

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

Matthew H. Alford  
Scripps Institution of Oceanography  
9500 Gilman Drive, mail code 0213  
La Jolla, CA 92093  
phone: (858) 246-1646 email: [malford@ucsd.edu](mailto:malford@ucsd.edu)

Luc Rainville  
Applied Physics Laboratory  
1013 NE 40<sup>th</sup> Street  
Seattle, WA 98105  
phone: (206) 685-4058 fax: (206) 543-6785 email: [rainville@apl.washington.edu](mailto:rainville@apl.washington.edu)

Grant Numbers: N00014-09-1-0219, N00014-09-1-0279, N00014-09-1-0184

### **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 (particularly in straits) are severely impacted by internal waves. The research described here substantially improves both our understanding and predictive ability of linear internal tides 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) included 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 (Figures 1, 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 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 served 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

We reported on many of the main preliminary IWISE results in last year's annual report, and merely update these in this final report as our analysis has advanced. Andy Pickering, the student supported to work on IWISE results under an Early Student Support (ESS) award, completed two papers on these results: 1) a paper describing the variability in the observed fluxes at moorings A1 and S9, the first-ever full-depth moored measurements made in Luzon Strait, and 2) a detailed paper on turbulence observed at S9 (published in his thesis and in preparation for publication in JPO). Additionally, Alford led a group IWISE summary paper which was published in Nature.

## RESULTS

### *Internal Tides and Energy Fluxes*

Measurements of velocity and density are used to compute the energy and energy flux of the internal tide (Figure 2). A strong spring-neap modulation in energy and energy flux are seen in the timeseries (Figure 3) from S9 (black) and A1 (red). Besides the spring-neap cycle, there is significant variation in magnitude between spring tides. With the exception of the diurnal internal tide at A1, it appears that much of the variability in energy and flux can be attributed to variations in the barotropic forcing.

The 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 of ~30 kW/m) and directed towards the south (Figure 4). 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). 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.

We made significant advances in understanding the variability observed in energy flux. Between S9 and A1, the diurnal internal tide at A1 is the most variable, with only 30% of the signals coherent with the forcing. The direction of diurnal flux at A1 varies dramatically over the 50 day observation period, much more so than accounted for by the barotropic forcing. Hypotheses for this variability include 1)

remote signals from the Mariana ridge to the east; 2) reflected diurnal signals from the SCS continental slope; and 3) shifting of the local interference pattern between the ridges by the Kuroshio. By evaluating Maarten Buijsman's and Dong Ko's models, we have been able to determine that hypothesis 3) is responsible. That is, a 3D interference pattern created between the ridges (Buijsman et al, 2014) is shifted laterally by variable mesoscale fields, primarily the Kuroshio (Figure 5 a,d). The A1 mooring is at a large gradient in this pattern (Figure 5 b,e), accounting for the variability.

### *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 turbulence 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 turbulent 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 (Figure 6). Preliminary analysis shows that dissipation has a strong spring-neap cycle and appears to peak during westward (downslope) flow, probably due to breaking lee waves. We are collaborating on this analysis with M. Buijsman, who has provided high-resolution model output that will help to put the mooring observations in context. A model snapshot (Figure 7) shows a lee wave and turbulence developing near S9. Andy Pickering presented a paper last summer at the Turbulence conference in Santa Fe, and a manuscript is nearly complete.

### *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 8) shows that the Kuroshio was strong and nearly always present over the western half of the northern line. The measured velocities agree well with model output provided by Dr. Ko (gray arrows). 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.

### *Propagation of Internal Tides Generated near Luzon Strait: Observations from Autonomous Gliders*

As part of the OKMC (Origins of the Kuroshio and Mindanao Currents) DRI, long-endurance, autonomous Seagliders are used to characterize the Kuroshio variability. These surveys, along with the Spray and Seaglider surveys conducted in 2007-2008 in the Kuroshio, can be used to estimate the amplitude and phase of the linear semidiurnal and diurnal internal waves in this energetic region, particularly in the previously poorly sampled area near the eastern ridge and on the Pacific side of Luzon Strait.

Nearly 23,000 glider profiles (Figure 9), collected during 29 different missions since 2007, are used to quantify the mean and variability of the internal wave field in the upper 1000 m of the water column. The phase progression of internal waves as they propagate away from their generation sites is directly

captured. Fitting a mode-1 vertical structure to the displacements observed by the gliders, the total (depth-integrated) energy of the semidiurnal and diurnal internal tide can be estimated. Furthermore, by looking at the spatial variations of the phases of the fits, one can determine the propagation direction of the internal tides (Figure 10). The glider-based observations are used to map the mode-1 semidiurnal and diurnal internal wave fields, providing the baroclinic energy flux over a roughly 600 by 800-km region based strictly on in-situ observations (Figure 11).

The gliders reveal a rich internal wave field in and around Luzon Strait. If the internal tides were generated by the regular barotropic tidal currents always acting on the same stratification and bathymetry, and if they propagated through an ocean without mesoscale or large-scale structure (or a time invariant structure), the amplitude and phase of the internal tide displacements at a given position and depth would remain proportional to and phased locked with the barotropic tidal forcing at the ridge. However, observations show significant variations, even for estimates at the same location. By providing persistence and broad spatial coverage, gliders constitute a powerful tool that complements very well the direct observations from moorings and LADCP/CTD stations collected during IWISE. This work is done in collaboration with Craig Lee (APL/UW), and Dan Rudnick and Shaun Johnston at Scripps Institution of Oceanography (see Rainville et al., 2013)

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 IWISE 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**

Andy Pickering graduated December 2014 and began a postdoc with Jonathan Nash (OSU) immediately after.

### **RELATED PROJECTS**

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.

Within IWISE, we continue to work closely with modelers (especially Klymak, Simmons, Ko, 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 has served as a ‘backbone’ for other shipboard measurements (especially St. Laurent, Lien & Pinkel), and helped 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. This analysis is ongoing.

We helped deploy and recover 2 Spray Gliders (Rudnick & Johnston). The gliders were deployed in the deep basin west of the ridges. We collaborated on a paper with Johnston, Rudnick, and Simmons describing internal tides measured by the gliders and moorings, which was recently published (Johnston et al., 2013).

We collaborated with M. Buijsman on his 3-D modeling paper (now out at *JPO*), and provided mooring data to help validate the model.

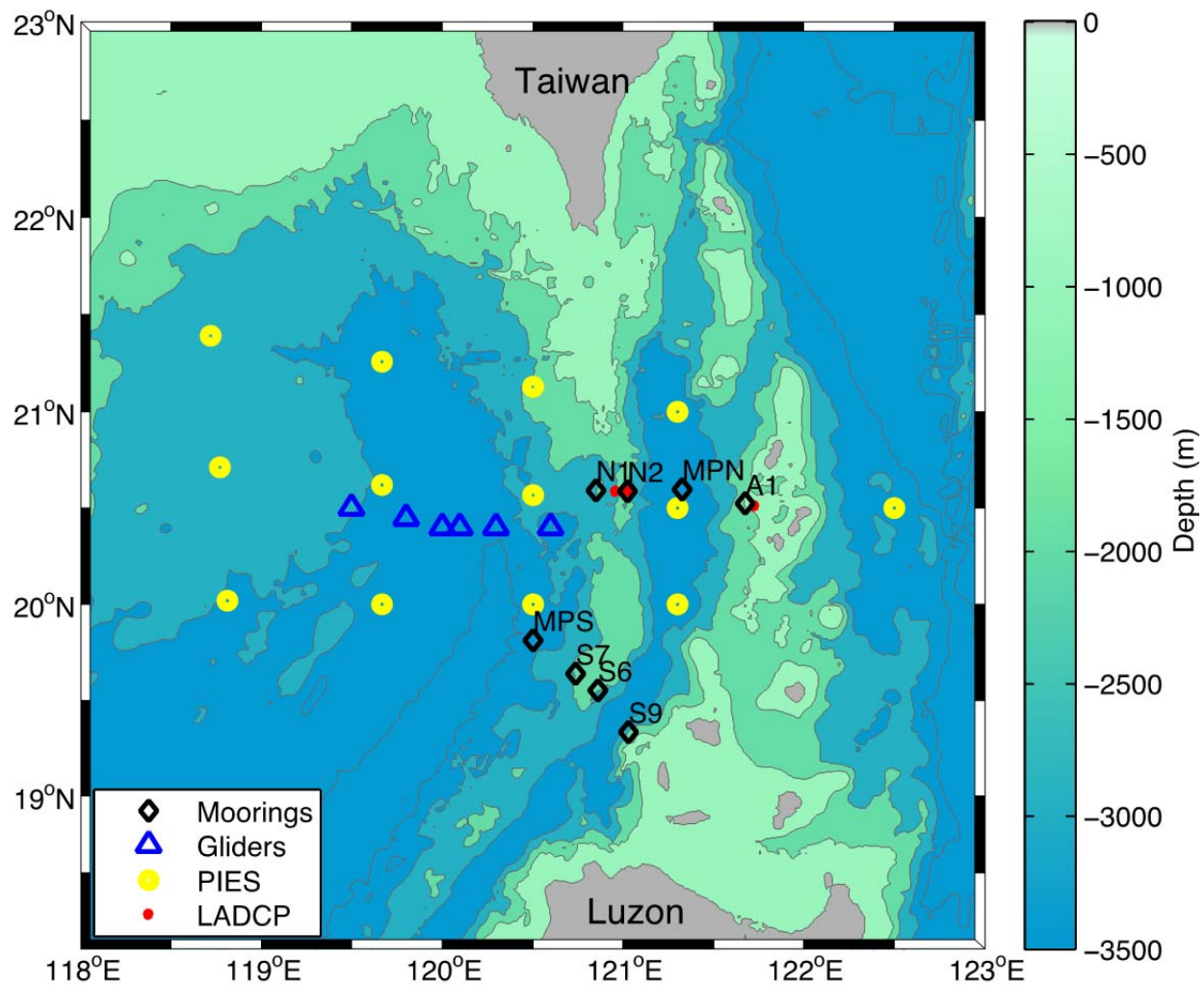
With regard to other DRI's, the understanding of the generation process of the NLIW, which is the goal of IWISE, fills a major void in the NLIWI DRI. Our mooring data, combined with the PIES we deployed during summer 2011, will help to further understand the evolution of IT into NLIW.

We also compiled shipboard ADCP data from opportunistic Kuroshio transects made by the R/V *Revelle* during the main experiment. These data, showing the vertical and horizontal structure of the current, will be useful both for our studies and for the larger ONR community studying the Kuroshio.

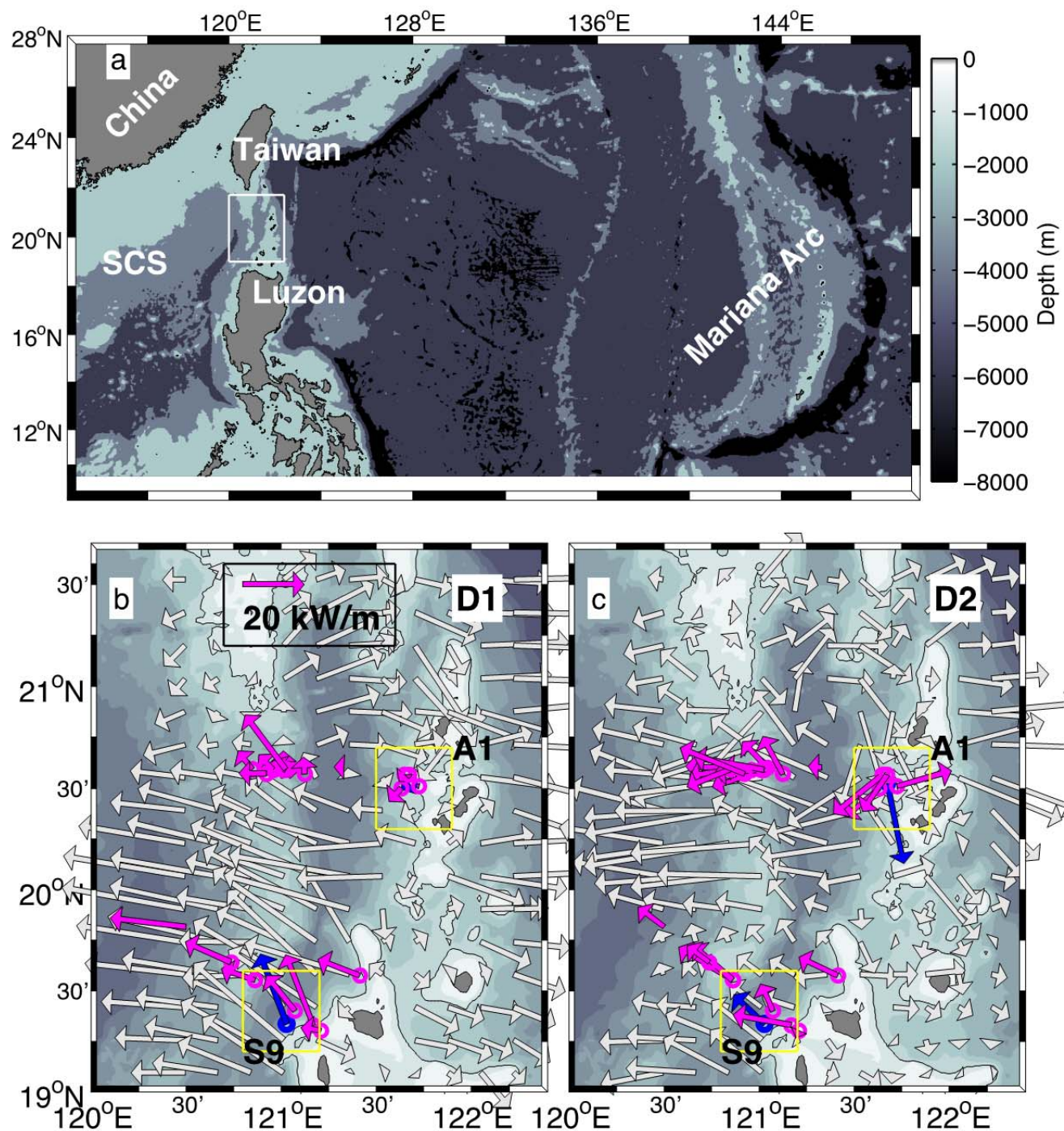
## **PUBLICATIONS**

- 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.
- Buijsman, Maarten C, J. M. Klymak, S. Legg, M. H. Alford, D. Farmer, J. A. MacKinnon, J. Nash; J. Park, A. Pickering, and H. Simmons, 2013: Three Dimensional Double Ridge Internal Tide Resonance in Luzon Strait. *J. Phys. Oceanogr* 44(3):850–869, 2014.
- Farmer, D.M., M.H. Alford, R.-C. Lien, Y.J. Yang, M.-H. Chang, and Q. Li. 2011. From Luzon Strait to Dongsha Plateau: Stages in the life of an internal wave. *Oceanography* 24(4):64–77, <http://dx.doi.org/10.5670/oceanog.2011.95>.
- Johnston, T.M. S, D. L. Rudnick, M. H. Alford, A. Pickering, and H. Simmons, 2013: Internal tidal energy fluxes in the South China Sea from density and velocity measurements by gliders. *J. Geophys. Res.* 118(8):10.1002/jgrc.20311, 2013.
- Klymak, J.M., S. Legg, M.H. Alford, M. Buijsman, R. Pinkel, and J.D. Nash. 2012. The direct breaking of internal waves at steep topography. *Oceanography* 25(2):150–159, <http://dx.doi.org/10.5670/oceanog.2012.50>.
- Rainville, L., C.M. Lee, D.L. Rudnick, and K.-C. Yang. Propagation of Internal Tides Generated near Luzon Strait: □ Observations from Autonomous Gliders. 2013. *J. Geophys. Res.*, **118**, 1–14, doi:10.1002/jgrc.20293, 2013.

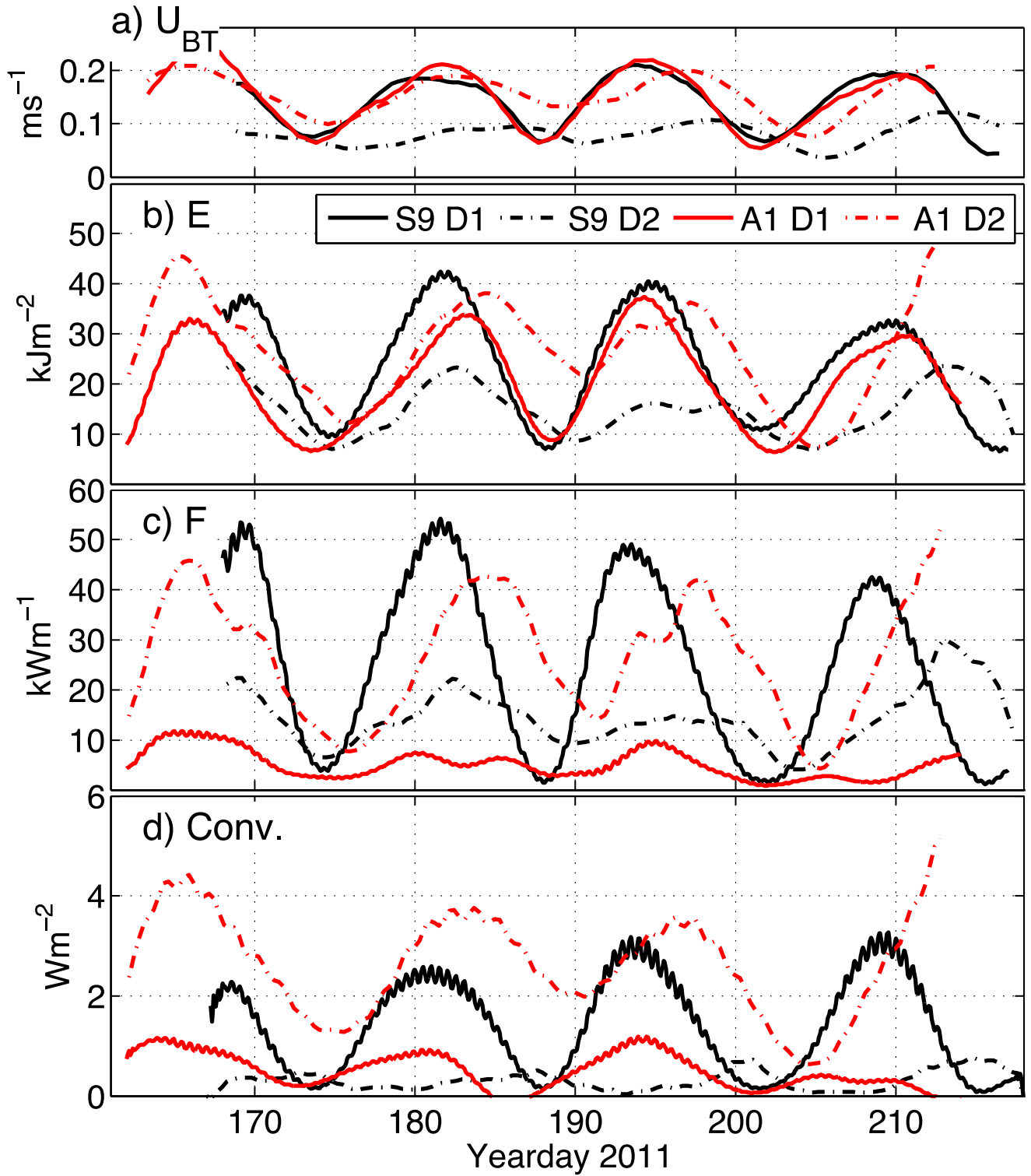
## **Figures**



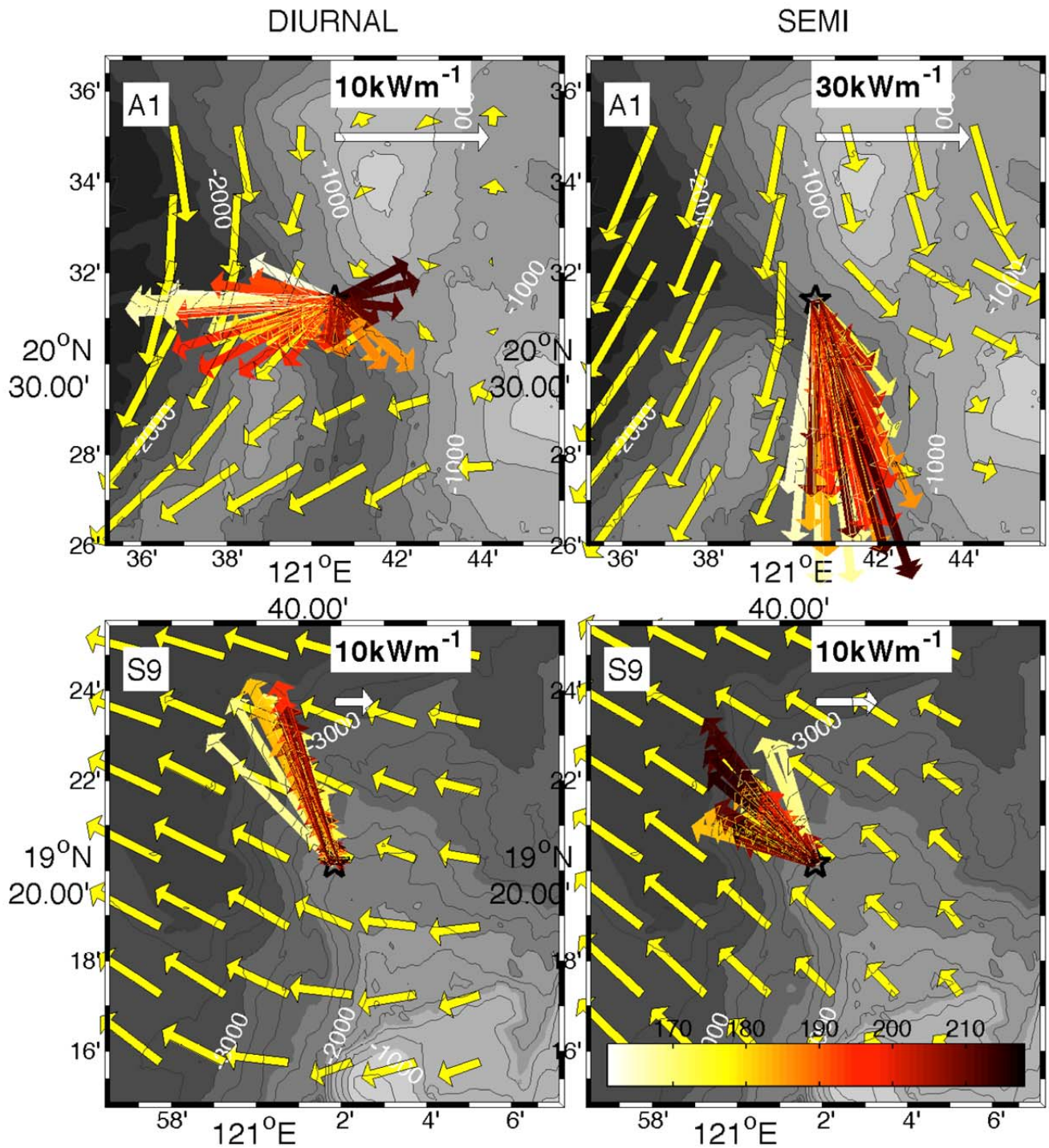
**Figure 1: Map of 2011 IWISE observations discussed in this report. Not shown are 4 T-chain moorings deployed close to N2.**



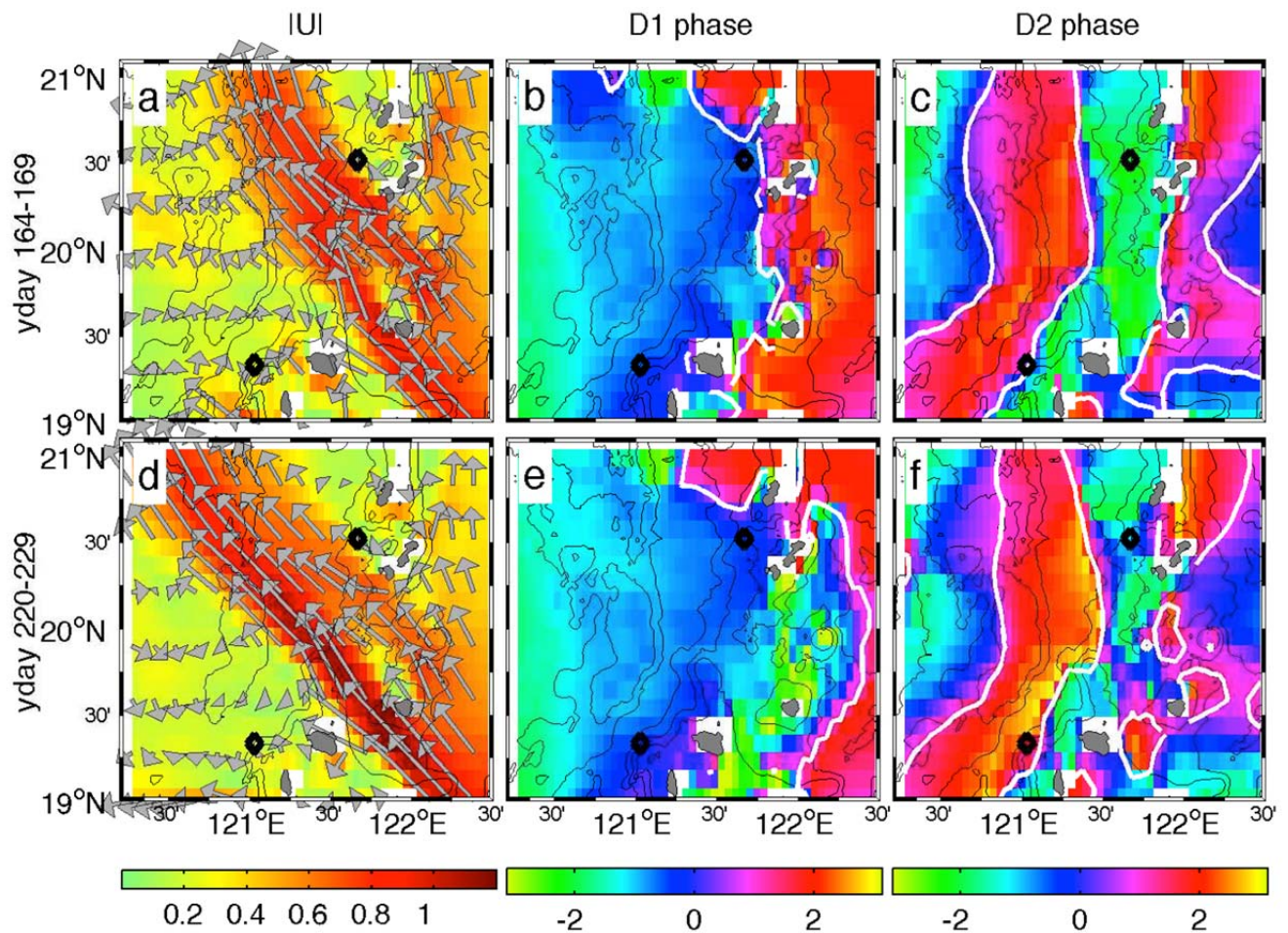
**Figure 2:** (a) Overview map showing Luzon Strait and surrounding region. (b,c) Time-mean energy flux vectors from MITgcm model (white, Buijsman), pilot observations (magenta), and main experiment moorings (blue). Observations were concentrated along a northern and southern line.



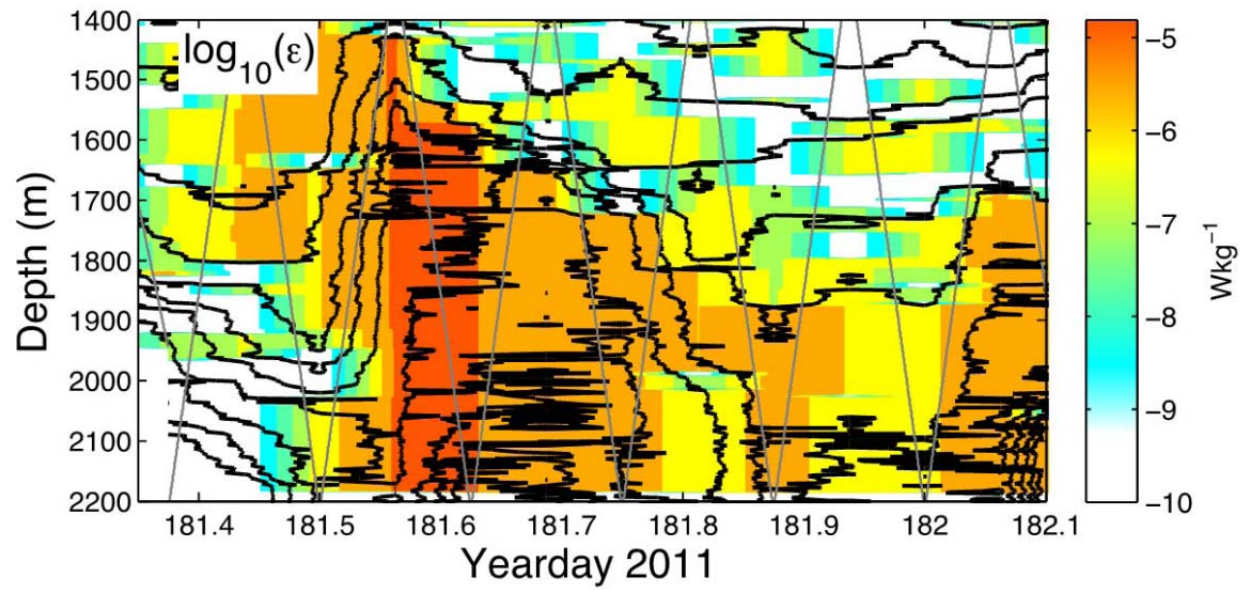
**Figure 3: Barotropic velocity, energy, and flux at moorings A1 and S9. (a) Barotropic velocity (blue) and amplitude of BT velocity, computed from sliding harmonic fit with 3 day window. (b) Depth-integrated energy (APE + HKE). (c) Depth-integrated energy flux. (d) Barotropic to baroclinic conversion.**



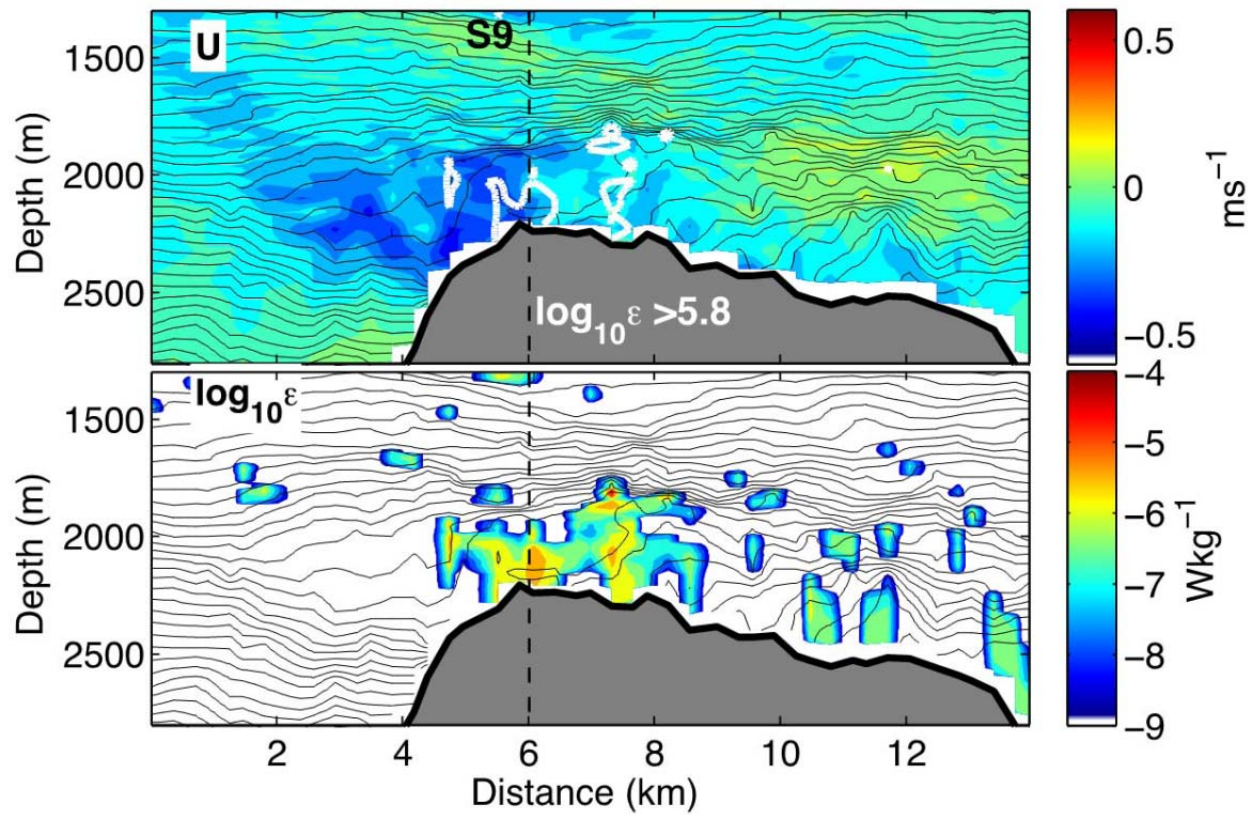
**Figure 4: Depth-integrated energy fluxes measured at moorings A1 (top) and S9 (bottom). Diurnal fluxes are shown on the left, and semidiurnal on the right. Color of vectors indicates time (yearday 2011). Yellow vectors are time-mean energy fluxes from the UAF model (Simmons).**



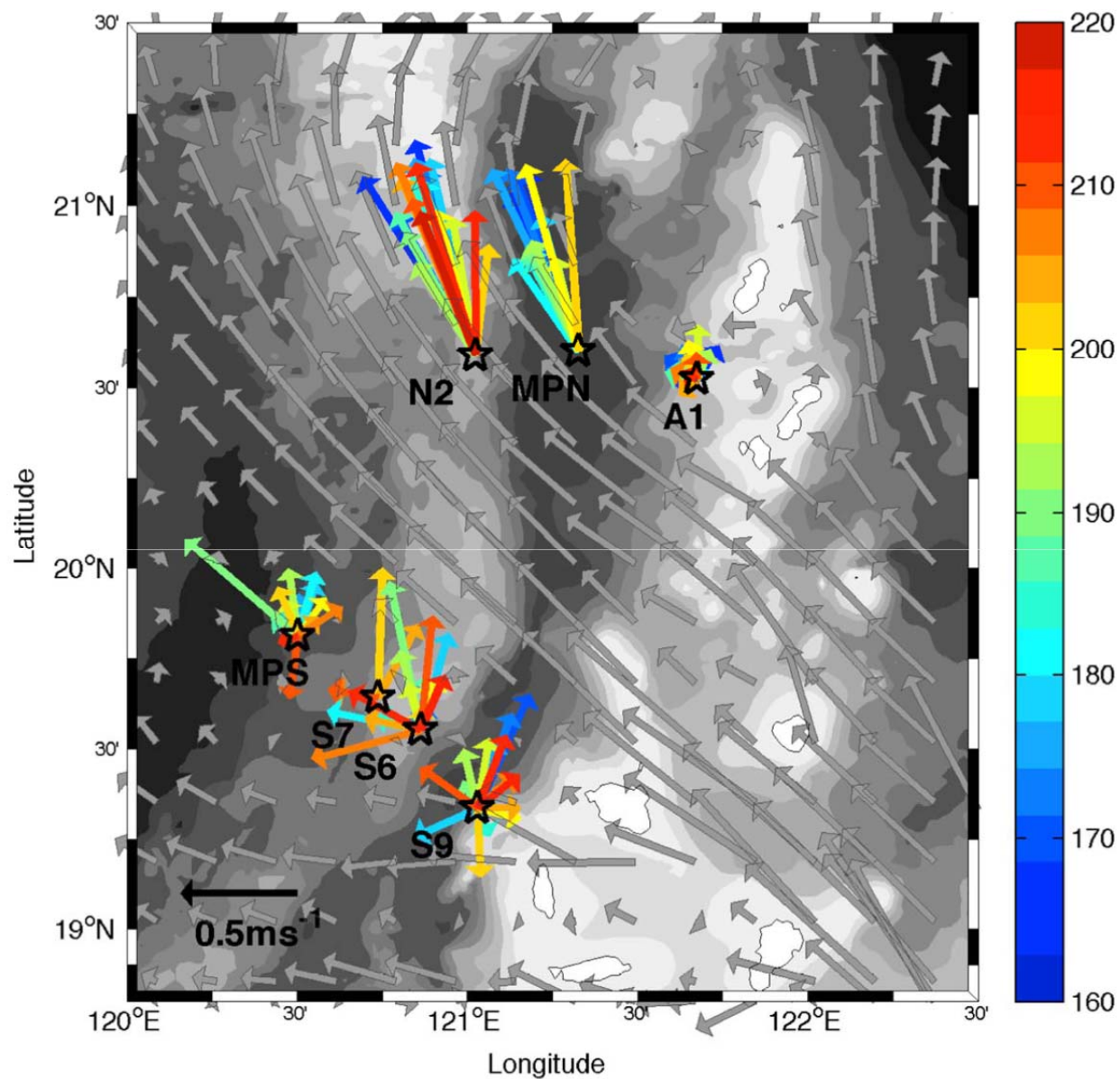
**Figure 5: Kuroshio and phase of baroclinic pressure in Luzon Strait during two different time periods (top row vs. bottom row). (a,d) Low-pass filtered velocity from LZS model in Luzon Strait. (b,e) Phase of mode-1 diurnal baroclinic pressure. The same contour is shown in white to illustrate shifting of the large scale pattern. (c,f) Same, but for semidiurnal frequency.**



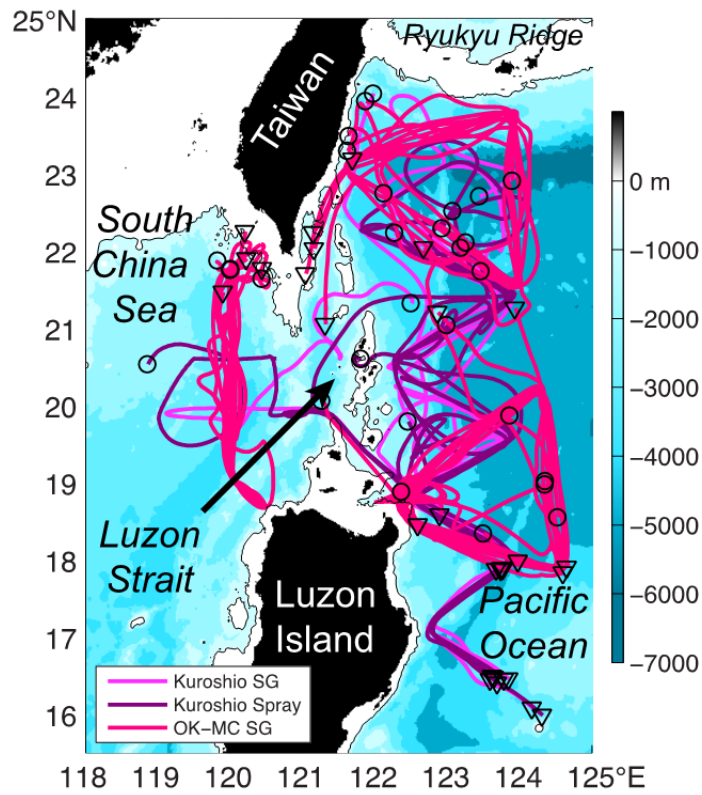
**Figure 6:** *Turbulent dissipation rate (color) inferred from density overturns at mooring S9. Black lines are isopycnals. Gray lines show the sawtooth sampling pattern of the moored profiler.*



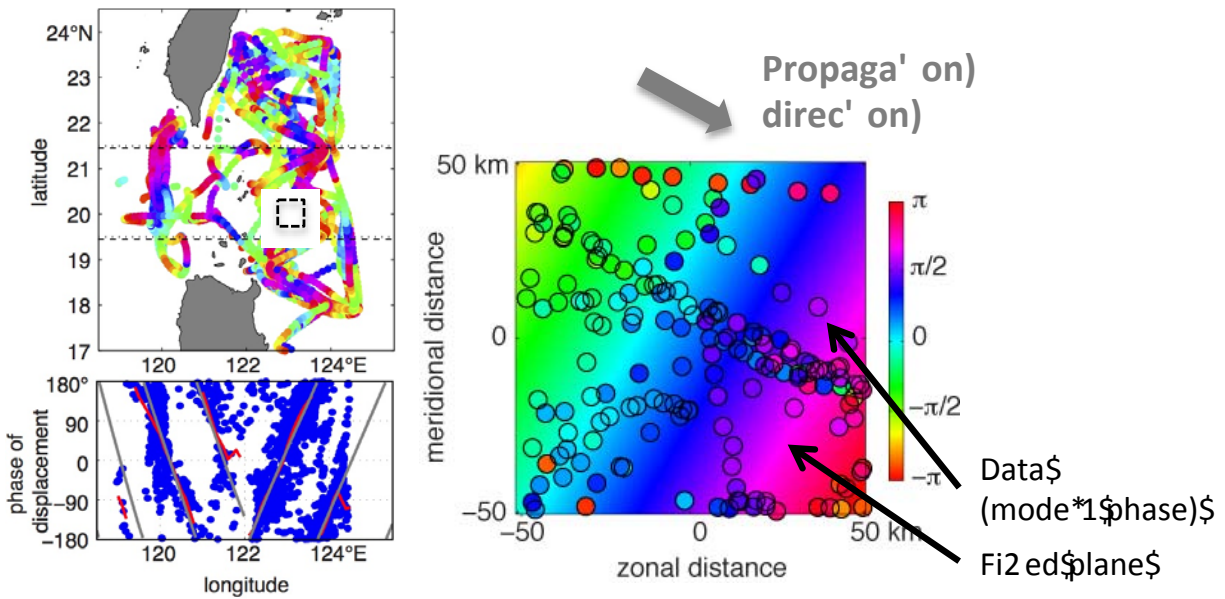
**Figure 7:** Snapshot from MITgcm model transect through mooring S9. (Top) zonal velocity and isotherms. Regions of high turbulent dissipation rate are contoured in white. (Lower) Turbulent dissipation rate (color) and isotherms.



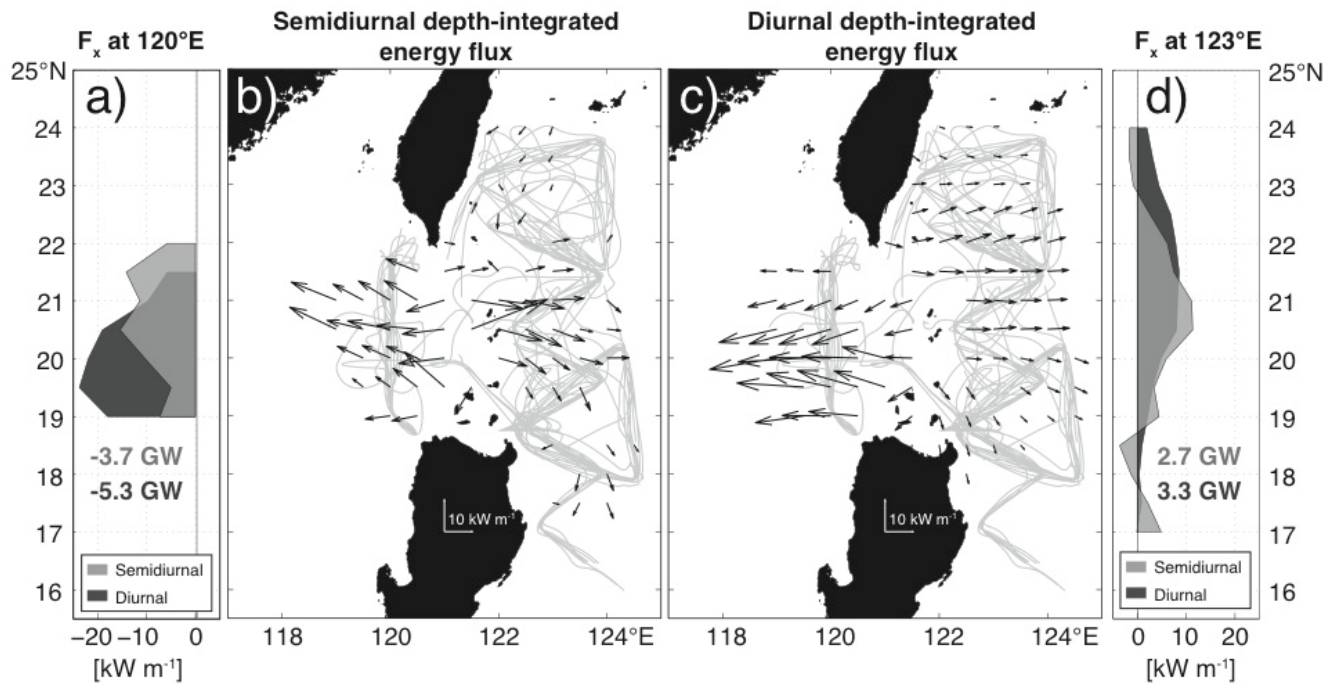
**Figure 8:** Low-passed velocity from moored ADCP's, averaged over the upper 150m. Vector colors indicate time (yearday 2011). Gray arrows are velocity at 150m from NRL EASNFS model provided by Dr.Ko, averaged over the duration of the mooring deployment. Note the strong and relatively constant northward flow over the western half of the northern line. Velocity scale is shown at lower left.



**Figure 9:** Tracks of the 29 glider missions used in this study, collected as part of the Kuroshio (Seagliders and Spray gliders) and OKMC (Seagliders only) projects. Launch and recovery positions are indicated by the triangles and circles, respectively.



**Figure 10: Top left: Phase of the semidiurnal internal tide at 500 m as a function of location. Estimates in Luzon Strait (between 19.5° and 21.5°) are plotted as function of longitude in the bottom panel, showing progression equal to the mode-1 phase speed (gray lines). The direction of propagation can be estimated by looking at the spatial variations of the phase.**



**Figure 11: Maps of the (b) semidiurnal and (c) diurnal mode-1 depth-integrated energy flux estimated from glider data alone. Glider tracks are shown in thin gray. The zonal energy fluxes along 120 and 123°E are shown in (a,d).**

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |                             |                                   |                                      | Form Approved<br>OMB No. 0704-0188                        |                                                             |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------|-----------------------------------|--------------------------------------|-----------------------------------------------------------|-------------------------------------------------------------|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. <b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b> |                             |                                   |                                      |                                                           |                                                             |
| 1. REPORT DATE (DD-MM-YYYY)<br>01-March-2016                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                             | 2. REPORT TYPE<br>Final Technical |                                      | 3. DATES COVERED (From - To)<br>01-Jan-2009 - 30-Jun-2015 |                                                             |
| 4. TITLE AND SUBTITLE<br>Moored Observations of Internal Wave Beams in Luzon Strait: 3-D Structure Dissipation and Evolution                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                             |                                   |                                      | 5a. CONTRACT NUMBER                                       |                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                   |                                      | 5b. GRANT NUMBER<br>N00014-09-1-0219                      |                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                   |                                      | 5c. PROGRAM ELEMENT NUMBER                                |                                                             |
| 6. AUTHOR(S)<br>Mathew Alford<br><br>Luc Rainville                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                             |                                   |                                      | 5d. PROJECT NUMBER                                        |                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                   |                                      | 5e. TASK NUMBER                                           |                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                   |                                      | 5f. WORK UNIT NUMBER                                      |                                                             |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>University of Washington - Applied Physics Laboratory<br>4333 Brooklyn Avenue NE<br>Seattle, WA 98105-6613                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |                             |                                   |                                      | 8. PERFORMING ORGANIZATION REPORT NUMBER                  |                                                             |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>Office of Naval Research (ONR32)<br>875 North Randolph Street<br>Arlington, VA 22203-1995                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                             |                                   |                                      | 10. SPONSOR/MONITOR'S ACRONYM(S)<br>ONR                   |                                                             |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                   |                                      | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)                    |                                                             |
| 12. DISTRIBUTION / AVAILABILITY STATEMENT<br><br>Distribution Statement A: Approved for public release; distribution is unlimited.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |                             |                                   |                                      |                                                           |                                                             |
| 13. SUPPLEMENTARY NOTES                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                             |                                   |                                      |                                                           |                                                             |
| 14. ABSTRACT<br>Knowledge of the general problems of internal waves and ocean mixing are 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 (particularly in straits) are severely impacted by internal waves. The research described here substantially improves both our understanding and predictive ability of linear internal tides and NLIWs in Luzon Strait and the South China Sea.                                                                                                                                                                                                                               |                             |                                   |                                      |                                                           |                                                             |
| 15. SUBJECT TERMS<br>Internal waves, ocean mixing, Luzon Strait, energy flux of internal tide                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                             |                                   |                                      |                                                           |                                                             |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                             |                                   | 17. LIMITATION OF ABSTRACT<br><br>UU | 18. NUMBER OF PAGES<br><br>16                             | 19a. NAME OF RESPONSIBLE PERSON<br>Mathew Alford            |
| a. REPORT<br>Unclassified                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 | b. ABSTRACT<br>Unclassified | c. THIS PAGE<br>Unclassified      |                                      |                                                           | 19b. TELEPHONE NUMBER (include area code)<br>(858) 246-1646 |