Internal Tides and Solitary Waves in the Northern South China Sea:
A Nonhydrostatic Numerical Investigation

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LONG-TERM GOALS

The goal of this project is to understand processes relevant to the generation, propagation and dissipation of finite-amplitude internal solitary waves observed in the region from the Luzon Strait to the Chinese continental shelf.

OBJECTIVES

With data available from field observations in Non-Linear Internal Wave Initiative (NLIWI), this project is to perform simulation of finite-amplitude internal solitary waves under realistic scenarios in the northern South China Sea. The objective is to provide information on the characteristics of nonlinear internal waves for comparison with data collected from remote sensing, mooring measurements, and shipboard observations.

APPROACH

Processes of wave generation, propagation and dissipation are studied by numerical simulation using a nonhydrostatic ocean model under different scenarios of bottom topography and stratification. Experiments include wave generation by ridges in the Luzon Strait and by density fronts, wave propagation across the deep basin with a shoaling thermocline, wave reflection and diffraction near the Dongsha (Tungsha) Island, wave generation and dissipation on the continental slope, and characteristics of higher-mode waves.

WORK COMPLETED

Model development is completed this year. The object-oriented programming technique has been successfully implemented for nonhydrostatic ocean modeling in both Matlab and C++. A paper summarizing this novel approach has been published (Shaw and Chao, 2006).

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A paper describing how a circular island reflects and diffracts solitary waves is in press (Chao et al., 2006a). This study was described in last year's report.

Modeling studies this year include the evolution of internal tide to solitary waves and the effects of a two-ridge system on internal waves. The evolution study is focused on the generation and attenuation/enhancement of internal tides and solitary waves in the region between the Luzon Strait and the continental shelf of China, an east-west distance of about 250 km. The study of waves in a two-ridge system emphasizes the blocking of the west ridge on waves generated by the east ridge. The result of the latter study has been combined with those derived from a regional hydrostatic model to assess the wave behavior affected by these ridges. A manuscript has been submitted (Chao et al., 2006b).

RESULTS

1) Evolution of internal tides

An experiment has been carried out with a sill depth of 400 m below the surface and a thermocline centered at 200 m. The semidiurnal barotropic tide has a moderate speed of 0.75 m/s over the ridge peak at $x = 0$ km. The barotropic velocity starts with zero velocity at $t = 0$ and an ebb flow to the east afterward. Westward-propagating internal waves start when the tide reverses to flood after 6 hours (Figure 1). At the end of 12.42 hours, a linear wave is located at $x = -75$ km and intensifies to become a tidal bore at $x = -110$ km by 18.63 hours. Further strengthening of the tidal bore can be seen at 24.84 hours. Finally, upward velocity forms behind the downward motion at the wave front by 31.05 hours, indicating the beginning of a rank-ordered solitary wave packet. In this case, the rank-ordered wave packet does not develop until after 250 km from the source. In addition to the first-mode waves, strong mode-2 waves are also generated. The phase speed of these waves is less than half of the fast-propagating first-mode waves. They remain near the generation region. Their propagation is significantly affected by the oscillating barotropic tides.

A sequence of experiments has been carried out to quantify this process. Figure 2 shows the maximum downward velocity at the wave front for different ridge heights and current strengths. The Froude number, defined as the depth-averaged flow speed divided by the phase speed over the ridge, is used as a parameter. The lowest curve (Froude number = 0.41) represents the case shown in Figure 1 where a tidal bore dominates during the first 30 hours, and a solitary wave packet slowly develops. In this case, a single wave trough is likely to be observed in the region between the ridges and the continental shelf in the northern South China Sea. For a larger Froude number, i.e., a higher ridge or faster tidal flow, rank-ordered internal solitary waves quickly develop, and a multiple-wave structure could be observed. For these strong waves, the maximum vertical velocity reaches its peak value in 15 to 20 hours and decays rapidly afterward.

Internal solitary waves are generated by two possible mechanisms. One is the formation of lee waves by flow over a ridge. The other is the transfer of energy from the barotropic tides to the baroclinic tides. In Figure 1, large-amplitude lee waves are mostly confined near the ridge, and a linear wave is clearly seen propagating out of the source region. The internal tide seems to be the source of solitary waves developed here; strong second-mode waves near the source region may be associated with the lee waves. In the Luzon Strait, the Froude number is likely low because the sill is generally deep and

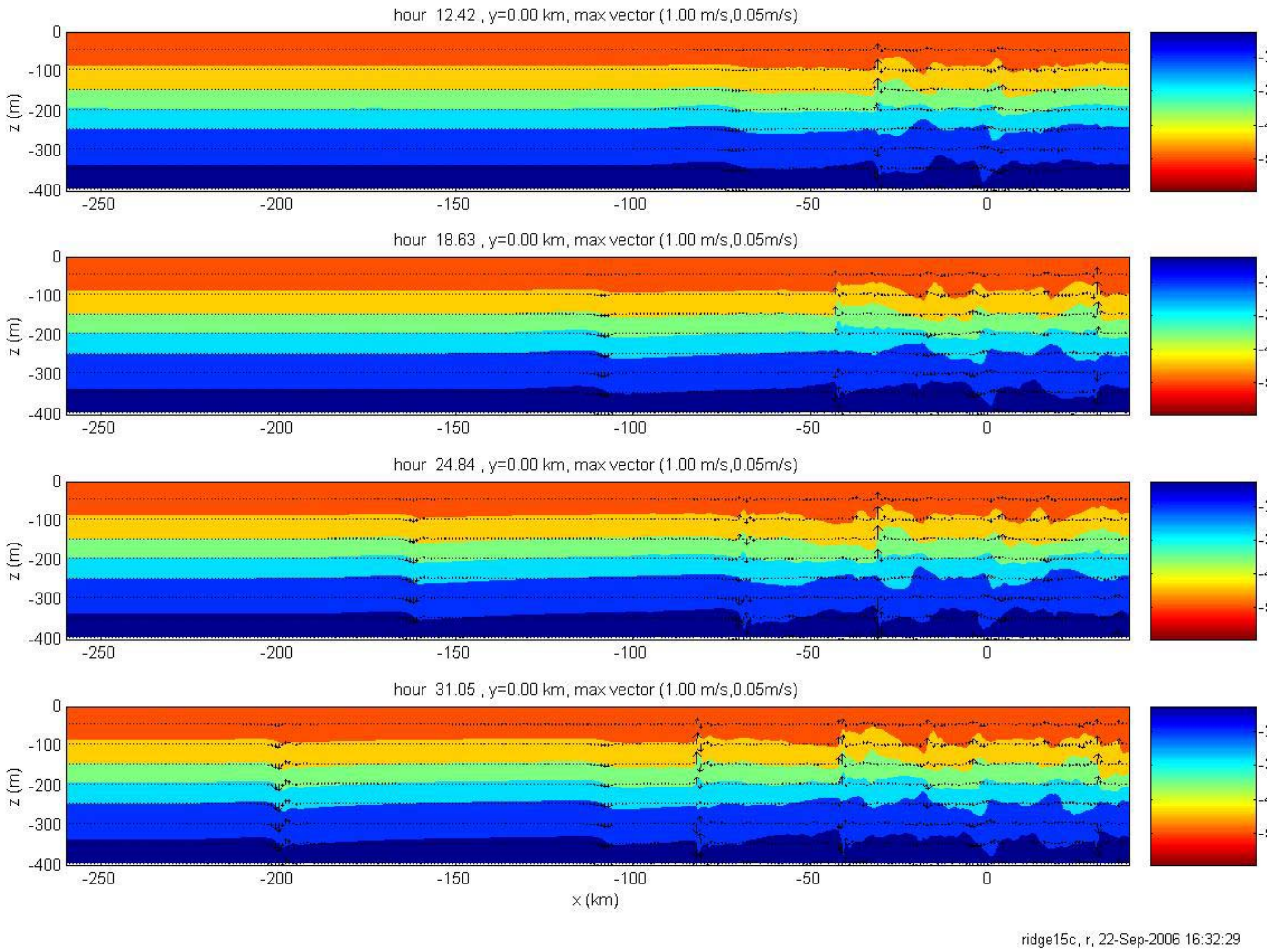

Figure 1: Evolution of the internal tide into a tidal bore and rank-ordered solitary waves. Contours represent perturbation density in kg/m3. Waves are generated by the barotropic tides over a ridge at x = 0 km.

below the thermocline except near a few islands. The two lower curves in Figure 1 likely represent the situation in the Luzon Strait.

The evolution of the internal tide into a solitary-wave packet is sketched in Figure 3. The ridge first converts energy in the barotropic tides to westward propagating internal tides (Figure 3a). Because the wave trough propagates faster than the crest, the wave steepens and transforms the internal tide to an internal bore (Figure 3b). The internal bore further intensifies (Figure 3c) and develops into a packet of rank-ordered internal solitary waves (Figure 3d). The time required for the development depends on the Froude number. For large Froude numbers, a strong rank-ordered solitary wave packet is developed immediately when the ebb tide turns to flood tide, and the maximum vertical velocity peaks soon after. For a moderate Froude number, the tidal bore could persist over a distance of 250 km or more, and the wave strength keeps increasing. The distance for solitary waves to appear also depends on the tidal frequency. The wavelength of the diurnal internal tide is twice as long as that of the semidiurnal internal tide, requiring longer distance for wave steepening.

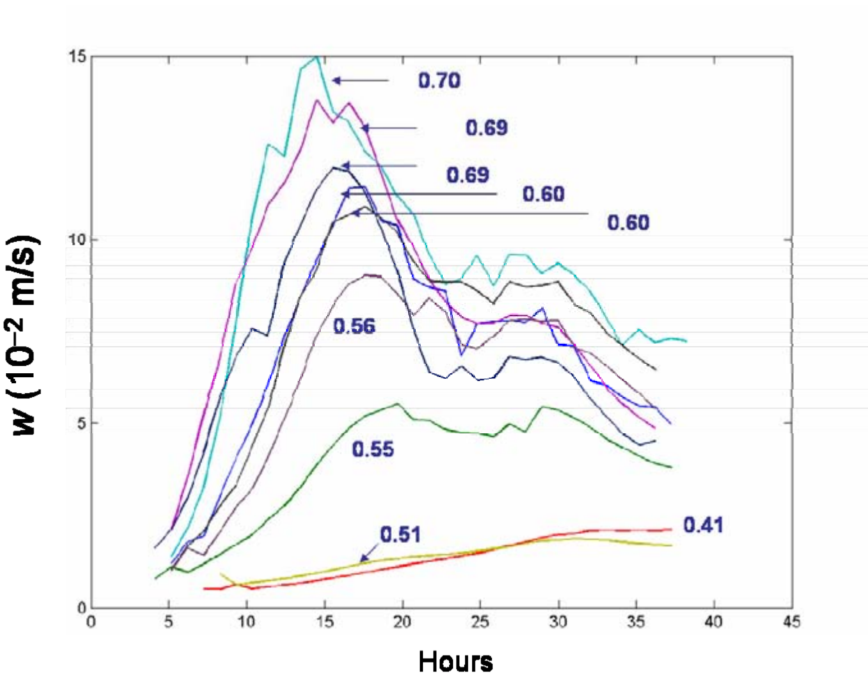

Figure 2: Development of the maximum downward velocity at the wave front of the first-mode wave as a function of time. Each curve is labeled by its Froude number, which parameterizes the effects of ridge heights and strengths of the barotropic tide.

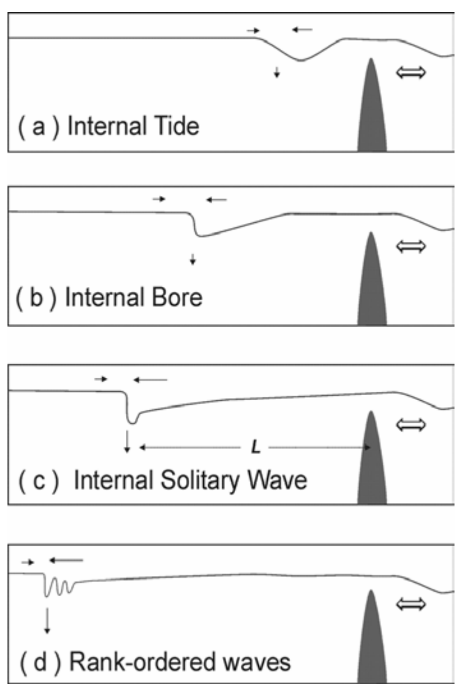

Figure 3: Nonlinear evolution from the barotropic tide to a tidal bore, and to internal solitary waves.

2) The effect of the west ridge in the Luzon Strait

Experiments with a double-ridge construction shed light on the propagation of internal waves over the west ridge. Waves are generated by an east ridge 400 m below the surface. A second ridge is placed 120 km to the west to represent the west ridge in the Luzon Strait. Figure 4a shows the incoming internal tide (labeled by IT) before it reaches the west ridge at hour 12. At hour 18 (Figure 4b), shoaling bottom depth seems to transform the internal tide to an internal bore (labeled by IB) but the development is a little out of synchronization with the overall wave development and therefore does not help subsequent growth of internal solitary waves (labeled by IS). At hour 24 and 30 (Figure 4c,d), the internal solitary wave is a little weaker than in the case without a west ridge. So the west ridge dampens the wave slightly.

Increasing the west ridge height to the depth of the east ridge corresponds to the setting in the northern reaches of the Luzon Strait near Taiwan. Figure 5 shows that the wave is almost totally blocked by the west ridge. On the other hand, the west ridge becomes a new source of internal waves, generating internal bores and internal solitary waves to its west at the semidiurnal frequency.

Wave transmission through a single ridge at different ridge heights has been studied. The maximum thermocline displacement, east velocity (u), and upward velocity (w) of transmitted waves after being normalized by similar runs without a ridge are shown in Figure 6. The depth of the first-baroclinic-mode nodal point where the horizontal velocity is zero determines how much wave energy is transmitted. When the ridge is below this depth, internal solitary waves are not significantly blocked by the ridge.

IMPACT/APPLICATIONS

Satellite observations (Zhao et al., 2004) have shown that most waves in the deep ocean between the Luzon ridges and the continental shelf are tidal bores, i.e., a single wave trough behind the wave front. The experiments on wave evolution suggest that solitary waves in the deep water of the northern South China Sea could be generated by a moderate tidal flow over a low ridge, corresponding to the curve with a Froude number 4.1 in Figure 2. For these waves, the tidal bore does not develop into a wave packet of multiple troughs and crests over the distance between the Luzon ridges and the continental slope along 21°N. Thus, tidal bores at the semidiurnal tidal periods are mostly observed in the deep water of the northern South China Sea. The appearance of the diurnal period is due to the difference in strengths of two consecutive semidiurnal peaks (Yang et al., 2004).

The numerical study of a two-ridge system suggests the generation of internal tides and solitary waves by the middle portion of the east ridge and the northern portion of the west ridge. The middle portion of the west ridge mainly damps the internal tides originating from the east ridge.

RELATED PROJECTS

This project is a continuation and expansion of our ONR-supported study entitled "Nonhydrostatic numerical investigations of oscillating flow over sills: generation of internal tides and solitary waves"

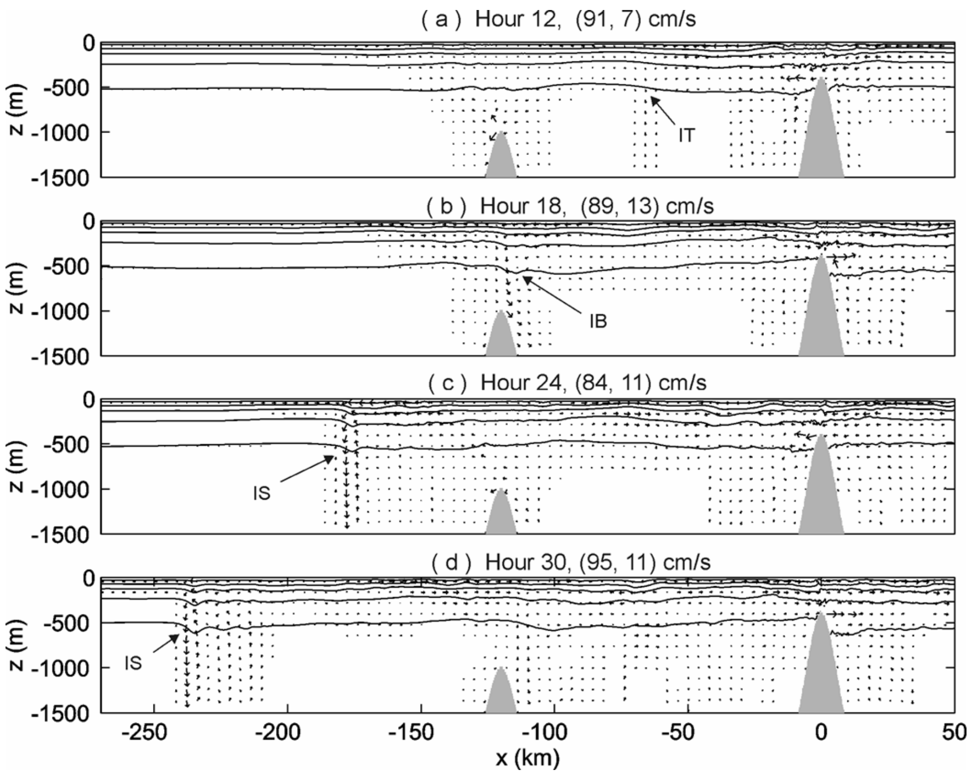

Figure 4: Experiment with two ridges, showing wave transmission across the west ridge. [The east ridge is 400 m below surface. The west ridge is 1000 m below surface.]

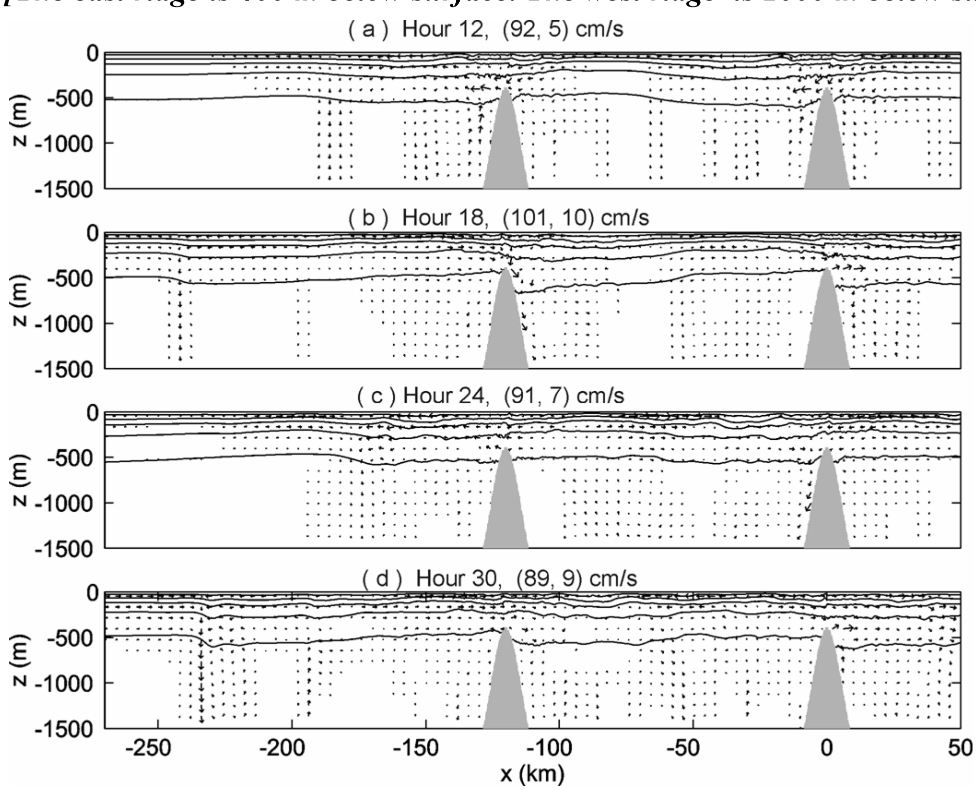

Figure 5: Experiment with two ridges. Both ridges are 400 m below surface. The transmitted wave is mostly blocked by the west ridge.

(ONR contracts N00014-04-1-0419 to Shenn-Yu Chao and N00014-04-1-0430 to Ping-Tung Shaw). Satellite and radar imagery and mooring data obtained in NLIWI field experiments have been used in this study. This study also utilizes results from the nowcast/forecast model of Naval Research Laboratory by D. S. Ko and the field observation in the South China Sea by R. C. Lien.

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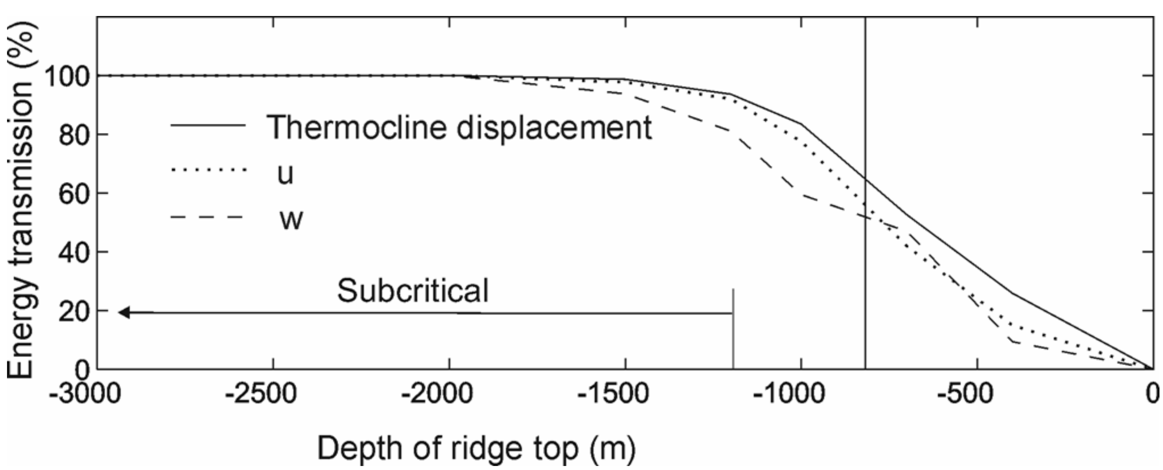

Figure 6: Normalized strength of transmitted internal solitary waves after passing through a single ridge as a function of the ridge peak depth.