Evolution of nonlinear internal waves in the East and South China Seas

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Abstract. Synthetic Aperture Radar (SAR) images from ERS-1 have been used to study the characteristics of internal waves northeast and south of Taiwan in the East China Sea, and east of Hainan Island in the South China Sea. Rank-ordered packets of internal solitons propagating shoreward from the edge of the continental shelf were observed in the SAR images. On the basis of the assumption of a semi-diurnal tidal origin, the wave speed can be estimated and is consistent with the internal wave theory. By using the SAR images and hydrographic data, internal waves of elevation have been identified in shallow water by a thicker mixed layer as compared with the bottom layer on the continental shelf. The generation mechanism includes the influences of the tide and the Kuroshio intrusion across the continental shelf for the formations of elevation internal waves. The effects of water depth on the evolution of solitons and wave packets are modeled by the nonlinear Kortweg-deVries (KdV) type equation and linked to satellite image observations. The numerical calculations of internal wave evolution on the continental shelf have been performed and compared with the SAR observations. For a case of depression waves in deep water, the solitons first disintegrate into dispersive wave trains and then evolve to a packet of elevation waves in the shallow water area after they pass through a “turning point” of approximately equal layer depths that has been observed in the SAR image and simulated by the numerical model. The importance of the dissipation effect in the coastal area is also discussed and demonstrated.

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 [Sundstrom and Elliott, 1984; Apel et al., 1985; Apel, 1995]. Their observations provide insight into the soliton generation process and explain the role they play in the transfer of energy from tides to ocean mixing. However, almost all of the nonlinear internal waves observed in nature previously were made one depression waves. Salusti et al. [1989] first observed two moving internal wave packets consisting of elevation waves and depression waves separated by a 12-hour period, using a thermostor chain in the eastern Mediterranean Sea during a pilot experiment in the Rio-Antirrio strait, western Greece, in July 1986. The change of polarity in internal waves is caused by the change of the mean thermocline depth. Similar change of internal wave polarity was observed by A. N. Serebryany (private communication, 1995) at the shelf of the Sea of Japan in September 1982. These nonlinear internal waves were apparently generated by internal turbulent mixing or baroclinic shear instability over bottom features.

The East China Sea is rich in resources, which have been exploited extensively. The Kuroshio, the major western boundary current of the Pacific, forms the eastern boundary of the East China Sea as it skirts the shelf edge in the Okinawa Trough. The Kuroshio Edge Exchange Process (KEEP) project studies a major site for the exchange of material between the East China Sea and the Kuroshio at a permanent upwelling region northeast of Taiwan [Liu et al., 1992]. The upwelling is induced by the intrusion of the Kuroshio across the continental shelf [Hsueh et al., 1993]. The Kuroshio fronts and cold eddies in the upwelling region have been observed by advanced very high resolution radiometer (AVHRR) images [Liu et al., 1992]. KEEP-II, a 5-year field program started in 1994, has made direct observations northeast of Taiwan where the Kuroshio collides with the continental shelf. This unique data set may provide some ground truth for the internal wave study in this area. However, owing to the low sampling rate, the data collected during KEEP did not show any high-frequency internal waves. Further collections of internal wave data with a higher sampling rate (every half minute) have been planned and are under way. Internal wave packets were also observed by the crew of the space shuttle Challenger as they orbited over Hainan Island in the South China Sea. The Kuroshio intrudes 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 are probably generated by the shallow ridges in the Luzon Strait.
It has been known for over 2 decades that internal waves have surface signatures recognizable in satellite images of sea surface [Fiu and Holt, 1982]. The synthetic aperture radar (SAR) images from the First European Remote Sensing Satellite (ERS-1) have been used to study the characteristics of internal waves northeast of Taiwan [Liou et al., 1995] and in the Strait of Gibraltar [Braudet et al., 1996]. Rank-ordered packets of internal solitons propagating shoreward from the edge of the continental shelf were observed in many SAR images. By using the SAR images and hydrographic data, internal waves of elevation can be identified from a thicker mixed layer as compared with the bottom layer on the continental shelf. The effects of water depth on the parameters of solitons and wave packets can be linked to the observations from SAR images.

A solitary wave theory that describes the evolution of nonlinear internal waves has been developed and expanded to include effects of vertical shear, variable initial topography, radial spreading, and dissipation by Liu et al. [1985] for the Sulu Sea internal soliton study [Apel et al., 1985]. Internal solitary waves on a shelf with shoaling effects have been studied by Liu [1988] in the New York Bight. Another mechanism of internal solitary wave attenuation is caused by shear-induced dissipation, which is associated with turbulent mixing and widening of the pycnocline [Bogucki and Garrett, 1993]. All these mechanisms of wave evolution can be simulated numerically by solving the nonlinear Kortweg-deVries (KdV) type equation with varying coefficients corresponding to the changing environments as demonstrated by Liu et al. [1985] and Liu [1988]. For the case of depression waves, the disintegration of solitons into dispersive wave packets after they pass through a “turning point” of approximately equal layer depths (critical depth) has been studied numerically by Helfrich et al. [1984].

In this paper, the internal wave evolution at northeast and south of Taiwan in the East China Sea and east of Hainan Island in the South China Sea is studied on the basis of the ERS-1 SAR data for addressing a wide range of processes. The nonlinear wave evolution on a shelf is formulated by a KdV type equation to include changing depth and dissipation effects in the next section. The selective sets of SAR images in the East and South China Seas are presented in section 3. Section 4 presents the numerical study of the evolution of nonlinear depression waves through the critical depth and the disintegration of solitons into internal wave packets with variable bottom topography and dissipation. Finally, this nonlinear internal wave analysis of the ERS 1 SAR data is summarized and discussed in section 5.

2. Model of Nonlinear Internal Wave Evolution on a Shelf

The evolution of nonlinear internal wave trains on a continental shelf has been formulated by Liu [1988]. The dissipation effects on solitary wave evolution are considered to be important in the shallow water owing to internal wave breaking and strong turbulent mixing. The evolution equation of wave amplitude \( A(z,t) \) with variable coefficients is

\[
A_z + C_0 A_t + \alpha A A_z + \kappa A_z^3 + \beta A_{zz} + e^{-\frac{1}{2} \varepsilon A_{zz}} = 0, \tag{1}\]

where the parameters \( \alpha, \kappa, \beta, \gamma, \varepsilon \) and \( e \) are the coefficients for the nonlinear, higher-order nonlinear, dispersion, shoaling, and dissipation effects.

For a two-layer system with \( \Pi_1 \) and \( \Pi_2 \), which are mixed layer and bottom layer thickness, the nonlinear and dispersion coefficients are

\[
\alpha = \frac{3}{2} \frac{H_1 - H_2}{H_1 H_2} C_0, \quad \beta = \frac{1}{6} \Pi_1 H_2 C_0 \tag{2}
\]

and the linear wave speed is given by

\[
C_0 = \left[ \Delta p g H_1 / \rho (H_1 + H_2) \right]^{1/2} \tag{3}
\]

where \( g \) is the gravity constant, \( \rho \) is the density of water, and \( \Delta p \) is the density difference between two layers. The evolution of solitons is based upon the balance of nonlinear effects with the dispersive effect. Note that \( \alpha \) changes sign when the water depth is across the critical depth, where \( H_1 = H_2 \) (turning point). The sign of the nonlinear term depends on the wave amplitude; depression wave has the opposite sign of elevation wave in amplitude. When the mixed layer depth is thinner than the bottom layer, \( H_1 < H_2 \), only depression waves can be evolved. While the mixed layer is thicker than the bottom layer, \( H_1 > H_2 \), only the elevation waves can be evolved. Near the critical depth, the higher-order nonlinear coefficient \( \kappa \) is important and is given by [Helfrich et al., 1984]

\[
\kappa = -3 \frac{H_1^2 - H_1 H_2 + H_2^2}{(H_1 H_2)^2} C_0 \tag{4}
\]

The coefficient for the shoaling effect, \( \gamma \), is in the order of \(-2 \times 10^{-5} \, s^{-1} [Liu, 1988]\). In this study we will neglect the shoaling effect, since it is small and can be compensated by the dissipation effect. Liu et al. [1985] and Liu [1988] reported an effective horizontal eddy viscosity for solitons of \( e = 1 - 10 \, m/s^2 \). Because eddy viscosity is not a property of a fluid, its value may vary with location and water depth. It is possible that local, incipient shear flow instability or wave breaking could be a cause leading to an eddy viscosity of such value. For shallow water the bottom friction and induced mixing can be another dissipation mechanism.

A numerical approach using Fornberg’s pseudo-spectral method [Liu et al., 1985] has been developed to solve the evolution equation (1). A fast Fourier transform (FFT) algorithm is used in the spatial coordinate, and the split-step method is used for time derivatives. The period and mesh size have to be chosen with care in order to obtain an accurate numerical solution. The time step was chosen in order to maintain numerical stability; the computational reference frame was chosen to move in the direction of wave propagation at a certain constant speed such that the wave train remains in the computational domain. Thus changes in wave speed as well as shape will become apparent in a space-time evolution plot. Also, the Hanning window is used to filter out any waves entering the computational domain from the adjacent domain.

Numerical simulations can be performed by using the observed internal wave field near the generation area as an initial condition to produce the wave evolution on the continental shelf and compare with the observations downstream. A parametric study for various environmental conditions can be carried out to demonstrate and to assess the nonlinear effects such as bottom topography, shoaling (across critical depth), and dissipation and mixing on internal wave evolution. The inclusion of these physical processes is essential to improve quantitative understanding of the coastal dynamics.

3. ERS-1 SAR Observations

The map of Taiwan and the study area of the East China Sea arc shown in Figure 1 superimposed on the bathymetry for
reference. The SAR coverage area is indicated by the box. The 100-m and 200-m depth contours are plotted as dashed and solid lines. Depth contours of 1000 m, 2000 m, 3000 m, and 4000 m are specified with 500-m interval. We have used SAR images from ERS-1 to study the characteristics of internal waves northeast of Taiwan. In all SAR images the flight direction is indicated by an arrow. An ERS-1 SAR image (100 × 137 km) collected on November 10, 1993, shows a complicated internal wave pattern with wave generation, wave refraction, and wave current interaction [Liu et al., 1994] in Figure 2. Taiwan is located near the bottom of Figure 2, with the city of Taipei clearly identifiable at the center of the bottom edge. The dark area northeast of Taiwan is an upwelling induced by the Kuroshio intrusion on the continental shelf. Note that the internal wave packets are propagating in both onshore and offshore directions.

Rank-ordered packets of internal solitons propagating shoreward from the edge of the continental shelf were observed in the SAR images collected during September–October 1992. Two internal wave packets separated by approximately 30 km were identified from a SAR image of northeast of Taiwan collected on October 21, 1992 [Liang et al., 1995, Figure 2]. Each wave is characterized by a dark band followed immediately by a bright band that is different from the previous observations of nonlinear depression waves (a bright band followed immediately by a dark band) in the New York Bight [Liu, 1988]. The reversed pattern in Figure 2 of Liang et al. [1995] indicates the existence of underlying nonlinear elevation internal waves. Based on the assumption of a semidiurnal tidal origin (12.4 hours), the wave speed can be estimated to be 0.66 cm s\(^{-1}\) and is consistent with that obtained from the internal wave theory. By using the SAR images and hydrographic data
Figure 2. ERS-1 SAR image (100 × 137 km) collected northeast of Taiwan on November 10, 1993, showing a complicated internal wave pattern (copyright ESA 1993). The locations of upwelling, internal waves, and conductivity-temperature-depth (CTD) casts are indicated by letters.
[Hueh, 1993], internal waves of elevation have been identified because of a thicker mixed layer as compared with the bottom layer on the continental shelf. The temperature, salinity, and density profiles from a conductivity-temperature-depth (CTD) cast on November 12, 1995, at coordinate 25°42'N, 122°29'E, which is at the vicinity of internal waves observed in the SAR image, are shown in Figure 3a for reference. Notice that the mixed layer thickness is about 65 m in the water of 100-m depth, which represents typical late autumn condition. Another CTD cast representing the summer condition with a shallow mixed layer collected on July 3, 1996, at 26°19'N, 121°15'E, north of Taiwan is shown in Figure 3b for comparison.
Figure 4. Surface signature patterns of two ERS-1 SAR images (100 × 100 km) collected east of Hainan Island in the South China Sea in June and April 1993, indicating the existence of underlying (a) depression and (b) elevation internal waves, respectively (copyright ESA 1993).
The elevation internal waves were also observed on the east shelf of Hainan Island in the South China Sea. Surface signature patterns of two ERS-1 SAR images (100 × 100 km) of east of Hainan Island in the South China Sea (center coordinate at 21.35°N and 115.6°E) collected on June 16 and April 7, 1993, indicate the existence of underlying depression and elevation internal waves, respectively (Figure 4a and 4b) due to the change of mixed layer depth in different seasons. During summer the mixed layer is shallow, and its thickness is thinner than the bottom layer. During winter-spring the mixed layer deepens as a result of strong winds, and its thickness is thicker than the bottom layer. A schematic diagram has been established to describe the interaction of internal waves, surface current field, wind waves, and the resultant SAR image intensity variation as shown in Figure 5. When the mixed layer depth is thinner than the bottom layer, $H_1 < H_2$, only depression waves can be evolved (Figure 4a) as indicated in equation (2). While the mixed layer is thicker than the bottom layer, $H_1 > H_2$, only the elevation waves can be evolved (Figure 4b). The elevation waves induce a reversed flow field as compared with the depression waves. Thus the surface pattern of elevation internal waves observed in the SAR image is reversed as compared with that of the depression waves.

The surface signature of internal waves can be different when the surface slicks or films are abundant owing to active biological processes in the coastal water such as in the Taiwan coastal area. The reason that oil slicks are detected on radar images is that oil films have a dampening effect on short surface waves [Ermakov and Petlinovskiy, 1984; Alpers and Hannerfuss, 1989]. The dark appearance of surface slicks on radar images is due to the smoothing of the ocean surface caused by the damping of short backscattering waves. Therefore the convergence of surface slicks induced by the underlying internal waves will show a series of dark bands in the SAR images (12.5 × 12.5 km) as indicated in the right part of Figure 6. In the left part of SAR image (Figure 6), a depression internal wave packet can be identified as a bright band followed immediately by a dark band as induced by the surface current (strain rate). Therefore the surface signatures of internal waves caused by surface slicks (dark bands only) are different from those due to surface current strain rate (a bright band followed immediately by a dark band).

The generation mechanisms include influences of the tide and the Kuroshio for the formations of both elevation internal waves and depression waves in different ocean environment conditions. Near northeastern Taiwan, the Kuroshio intrudes onto the continental shelf immediately after passing north of Taiwan. A cold water anomaly, manifested as upwelling of the subsurface Kuroshio water, has been frequently observed at the shelf break of the East China Sea to the north of Taiwan. A schematic diagram of internal elevation wave generation process is proposed and shown in Figure 7. The upwelling induced by the Kuroshio intrusion at the shelf break may have a damping effect on the mixed layer bottom. The disturbance of the domed area is then driven by the semidiurnal tide onto the shelf and evolves into a rank-ordered elevation wave packet in the shallow area or a rank-ordered depression wave packet in the deep area depending on the mixed layer depth.
Figure 6. Subscene of ERS-1 SAR image (12.5 × 12.5 km) collected northeast of Taiwan on May 31, 1995, showing internal wave patterns caused by surface slicks (indicated by the arrow on the right side) and by surface current (indicated by the arrow at the top). Copyright ESA 1993.

Figure 7. Schematic diagram of internal elevation wave generation process with upwelling induced by the Kuroshio intrusion at the continental shelf break.
The tidal flow over topographic features such as a valley, island or continental shelf in a stratified ocean can produce depression type disturbances in deep water, as has also been observed in the Taiwan area (Figure 2). The evolution of solitons is based upon the balance of nonlinear effect with the dispersive effect. The sign of nonlinear term depends on the wave amplitude; a depression wave has the opposite sign of an elevation wave in amplitude. Therefore only the elevation waves can be evolved nearshore because the bottom layer thickness is thinner than the mixed layer depth over the sloping shelf. Then the depression solitons from the shelf break will disintegrate into dispersive wave packets in the shallow water area after they pass through a “turning point” of approximately equal layer depths (critical depth where the nonlinear term is zero and changes sign). Two disintegrated internal wave packets have been observed in the SAR subscape (25 × 25 km) image collected on September 16, 1992 (Figure 8a) in a shallow water area on the shelf north of Taiwan. The wavelength of internal waves in wave packets is about 260 m, which is almost the same wavelength as the swell system propagating in the southwest direction that can be seen in the background. Figure 8b shows the two-dimensional wave spectrum of the SAR scene. Note that the swell of 289-m wavelength is coming from 46° (with respect to north) and the internal waves are coming
from the east as indicated in the spectrum. The wave packet size is about 1 km, which is the size of a depression soliton observed before near the shelf break.

The Kuroshio moving north from Philippine Basin branches out near the south tip of Taiwan. A 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. The surface signature pattern of huge internal soliton packets has been observed in the ERS-1 SAR image (100 × 200 km) collected on June 16, 1995, as shown in Figure 9. The soliton crest is >200 km long, and each packet contains >10 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 largest internal waves that have been observed in this area. The internal wave amplitude is larger than 100 m on the basis of the CTD casts from Taiwan’s research ship during their South China Sea expedition (J. Wang, private communication, 1995). These huge wave packets propagate and evolve into the deep South China Sea and will reach the continental shelf of southern China. It is possible that the internal wave packets observed in the South China Sea east of Hainan are due to the evolution of these waves. The distance and degree of intrusion of high-temperature and high-salinity Kuroshio water into the Taiwan Strait and the South China Sea with heat flux and momentum flux are still open issues.

4. Numerical Study and Model Results

A series of numerical experiments were performed by solving the initial value problem described by equation (1) with a well developed soliton solution as an initial condition. The steady state depression wave solution of the KdV equation is given by

\[ A(x, t) = -A_0 \text{sech}^2 \left(\frac{x - Ct}{l}\right), \]  (5)

where \( A_0 \) is the wave amplitude, the wave speed \( C \) is

\[ C - C_0 \left(1 + \frac{A_0 (H_2 - H_1)}{2H_1 H_2}\right), \]  (6)

and the half width \( l \) is

\[ l = \frac{2H_1 H_2 [3A_0 (H_2 - H_1)]^{-1/2}}{\text{and the half width} l} \]

(7)

In the north of Taiwan area, the density contrast \( \Delta \rho/\rho = 10^{-3} \). The first case was made for an initial profile corresponding to a single depression soliton in finite/deep water of depth \( H \) propagating towards a cosine-shaped transition to shallow water:

\[ H_2 = H_{20}, \quad x < 0, \]  (8a)

\[ H_2 = H_{20} + 0.5(H_{20} - H_{2e}) [\cos (\pi x/L) - 1], \]  (8b)

\[ 0 < x < L, \]  (8c)

\[ H_2 = H_{2e}, \quad x > L, \]

where \( L \) is a characteristic length of the depth variation.

The numerical simulations of nonlinear internal wave evolution on the shelf show the change of polarity through critical depth (Figure 10). A solitary depression wave is used as the initial condition at water depth of 160 m with \( A_0 = 10 \) m. The mixed layer thickness, \( H_1 = 60 \) m, the initial bottom layer thickness \( H_{20} = 100 \) m, the final bottom layer thickness \( H_{2e} = 40 \) m, and the characteristic length \( L = 20 \) km (with steep slope) are chosen for Figure 10a. Note that the critical depth is reached after 6 hours (at \( x = 0.6 L \)) approximately. However, the solitary wave disintegrates into a wave packet after 10 hours (near \( x = L \)), and it continues to evolve as a train of rank-ordered elevation internal solitons after 22 hours. It is found that from a single depression soliton, more than five elevation solitons can merge. For sensitivity analysis, a series of parametric study have been performed with variable wave amplitude, water depth, bottom slope, and dissipation. In general, all numerical results show the change of polarity through critical depth. Two typical cases are shown in Figure 10b for mild bottom slope, and in Figure 10c for steep slope with dissipation. For mild bottom slope with characteristic length of 100 km (Figure 10b), the evolution is much slower, and the solitary wave disintegrates into a wave packet after 30 hours (near \( x = L \)) and continues to evolve as a train of rank-ordered elevation internal solitons after 55 hours. For steep bottom slope with dissipation coefficient \( \varepsilon = 1 \) m/s (Figure 10c), the solitary wave disintegrates into a wave packet after 10 hours, but its amplitudes damp to only the half of no-dissipation case in Figure 10a.

Next, the case of two rank ordered depression solitons \( (A_0 = 10 \text{ and } 7 \text{ m}) \) separated by 75 km is studied. Two wave packets start to evolve and merge after 6 hours near the critical depth. However, without dissipation they are well overlapped after 11 hours, as is shown in Figure 11a. The dissipation effects are expected to be important in this situation, since the interaction of wave packets may steepen the wave amplitude. Thus the eddy viscosity could be eroding the sharp peaks of the large solitons, reducing their amplitudes and increasing their half-widths at the same time. Figure 11b shows the evolution of two depression solitons through the critical depth with a dissipation coefficient \( \varepsilon = 1 \) m/s. Notice that two wave packets are well separated with much shorter wavelengths, which is quite similar to the observation from SAR image in Figure 8. Although the in situ measurements are not available for this situation, the numerical calculations describe the potential i-
Figure 9. Mosaic of ERS-1 SAR images (100 x 200 km) collected south of Taiwan in Luzon Strait on June 16, 1995, showing huge internal soliton packet (copyright ESA 1995).
Figure 10. Numerical simulations of nonlinear internal wave evolution on the shelf showing the change of polarity through critical depth for (a) steep slope, (b) mild slope, and (c) steep slope with dissipation $\varepsilon = 1$ m$^2$/s.

terpretation of SAR observations. These types of processes, by which depression solitons disintegrate into wave packets and then evolve to elevation solitons, have never been observed and reported before. While further in situ measurements are needed to verify the SAR observations, the numerical predictions developed here should remain as an interesting topic.

The essential element of the surface effects is the interaction between the internal-wave-induced surface current field and the wind-driven ocean surface waves. This interaction has been studied, notably by Hughes [1978] and Holliday et al. [1987]. Basically, the analysis is based on a near-equilibrium spectral transport model to estimate the roughness modulation by a variable surface current. The effect of the surface current is to alter the spectrum from its equilibrium value, while the natural processes of wave energy input from the wind, wave breaking, and other nonconservative processes act to restore the ambient equilibrium spectrum. According to a first-order radar-imaging theory [Alpers, 1985], the relative variation of the normalized radar cross section (relative modulation) associated with internal waves is related to the horizontal gradient of the surface velocity, the strain rate [Liu, 1988]. The proportional coefficient depends on radar wavelength, radar incidence angle, angle between the radar look direction and the internal wave propagation direction, azimuth angle, and wind velocity. Thus to first order (for a linear SAR system), the variation of the SAR image intensity is proportional to the gradient of the surface velocity, or the strain rate. Figure 12a shows the relative modulation of a cross section in the SAR image along the wave packet propagation direction in Figure 8a with two packets as indicated by arrows. The strain rate has been calculated for the final numerical results in Figure 11a as shown in Figure 12b. The strain rate values are of the order of $10^{-2}$ s$^{-1}$, which are consistent with the observed data from New York Right internal waves [Liu, 1988]. The patterns of two wave packets are similar for the SAR observation in Figure 12a and for the numerical results in Figure 12b. The wavelength of the wave packets in Figure 12b is found to be 340 m, which is also close to the wavelength of 260 m from the SAR image in Figure 12a. Since we do not have in situ measurements for the numerical simulation, this qualitative comparison demonstrates the connection between the numerical model and the SAR radar cross section observation of internal waves.
5. Discussion
Many SAR images from ERS-1 have been collected and used to study the characteristics of internal waves northeast and south of Taiwan in the East China Sea and east of Hainan Island in the South China Sea. Rank-ordered packets of internal solitons propagating shoreward from the edge of the continental shelf were observed in SAR images. The wave speed can be estimated on the basis of assumption of a semidiurnal tidal origin and is consistent with the internal wave theory. By using 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, for the formations of both elevation internal waves and depression waves under different ocean conditions have been proposed. The effects of water depth on the evolution of solitons and wave packets are modeled by a KdV type equation and linked to the satellite SAR observations of elevation internal waves and disintegrated internal wave packets. For a case of depression waves in deep water, the solitons first disintegrate into dispersive wave trains and then evolve into a packet of elevation waves in the shallow water area after they pass through a “turning point” of critical depth has been simulated by a numerical model. Examples of the numerical model results of nonlinear internal wave evolution on the shelf with topographic and dissipation effects are presented in this paper to interpret the observations in the SAR images.

The essential element of the surface effects is the interaction between the internal-wave-induced surface current field and the wind-driven ocean surface waves. For a linear SAR system the variation of the SAR image intensity is proportional to the gradient of the surface velocity, or to the strain rate. The proportionality depends on radar wavelength, radar incidence angle, angle between the radar look direction and the internal wave propagation direction, azimuth angle, and wind velocity. For the high-wind-speed condition, the internal wave signal may be too weak to be observed by radar owing to low signal-to-noise ratio. When the internal waves propagate in the crosswind direction, the wave-current interaction is also relatively weak, and so is the radar backscattering for SAR observation. The strain rates have been calculated for the internal wave packets and their values are consistent with the observed data from New York Bight internal waves. Without in situ field measurements for detailed numerical simulations, the comparison of relative modulation from SAR data and strain rate from model are reasonable qualitatively.

It is clear that these internal wave observations in the East and South China Seas provide a unique resource for addressing a wide range of processes, including the following: generation of elevation internal waves by upwelling due to the Kuroshio intrusion across the continental shelf, evolution of depression waves through the critical depth, disintegration of solitons into internal wave packets, dissipation effects of internal wave breaking and turbulent mixing on wave propagation, shoaling effects of variable bottom topography on wave evolution, and wave packet interaction. These types of processes

Figure 11. Numerical simulations of nonlinear internal wave evolution on the shelf showing the disintegration of two solitons into two wave packets for the cases (a) with no dissipation and (b) with dissipation $\varepsilon = 1 \text{m}^2/\text{s}$.

Figure 12. (a) The relative modulation of a cross section in the SAR image (Figure 8a) along the wave packet propagation direction, and (b) the surface strain rate from the final results of Figure 11a with two internal wave packets indicated by arrows.
by which the depression solitons disintegrate into wave packets and then evolve into elevation solitons have never been observed and reported before. Moderate elevation internal waves could be generated in waters where the mixed layer is still shallow in comparison with the lower bottom layer. However, owing to the nonlinear effects, these elevation internal waves will not survive and will evolve to a dispersive wave train. Further in situ measurements are needed to verify the SAR observations. A SAR image provides only a snapshot of the internal wave evolution, but a large spatial coverage over the field measurement area. However, the repeat cycle for ERS-1 SAR is 35 days for general purposes. Therefore the entire evolution from depression to elevation internal waves cannot be observed by SAR instantaneously. Based on the SAR image for field test planning, two moorings at upstream and downstream of “critical depth” can be deployed to verify the numerical results. Numerical simulations can be performed by using the observed internal wave field near the generation area as an initial condition to produce the evolution of the continental shelf and then to compare with the observations. On the basis of observations of internal wave evolution from SAR images and model predictions, the ratio of mixed layer depth to the bottom layer depth can be estimated. Furthermore, the mixed layer depth can be derived also from the internal wave speed, which is estimated from the distance of sequential wave packets in the SAR images (based on the assumption of semidiurnal tidal generation).

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