Bullet Train of Non-linear Internal Waves from Luzon Strait

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In the northeastern South China Sea, a series of fast moving (about 2.9 m/s) non-linear internal waves (NLIWs) emanated westward from the Luzon Strait. Their propagation speed is faster than NLIWs previously observed in the world oceans, their amplitude reached 140 m or more, and are the largest free propagating NLIWs so far observed in the interior ocean. These NLIWs energized the top 1500 m of the water column, heaving it up and down in 20 min. Their associated energy density and energy flux are the largest observed to date. The exact source of these giant NLIWs is still under study and to be determined.

Background:

Non-Linear Internal Waves (**NLIW**s) are often found in shelf regions. They are typically thought to be generated by tidal currents over steep topography (sill, seamount, shelf break, etc.) or sometimes by the instability of current shears. An ERS-1 SAR image of a non-linear internal waves (NLIW) near Luzon Strait (LS) in 1995/6/16 (http://sol.oc.ntu.edu.tw/IW/1995/ERS1.htm) showed quite different features than NLIW images nearer Taiwan (Liu et al., 1994). Existing theories and experience were insufficient to explain the location, shape and size of NLIW in that SAR image.

To the west of LS, the HengChun Ridge (HCR) connects the southern tip of Taiwan to the continental shelf north of Luzon Island; Batan Islands and Babuyan Islands spread east of HCR. After passing the northeast corner of Luzon Island, the Kuroshio flows around Babuyans and Batans before entering LS from southeast direction and exiting LS near the southern tip of Taiwan Island.

Bole et al. (1994) hypothesized that the NLIWs in the northern South China Sea (SCS) originate from the sills between Batan Islands, just like the NLIWs of Sulu Sea originate from the sills between islands over the eastern border of Sulu Sea. This hypothesis has two major difficulties in explaining 1995/6/16 ERS-1 SAR image. First, the sills do not seem to be the centers of arcs of the NLIW fronts in the SAR image; second, no other NLIWs have been observed in the 120 km zone between HCR and Batan Islands.

An alternative generation hypothesis the instability of the western boundary of the Kuroshio. This hypothesis has difficulty explaining the misalignment between the western boundary of the Kuroshio which runs NW-SE and the NLIW which are aligned N-S.

The HengChun Ridge (HCR) may serve as a deep “sill” (over 1200 m) for NLIW generation. HCR is far deeper than most sills that generate NLIW and there is also slight misalignment between the SAR NLIW image and the top of HCR. But, the shape of NLIWs in LS aligns with the eastern slope of HCR(Fig. 1a). This slope represents the steepest bathymetry in LS, and therefore is an excellent place for generating waves.

Method of observation

The field and satellite observation program was designed to locate and quantify the occasional appearing NLIWs from LS. It includes components to:

(1) examine satellite SAR coverage (ERS-2, Envisat and Radarsat) for the surface manifestation of NLIW, as well as analyze optical images from MODIS of Aqua and Terra satellites;
(2) track NLIWs with a profiling CTD and deep Doppler sonar from R/V Roger Revelle;
(3) deploy thermister-chain (T-chain) at (21N, 121.25E) from R/V Fishery Researcher 1 (FR1) to detect any NLIW signal between HCR and Batan Islands;
(4) deploy three T-chains west of HCR (Fishing boats FB1 & FB2 and R/V Ocean Researcher 3, OR3) to observe the westward propagation of NLIWs from LS.

Results

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

NLIWs were not found between HCR and Batan Islands. They are either formed west of HCR, or formed near Batan Island but have not yet matured before passing HCR. Additional observations of the energy flux of internal tide in the Luzon Strait is needed.

Table 1. The time and longitude of NLIWs that were observed by various ships and Radarsat on May 11-13, 2005.

	Day	Local hour	Longitude E	Latitude N
OR3	May 11	5.667	120.488	20
FB2	May 11	10.08	119.913	20.4
Revelle	May 11	10.3	119.9	20.5
Radarsat	May 11	18.02	119.141	20.4
FB1	May 11	19.824	118.935	20.4
MODIS	May 12	12.833	119.70	20.4
Radarsat	May 13	5.933	117.95	20.4
MODIS	May 13	13.583	117.2~117.4	20~20.8

The satellite images of large NLIWs were verified with the ship measurement in Fig. 3. Figure 3a are plots of T(z, t) that were observed by T-chain (strings of temperature-depth loggers) from fishing boats FB1 near (20.4N, 119E) and FB2 near (20.4N, 120E). Westward propagating large amplitude NLIWs first passed FB2 at 120E and then FB1 at 119E with a 10-hour lag. The same NLIWs were also observed by ADCP of R/V Ocean Researcher 3 at (20N, 120.5E), and sonars (Fig. 1) of R/V Roger Revelle near (20.5, 119.5E).

Conclusions

ERS SAR images between 1995 and 2004 show a low rate of occurrence of these fast-moving NLIWs. Five-ship field surveys across Luzon Strait revealed trains of giant NLIWs emanating from Luzon Strait. But the relative contributions from Hengchun Ridge (120.8E) and from Batans (122E) need to be studied further in upcoming 2006 and 2007 field experiments. This will involve deploying a line of ADCP moorings, and surveying with deep penetrating sonar and fast CTD to capture the NLIW in the top 1000 m of water column. Modeling studies will help explain the data from the complex and energetic marine environment of Luzon

Acknowledgment

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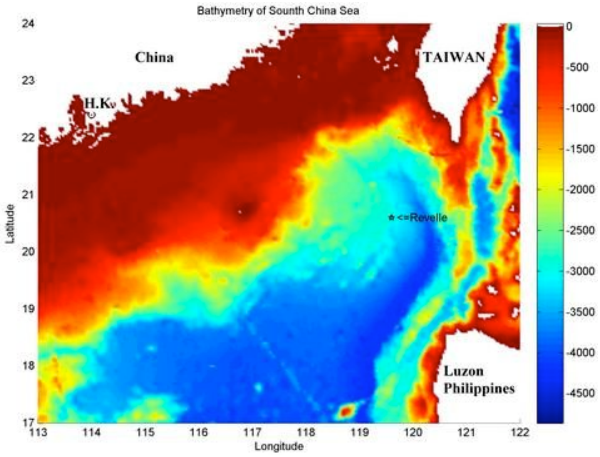
(a)



(b)

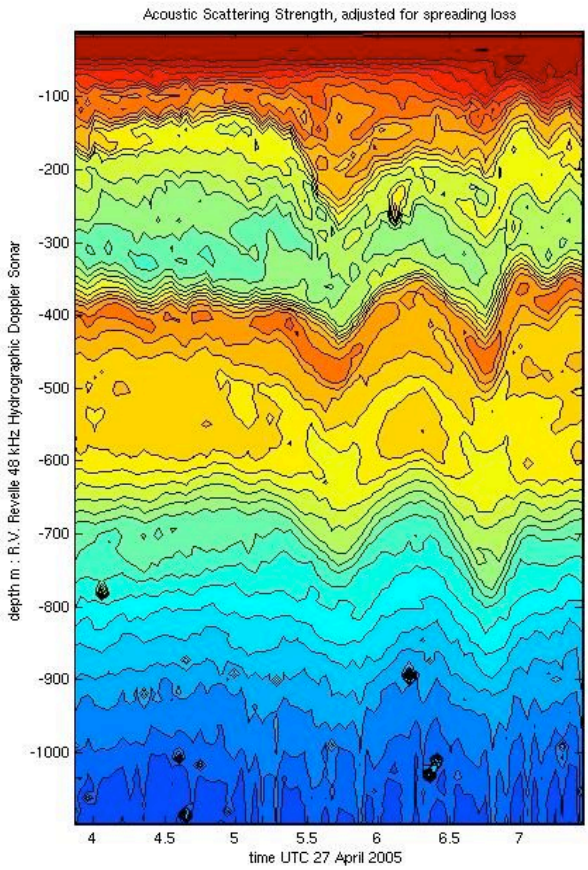


Fig. 1 (a) Nonlinear Internal Waves from HengChun Ridge between Taiwan and Luzon were mapped with 48 kHz sonar on R/V Roger Revelle in April-May 2005. Color table is depth in meters.
(b) Contours are isolines of equal acoustic scattering strength corrected for spherical spreading.

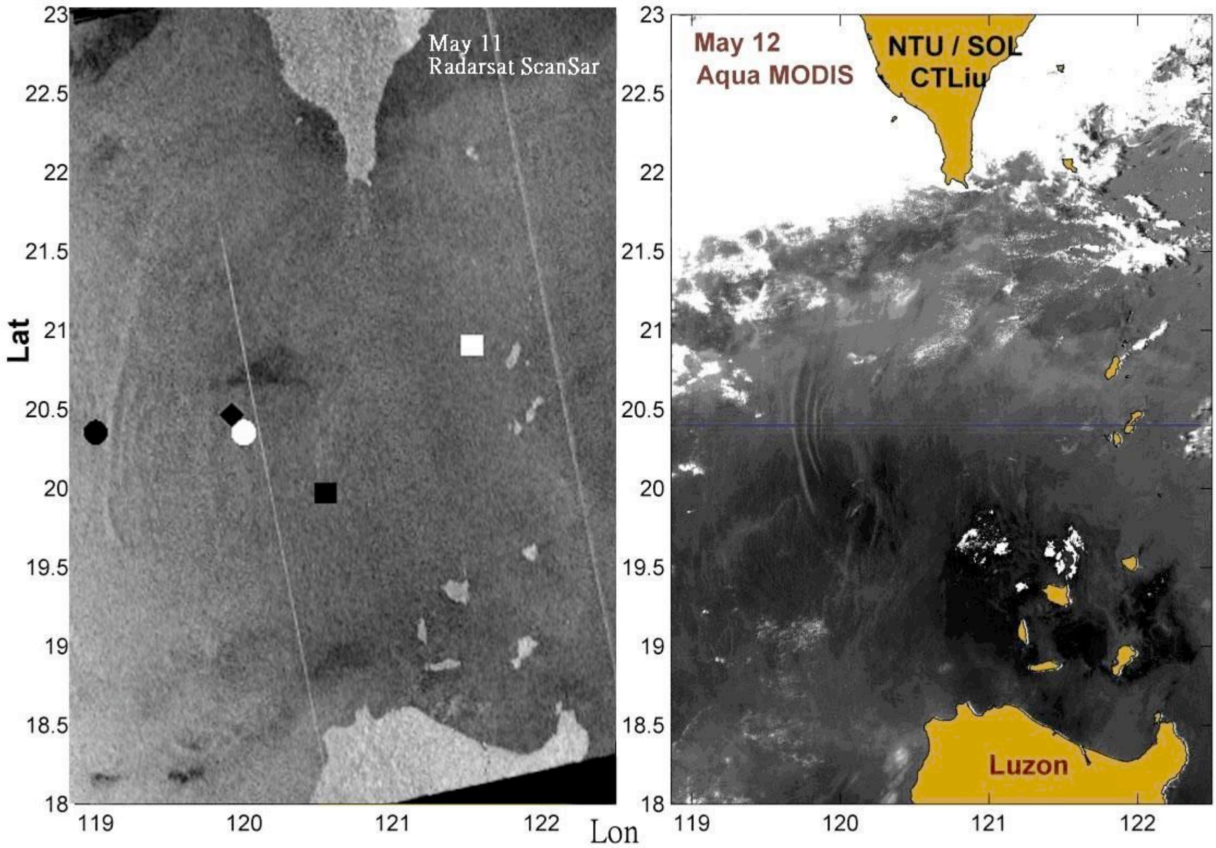


Fig. 2a RADARSAT ScanSAR image (from FRSC of Taiwan) of 2005 May 11 and MODIS images of May 12 west of Luzon Strait. NLIW fronts are packets of bright and dark lines. The markers are ship locations of May 11, 2005: ●: FB1 (20.4N, 119E), ○: FB2 (20.4N, 120E), ◆: Revelle (20.5N 119.9E), ■: OR3 (20N, 120.5E), and □: FR1 (21N, 121.25E).

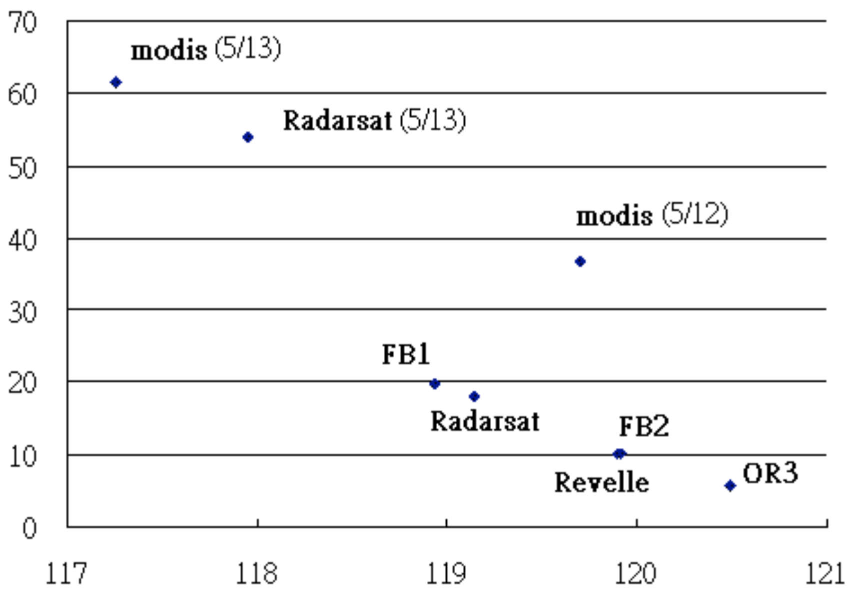


Fig. 2b Local time (hours from 00:00 of 2005/5/11) vs. longitude of NLIW fronts at various ships and at 20.4N in satellite SAR and MODIS images. The mean propagation speed of NLIW near 120E is about 2.9 m/s, with amplitude near 140m on 2005/5/11 at (20.4N, 120E)

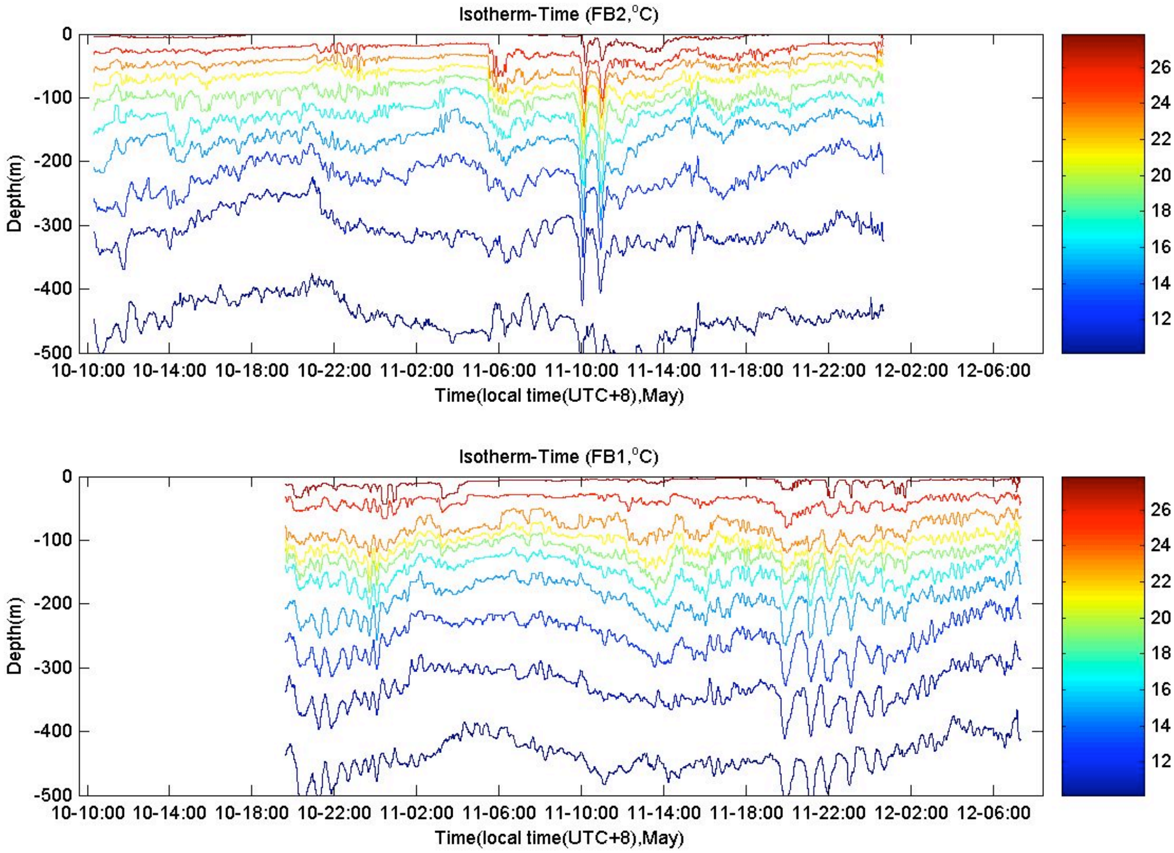


Fig. 3a Isotherms observed at two fishing boats as measured by thermister-strings. The time mark 10-10:00 means 2005/5/10 10:00 local time (UTC+8).

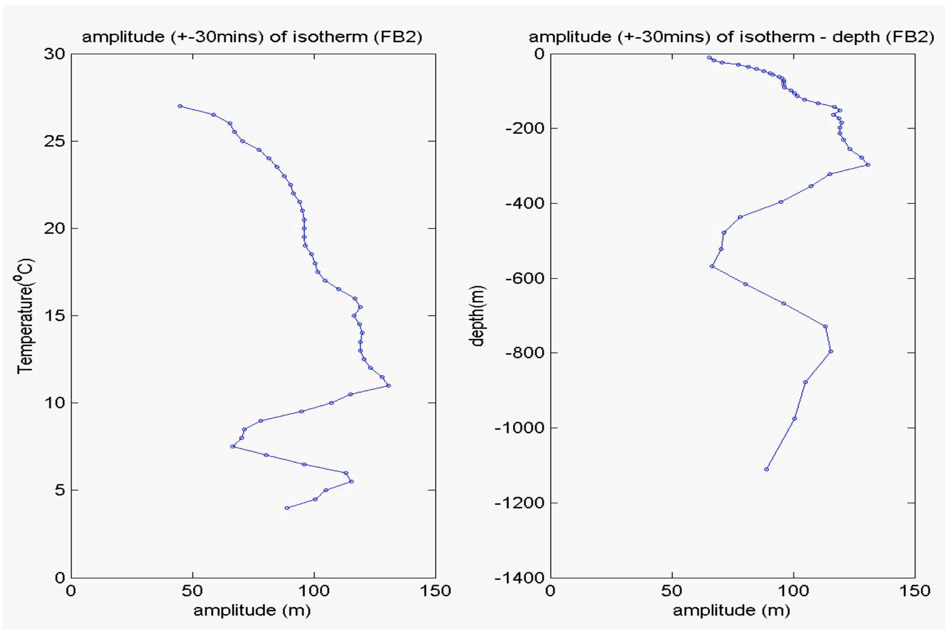


Fig. 3b The amplitude (downward displacement) of isotherms as a function of temperature (left) and depth (right), due to the passing of the first NLIW near 10 am of May 11 at FB2 (120E, 20.4N)