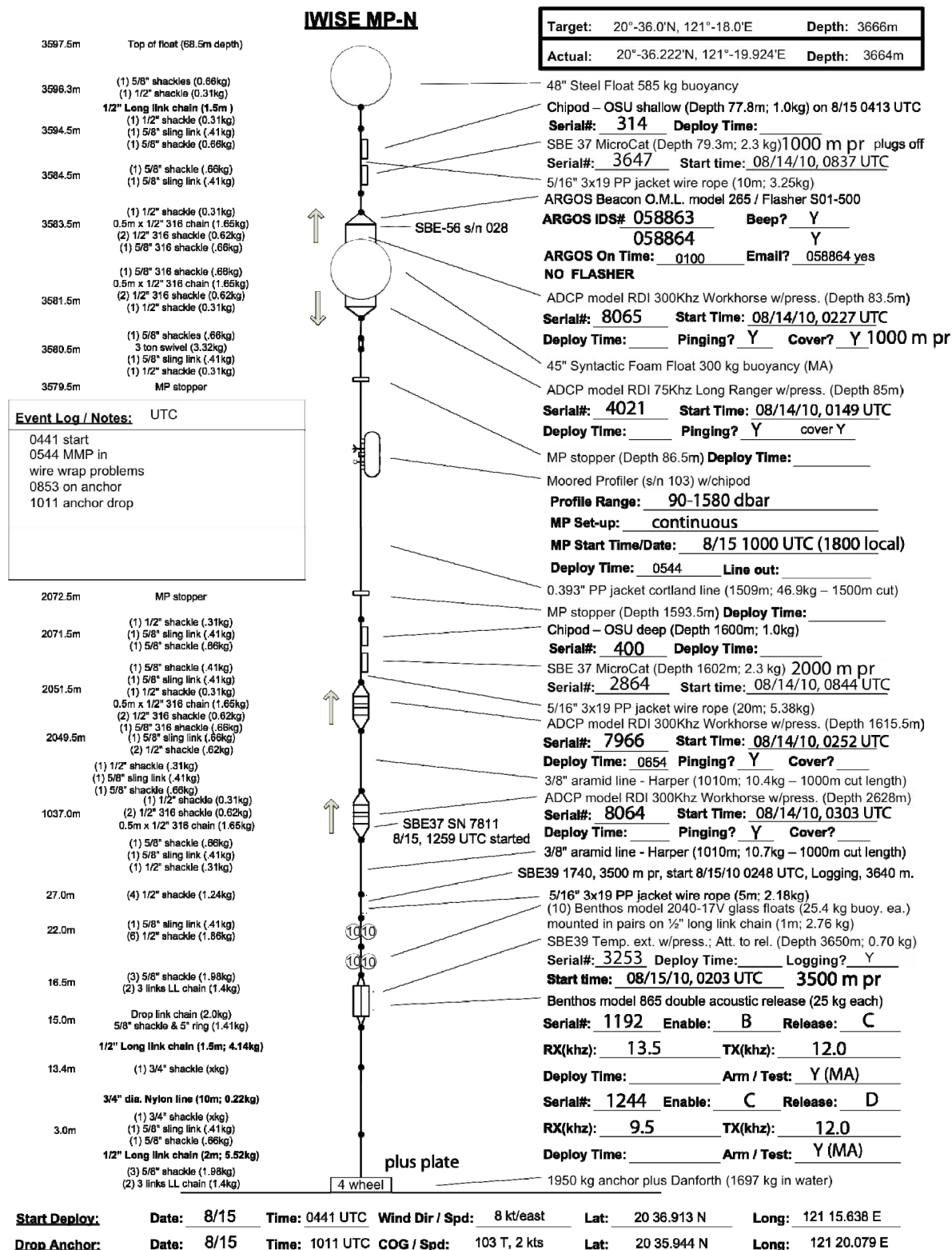
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Jan, S., R. Lien, and C. Ting. Numerical study of baroclinic tides in Luzon Strait. *Journal of Oceanography*, 64(5):789–802, 2008.

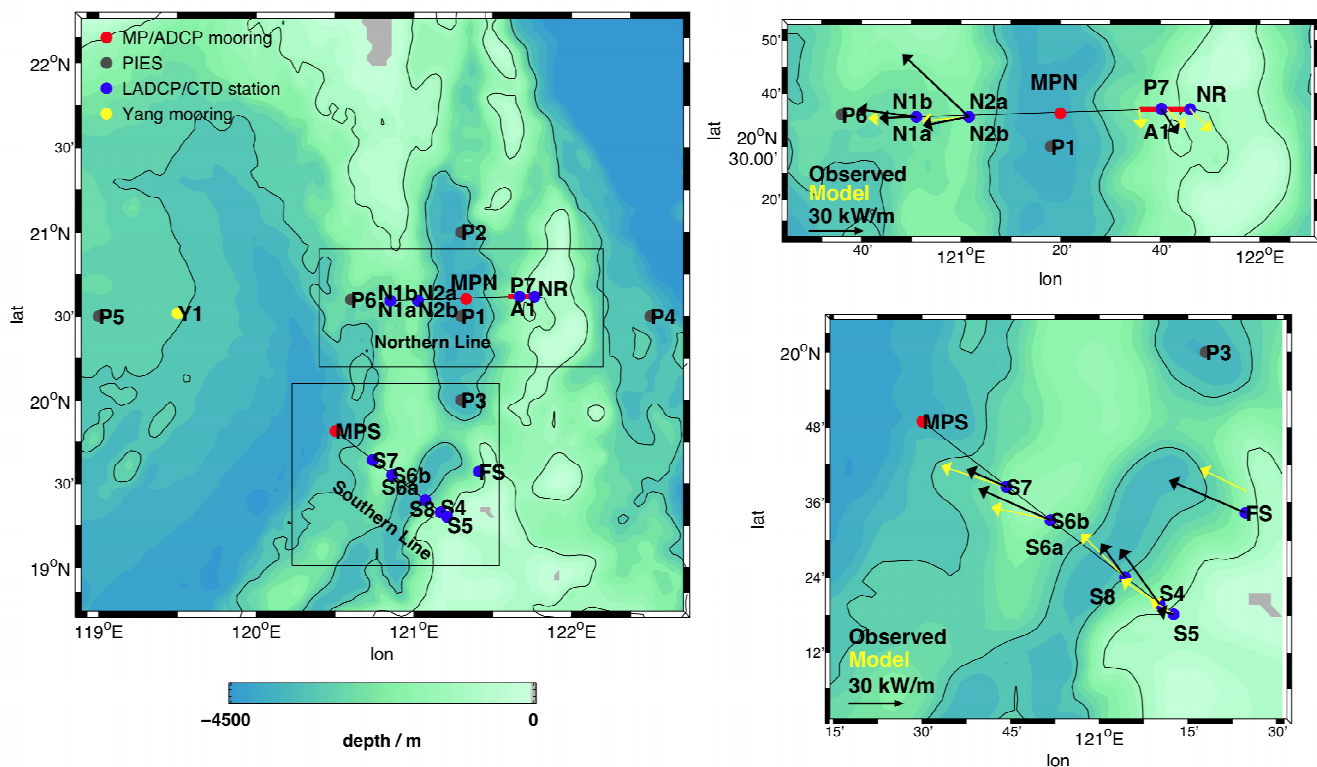
## **PUBLICATIONS**



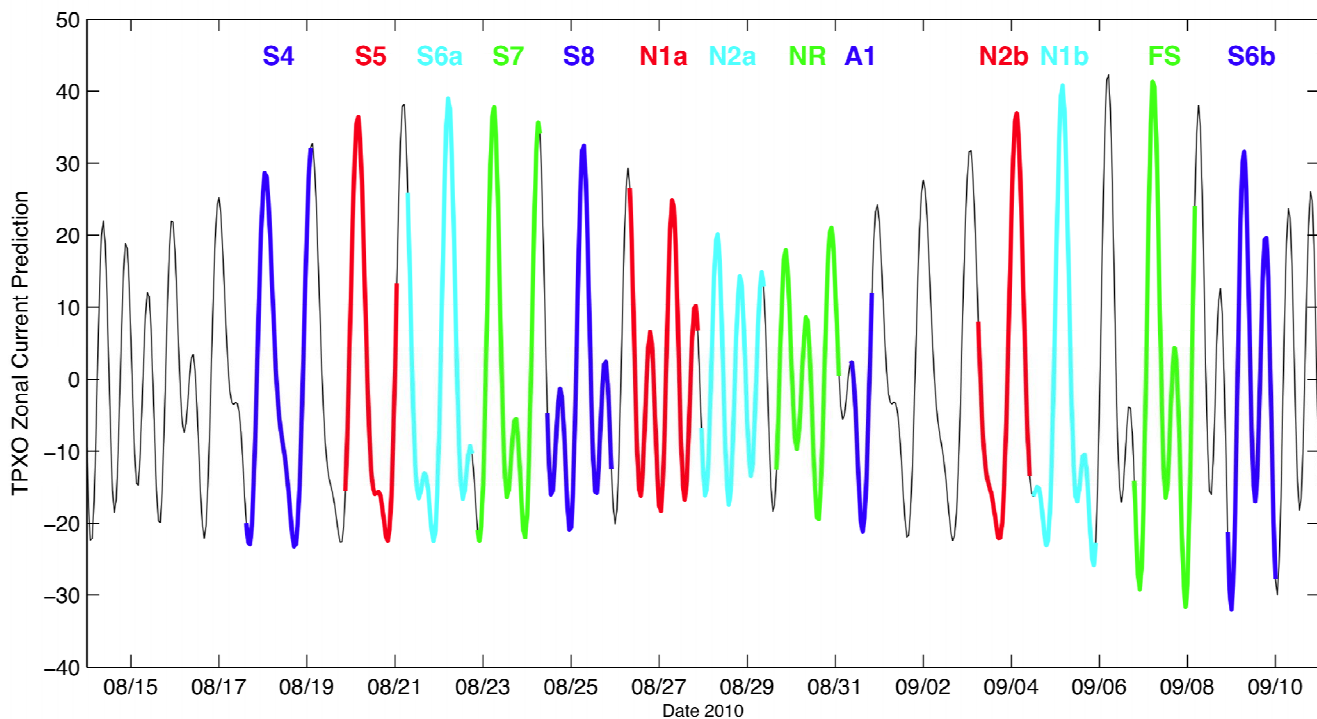
*Figure 1: Tidal conversion (colors) and energy flux vectors at spring tide (from Jan et al., 2008) also showing the preliminary mooring array configuration (circles, red with OSU Chi-pods). Note that the array spans a region of both expected strong off-ridge fluxes and internal tide generation.*



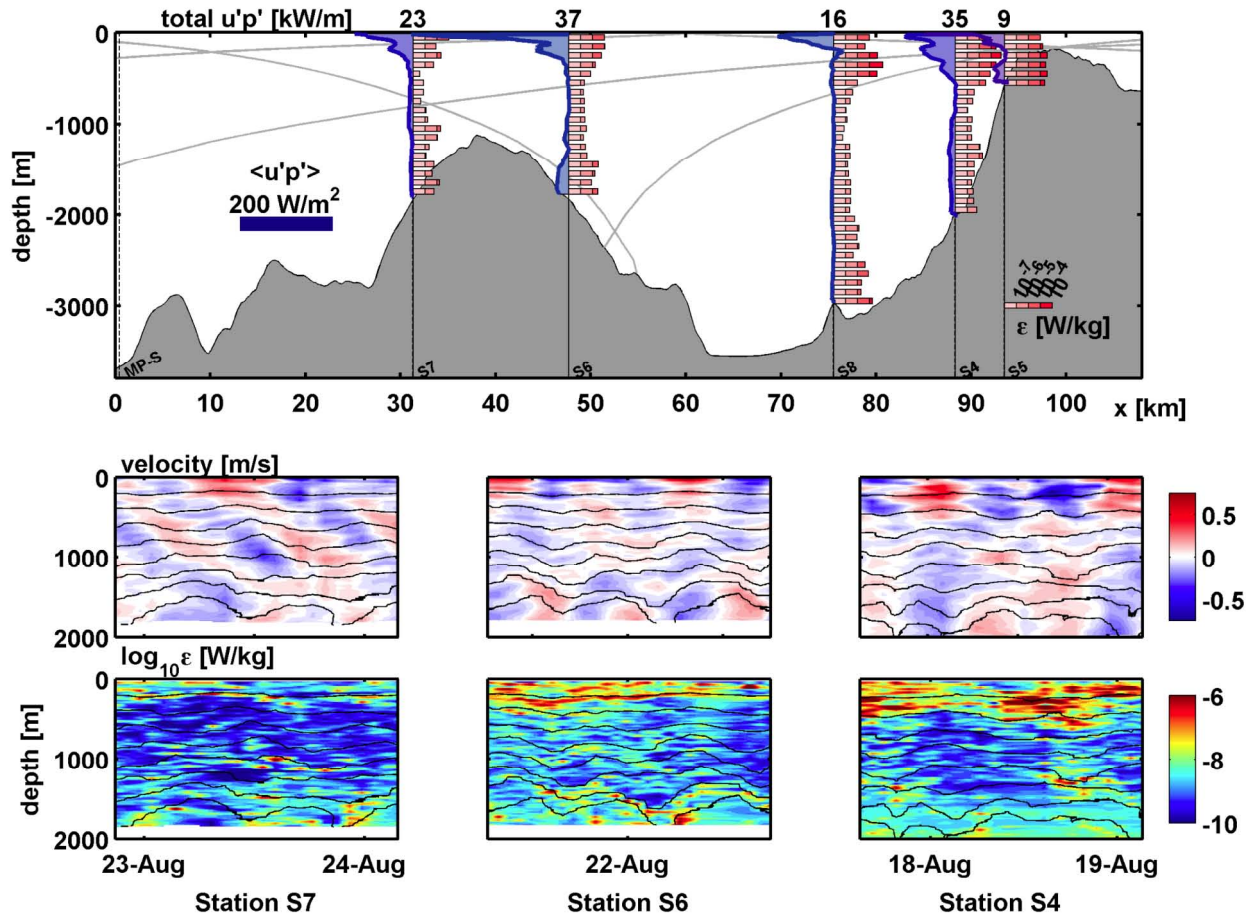
**Figure 2: Mooring diagram for THE MP-N mooring, showing the MP, upward (300kHz) and downward(75kHz) looking ADCPs, OSU chi-pods, and SBE MicroCAT and T-logger. The MP-S mooring was similar.**



**Figure 3: Model bathymetry and all IWISE stations. Measured (black) and modeled fluxes (yellow) are also plotted. The regions shown in close-up at right are shown with boxes at left.**



**Figure 4: Barotropic Tides during IWISE pilot, predicted with TPXO6.2, and completed IWISE stations.**



**Figure 5:** Top: Blue shading shows across-axis component of the energy flux (aligned 37 deg N of W) at 5 stations spanning the southern ridge. Also shown is the time-average TKE dissipation, computed from the CTD-chi measurements. Lower panels show time series of velocity and dissipation at stations S7, S8, and S4. Near the ridge, TKE dissipation is strongly-enhanced in the upper 500 m, and decays with distance from the ridge crest. Far from the ridge, regions of intense dissipation occur on semidiurnal timescales and propagate upward in time.