NONLINEAR INTERNAL WAVES IN THE SOUTH CHINA SEA

Antony A. K. Liu
Oceans and Ice Branch, NASA Goddard Space Flight Center
E-mail: liu@neptune.gsfc.nasa.gov
and
Ming-Kuang Hsu
Department of Oceanography, National Taiwan Ocean University
E-mail: hsumk@sun4.oce.ntou.edu.tw

1. INTRODUCTION

The tidal flow over topographic features such as a sill or continental shelf in a stratified ocean can produce nonlinear internal waves of tidal frequency and has been studied by many investigators (Liu et al., 1985). 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. These nonlinear internal waves are apparently generated by internal turbulent mixing or baroclinic shear instability due to tidal flow over bottom features. It has been demonstrated that surface signatures of these nonlinear internal waves are observable in the Synthetic Aperture Radar (SAR) images from Russian Almaz-1 and from the First and Second European Remote sensing Satellite ERS-1/2 (Liang et al., 1995). Furthermore, many interesting internal waves and related processes have been studied using SAR images in the East and South China Seas (ESC and SCS) and Yellow Sea, such as upwelling, Kuroshio meandering, fronts, pollution, ship wakes, and internal waves (Liu et al., 1998). However, the satellite observations and internal wave model simulations have not been validated and calibrated by the in-situ measurements yet. A field test has been planned by US Office of Naval Research (ONR)'s Asian Seas International Acoustics Experiment (ASIAEX) and this joint experiment from US, Russia, Japan, Korea, Singapore, Taiwan and China will be conducted in the East and South China Seas starting in year 2000. More than six research ships with scientists from the US and China will participate in this experiment in 2001. These upcoming field experiments provide a unique opportunity to study the evolution of nonlinear internal waves and to validate SAR-observed internal wave signatures in the East and South China Seas. A validated and calibrated model can be very useful for understanding of shelf processes and for the applications of the internal wave effect on oil drilling platform, nutrient pump (for fishery) and sediment transport.

2. Nonlinear Internal Waves in the South China Sea

The Kuroshio moving north from Philippine Basin branches out near the south tip of Taiwan and part of the Kuroshio intrudes into the South China Sea through the Bashi Channel and the Luzon Strait. The internal tides and internal waves have been generated by the shallow ridges (200-300 m) in the Luzon Strait. Surface signature of huge internal wave packets has been observed in the ERS-1 SAR images (Liu et al., 1998). The crest of soliton is more than 200 km long and each packet contains 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. This is the biggest internal waves ever been observed in this area. The internal wave amplitude is larger than 100 m based on the CTD casts from Taiwan's research ship during their South China Sea expedition in 1995. These huge wave packets propagate and evolve into the South China Sea and finally reach the continental shelf of southern China. It is expected that the internal wave packets in the South China Sea are related to the branch out of Kuroshio. The distance and degree of intrusion of Kuroshio (with high temperature and high salinity water) into the Taiwan Strait and the South China Sea with heat flux and momentum flux is still an open issue.

Recently, the internal wave distribution maps in the SCS have been compiled from hundreds of ERS-1/2, RADARSAT and Space Shuttle SAR images from 1993 to 1999 by Hsu et al. (2000) as shown in Figure 1. Based on internal wave distribution map, most of internal waves in the northeast part of South China Sea are propagating westward. From the observations at drilling rigs near DongSha Island by Amoco Production Co. (Bole et al., 1994), the solitons may be generated in a 4 km wide channel between Batan and Sabtang islands in Luzon Strait. The sill between Batan and Sabtang islands is like a saddle point. The proposed generation mechanism is similar to the lee wave formation from a shallow topography in the Sulu Sea (Apel et. al, 1985). The disturbance of mixed area with downward displacement of the pycnocline is then driven by the semi-diurnal tide and evolves into a rank-ordered wave packet. But, the detailed wave generation mechanisms and locations are still not well understood since there are no measurements.

Based on the SAR images and hydrographic data, internal waves of elevation have been identified in shallow water due to a thicker mixed layer as compared with the bottom layer on the continental shelf. The generation mechanisms including the influences of the tide and the Kuroshio intrusion across the continental shelf for the formations of both elevation internal waves and depression waves under various ocean conditions are under investigation. The effects of water depth on the evolution of solitons and wave packets have been modeled by Kortweg-deVries (KdV)-type equation and linked to satellite image observations. Both depression and elevation internal waves have been observed by SAR at the same location in SCS on the shelf in April and June 1993 (in different seasons) respectively. The internal wave amplitude is larger than 100 m with surface rips of 1 km wide. The numerical results indicate that the depression internal waves evolve into rank-ordered solitons on the shelf with a shallow mixed layer. However, when the mixed layer is thicker than the bottom layer, only elevation waves can be evolved. Therefore, in the summer, where the mixed layer (about 50 m) is thinner than the bottom layer, depression wave train can be generated as observed in SAR images. During the spring/winter, elevation solitons can be evolved in the shallow water, because the mixed layer (about 120 m) deepens caused by winter monsoon and its thickness is thicker than the bottom layer on the shelf. Since the mixed layer is thicker in the spring, the surface signature of internal waves is also weaker as shown in Liu et al. (1998).

4. Recent SAR Observation Results

During the South China Sea Monsoon Experiment (SCSMEX) in May 1998, both depression and elevation internal waves have been observed in the same Radarsat ScanSAR image on May 4, 1998 near DongSha Island (Hsu and Liu, 1999). Figure 2 shows a subscene of RADARSAT image collected on May 4, 1998 of huge internal solitons near DongSha Island with crest more than 200 km long and wave speed of 1.9 m/s. There are three internal wave packets on this subscene and an eastward propagated reflected wave packet east of DongSar Island (barely visible). The depression waves were located in water of 500 m depth, while the elevation waves were in 200 m water. The depression internal waves (the first wave packet from the right) change its polarity after they passing through a "turning point" and became elevation internal wave packets (the first wave packet from the left) in the shallow water. The separation between these two wave packets were approximately two semi-diurnal cycle, i.e. 25 hours. As demonstrated by the numerical simulation, when the depression internal waves propagate onto the shelf in the spring, it will be converted to elevation waves in the shallow water after 20 hours (Liu et al., 1998) which is consistent with the SAR observations. Based on CDT casts on May 18 during the SCSMEX, the mixed layer depth is about 100-150 m, which is also consistent with the prediction from SAR observation of elevation internal waves.

The wave-wave interaction have been observed in many SAR images of the East and South China Seas. The internal solitons are nonlinear, thus their interaction are much more complicated than the regular linear waves. Based on the SAR images, near DongSha Island, the westward propagating huge internal solitons are often encountered and diffracted/broken by the coral reefs on the shelf. Figure 3 shows a Radarsat ScanSAR image collected north of the South China Sea on April 26, 1998, showing at least four packets of internal waves. The internal wave packets propagated toward the DongSha coral reefs, the internal wave packets diffracted by Dongsha coral reefs into two packets of internal waves, and then interacted with each other and re-merged as a single wave packet. After the nonlinear wave-wave interaction, the phase of wave packet is shifted and wavelength is also changed in the South China Sea.

In a recent mooring result on April 10, 1999, the thermistor chain data indicating the mode-two internal waves with negative temperature fluctuation in the mixed layer and positive value in the bottom layer. The mode-two waves are lagging behind the diurnal tide by about 4-hours since mode-two waves have slower wave speed than mode-one waves. The ADCP data from 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 110m (zero-crossing in temperature) from thermistor, and ADCP shows a mixed layer depth of 120m (maximum current). The maximum current induced by these mode-wave was over 1 m/s. The generation of these mode-two waves is most likely due to the intrusion of seasonal thermocline at the shelf break. However, the mode-two solitons have never been observed by SAR (similar to elevation waves but with lower speed) and their generation mechanism requires further study.

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Figure Captions

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

Figure 2. Subscene of RADARSAT image collected on May 4, 1998. There are three internal wave packets on this subscene and an eastward propagated reflected wave packet east of DongSar Island (barely visible). The depression internal waves (the first wave packet from the right) change its polarity after they passing through a "turning point" and became elevation internal wave packets (the first wave packet from the left) in the shallow water.

Figure 3. RADARSAT ScanSAR image collected north of the South China Sea on April 26, 1998, showing at least 4 packets of internal waves. The internal wave packets propagated toward the Dongsha coral reefs, the internal wave packets

diffracted by Dongsha coral reefs into two packets of internal waves, and then interacted with each other and re-merged as a single wave packet.