Continental Shelf Research 59 (2013) 18–27

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Generation and evolution of mode-two internal waves in the South China Sea

Antony K. Liu [a], Feng-Chun Su [b,*], Ming-Kuang Hsu [c], Nan-Jung Kuo [d], Chung-Ru Ho [d]

[a] Ocean Remote Sensing Institute, Ocean University of China, Qingdao, China
[b] National Museum of Marine Science & Technology, Keelung, Taiwan
[c] Technology and Science Institute of Northern Taiwan, Taipei, Taiwan
[d] National Taiwan Ocean University, Keelung, Taiwan

ARTICLE INFO

Article history:
Received 30 May 2011
Received in revised form
24 February 2013
Accepted 26 February 2013
Available online 14 March 2013

Keywords:
Mode-two internal wave
South China Sea
Soliton

ABSTRACT

The objective of this study is to investigate the generation and evolution of mode-two internal waves on the shelf break. In this study, some historical mooring and satellite data have been investigated for the detection of mode-two solitons in the ocean. A recent field experiment in May 2009 near Dong-Sha Island in the South China Sea (SCS) is first described and analyzed. During the experiment, a small mode-two wave was observed following a huge mode-one soliton on the shelf. Then, the environmental conditions for the evolution of mode-two internal waves were assessed for parametric and sensitivity study based on the CTD data from previous experiment in SCS. The generation of mode-two waves on the shelf by disintegration of mode-one solitons in the deep ocean is proposed and analyzed based on the theory of modal-decomposition. For comparison, the soliton characteristics of mode-one and -two waves from environmental parameters have been estimated. It's been shown that the soliton width of large mode-two waves is much wider than mode-one waves.

1. Introduction

The ocean current over topographic features such as a sill or continental shelf in a stratified flow can produce nonlinear internal waves of tidal frequency and has been studied by many researchers (Apel, 2003; Lynch et al., 2004). Their observations provide insight into the internal wave generation process and explain the role they play in the transfer of energy from tide to ocean mixing. It has been demonstrated that surface signatures of these nonlinear internal waves are observable in the Synthetic Aperture Radar (SAR) images, such as in the South China Sea (SCS) (Liu and Wu, 2001; Zheng et al., 2007) from Russian Almaz-1 and from the First and Second European Remote Sensing Satellite (ERS-1/2). Recently, the internal wave distribution maps in the northeast of SCS and near Hainan Island have been compiled from hundreds of ERS-1/2, RADARSAT and Space Shuttle SAR images from 1993 to 1998 by Hsu and Liu (2000). Based on internal wave distribution map, most of internal waves in the northeast part of South China Sea are propagating westward. The wave crest can be as long as 200 km with amplitude larger than 150 m, this is due to the strong current from the Kuroshio branching out through the Luzon Strait into the South China Sea (Liu et al., 1998, 2006).

The Kuroshio moving north from the Philippine Basin branches out near the south tip of Taiwan and part of the Kuroshio intrudes into the South China Sea through the Luzon Strait. The surface signature of huge internal wave packets has been observed in various satellite images by different sensors (Su et al., 2008). The crest of the soliton is more than 200 km long and each packet consists of more than ten rank-ordered solitons with a packet width of 25 km. Within a wave packet, the wavelengths appear to be monotonically decreasing, front to rear, from 5 km to 500 m. These are the biggest internal waves ever been observed in the East Asia. The internal wave amplitude is larger than 100 m based on the moorings, echo sounders, and CTD casts (Duda et al., 2004; Ramp et al., 2004). These huge wave packets propagate and evolve into the South China Sea and finally reach the continental shelf of southern China. Fig. 1 shows an updated internal wave distribution map in the northern part of the SCS compiled from hundreds of ERS-1/2, ENVISAT, RADARSAT, and Space Shuttle SAR images. Notice that the surface signature of internal waves in the deep basin is relatively weak and is probably caused by the deeper thermocline and transition from the internal tide to the rank-ordered solitons. The density stratification can vary significantly along the shelf break.

The U.S. Office of Naval Research (ONR) and Taiwan's National Science Council (NSC) have carried out a series of very extensive research projects to study nonlinear internal waves in SCS for the last 10 years. The Asian Seas International Acoustics Experiment (ASIAEX) was a major field effort in coupled physical oceanography, geophysics, and environmental acoustics which took place during the consecutive springs of 2000 and 2001 in the South and East China Seas. Then came the Nonlinear Internal Waves Initiative

* Corresponding author. Tel.: +886 2 24696000x5025.
E-mail address: fengchunsu@gmail.com (F.-C. Su).

0278-4343/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.csr.2013.02.009

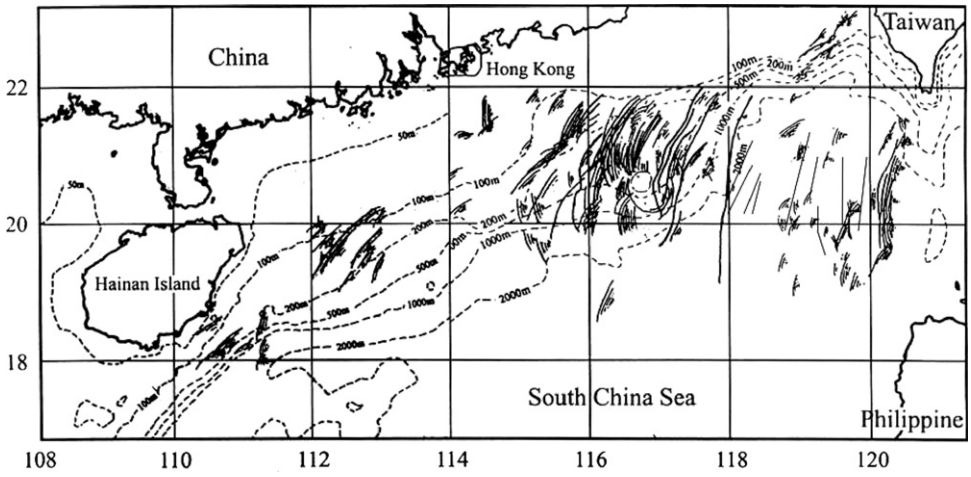

Fig. 1. Bathymetry and internal wave distribution map in the South China Sea.

(NLIWI), which is also sponsored by ONR; and its programmatic objectives are to observe and understand the generation, propagation, shoaling, transformation, and dissipation of NLIWs in the northeastern South China Sea. The South China Sea FY07 field experiment (SCS'07) is a part of the ONR NLIWI and is a joint test with Taiwan's SCS Ocean Process Experiment (SCOPE). SCS'07 joint field work includes satellite remote sensing (in real-time), acoustic propagation, four ships (R/V Ocean Research I, Ocean Research II, and Fisheries Research I from Taiwan and R/V Melville from U.S.) with Seasors, Seagliders, drifters, and moorings, covering the Luzon Strait, SCS basin, and Dong-sha Island areas.

In this study, the generation of mode-two nonlinear internal waves in the ocean based on the modal decomposition theory is proposed. This modal decomposition model is not new for general wave dynamics such as the propagation of sound waves in shallow water, but is used for the first time on new observation of mode-two nonlinear internal waves in SCS. In order to test the sensitivity of environmental condition on mode-two wave evolution, a series of Conductivity–Temperature–Depth (CTD) data collected during the joint hydrographic survey in May 2006 by Ocean Research-3 in the SCS have been used. This 2006 ship survey is an intensive field experiment to cover large area in the northeastern South China Sea for the internal wave study. A short (3 days) internal wave experiment with limited scope to focus on the search for mode-two waves was carried out in May 2009, with ship towed thermistor chain and moorings at the same location of mode-two waves previously observed. Since there has no CTD casting during the short 2009 field experiment, and so the model calculations are based on CTD data from 2006 at the same month and location in SCS to demonstrate the feasibility of modal decomposition theory for mode-two wave generation and evolution.

2. Field experiment in SCS

Mode-two internal waves have been studied and observed in the laboratory experiments for many years and the experiments were conducted by Kao and Pao (1979) in a long channel in which a mixed region was allowed to collapse in the thermocline region of a stratified fluid for mode-two internal solitary wave generation (Hartman and Lewis, 1972). During the ASIAEX pre-test, a new wave process on the shelf break has been observed from a mooring near Dong-Sha Island on April 10, 1999. The thermistor chain data (Fig. 2) show a mode-one soliton with negative temperature fluctuations at all depth, and also indicate the mode-two internal waves with negative temperature fluctuations in the

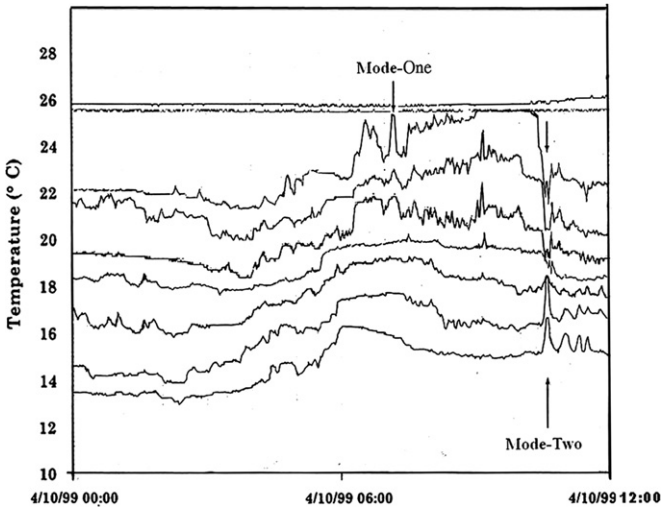

Fig. 2. Temperature time series collected from thermistors at different depths on April 10, 1999 near Dong-sha Island. The mode-two waves are lagging behind the mode-one waves by approximately 4 h.

mixed layer and positive values in the bottom layer (Liu et al., 2005). In Fig. 2, the local water depth is about 426 m. The first near surface sensor is located at 1 m depth with depths of 30 m, 60 m, 75 m, 90 m, 105 m, 120.m, 150 m, and 180 m for other thermistors on the chain. These mode-two waves are lagging behind the diurnal tide (with mode-one waves) by about 4 h since mode-two waves have slower wave speed than mode-one waves. The Acoustic Doppler Current Profiler (ADCP) data from the mooring also confirm the mode-two internal solitons on April 10, 1999 with two zero-crossings in current profile and are consistent with the thermistor chain data. The mixed layer depth was about 110 m (at location of zero-crossing in temperature profile) from thermistor data, and the ADCP data show a mixed layer depth of 120 m (at locations for maximum current). The maximum current induced by these mode-two waves was over 1 m/s. Yang et al. (2009) has reported the observations of these baroclinic mode-two internal waves on the continental slope of the northern SCS. They found that among mode-two waves in the summer, 90% appeared after mode-one waves. Due to their different wave speeds mode-one and mode-two waves will separate after decomposition on the shelf. Based on the observation of 4-h lagging or separation between mode-one and mode-two waves (with about half of mode-one wave speed), the location of generation for mode-two