Bullet Train of Giant Nonlinear Internal Waves from Luzon Strait

Cho-Teng Liu[1], Ming-Kuang Hsu[2], Hsien-Wen Chen[3], Dee-Way Wang[1], Yuan-Jie Chyou[1] and Chang-Wei Lee[1]

[1] Institute of Oceanography, National Taiwan University, Taipei, Taiwan, ROC 106, ctliu@ntu.edu.tw
[2] Northern Taiwan Institute of Science and Technology, Taipei, Taiwan, ROC 106, hsu.ming.kuang@gmail.com
[3] Department of Water Police, Central Police University, Taoyuan, Taiwan, ROC 106, una146@sun4.cpu.edu.tw

ABSTRACT:

In the northeastern South China Sea (SCS), fast westward moving (about 2.9 m/s) non-linear internal waves (NLIWs) are emanated nearly daily from the Luzon Strait. Their propagation speed is faster than NLIWs previously observed in the deep water of world oceans, their amplitude of 140 m or more is the largest free propagating NLIWs so far observed in the deep 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. During 2005 and 2006 experiment, they were found west of the HengChun Ridge (HCR) that links Luzon and Taiwan Islands. This coincides with founding in satellite images, no NLIW front was found east of HCR. But, the turbulent environment east of HCR may prohibit surface signature of NLIWs that were emanated from sills between Batan Islands. The relative contribution of the two ridges on NLIW in Luzon Strait is still under study.

KEWORDS: nonlinear, internal wave, South China Sea, Luzon Strait

1. INTRODUCTION

Non-Linear Internal Waves (**NLIWs**) are often found in shelf regions. They are generated mostly by tidal currents over steep topography (sill, seamount, shelf break, etc.) and some by the instability of current shears or isopycnal (equal-density) surfaces. The 1995/6/16 ERS-1 SAR image of Luzon Strait (LS) shows quite different NLIW features like other NLIWs near Taiwan (Liu et al., 1994). Existing theories and experience were insufficient to explain the location, shape and size of NLIW in that SAR image.

In LS, there are HengChun Ridge (HCR) connecting the southern tip of Taiwan Island 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, 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 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 of Luzon Strait (http://sol.oc.ntu.edu.tw/IW/1995/ERS1.htm). First, the sills do not seem to be centers of arcs of NLIW fronts in the SAR image; second, no other NLIW was observed in the 120 km zone between HCR and Batan Islands.

Another popular hypothesis on the generation of NLIW in LS is the instability of the western boundary of Kuroshio. It has difficulty in explaining the misalignment between the western boundary of Kuroshio that is in the NW-SE direction and the NLIW in NS direction.

The deep HengChun Ridge (HCR, over 1200 m) may serve as a deep "sill" between Taiwan and Luzon for NLIW generation. HCR is far deeper than most sills that generate NLIWs and there is also slight misalignment between NLIW and the top of HCR. But, the shape of NLIW in LS aligns with the eastern slope of HCR (http://sol.oc.ntu.edu.tw/IW/1995/ERS1.htm). This slope has the steepest bathymetry in LS, and therefore an excellent place for the strong tidal current across LS to move the isopycnals up and down and to generate NLIW near the top of this slope.

2. METHOD OF OBSERVCATION

The field and satellite observation program was designed to locate and analyze the occasional appearing NLIWs from LS. The 2005 experiment includes:

(1) schedule all possible satellite SAR coverage (ERS-2, Envisat and Radarsat) for the surface manifestation of NLIW;

(2) analyze all optical images from MODIS of Aqua and Terra satellites;
(3) track NLIW with fast CTD and deep sonar from R/V Roger Revelle;
(4) 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;
(5) 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.

3. RESULTS

NLIWs were spotted on Radarsat SAR image of 2005 April 25 at near real time mode. Alert was sent immediately to R/V Roger Revelle which mapped a 1000 m deep NLIW with 48kHz sonar. Fig. 1 shows the downward displacement equal-scattering layers in the top 1000 m, during the passing of NLIWs on April 27. The time and longitude of NLIWs along 20.4N are listed in Table 1 and plotted in Fig. 2 as they were observed by T-chain from ships in May 11-13, 2005, and by satellite images of LS from Radarsat SAR and Aqua MODIS (Fig. 3). Regression analysis shows that NLIWs propagated westward from Luzon Strait at average speed of 2.9±0.1 m/s. But, these giant NLIWs were not found between HCR and Batan Islands. This is to say that the they either formed west of HCR, or formed near Batan Island but not yet matured before passing HCR. More detailed measurement on 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	5.67	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	19.80	118.935	20.4
MODIS	May 12	12.83	119.70	20.4
Radarsat	May 13	5.93	117.95	20.4
MODIS	May 13	13.58	117.2~117.4	20~20.8

The satellite images of large NLIWs were verified with ship measurement in Fig. 4 & 5. Figure 4 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 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).

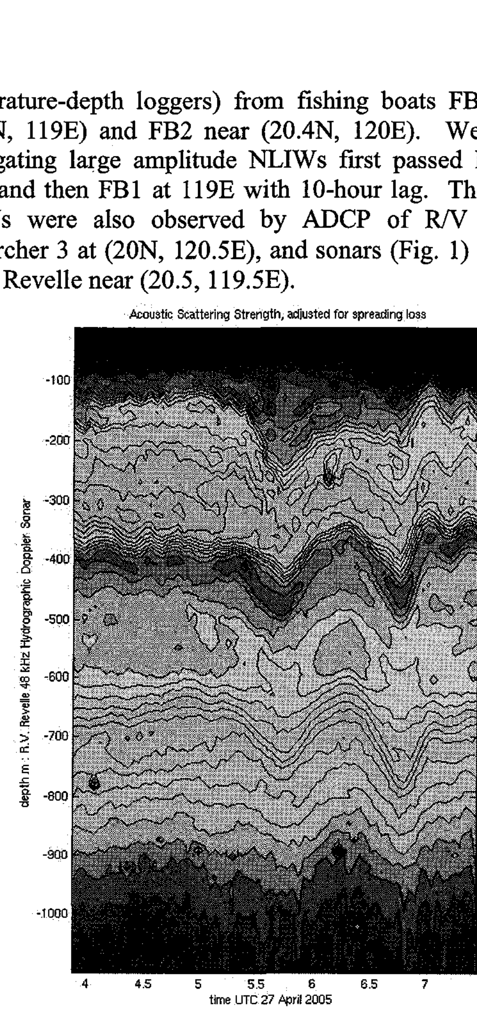

Fig. 1 NLIWs that were mapped with 48 kHz sonar. Contours are isolines of equal acoustic scattering strength.

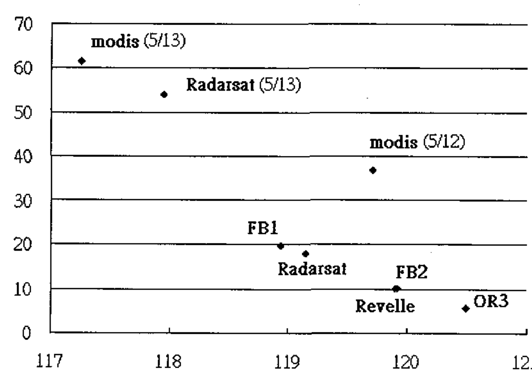

Fig. 2 Local time (hours from 00:00 of 2005/5/11) vs. longitude of NLIW fronts at various ships and at 20.4N in satellite SAR and MODIS images. The mean propagation speed of NLIW near 120E is about 2.9 m/s, with amplitude near 140m on 2005/5/11 at (20.4N, 120E)

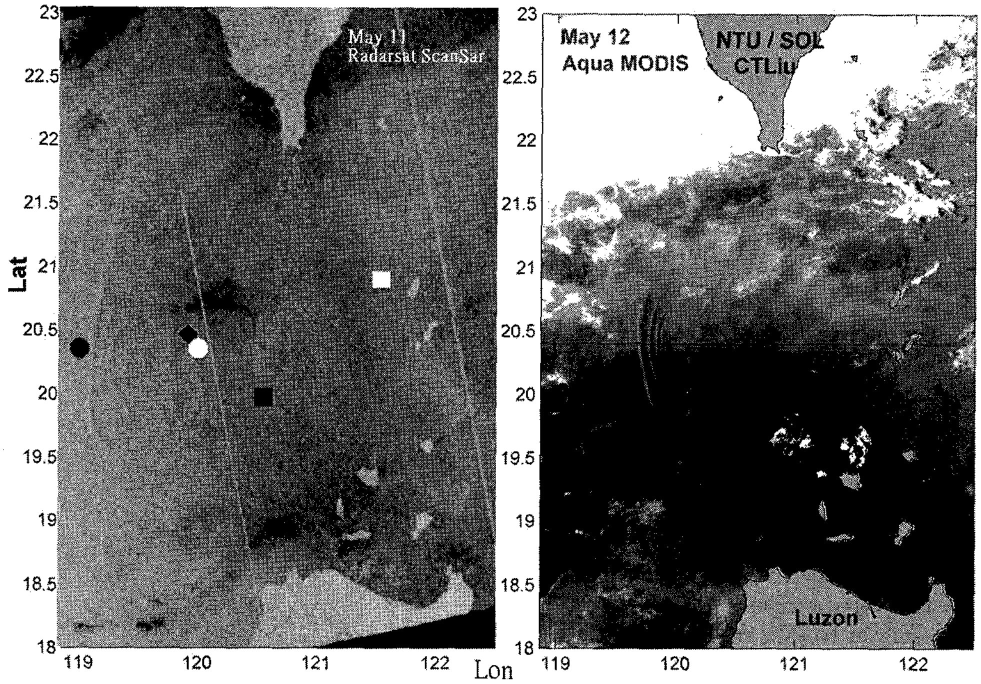

Fig. 3 RADARSAT ScanSAR image of 2005 May 11 and MODIS images of May 12 west of Luzon Strait. NLIW fronts are packets of bright and dark lines. The markers are ship locations of May 11, 2005: ●: FB1 (20.4N, 119E), ○: FB2 (20.4N, 120E), ◆: Revelle (20.5N 119.9E), ■: OR3 (20N, 120.5E), and □: FR1 (21N, 121.25E).

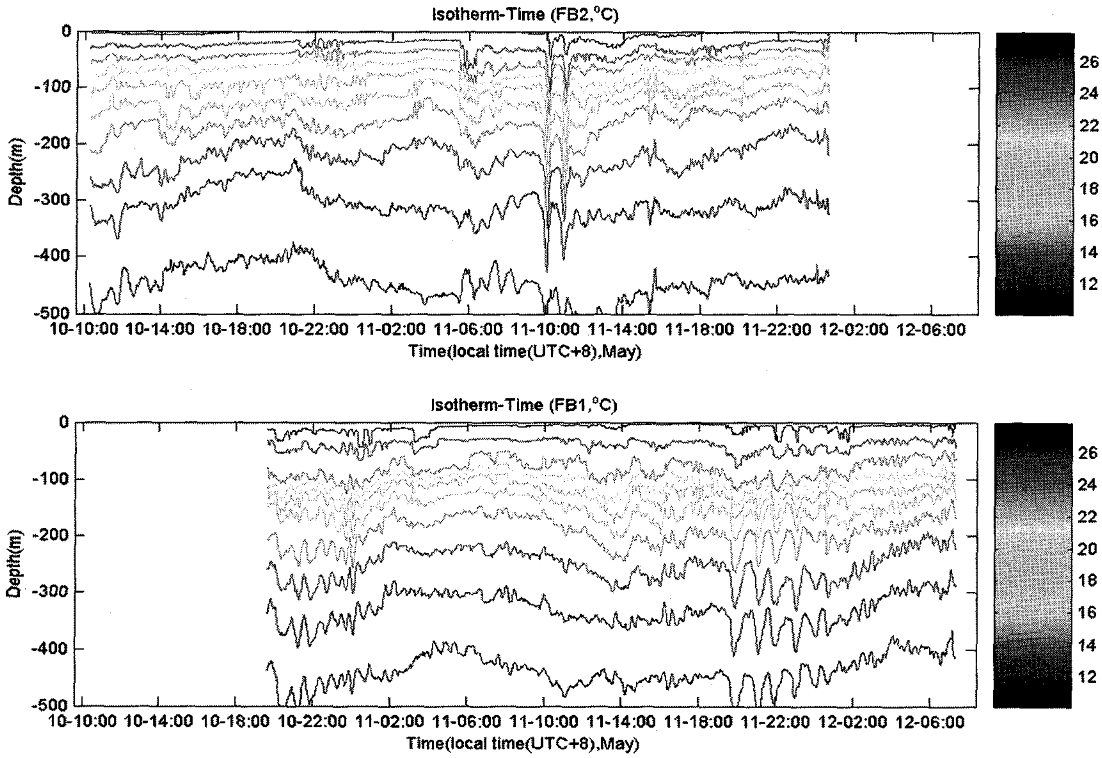

Fig. 4 The movement of isotherms at the two fishing boats as measured by thermister-strings. The time mark 10-10:00 means 2005/5/10 10:00 local time (UTC+8).

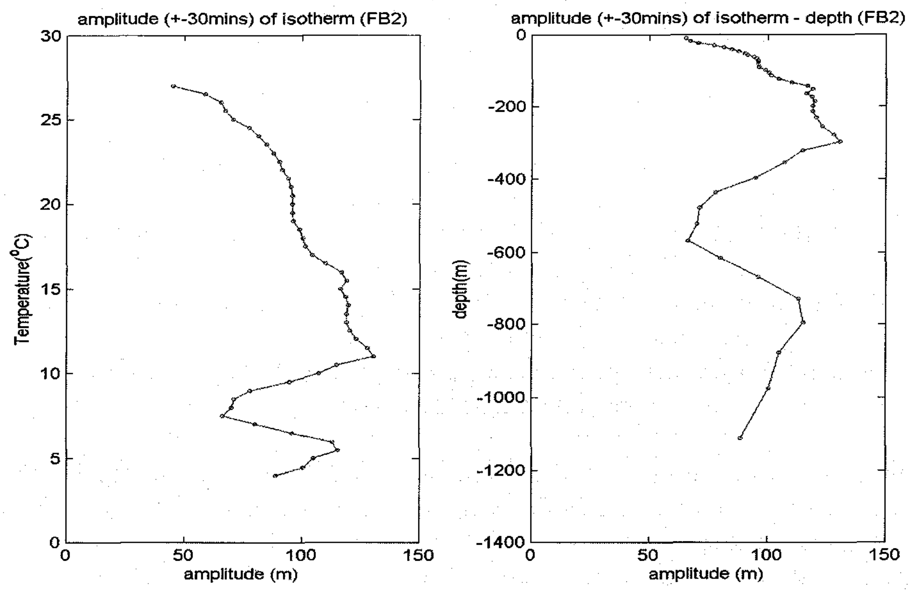

Fig. 5 The amplitude (downward displacement) of isotherms as a function of temperature (left) and depth (right), due to the passing of the first NLIW near 10 am of May 11 at FB2 (120E, 20.4N)

4. CONCLUSIONS

ERS SAR images between 1995 and 2004 show low rate of occurrence of these fast-moving NLIWs. Five-ship field surveys across Luzon Strait revealed trains of giant NLIWs from Luzon Strait. But the relative contributions from Hengchun Ridge (120.8E) and from Batans (122E) need to be studied further in 2007 field experiments. It requires deployment of a section of ADCP moorings, or surveying with deep penetrating sonar and fast CTD to capture the fast moving NLIW in the top 1000 m of water column. Model studies will help greatly in explaining the data from complex and energetic marine environment of Luzon Strait that has strong velocity shears from Kuroshio (about 1 m/s) and tidal currents (up to 1.5 m/s at 1200 m depth).

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