Generation and Evolution of Internal Waves in Luzon Strait

Ren-Chieh Lien
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, Washington 98105
Phone: (206) 685-1079 fax: (206) 543-6785 email: lien@apl.washington.edu

Frank Henyey
Applied Physics Laboratory
University of Washington
1013 NE 40th Street
Seattle, Washington 98105
Phone: (206) 543-4865 fax: (206) 543-6785 email: frank@apl.washington.edu

Award Number: N00014-09-1-0279

LONG-TERM GOALS

Our long-term scientific goals are to understand the dynamics and identify mechanisms of small-scale processes—i.e., internal tides, inertial waves, nonlinear internal waves (NLIWs), and turbulence mixing—in the ocean and thereby help develop improved parameterizations of mixing for ocean models. Mixing within the stratified ocean is a particular focus as the complex interplay of internal waves from a variety of sources and turbulence makes this a current locus of uncertainty. For this study, our focus is on the generation, propagation, evolution, and dissipation of small-scale internal waves and internal tides as the Kuroshio and barotropic tides interact with the two prominent submarine ridges in Luzon Strait.

OBJECTIVES

The primary objectives of this observational program are to quantify 1) the generation of NLIWs and internal tides in the vicinity of Luzon Strait, 2) the energy flux of NLIWs and internal tides into the Pacific Ocean and South China Sea (SCS), 3) the effects of the Kuroshio on the generation and propagation of NLIWs and internal tides, 4) the seasonal variation of NLIWs and internal tides, and 5) to study other small-scale processes, e.g., hydraulics and instabilities along internal tidal beams and at the Kuroshio front.

APPROACH

<u>Near-field</u>

In the Luzon Strait (Fig. 1), observations were taken using the combined 600-m-long towed CTD chain (TOWCTD) equipped with 40 CTD sensors and the Doppler sonar on the R/V *Revelle*. These instruments took high-frequency, Δt <1 min, and high vertical resolution, Δz = 5−20 m, measurements of temperature, salinity, and density, and oceanic velocity from near the surface to ~600-m depth.

Far-field

Full water column velocity and temperature observations were taken using one subsurface mooring with a near-bottom upward-looking 75-kHz ADCP and one surface mooring with three ADCPs, temperature loggers, and a series of CTD sensors at a sampling rate of Δt = 1 min, capable of measuring internal tides and NLIWs on the continental slope east of Dongsha Island, ~200 n mi west of Luzon Strait (Fig. 1).

WORK COMPLETED

Near-field Experiment

From 25 July through 4 August 2011, we conducted an intensive survey in the Luzon Strait using a 600-m-long towed system (TOWCTD) equipped with 20–40 CTD sensors. The TOWCTD was developed specifically for this experiment. It provides CTD observations via inductive modem allowing us to identify the energetic small-scale processes in real time. All CTD sensors sample temperature, salinity, and pressure at a 10-s interval. The primary scientific objectives of this cruise were 1) to measure nonlinear internal waves in Babuyan channel, 2) to measure lee waves behind the sill west of Babuyan channel, 3) to quantify internal tide generation in southern Luzon Strait, and 4) to measure internal tide evolution in southern Luzon Strait.

Far-field Experiment

One surface buoy mooring (TC1), one subsurface mooring (TC2), and two bottom pressure moorings (TC1-BPR and TC2-BPR) were deployed on the Dongsha slope from the Taiwanese R/V *Ocean Researcher 1* on 27–31 May 2011. The surface and subsurface moorings were placed 6 km apart on the slope. Three ADCPs, fourteen CTD sensors, and three temperature loggers were equipped on the surface mooring (TC1). The subsurface mooring (TC2) was equipped with one 75-kHz ADCP, ten temperature sensors, and three CTD sensors. On 1–6 June 2011 the surface and subsurface moorings were recovered by the Taiwanese R/V *Ocean Researcher 2*. The subsurface mooring was redeployed with an upward-looking 75-kHz ADCP, without temperature or CTD sensors. It was recovered in August 2011 by the R/V *Ocean Researcher 3*.

Analysis

We analyzed measurements taken by the TOWCTD and moorings during the 2011 intensive survey, as well as the earlier mooring measurements taken in the far field.

RESULTS

Properties and Energetics of Internal Solitary Waves

Five large-amplitude internal solitary waves (ISWs) propagating westward on the upper continental slope in the northern South China Sea were observed by moored and shipboard instruments in

May–June 2011 with nearly full-depth measurements of velocity, temperature, salinity, and density (Fig. 2). As they shoaled at least three waves reached the convective breaking limit: along-wave current velocity exceeded the wave propagation speed *C* (Fig. 3). Vertical overturns of ~100 m were observed within the wave cores; estimated turbulent kinetic energy was up to 1.5 x 10^{-4} W kg^{-1}. In the cores and at the pycnocline, the gradient Richardson number was mostly < 0.25. The maximum ISW vertical displacement was 173 m, 38% of the water depth. Observed ISWs had greater available potential energy (*APE*) than kinetic energy (*KE*). The energy flux nearly equaled the *CE*, where *C* is the wave propagation speed and *E* the wave total energy. The Dubriel–Jacotin–Long model with and without a background shear predicts neither the observed *APE* > *KE* nor the subsurface maximum of the along-wave velocity for shoaling ISWs, but does simulate the total energy and the wave shape. Including the background shear in the model leads to the formation of a surface trapped core.

<u>Convective Instability of ISWs</u>

To further explore the interannual variability of ISWs in the region, we analyzed three sets of mooring measurements taken over nearly one year in 2006–2007 at the upper flank of the continental slope east of Dongsha plateau. The convective instability condition of ISWs at two mooring sites (LR1 in water depth 600 m and LR2 in water depth 430 m) was examined (Fig. 4). LR2 was located near the 2011 far-field experiment surface mooring site. Over the observation period (June 2006 – May 2007) 25% of ISWs at LR2 encountered convective instability, and the occurrence had a fortnightly cycle. At LR1 only 6% of ISWs encountered convective instability. During fall and spring, the convective instability was observed less often.

<u>Watermass Anomaly Spectra</u>

Previous studies found that salinity anomaly gradient spectra along isopycnals are approximately flat over the horizontal wavelengths from 30 m to 10 km (Kunze et al. 2015). Observations taken from the towed CTD chain in Luzon Strait provide high vertical resolution of salinity anomalies at horizontal scales between 10 m and 10 km. In contrast to previous studies, salinity anomaly gradient spectra in Luzon Strait often showed an increase (blue spectral shape) around 1 cpkm and become flat at higher horizontal wavenumbers (Fig. 5). Processes responsible for the salinity anomaly gradient increase above 1 cpkm are to be determined.

IMPACT/APPLICATION

Numerical models suggest strong internal tides are generated as barotropic tides interact with two prominent submarine ridges in the Luzon Strait. These internal tides are believed to be the sources of nonlinear internal waves often observed in the South China Sea. The strength of internal tides is modulated by the barotropic tidal forcing, the strength of the Kuroshio current, the background stratification, and the strength of the Kuroshio front. It is important to quantify the barotropic to baroclinic tidal energy conversion, dissipation within the Luzon Strait, the energy fluxes toward the South China Sea and Pacific Ocean, and the ultimate fate of the internal tidal energy.

RELATED PROJECTS

<u>Studying the Origin of the Kuroshio with an Array of ADCP-CTD Moorings (N00014-10-1-0397) as a part of the OKMC DRI</u>: The primary objectives of this observational program are to quantify the

origin of the Kuroshio, to quantify its properties at the origin and as it evolves downstream, and to study the effects of mesoscale eddies on Kuroshio transport. Kuroshio transport off Luzon is computed using direct velocity measurements from a moored array. The annual mean transport is 15 Sv. Large variations of >10 Sv within 10s of days are caused by westward propagating eddies interacting with the Kuroshio.

PUBLICATIONS (wholly or in part supported by this grant)

Alford et al. (2015). The formation and fate of internal waves in the South China Sea, *Nature*, **521**, 65–69, doi:10.1038/nature14399.

Kunze, E., J. M. Klymak, R.-C. Lien, R. Ferrari, C. M. Lee, M. A. Sundermeyer, and L. Goodman (2015). Submesoscale water-mass spectra in the Sargasso Sea, *J. Phys., Oceanogr.*, **45**, 1325–1338. doi: 10.1175/JPO-D-14-0108.1. [published, refereed]

Lien, R.-C., F. Henyey, B. Ma, and Y.J. Yang (2014). Large-amplitude internal solitary waves observed in the northern South China Sea: Properties and energetics, *J. Phys. Oceanogr.*, **44**, 1095–1115, doi: 10.1175/JPO-D-13-088.1. [published, refereed]

Ma, B., R.-C. Lien, and D. S. Ko (2013). The variability of internal tides in the Northern South China Sea, *J. Oceanogr*., **69**, 619–650, doi: 10.1007/s10872-013-0198-0. [published, refereed]

Lien, R.-C., E.A. D'Asaro, F. Henyey, M.-H. Chang, T.-Y. Tang, Y.-J. Yang (2012). Trapped core formation within a shoaling nonlinear internal wave, *J. Phys. Oceanogr.*, **42**, 511–525, doi: 10.1175/2011JPO4578.1. [published, refereed]

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**, 64–77, doi: 10.5670/oceanog.2011.95. [published, refereed]

Chang, M.-H., R.-C. Lien, Y.-J. Yang, and T.-Y. Tang (2011). Nonlinear internal wave properties estimated with moored ADCP measurements, *J. Atmos. Ocean. Technol.*, **28**, 802–815, doi: 10.1175/2010JTECHO814.1. [published, refereed]

Klymak, J. M., M. H. Alford, R. Pinkel, R.-C. Lien, Y.-J. Yang, and T.-Y. Tang (2011). The breaking and scattering of the internal tide on a continental slope, *J. Phys. Oceanogr.*, **41**, 926–945, doi: 10.1175/2010JPO4500.1. [published, refereed]

Alford, M. H., R.-C. Lien, H. Simmons, J. Klymak, S. Ramp, Y.-J. Yang, D. Tang, and M.-H. Chang (2010). Speed and evolution of nonlinear internal waves transiting the South China Sea, *J. Phys. Oceanogr.*, **40**, 1338–1355, doi: 10.1175/2010JPO4388.1. [published, refereed]

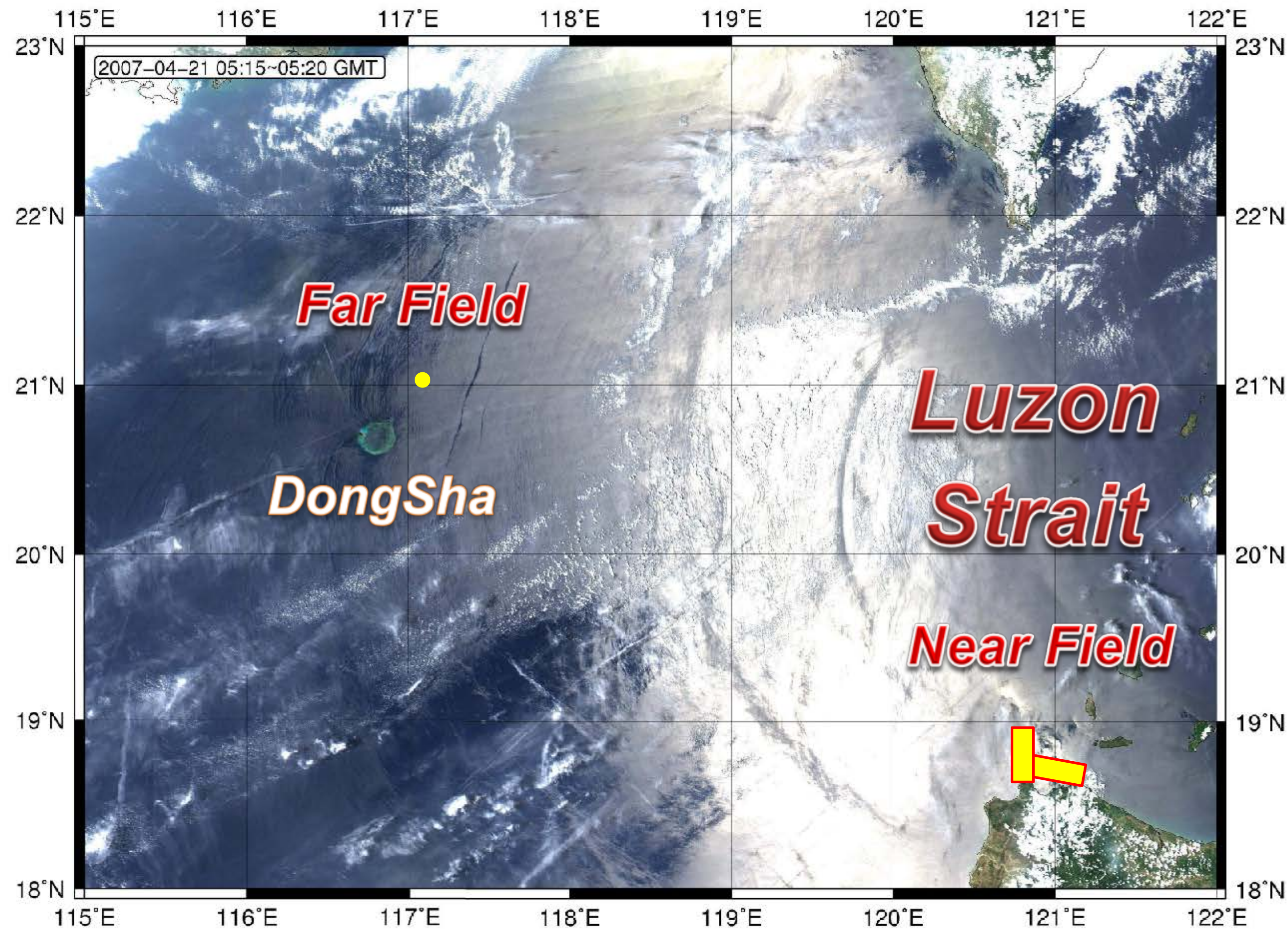

Figure 1. MODIS image taken in 2007 and the general area of near-field and far-field experiments. The near-field was performed using a towed CTD chain (TOWCTD) during 25 July – 4 August 2011 in the southern Luzon Strait (the two yellow boxes). The far-field was performed using a surface mooring and a subsurface mooring (yellow dot).

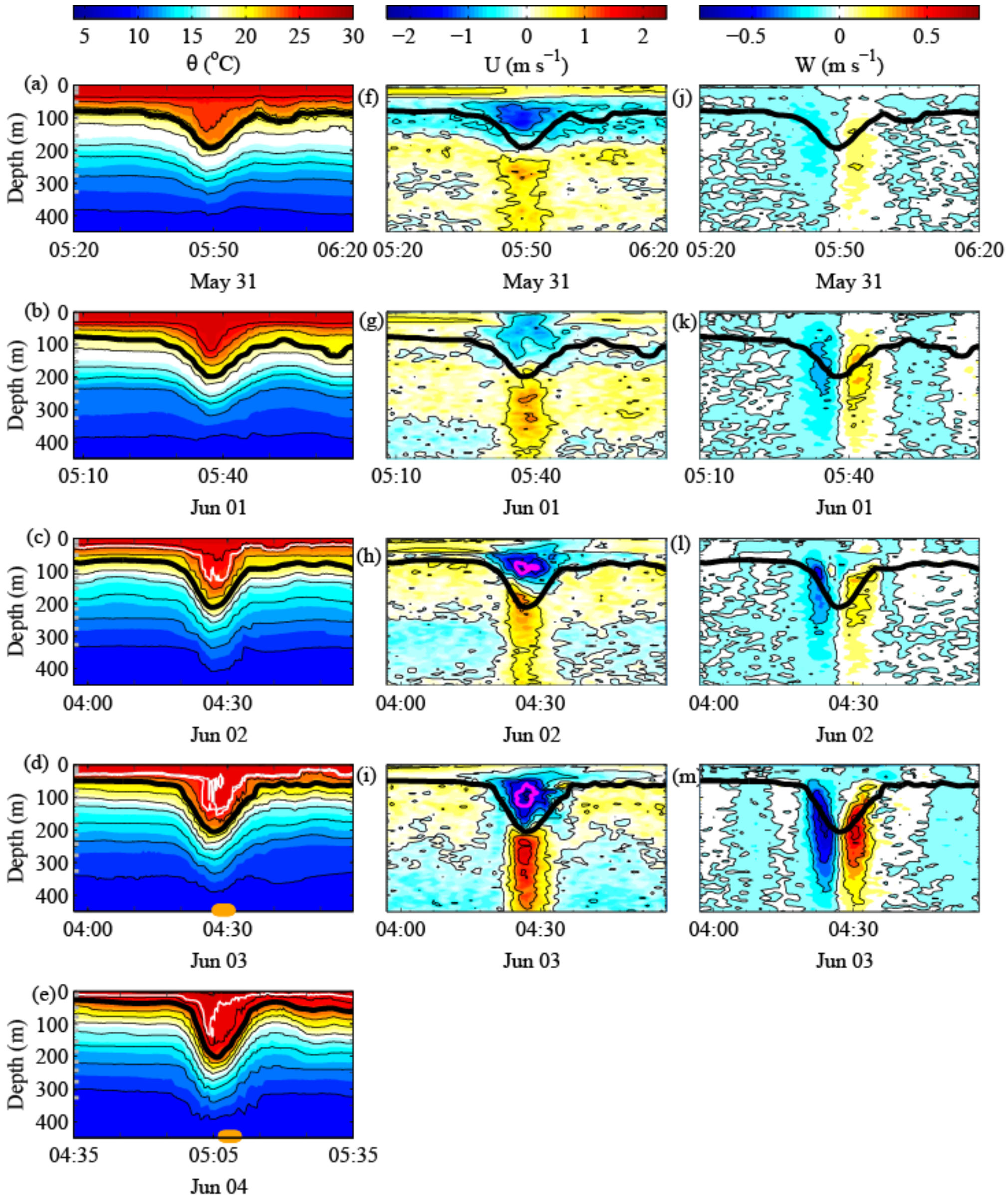

Figure 2. Contour plots of temperature (a–e), along-wave velocity (f–i), and vertical velocity (j–m) of five ISWs observed 31 May–4 June 2011. Thick black curves represent the isopycnal of the maximum vertical displacement. The magenta curves in panels (h) and (i) are contours of the wave propagation velocity. Within the magenta contours, the current velocity is greater than the wave propagation velocity, indicating convective instability. The brown dots in panels (d) and (e) represent near bottom gravitational instability events behind the waves.

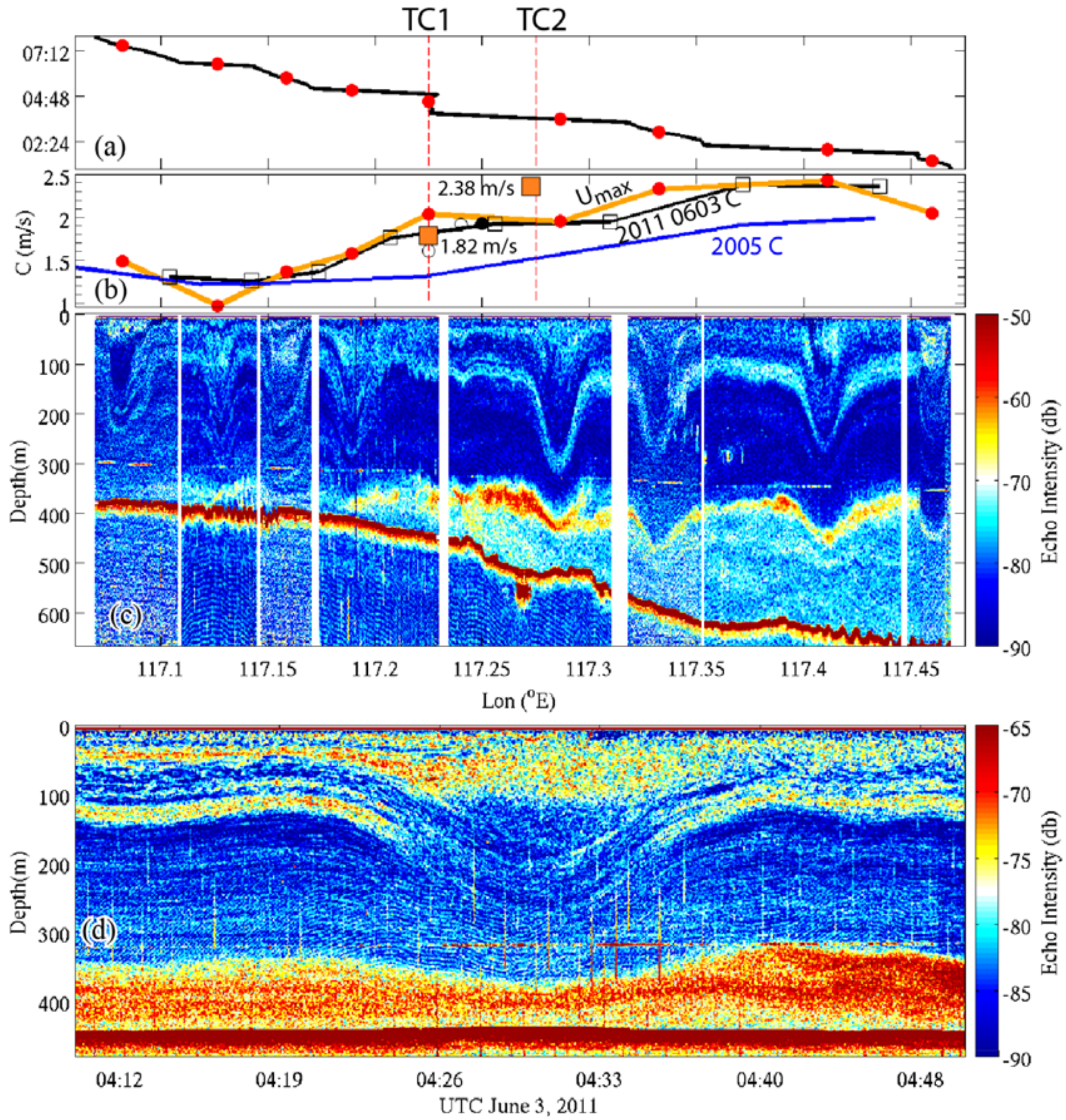

Figure 3. Echo sounder measurements of an ISW taken on 3 June 2011 as the R/V Ocean Researcher 3 tracked the wave. Panel (a) shows the ship track as a function of time and longitude. The red dots indicate the time and longitude of the center of the wave. The black curve and black squares in panel (b) show the wave propagation speed computed from the positions and times of the wave center, and the brown curve with the red dots represents the maximum along-wave velocity. The black dot shows the estimate of wave propagation speed computed using the difference of arrival time on the subsurface and surface moorings. Two brown squares show the wave propagation speed computed using the shipboard radar. The blue curve shows the propagation speed of a similar wave observed at the same location in 2005 (Lien et al., J. Phys. Oceanogr., 42, 511-525, 2012). Panel (c) shows the echo sounder images during eight encounters with the wave. Panel (d) shows the echo sounder during the 5th encounter when the ship was maintained on station about 4 km north of the surface mooring. The two vertical lines on panels (a) and (b) mark the positions of the surface mooring (TC1) and the subsurface mooring (TC2).

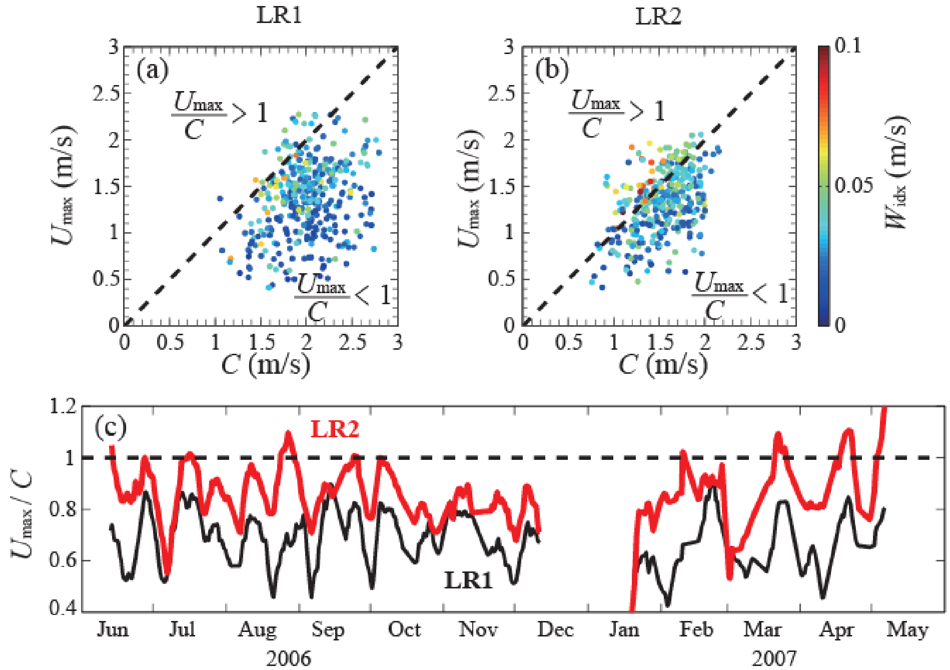

Figure 4. Scatter plots between maximum current velocity, U_{max}, and propagation speed C of ISWs observed at two mooring sites, (a) LR1 and (b) LR2. W_{idx} is the vertical speed averaged during the wave period. Panel (c) shows the temporal variation of the convective instability condition at LR1 and LR2. The dashed lines indicate $U_{max}/C = 1$.

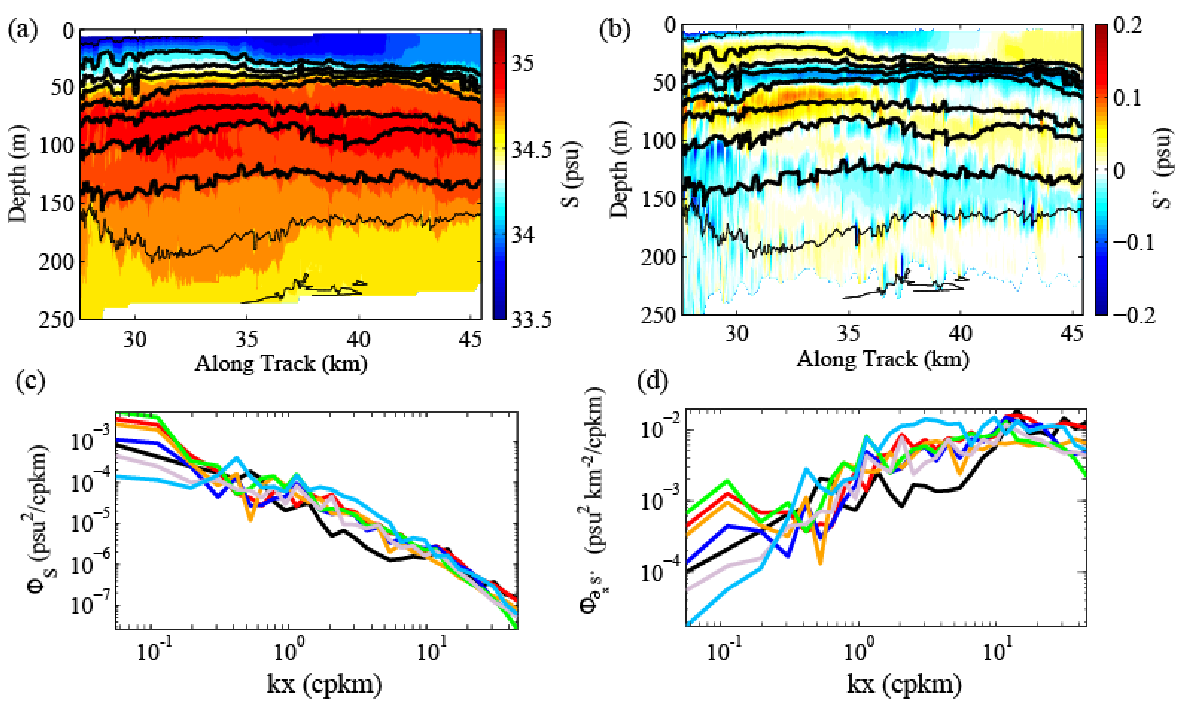

Figure 5. Watermass anomaly gradient spectra computed from measurements taken by towed CTD chain in Babuyan Channel. (a) Salinity contour, (b) salinity anomaly on isopycnal surfaces, (c) salinity spectra on isopycnals, and (d) salinity gradient spectra on isopycnals. Black curves in panels (a) and (b) represent isopycnals.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* March 2016	**2. REPORT TYPE** Final Technical	**3. DATES COVERED** *(From - To)* 1 Jan 2009 – 31 Dec 2015

4. TITLE AND SUBTITLE Generation and Evolution of Internal Waves in Luzon Strait	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER N00014-09-1-0279
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Ren-Chieh Lien	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Washington – Applied Physics Laboratory 4333 Brooklyn Avenue NE Seattle, WA 98105-6613	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research (ONR 32) 875 North Randolph Street Arlington, VA 22203-1995	**10. SPONSOR/MONITOR'S ACRONYM(S)** ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The primary objectives of this observational program are to quantify 1) the generation of NLIWs and internal tides in the vicinity of Luzon Strait, 2) the energy flux of NLIWs and internal tides into the Pacific Ocean and South China Sea (SCS), 3) the effects of the Kuroshio on the generation and propagation of NLIWs and internal tides, 4) the seasonal variation of NLIWs and internal tides, and 5) to study other small-scale processes, e.g., hydraulics and instabilities along internal tidal beams and at the Kuroshio front.

15. SUBJECT TERMS

Internal tides, inertial waves, nonlinear internal waves, turbulence mixing

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Ren-chieh Lien
a. REPORT Unclassified	**b. ABSTRACT** Unclassified	**c. THIS PAGE** Unclassified	UU	8	**19b. TELEPHONE NUMBER** *(include area code)* 206-685-1079