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Numerical assessment of factors affecting nonlinear internal waves in the South China Sea

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ABSTRACT

Nonlinear internal waves in the South China Sea exhibit diverse characteristics, which are associated with the complex conditions in Luzon Strait, such as the double ridge topography, the Earth's rotation, variations in stratification and the background current induced by the Kuroshio. These effects are individually assessed using the MITgcm. The performance of the model is first validated through comparison with field observations. Because of in-phased ray interaction, the western ridge in Luzon Strait intensifies the semidiurnal internal tides generated from the eastern ridge, thus reinforcing the formation of nonlinear internal waves. However, the ray interaction for K_1 forcing becomes anti-phased so that the K_1 internal tide generation is reduced by the western ridge. Not only does the rotational dispersion suppress internal tide generation, it also inhibits nonlinear steepening and consequent internal solitary wave formation. As a joint effect, the double ridges and the rotational dispersion result in a paradoxical phenomenon: diurnal barotropic tidal forcing is dominant in Luzon Strait, but semidiurnal internal tides prevail in the deep basin of the South China Sea. The seasonal variation of the Kuroshio is consistent with the seasonal appearance of nonlinear internal waves in the South China Sea. The model results show that the westward inflow due to the Kuroshio intrusion reduces the amplitude of internal tides in the South China Sea, causing the weakening or absence of internal solitary waves. Winter stratification cannot account for the significant reduction of nonlinear internal waves, because the amplitude growth of internal tides due to increased thermocline tilting counteracts the reduced nonlinearity caused by thermocline deepening.

1. Introduction

Nonlinear internal waves in the South China Sea are among the largest internal waves in the world. Their amplitude can reach 170 m (Klymak et al., 2006). Satellite observations show that these waves are centered at ~20.5°N in the deep basin and propagate in a WNW direction with crest lengths of more than 200 km and widths of ~10 km (Zhao et al., 2004; Jackson, 2009). Because of their dramatic impact on underwater structures and activities, studies on their generation and propagation raised more and more attention in recent decades (Duda and Farmer, 1998).

Complex hydrographic conditions in the South China Sea are responsible for diverse features of nonlinear internal waves. Both satellite images and field observations reveal two types of internal solitary waves: rank-ordered multiple wave packets and single wave packets, respectively defined as a-waves and b-waves by Ramp et al. (2004). The internal tides are modified into a cusp-shape with a smooth crest and a sharp trough (Farmer et al., 2009), known as corner waves (Helfrich and Grimshaw, 2008). The temporal variation and spatial distribution of nonlinear internal waves present special patterns: internal solitary waves are seldom found east of 120.5°E, including the east side of Luzon Strait in the Pacific Ocean (Jackson, 2009); the appearance of internal solitary waves is intermittent and is associated with the magnitude of semidiurnal forcing in Luzon Strait rather than diurnal forcing (Li and Farmer, 2011); in winter, the magnitude of waves is significantly suppressed (Ramp et al., 2010) and the waves are rarely observed by satellites (Zheng et al., 2007).

Three mechanisms could potentially explain the generation of nonlinear internal waves in the South China Sea: nonlinear internal waves evolve from internal tides due to shock formation (Lee and Beardsley, 1974; Farmer, 1978; Liu et al., 1998; Zhao and Alford, 2006); nonlinear internal waves evolve from unsteady lee waves generated near the ridges (Maxworthy, 1979); nonlinear internal waves are generated from energy scattering due to the interaction between internal wave beams and thermocline (Gerkema, 2001). Field observations are sparse and make it difficult to provide sufficient evidences to examine the validity of each mechanism. Previous studies mostly focused on a "teleconnection" between tides in Luzon Strait and observations on shelf (e.g., Ramp et al., 2004; Zhao and Alford, 2006). The intermediate process in the deep basin was ignored. This paper will particularly focus on the deep basin.

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Numerical models have been employed to study the generation and propagation of nonlinear internal waves in the South China Sea. Initially, the KdV-type weakly nonlinear models were adapted to demonstrate the formation of internal solitary waves from internal tides due to nonlinear steepening (Liu et al., 1998; Cai et al., 2002). More recently, 2-layer fully nonlinear models with consideration of rotation were developed to interpret diverse structures of the observed nonlinear internal waves (Helfrich and Grimshaw, 2008; Li and Farmer, 2011). These simplified two-layer models provide a clear description of the physics of wave generation and propagation, although they need further examination in continuously stratified fluid.

Extending to continuously stratified models, Buijsman et al. (2010a) demonstrated that internal tides are initiated from an upstream-leaning lee beam emitted from the eastern ridge and then evolve nonlinearly into solitary waves. Three-dimensional simulation by Zhang et al. (2011) revealed that the single and multiple internal solitary wave packets are respectively generated by diurnal and semidiurnal internal wave beams emitted from different portions of Luzon Strait. Most (~70%) of the internal tide energy is generated from the eastern ridge (Jan et al., 2008). However, the role of the western ridge is not clear. Chao et al. (2007) proposed that the western ridge dampens any incident internal waves from the eastern ridge, but the western ridge in the northern strait is a secondary generation site for M_2 internal tides. However, Echeverri and Peacock (2010) found that the existence of the western ridge may enhance internal tide generation. The internal waves generated from the two ridges interact with each other and may lead to standing internal waves. Models show enhanced mixing between the ridges (Buijsman et al., 2012), but the impact of the double ridges on the behavior of nonlinear internal waves in the far field has not yet been presented.

The Kuroshio passes through Luzon Strait. Du et al. (2008) showed that the Kuroshio intrusion increases the occurrence of nonlinear internal waves due to enhanced disturbance. However, Warn-Varnas et al. (2010) showed that internal solitary waves are reduced by the Kuroshio intrusion because of the interaction between wave generation and the double-ridge topography. The existence of the Kuroshio may increase the energy flux of the generated internal tides by up to 40%, depending on the transport and location of the Kuroshio (Jan et al., 2012). Weakened stratification in winter due to intensified surface mixing by the Kuroshio intrusion and the monsoon may reduce the amplitude of internal solitary waves (Shaw et al., 2009), as well as their surface signature.

Recent in situ observations revealed diverse features of nonlinear internal waves in the South China Sea to be related to multiple environmental factors during their generation and propagation (Farmer et al., 2009; Alford et al., 2010; Ramp et al., 2010). This leads to different understandings of these waves and call for a systematic study. Instead of repeating numerical simulations, four major factors, topography, rotation, stratification and the Kuroshio intrusion, are individually assessed in this paper. First, hydrographic conditions and tidal analysis in Luzon Strait are investigated in Sections 2 and 3, respectively. The MIT general circulation model (MITgcm) is employed for its state-of-the-art technique in processing nonlinear and nonhydrostatic problems. The model configuration and a control test are introduced in Section 4, in which the model performance is validated through comparison with in situ observations. Then, the effects from the above four factors are individually evaluated in Section 5, followed by a summary and discussion in Section 6.

2. Bathymetry and stratification

Luzon Strait (Fig. 1) lies between Taiwan and the Philippines, connecting the South China Sea and the northwestern Pacific Ocean. Two ridges stretch along the strait: Lan-Yu Ridge in the east extending south through Batan Islands is shallower in the south; Heng-Chun Ridge on the western side of the strait is shallower in the north with a depth transition occurring at ~21°N. Although its path is variable, the Kuroshio sometimes encroaches over the eastern ridge in a curved trajectory before returning to the northeast. Strong tidal currents occur in the shallow passes, in particular between Batan and Itbayat Islands. These locations have been proposed as the active sites for internal wave generation (Ramp et al., 2004; Zhao and Alford, 2006). Measurements of tidal currents are sparse and the tidal information used in this paper is predicted from the TPXO model (Egbert and Erofeeva, 2002).

Fig. 2 shows the profiles of temperature, salinity, density and buoyancy frequency measured from CTD casts during three cruises in 2007. The stratification is primarily determined by the

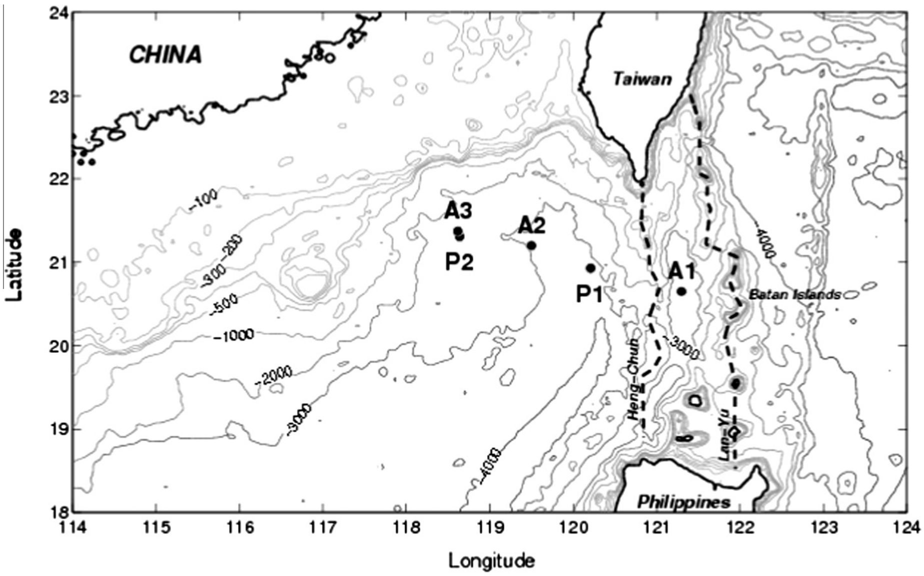

Fig. 1. Topography of the South China Sea and locations of the pressure sensor equipped inverted echo sounders deployed in 2005 (P1, P2) and 2007 (A1, A2, A3). The black dashed lines indicate the two ridges along Luzon Strait.