Nonlinear Internal Waves From Luzon Strait

In the northeastern South China Sea, fast westward moving nonlinear internal waves (NLIWs) emanate nearly daily from the Luzon Strait during spring tide. Their propagation speed of about 2.9 meters per second is faster than NLIWs previously observed in the world's oceans. The amplitudes of these waves reach 140 meters or more, and they are the largest free propagating NLIWs observed to date in the interior ocean. These NLIWs energize the top 1500 meters of the water column, moving water up and down at timescales as short as 20 minutes. While their associated energy density and energy flux are the largest observed to date, the exact source of these giant waves has yet to be determined.

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NLIWs, which are often found in shelf regions, typically are thought to be generated either by tidal currents [*Alpers*, 1985] that flow over steep topography (such as sills, seamounts, or shelf breaks) or sometimes by the instability of current shears. Most synthetic aperture radar (SAR) images of the northern South China Sea show NLIWs [*Hsu et al.*, 2000], but the best SAR image of NLIWs in the Luzon Strait is the European Remote Sensing Satellite ERS-1 SAR image of 16 June 1995 (http://sol.oc.ntu.edu.tw/IW/1995/ERS1.htm). This image shows that features of NLIWs in the deep Luzon Strait are quite different from those over the shallow East China Sea shelf near Taiwan [*Liu et al.*, 1994]. Existing theories and field studies [*Liu et al.*, 1998] point to the generation of NLIW in shallow water regime from point source, but are insufficient to explain the location (no sill or shelf break nearby), shape, and size of Luzon Strait NLIWs in that SAR image.

NLIWs account for a significant portion of the tidal energy budget, and understanding NLIWs is important for studies of the energy balance of tidal motions and underwater sound propagation. The dissipation of NLIWs also has biogeochemical effects. They may resuspend sediment and mix seawater across the thermocline, thereby pumping nutrients upward to the oligotrophic surface water to sustain biological growth. Furthermore, the high speeds of NLIWs pose a threat to offshore drilling platforms, and their large vertical motions can affect underwater moving vehicles.

To study the existence, generation, and propagation of NLIWs in the South China Sea, a satellite and field investigation was carried out in the source region, Luzon Strait, during the springs of 2005 and 2006.

Possible Origins of NLIWs in the Luzon Strait

In studying ocean waves that can move offshore platforms, *Bole et al.* [1994] hypothesized that the NLIWs in the northern South China Sea originate from sills that

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form saddle-like topography between the Batan Islands, just as the NLIWs of the Sulu Sea [*Apel et al.*, 1985] originate from the sills between islands southeast of the Sulu Sea. This hypothesis has two major difficulties in explaining the 16 June 1995 ERS-1 SAR image. First, the sills between the Batan Islands (Batans) do not seem to be the centers of arcs of the NLIW fronts in the SAR image. Second, most NLIWs can be traced within 30 kilometers of their source region (sill or sea mount), but there are no NLIWs that have been observed within 120 kilometers of the sills between the Batans.

An alternative hypothesis for NLIW generation is the instability of the western boundary of the Kuroshio Current (the largest current in the Pacific Ocean), which flows along the east coast of Luzon and Taiwan, and curves in and out of Luzon Strait before reaching Taiwan. However, this hypothesis has difficulty in explaining the misalignment between the western boundary of the Kuroshio, which runs northwest-southeast, and the NLIWs, which are aligned north-south.

The Hengchun Ridge (HCR), at a depth of more than 1200 meters below sea level, may serve as a deep 'sill' for NLIW generation. The HCR is far deeper than most sills that generate NLIWs, and there is also a slight misalignment between the SAR NLIW image and the top of the HCR. However, the shapes of NLIWs in Luzon Strait align with the eastern slope of the HCR (Figure 1a). This slope represents the steepest bathymetry in Luzon Strait, and therefore it is an excellent location for generating waves.

Observing Waves in the Luzon Strait

Along 21°N latitude, ERS SAR images taken from 1994 to 2004 show abundant NLIWs west of 118°E, but few east of 118°E to HCR, and none between HCR and the Batans. Many hypotheses were raised on the generation mechanism and source regions of NLIWs west of 118°E, and on the scarcity of NLIWs east of 118°E. To search for and characterize NLIWs east of 118°E, interested scientists planned a five-ship field survey across Luzon Strait in April-May 2005.

This field and satellite observation program was designed to locate and quantify the occasionally appearing NLIWs from the Luzon Strait. The observations from April 18 to May 15 of 2005 include components to (1) examine satellite SAR coverage (ERS-2, Envisat, and RADARSAT) for the surface manifestation of NLIWs, as well as analyze optical images from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua and Terra satellites; (2) track NLIWs with a profiling conductivity-temperature-depth (CTD) and deep Doppler sonar from the research vessel (R/V) *Roger Revelle*; (3) deploy thermistor-chains (T-chain) at (21°N, 121.25°E) from the R/V *Fishery Researcher 1* to detect any NLIW signal between HCR and the Batans; and (4) deploy three T-chains (strings of temperature-depth loggers) west of HCR (on Fishing Boat 1, Fishing Boat 2, and the R/V *Ocean Researcher 3*) to observe the westward propagation of NLIWs from Luzon Strait.

NLIWs were spotted on a 25 April 2005 RADARSAT SAR image at near real-time mode. The R/V *Roger Revelle* was alerted and subsequently mapped a 1000-meter-deep NLIW with a 48-kilohertz sonar. Figure 1b shows the downward displacement of scattering layers in the top 1000 meters during the passing of NLIWs on 27 April 2005. Satellite images from RADARSAT SAR and Aqua MODIS (Figure 2) also reveal the propagation of NLIWs west of the Luzon Strait. The time and longitude of NLIWs along 20.4°N are listed in Table 1 as they were observed by satellite images and T-chains from ships on 11–13 May 2005. Regression analysis shows that NLIWs propagated westward from Luzon Strait at an average speed of 2.9 ± 0.1 meters per second.

Thus, NLIWs are grown out of internal tidal (IT) waves that have peak energy density between HCR and the Batans. There are two possibilities for not finding NLIWs between HCR and the Batans: They could form and mature west of the HCR, or form near the Batans but not yet mature before passing the HCR. Additional observations of the energy flux of internal tides in the Luzon Strait are needed.

The satellite images of large NLIWs were verified with the ship measurements in Figure 3, which plots temperature profiles as a function of time, that were observed by T-chains from Fishing Boat 1 near (20.4°N, 119°E) and Fishing Boat 2 near (20.4°N, 120°E). Westward propagating large-amplitude (over 140 meters) NLIWs first passed Fishing Boat 2 at 120°E and then passed Fishing Boat 1 at 119°E with a 10-hour lag. The same NLIWs also were observed by an acoustic Doppler current profiler of R/V *Ocean Researcher 3* at (20°N, 120.5°E), by sonars (Figure 1) of R/V *Roger Revelle* near (20.5°N, 119.5°E), and by satellites (Table 1).

In summary, the field and satellite observations verified hypotheses that NLIW in the South China Sea do exist and that they propagate westward to the shallow region west of 118°E. The most likely source region of these giant NLIWs in the South China Sea is the near 2000-meter-deep HCR, instead of the shallow sill between the Batans. One unexpected observation is the amplitude (>140 meters) of the NLIWs, which is the largest in the deep ocean, and their propagation speed, which is among the fastest recorded for NLIWs. Their fast speed (about 260 km/day in the open South China Sea) is the reason why few images of ERS SAR caught them; the swath of ERS SAR is only 100 kilometers, while the gap between two consecutive ERS orbits is about 2700 kilometers.

Opportunities for Further Study

The results of the above studies revealed that daily trains of giant NLIWs emanate from Luzon Strait. Early results from related cruises in May and June 2006 confirm that these giant NLIWs emanate westward from Hengchun Ridge (120.8°E) nearly daily during spring tide.

However, the relative contribution of the Batans (122°E) need to be studied further in upcoming field experiments, planned for 2007. These experiments will involve deploying a line of acoustic Doppler current profiler moorings, and surveying with deep-penetrating sonar and CTD measurements in order to capture the NLIWs in the top 1000 meters of the water column. Modeling studies will help to explain the data from the complex and energetic marine environment of the Luzon Strait.

Acknowledgments

We dedicate this article to our late friend John Apel, who pioneered the study of NLIWs

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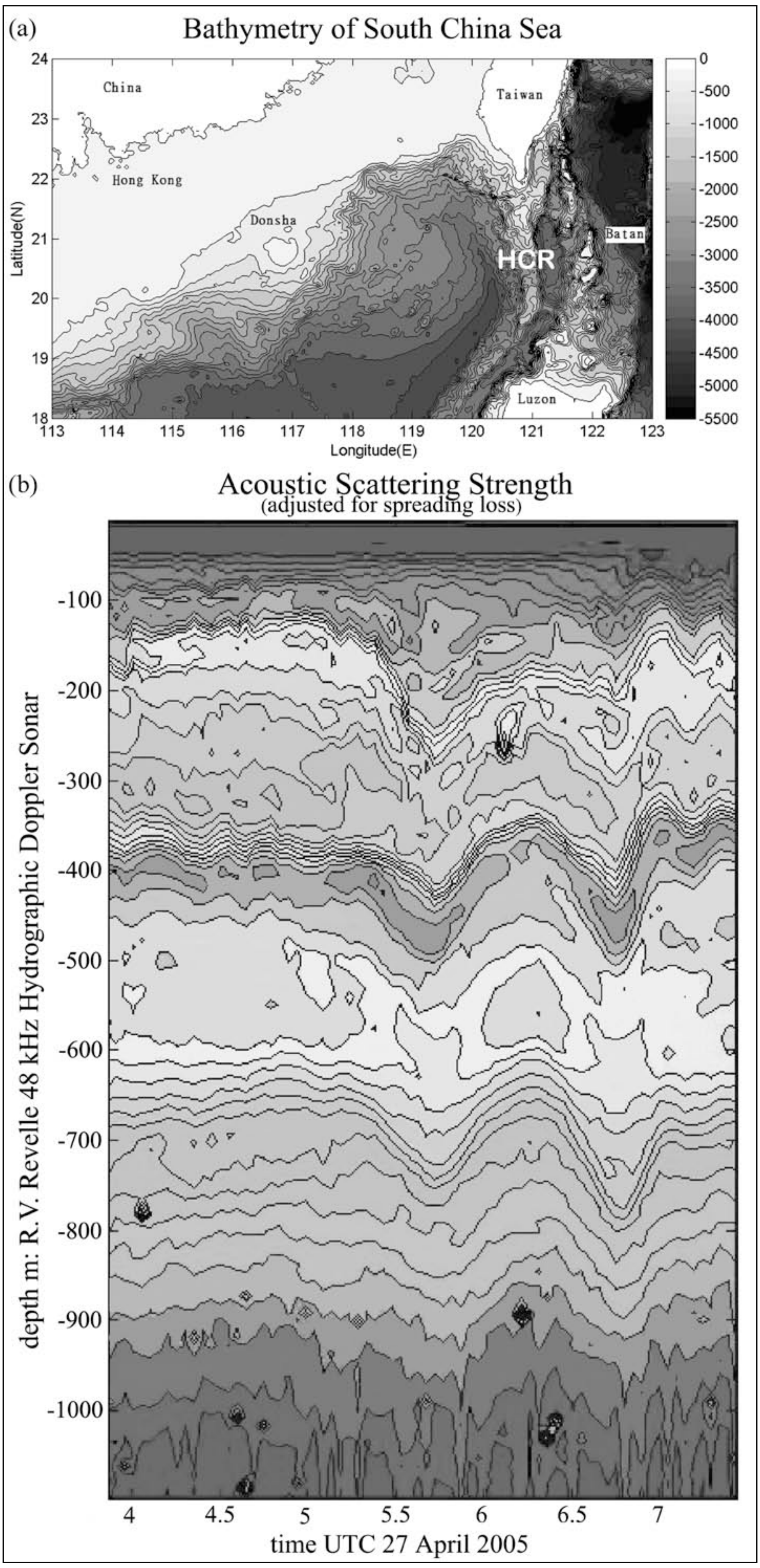

Fig. 1. (a) Bathymetry of the South China Sea. Gray color table is depth in meters. (b) Nonlinear internal waves (NLIWs) from Hengchun Ridge were mapped with 48-kilohertz sonar on the R/V Roger Revelle *at (119.6°E, 20.5°N) in April–May 2005. Contours are isolines of equal acoustic scattering strength corrected for spherical spreading.*

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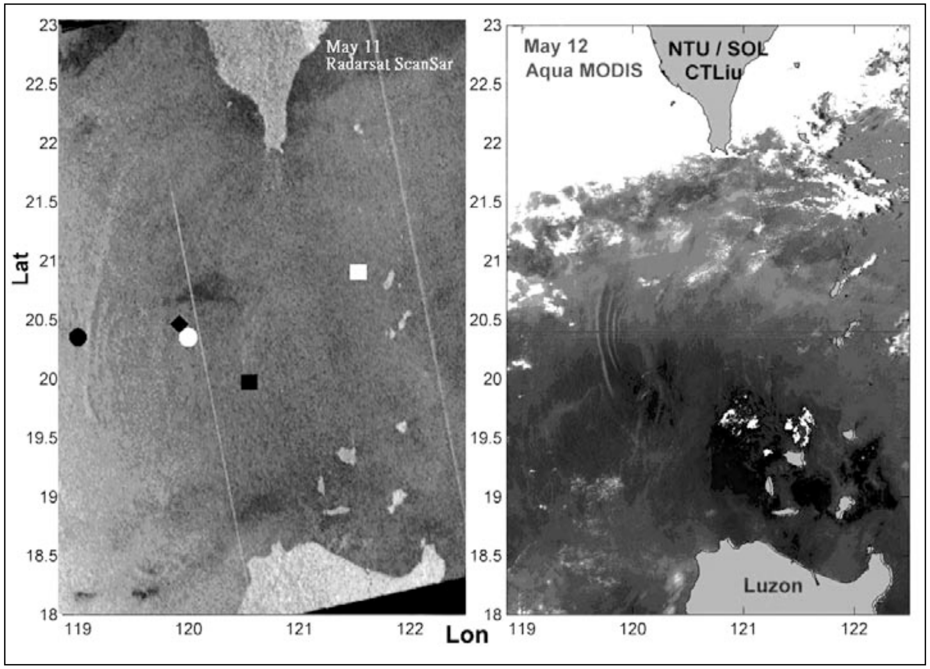

Fig. 2. RADARSAT ScanSAR image (from the Formosa Remote Sensing Center of Taiwan) of 11 May 2005 and MODIS image of 12 May 2005 west of Luzon Strait. NLIW fronts are packets of bright and dark lines. The markers are ship locations on 11 May 2005: solid circle, Fishing Boat 1 (20.4°N, 119°E); open circle, Fishing Boat 2 (20.4°N, 120°E); diamond Roger Revelle *(20.5°N 119.9°E), solid square,* Ocean Researcher 3 *(20°N, 120.5°E), and open square,* Fishery Researcher 1 *(21°N, 121.25°E).*

with field as well as satellite observations. We are grateful to Ruo-Shuan Tseng and Yu-Huai Wang (National Sun Yat-sen University, Kaohsiung, Taiwan), who led R/V *Ocean Researcher 3* and *Fishery Researcher 1* cruises; Laura David (University of the Philippines, Manila), who arranged the permission for research vessels to enter Filipino waters; Yih Yang [National Taiwan University (NTU)] for preparing the T-chains; Chin-Hsi Nan (NTU) for providing MODIS data; Yuen-Jie Chyou and Chang-Wei Lee (NTU), who led the fishing boats; and Antony K. Liu (Office of Naval Research Global-Asia), who guided our study and suggested the title of this paper. Thanks also go to the Formosa Remote Sensing Center for RADARSAT SAR images, the European Space Agency for ERS-1 and Envisat SAR images, and NASA for MODIS images. This study was cosponsored by the National Science Council of the Republic of China, the U.S. Office of Naval Research, and the University of the Philippines.

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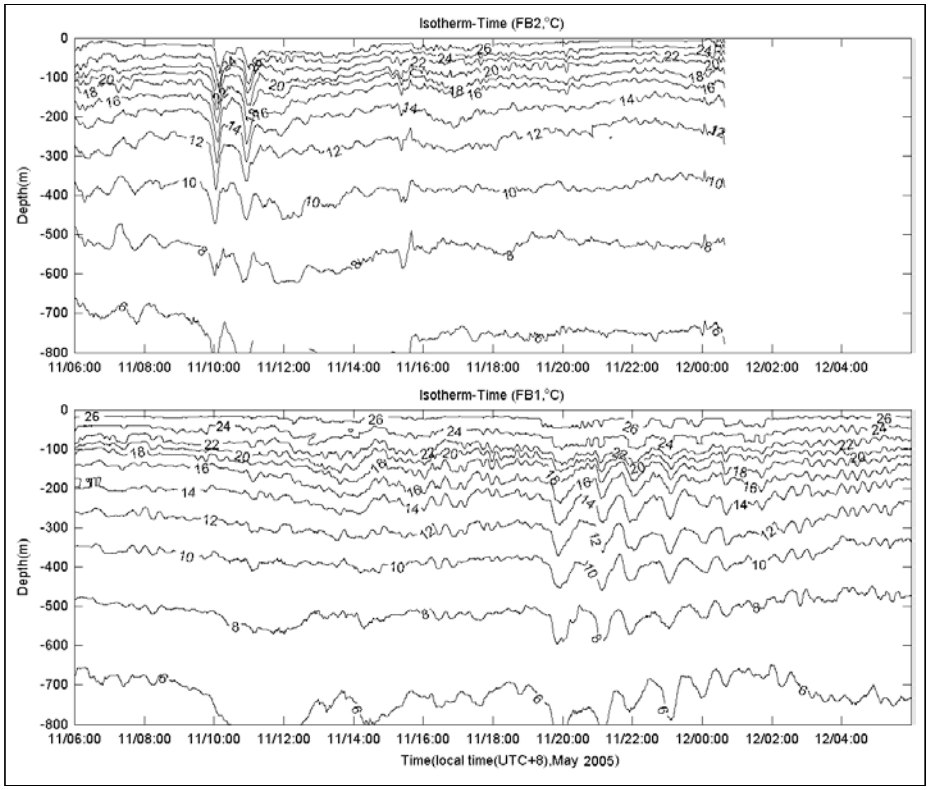

Fig. 3. Movement of isotherms at two fishing boats (FB1 and FB2) as measured by strings of temperature-depth loggers. The time mark 10/10:00 means 10 May 2005, 1000 Local Time (UTC + 8 hours).

Table 1. Time and Longitude of NLIWs Observed by Various Ships and RADARSAT on 11–13 May 2005

	Day	*Local Hour*	*Longitude East*	*Latitude North*
Ocean Researcher 3	11 May	5.667	120.488	20
Fishing Boat 2	11 May	10.08	119.913	20.4
Roger	11 May	10.3	119.9	20.5
RADARSAT	11 May	18.02	119.141	20.4
Fishing Boat 1	11 May	19.824	118.935	20.4
MODIS	12 May	12.833	119.70	20.4
RADARSAT	13 May	5.933	117.95	20.4
MODIS	13 May	13.583	117.2–117.4	20–20.8