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Seasonal variability and north–south asymmetry of internal tides in the deep basin west of the Luzon Strait

Zhenhua Xu [a,b,*], Baoshu Yin [a,b,*], Yijun Hou [a,b], Antony K. Liu [c]

[a] Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[b] Key Laboratory of Ocean Circulation and Waves (KLOCAW), Chinese Academy of Sciences, Qingdao 266071, China
[c] Ocean College, Zhejiang University, Hangzhou 310058, China

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ABSTRACT

Temporal and spatial variability of internal tides (ITs) in the deep basin west of the Luzon Strait were examined, based on two 9-month mooring current observations from autumn 2008 to summer 2009. The baroclinic current measurements exhibited north–south asymmetry and temporal variation. At the southern site (19.5°N), the kinetic energy of diurnal IT was dominant over that of semidiurnal IT by a factor of 3 to 4, whereas at the northern site (~21°N), the diurnal energy was comparable to or a little larger than semidiurnal energy. At both sites, the motions of semidiurnal IT were recognized as seasonally invariant, while diurnal IT showed notable seasonal variation, namely, stronger in summer and winter but weaker in spring and autumn. The seasonal variation was mainly modulated by the astronomical tides in the Luzon Strait rather than by the seasonal thermocline. Both diurnal and semidiurnal ITs contained stronger coherent signals than incoherent counterparts at two sites, but the IT at the southern site was more coherent than that at the northern site. Diurnal IT is more coherent than the semidiurnal IT at each site. The spatial–temporal variations were probably due to IT interferences from various sources within the Luzon Strait and modulation by varying background conditions.

1. Introduction

Internal tides (ITs) are commonly generated by barotropic tidal currents that flow over varying topography, such as shelf breaks, ridges and sills (Garrett and Kunze, 2007; Helfrich and Melville, 2006). They are usually accompanied by large amplitude pycnocline oscillations and strong horizontal currents. ITs play an important role in affecting ocean engineering structures and platform operations (Brandt et al., 1996; Cai et al., 2008; Duda et al., 2004; Wang et al., 1991; Wolanski et al., 2004; Xu et al., 2011a). After their generation from the source region, the first-mode ITs generally radiate away and can propagate thousands of kilometers (Alford, 2003; Rainville and Pinkel, 2006; Zhao et al., 2010), whereas higher-mode ITs usually break near the source region and induce local mixing (Klymak et al., 2011; St. Laurent and Garrett, 2002; Vlasenko et al., 2010). Breaking ITs are supposed to be one of the main energy sources for stimulating mixing, which is important for maintaining ocean circulation (Alford, 2010; Chen et al., 2003; St. Laurent, 2008).

The ITs in the northern South China Sea (SCS) are among the strongest of the world's oceans (Duda et al., 2004; Niwa and Hibiya, 2004; Yang et al., 2004). The ITs in the SCS mostly originate from the Luzon Strait (Jan et al., 2008; Shaw et al., 2009), propagate westward across the deep central basin (Duda et al., 2004; Farmer et al., 2009), steepen into internal solitary waves (ISWs), and dissipate over the SCS shelf zone (Lien et al., 2005; Liu et al., 1998, 2013; Ramp et al., 2004; Xu et al., 2010). Since the Asian Seas International Acoustics Experiment, the ITs in the northeastern SCS and the Luzon Strait were extensively surveyed based on field observations and numerical modeling results (Duda et al., 2004; Klymak et al., 2011; Liu et al., 2004; Simmons et al., 2011). In the northwestern SCS, some observational studies of ITs were also undertaken in recent years (Xu et al., 2011b, 2013).

Studies of ITs in the SCS are mainly based on field observations and numerical simulations. Although some modeling studies also investigated the seasonality of ITs, numerical simulations were mostly used to characterize short-term variation, owing to the limitation of computation capacity (Chao et al., 2007; Jan et al., 2008; Simmons et al., 2011). Note that most IT modeling studies cannot characterize the ISW generation process and thus tend to overestimate IT energy, especially for the semidiurnal ITs. Therefore, some researchers used long-term field current measurements to examine seasonal variability of ITs in recent years (Lee et al., 2012; Xu et al., 2013).

The ITs generated in the Luzon Strait can propagate over 1000 km before reaching the northwestern continental shelf. Mesoscale eddies are common features in the northern SCS (Wang et al., 2008). The

* Corresponding authors at: Institute of Oceanology, Chinese Academy of Sciences, 7 Nanhai Road, Qingdao 266071, China. Tel./fax: +86 532 82898502.
E-mail addresses: xuzhenhua@qdio.ac.cn (Z. Xu), bsyin@qdio.ac.cn (B. Yin).

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region is also influenced by tropical cyclones and Kushiro intrusion (Xu et al., 2013; Yuan et al., 2006; Zheng et al., 2007). Consequently, background currents and stratification of the water column in the northern SCS exhibit a variable and intermittent pattern. In the course of traveling through the complex background condition, ITs may lose coherence to the astronomical tides and show an incoherent nature (van Aken et al., 2007). Based on 8-month moored acoustic Doppler current profiler observations on the continental slope of the Dongsha Plateau, Lee et al. (2012) found that incoherent internal tidal motion accounted for about three fourths of the observed tidal energy. Xu et al. (2013) further suggested that diurnal ITs were more coherent than the semidiurnal ITs in the northwestern SCS. Coherent variance was found to account for about 40% of the diurnal motions, but a much smaller fraction (~10%) of the semidiurnal motions.

The Luzon Strait (~120.5–122°E) features two north–south parallel ridges with Luzon Island Arc to the east and Heng-Chun Ridge to the west, but the topography in the meridional direction is not symmetric. The eastern ridge, which is higher and longer than the western ridge (Fig. 1), was found to be the primary IT generation source (Jan et al., 2008), while the western ridge was responsible for modulating internal wave field (Chao et al., 2007). In addition, the western ridge is wider and shallower to the north, and the eastern ridge is wider and shallower to the south (Fig. 2). Therefore, the ITs within the Luzon Strait show highly spatial variability in both zonal and meridional directions, owning to the interferences of ITs from various source regions and complex topography effects during the reflection and refraction processes.

The variation of ITs at the Luzon Strait due to resonance was suggested on the basis of modeling studies (Echeverri and Peacock, 2010; Farmer et al., 2009). On the northern part of the Luzon Strait, where the ridge spacing is approximately equal to the mode-1 wavelength for semidiurnal motions, the potential for resonance leads to enhanced generation of semidiurnal ITs. On the southern part, the spacing between the two ridges is smaller and the western ridge is deeper, making the area non-resonance for semidiurnal ITs. The amplification of diurnal ITs with longer wavelength is not found due to their non-resonance at the whole Luzon Strait (Buijsman et al., 2012; Echeverri and Peacock, 2010; Farmer et al., 2009). Based on a set of 20-day data collected along a northern line and a southern line within the Luzon Strait, Alford et al. (2011) investigated the discrepancy of IT interference variations between the two lines.

On the other hand, ITs traveling westward and northwestward into the SCS will frequently steepen into ISWs, undergoing non-linear process and energy decay to the west of 120°E (Fig. 1). However, in the central basin of the northern SCS (~120°E) where the strong IT motions are less affected by the deep topographic features and can represent the wave energy traveling into the SCS to some extent (Jan et al., 2008; Johnston et al., 2013), long-term observations have not been reported yet.

In the present study, two 9-month ADCP observations located around 120°E are used to examine the characteristics and long-term variability of internal tidal currents in the deep SCS central basin. Two ADCP moorings were deployed at a northern site and a southern site, enabling us to compare the north–south variation and temporal discrepancy between diurnal and semidiurnal tides. The non-stationary features of ITs in the deep basin are also investigated and compared to those observed on the continental shelf and slope region.

The paper is organized as follows. Section 2 describes the topography of the study area, observational data, data processing methods and stratification structure. Section 3 presents the rotation spectrum of observed currents. Temporal variation and incoherent features of the ITs are described in Section 4. Section 5 compares the current variance estimated from the Oregon State TOPEX/Poseidon Global Inverse Solution (TPXO) with observed IT variance. Finally, conclusion and discussion are presented in Section 6.

2. Data and methods

2.1. Study area and data

The two mooring sites are located in the deep SCS central basin west of the Luzon Strait (Fig. 1). The water depth is 3360 m at the northern site (120.1°E, 21.1°N) and 4176 m at the southern site (120.0°E,

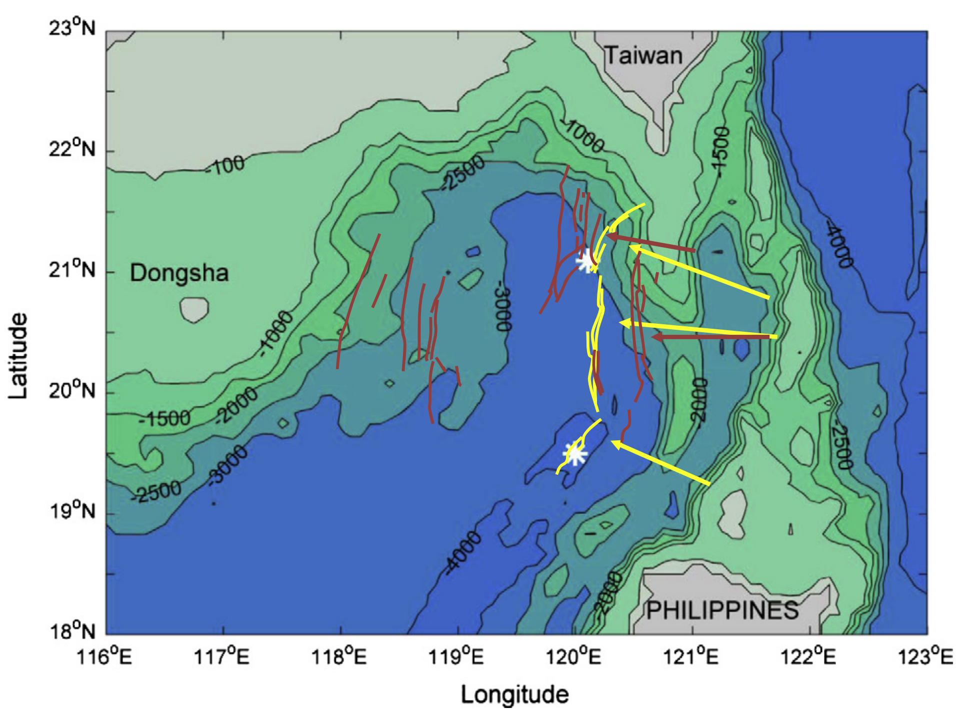

Fig. 1. Topography of the northeastern South China Sea. White stars indicate two mooring locations. Contours show isobaths in meters. Red and yellow lines represent crest lines of ISW packets interpreted from two SAR images. The red (yellow) arrows point from the source regions of ISWs marked by red (yellow) lines in the deep basin.