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14. ABSTRACT

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.

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Long-Range Acoustic Doppler Current Profilers for Internal Waves in Straits Experiment (IWISE)

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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. We use a combination of several existing instruments, several satellite products, simple models, and the development of new technology to study the physics of the ocean and the interaction between phenomena at different scales – in particular how mesoscale and large-scale features in the ocean impact the generation, propagation, and dissipation of internal waves. The research conducted in IWISE substantially improves both our understanding and predictive ability of linear and non-linear internal tides 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. The bulk of IWISE observations took place in Luzon Strait (Figure 1) during summer 2011. These were preceded by a pilot experiment in summer 2010 to shake out equipment, refine hypotheses and determine the best location for the assets in the main experiment.

Our contribution to the main experiment was a 7-element array of profiling moorings. 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 were 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 is enabling determination of the 3-D structure of the internal waves generated in the Strait.

WORK COMPLETED

Main Experiment

The main IWISE field campaign took place in summer 2011. Our contribution was to deploy the main array of 7 profiling moorings in Luzon Strait (Figure 2). An additional mooring with full-depth coverage (Nash's instruments) was deployed at site "A1" on the eastern side of the northern line. We also deployed 4 thermistor string moorings (Nash) around N2 on the western ridge, which will provide highely resolved (depth and time) measurements of turbulence. We also deployed 13 PIES for David Farmer's group, which remained in place until spring 2012 and will be used to study the evolution and seasonal cycle of NLIW. With remaining ship time on the mooring deployment and recovery cruises, we occupied 5 additional full-depth LADCP/CTD stations.

Based on the the results of the 2010 pilot experiment (Figure 2), we chose to re-occupy the same two measurement lines in 2011. *The goal of the moored array was to sample these locations for a longer period encompassing several tidal cycles and different Kuroshio states, in order to understand the temporal variabilty of the internal tide and dissipation*.

A combination of strong tidal flows and the Kuroshio resulted in larger-than-expected mooring knockdown during the pilot experiment, which prevented the McLane profiler from crawling for short periods. To overcome this issue, the moorings were redesigned with an upward looking ADCP and temperature chain measuring the upper few hundred meters there the Kuroshio flow is strongest. With these modifications, the McLane Profilers were able to profile nearly continuously in the upper ocean. This DURIP supported the acquisition of 4 Teledyne Long-Ranger ADCPs, which all provided continuous measurements of velocity over seeral hundred meters at each mooring location.

Luzon Strait continued to prove itself a challenging environment for moorings. Moorings on steep slopes needed to be placed accurately (within 100m of target), which was done nearly without exception owing to state-of-the-art modeling of anchor drops accounting for currents and ship speed. Fishing was another hazard – mooring MPS was unwittingly deployed over a submerged longline, parting the line and causing the loss of an MMP. This already challenging requirement was made more so by strong, time variable surface currents (caused by tides and Kuroshio). Upon recovery it was found that 6 out of 10 profilers failed to profile. After investigating it was found that this was caused by a blown fuse/diode, likely caused by large surface currents during deployment. This issue had never occurred before, and we have modified the fuses and launch procedures for future deployments. Despite these unfortunate failures, the mooring array returned excellent data in an extremely energetic and challenging environment (depth-coverage shown in Figure 3). The ~50 day timeseries at each mooring cover 4 spring-neap cycles, allowing us to achieve our goal of measuring the temporal variability of internal waves as tidal forcing and background conditions change. Moorings A1 and S9 measured nearly full-depth profiles of velocity, temperature, and salinity.

RESULTS

An overview of data collected by mooring S9 is shown in Figure 4. The top panel is the barotropic (depth-mean) tidal velocity measured by the mooring, showing the 4 spring-neap cycles observed. Raw east-west velocity is shown in the 2nd panel. Velocity was strong, often exceeding 0.5 m/s. Note the extremely strong near-bottom velocities that occur during spring tides (sometimes strong enough to prevent the MMP from crawling). The next 3 panels show the different frequency components (low-frequency, diurnal, and semidiurnal) of the total velocity, isolated with a bandpass filter. The velocity is largely tidal, with a low-frequency component that is largely constant over the full depth. The last panel shows an estimate of the turbulent dissipation rate, computed from density overturns measured by the moored profilers. Dissipation is very high compared to open-ocean values, and shows a strong spring-neap cycle.

Internal Tides and Energy Fluxes

Measurements of velocity and density are used to compute energy and energy flux in the internal tide. A strong spring-neap modulation in energy and energy flux are seen in the timeseries from S9 (figure 5) and A1 (figure 6). Besides the spring-neap cycle, there is significant variation in magnitude between spring tides. It appears that much of the variability in energy flux can be attributed to changes in the magnitude of barotropic forcing, which the nearly full-depth coverage of the moorings allows us to measure. We are currently investigating what causes the variability in observed barotropic currents.

The new moored observations complement and enhance the picture of energy flux patterns that emerged during the pilot. At mooring A1 (Nash) on the eastern ridge of the northern line, semidiurnal energy flux is very large (mean 58 kW/m) and directed towards the south (Figure 7). This energy flux, transverse to the expected direction of wave propagation, supports the notion of interference between waves generated at the western and eastern ridges. Diurnal energy fluxes are comparatively much weaker, though still quite large by open-ocean standards (10 kW/m). The direction of diurnal flux varies dramatically over the 50 day observation period. We suspect that the diurnal flux is also the result of interference between eastward and westward propagating waves, and that small changes in the phasing of either wave shift this interferene pattern. The phase changes could be caused by the Kuroshio, something we are currently investigating.

At mooring S9 on the southern line, there are fewer signs of an interference pattern. Time-mean internal tidal energy fluxes were 25 (14) kW/m for the diurnal (semidiurnal) frequency band. Energy flux was directed away from the eastern ridge towards the northwest, in the expected direction of wave propagation.

The presence of interference patterns can be made more quantitative by examining the ratio of flux to energy (Figure 8). For a free progressive wave, the ratio of flux to energy is equal to the group velocity. Observations at S9 generally follow this relation, but those at A1 do not. This provides quantitative evidence that interference between multiple waves is responsible for the observed flux pattern over the eastern ridge. Ongoing work seeks to determine if the two-ridge system also leads to resonance and enhanced energy or dissipation.

Lee Waves and Dissipation on Supercritical Slopes

A profiling mooring and 4 thermistor chains were deployed at station N2 on the western ridge, where the largest turublence was observed during the pilot experiment. Longer timeseries allows us to see how dissipation varies with different forcing (i.e. diurnal vs semidiurnal tides). These measurements resolved the unstable lee-waves leading to turbulence. Modeling studies (Buijsman 2012) suggest that turublent dissipation is increased during periods of semi-diurnal forcing, due to a resonance effect. This data and further modeling will allow us to better understand these processes.

Large density overturns were observed by the lower McLane profiler on S9, from which we can estimate the turbulent dissipation rate. Preliminary analysis shows that dissipation has a strong spring-neap cycle and appears to peak during westward (downslope) flow, probably due to lee wave formation. We will investigate these processes and compare them to similar processes on the northern ridge (ie N2), to further understand the effect of the two-ridge system on dissipation.

Kuroshio

One of the goals of the moored array was to study how internal tides and NLIW are affected by the Kuroshio current. The moorings measured velocity in the upper 300m with upward-looking ADCPs. These measurements will be used to determine the location, strength, and variability of the Kuroshio current and during the experiment. The low frequency velocity averaged over the upper 150m (Figure 9) shows that the Kuroshio was strong and nearly always present over the western half of the northern line. At other locations, the low-frequency flow is weaker and more variable in magnitude and direction. These data will be an important baseline for various other studies on the effect of the Kuroshio on internal tides, NLIW, and dissipation.

Evolution of IT

One of the striking aspects of previous observations and models in the region is the relatively simple and organized wave field that emerges from the complicated fields near the ridges. Another main goal of the moored array is to understand this evolution of the internal tide away from the generation site. Ongoing and future work will attempt to track the progression of internal tide signals along each mooring line and observe how they evolve.

IMPACT/APPLICATIONS

TRANSITIONS

RELATED PROJECTS

Within IWISE, we are working closely with modelers (especially Klymak, Simmons, and Buijsman), 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).

We are working closely with Nash, who came on the 2011 cruises and whose equipment was deployed at mooring A1, as well as the 4 temperature-string moorings surrounding mooring N2.

The mooring array will serve as a 'backbone' for other shipboard measurements (especially St. Laurent, Lien & Pinkel), and help interpret observations at far-field basin moorings (Yang/Ramp) by providing accurate time-series of barotropic velocity and internal tide energy flux at the ridges.

We helped deploy and recover 2 Spray Gliders (Rudnick & Johnston). The gliders were deployed in the deep basin west of the ridges. We are collaborating with Johnston and Rudnick on internal tides measured by the gliders (Johnston 2012).

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. Our mooring data, combined with the PIES we deployed during summer 2011, will help to further understand the evolution of IT into NLIW.

There are several connections between the measurements collected during IWISE and those collected in the other ONR programs that took place in the area, in particular during OK-MC and ITOP. The observations from all these programs are being synthesized to investigate the propagation of internal waves towards the Pacific Ocean.

REFERENCES

Alford, M. H., J. A. MacKinnon, J. D. Nash, H. Simmons, A. Pickering, J.M. Klymak, R. Pinkel, O. Sun, L. Rainville, R. Musgrave, T. Beitzel, K. Fu, and C. Lu, 2011:Energy flux and dissipation in Luzon Strait: two tales of two ridges. *J. Phys. Oceanogr*, **41**, 2211-2222,doi:10.1175/JPO-D-11-073.1

Buijsman, Maarten C., Legg, Sonya and Klymak, Jody (2012) Double ridge internal tide interference and its effect on dissipation in Luzon Strait. *J. Phys. Oceanogr*, **42**, 1337–1356. doi:10.1175/JPO-D-11-0210.1

PUBLICATIONS

Alford, M. H., J. A. MacKinnon, J. D. Nash, H. Simmons, A. Pickering, J.M. Klymak, R. Pinkel, O. Sun, L. Rainville, R. Musgrave, T. Beitzel, K. Fu, and C. Lu, 2011:Energy flux and dissipation in Luzon Strait: two tales of two ridges. *J. Phys. Oceanogr*, **41**, doi:10.1175/JPO-D-11-073.1,2211-2222.

Figures

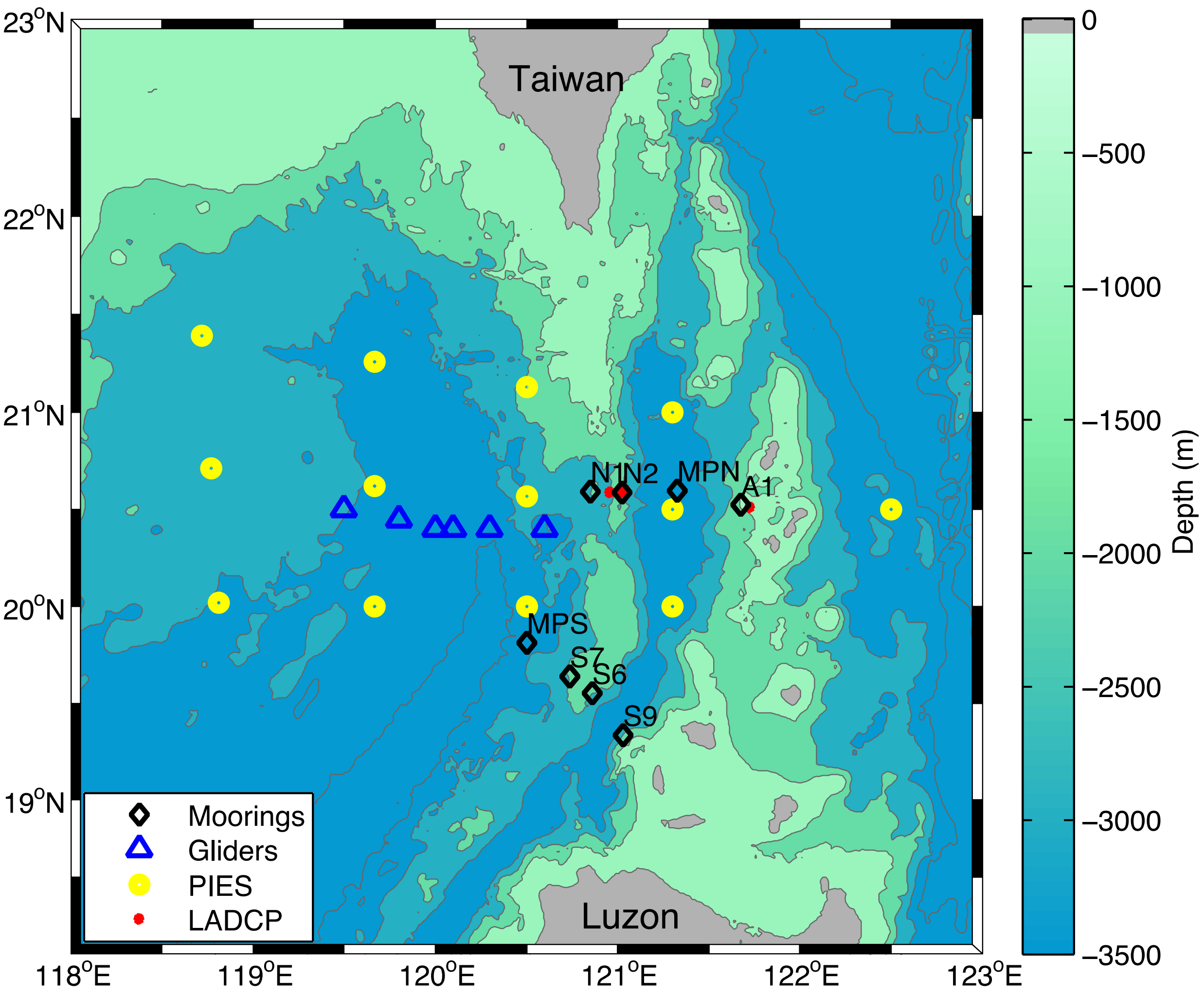

Figure 1: Map of 2011 IWISE observations discussed in this report. Not shown are 4 T-chain moorings deployed close to N2.

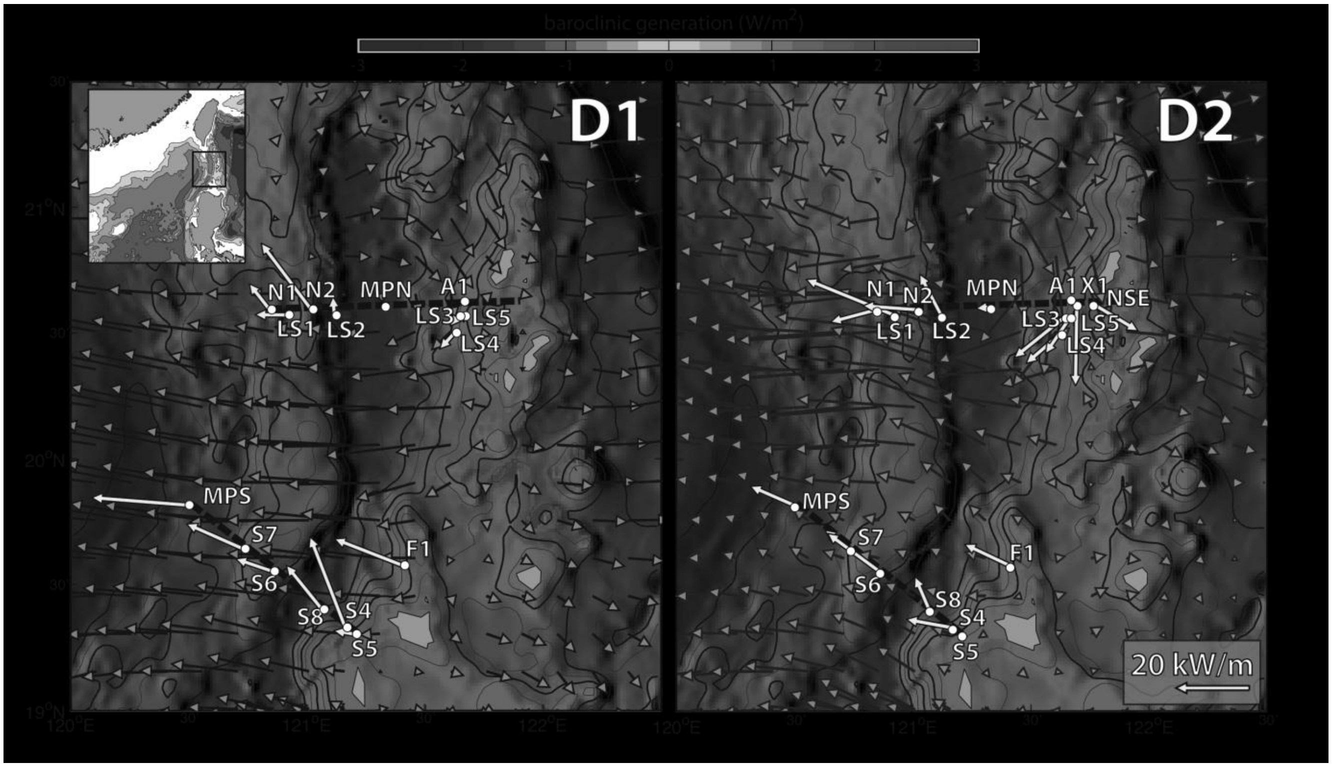

Figure 2: Tidal conversion (colors) and energy flux vectors from UAF model (green, Simmons) and Pilot observations (yellow). Observations were concentrated along two lines (dashed black). From Alford et al (2011).

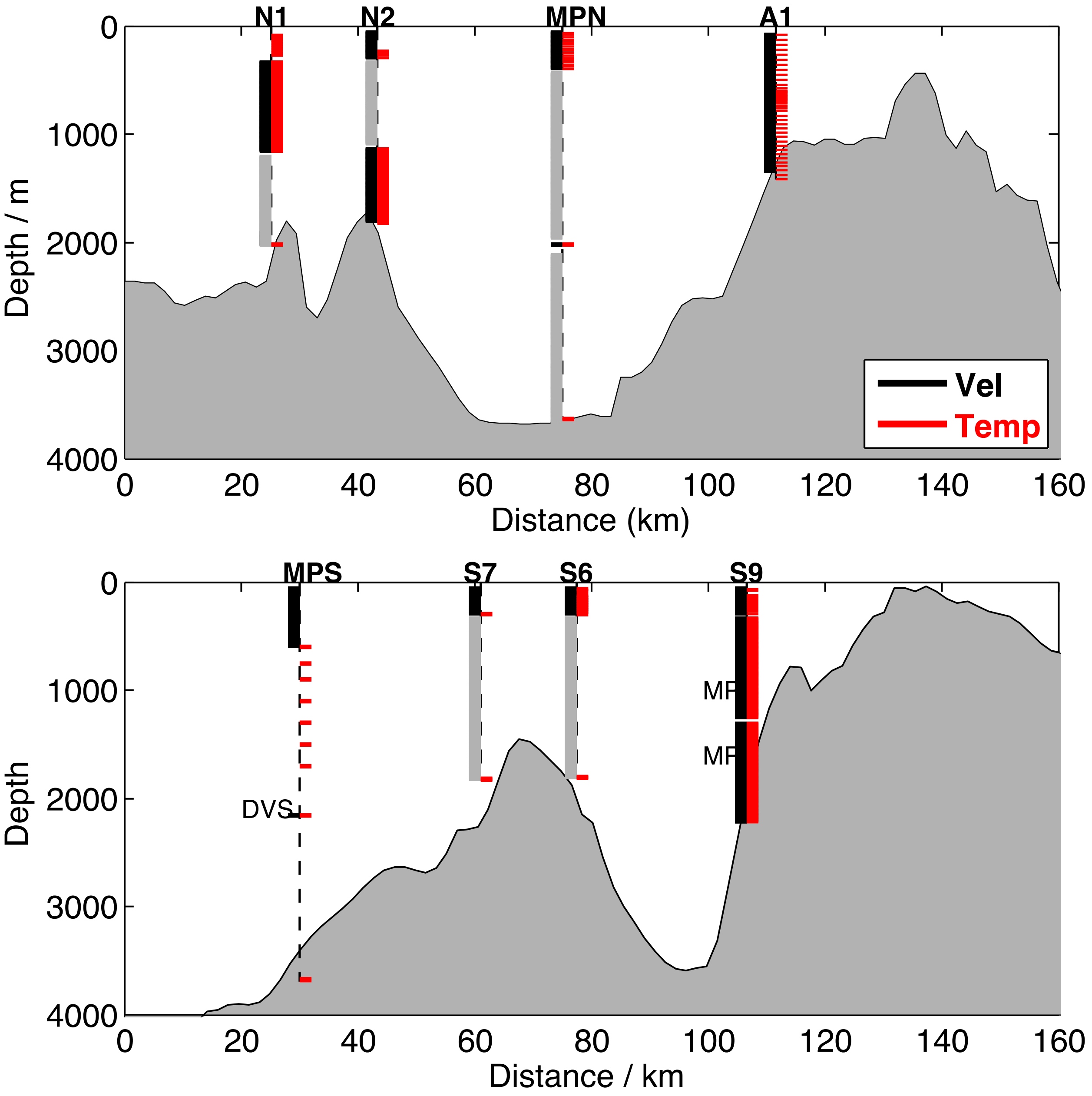

Figure 3: Cross-section of bathymetry along northern and southern lines, showing depth coverage of moorings. Black indicates velocity, red temperature. Light gray shows depths affected by blown MP fuses. Four T-chain moorings deployed close to N2 are not shown.

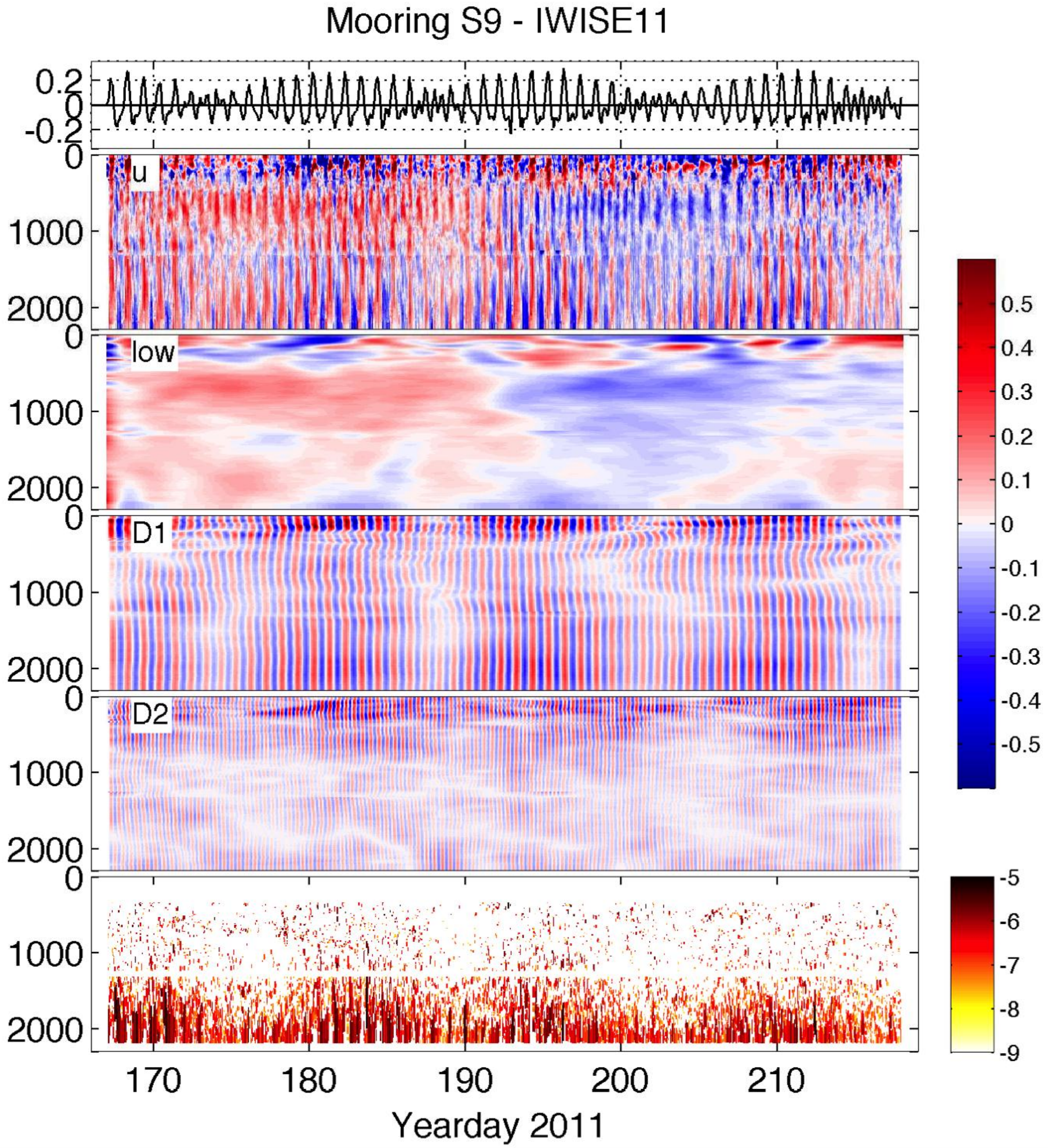

Figure 4: Overview of data from mooring S9. From top to bottom: Barotropic tidal velocity. Zonal velocity (total, low frequency, D1, and D2). All velocities in m/s . Bottom panel: (log*$_{10}$ *of) turbulent dissipation rate (W/kg) estimated from density overturns.

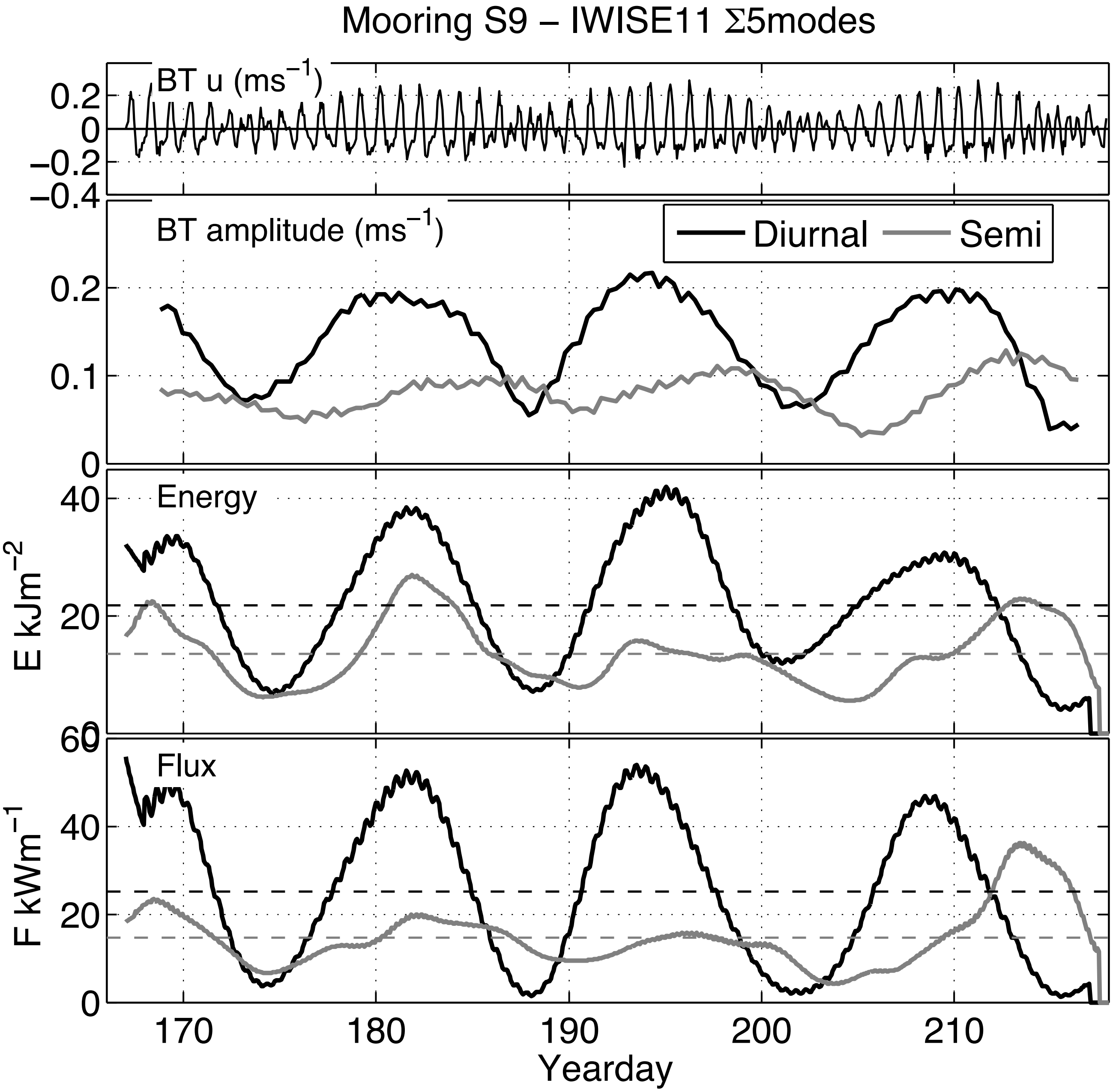

Figure 5: Barotropic velocity, energy, and flux at mooring S9. (a) Barotropic velocity (b) Amplitude of BT velocity, computed from sliding harmonic fit with 3 day window. (c) Depth-integrated energy. (d) Depth-integrated energy flux. For lower 3 panels, black indicates diurnal frequency, while gray indicates semidiurnal frequency.

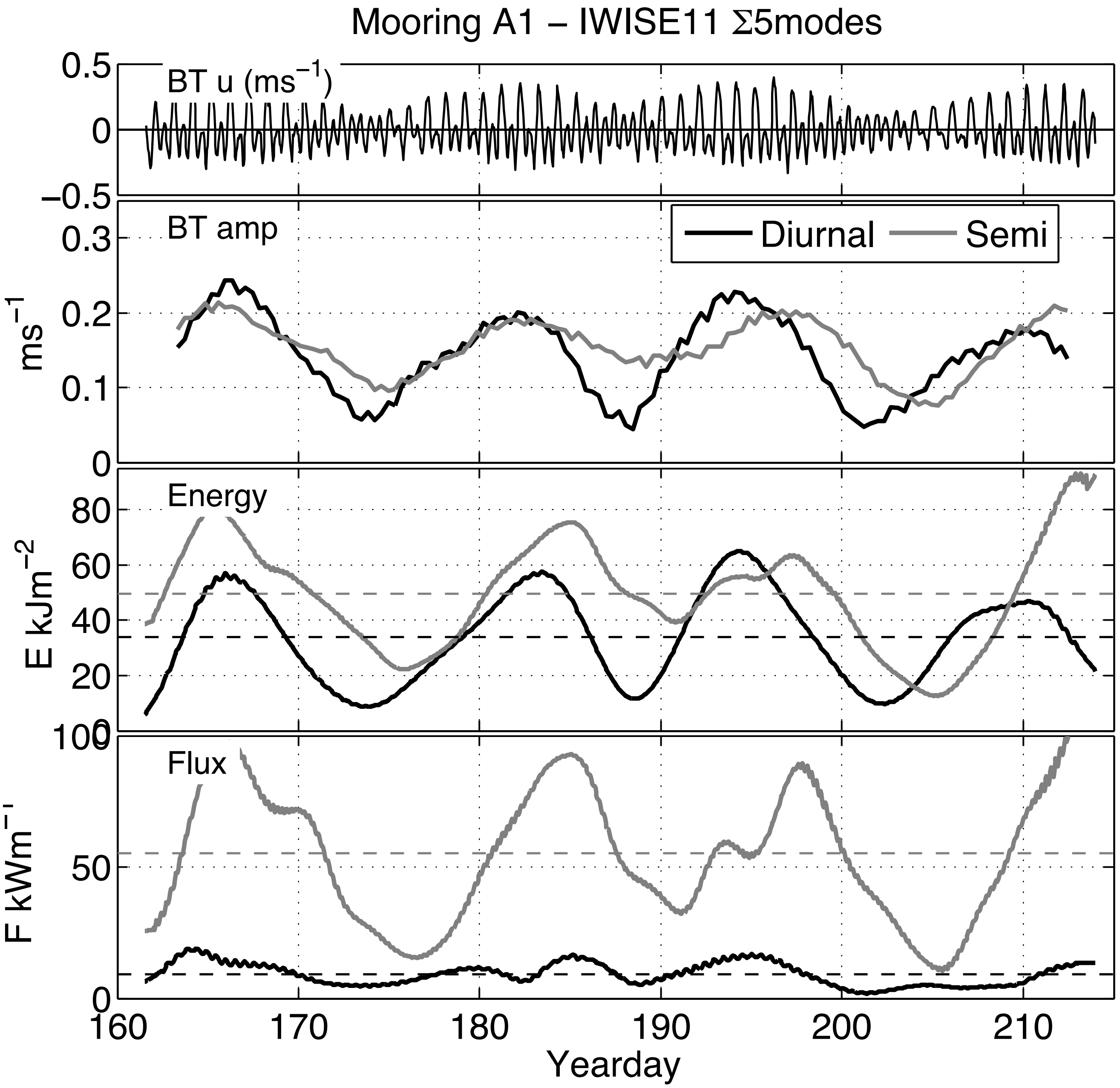

Figure 6: Barotropic velocity, energy, and flux at mooring A1. (a) Barotropic velocity (b) Amplitude of BT velocity, computed from sliding harmonic fit with 3 day window. (c) Depth-integrated energy. (d) Depth-integrated energy flux. For lower 3 panels, black indicates diurnal frequency, while gray indicates semidiurnal frequency.

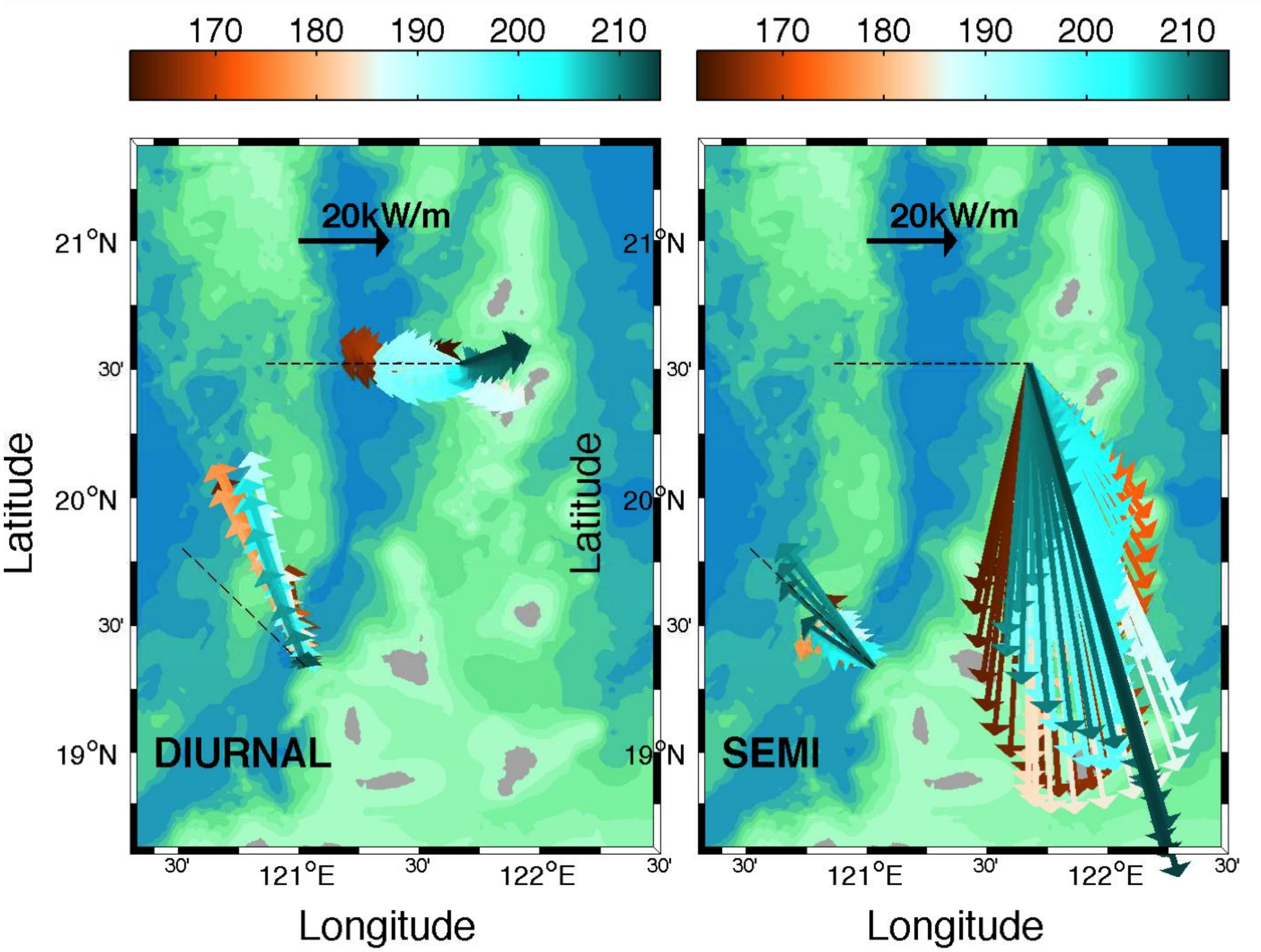

Figure 7: Depth-integrated energy fluxes from moorings S9 and A1 during 2011 IWISE experiment. Flux vectors are colored according to time (yearday 2011). Diurnal fluxes are shown on left, and semidiurnal on right. Note that flux direction at S9 is relatively constant, while direction changes significantly at A1 (especially diurnal band).

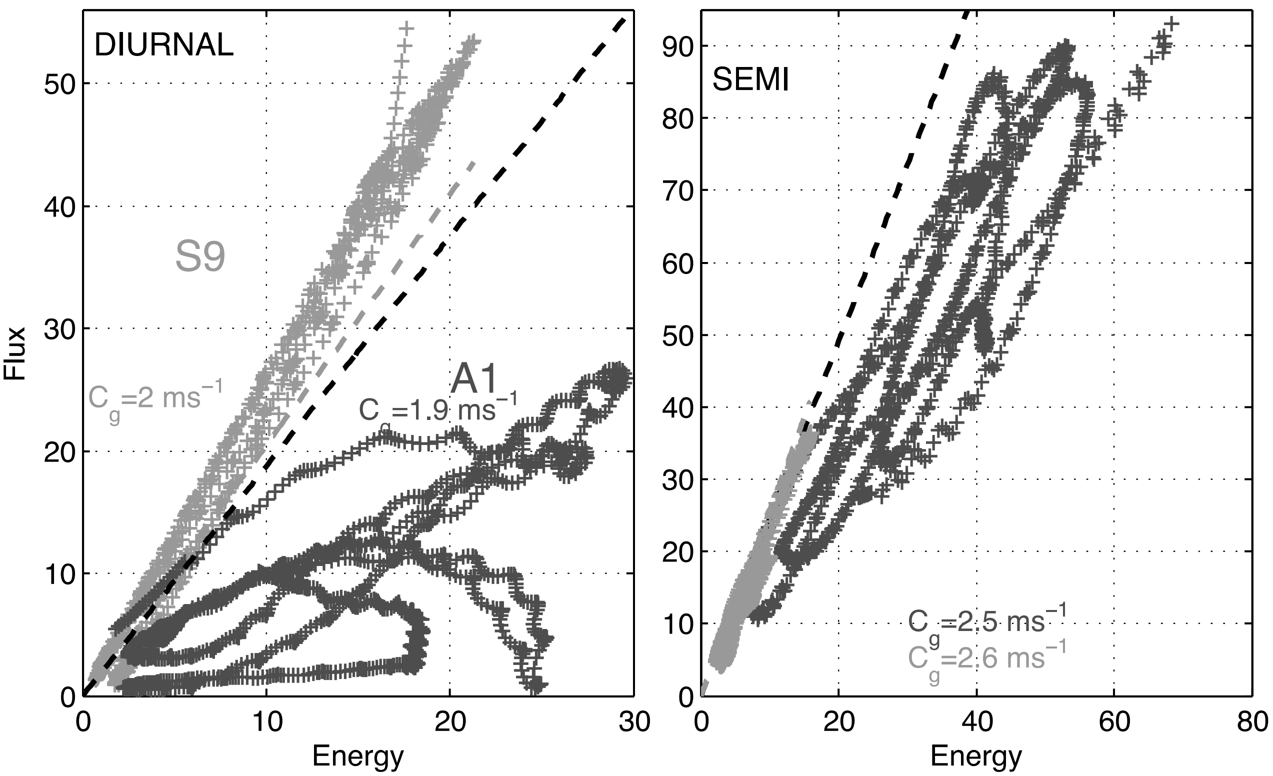

Figure 8 : Mode-1 energy flux (kW/m) versus energy (kJ/m^2) at moorings S9 (light) and A1 (dark). The left panel shows the diurnal band, and the right shows the semidiurnal band. Dashed lines show theoretical group speed; note that values for S9 tend to fall close to this line while those for A1 do not.

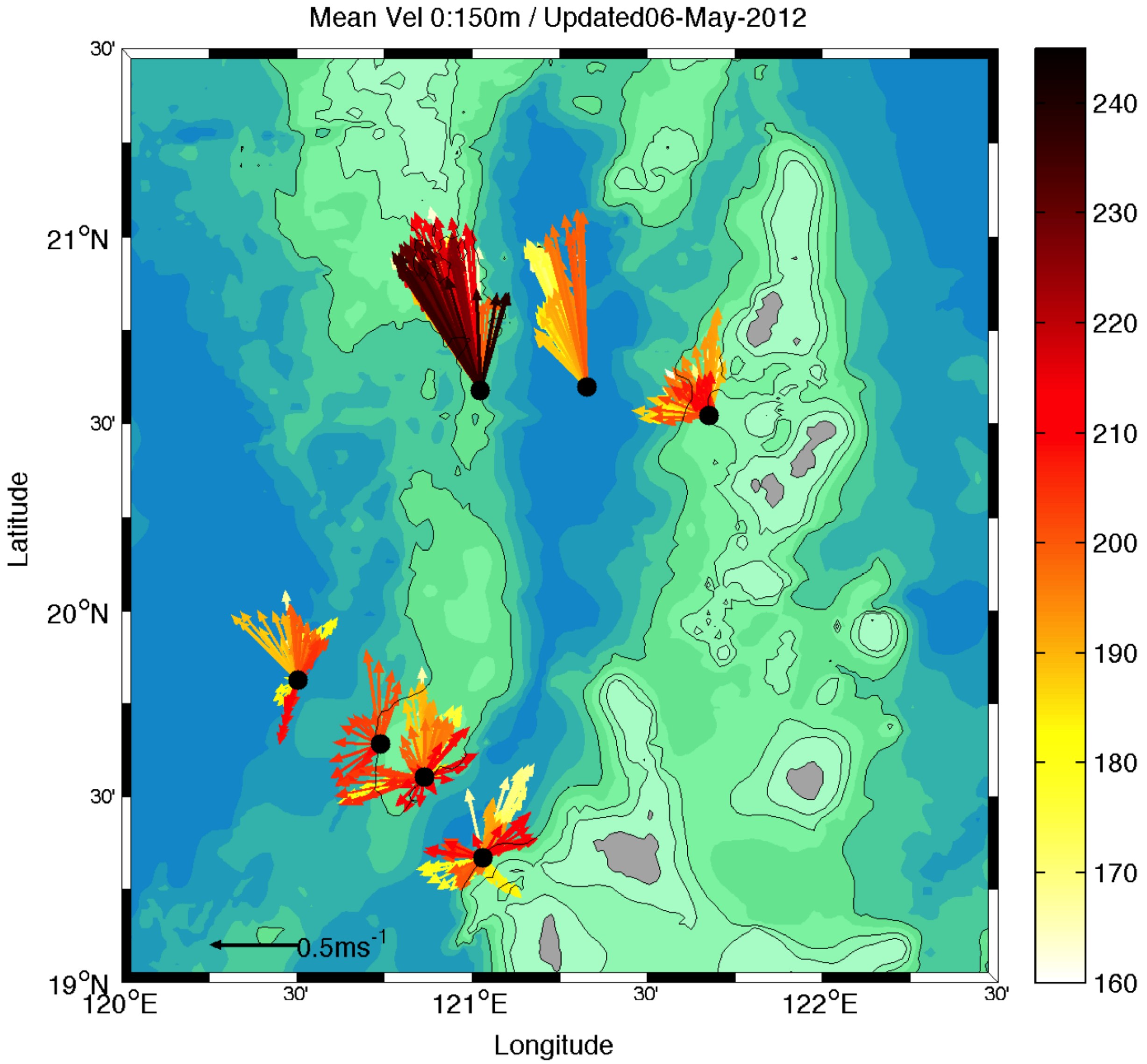

Figure 9 : Low-passed velocity from moored ADCP's, averaged over the upper 150m. Vector colors indicate time (yearday 2011). Note the strong and relatively constant northward flow over the western half of the northern line. Velocity scale is shown in lower left.