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Coherent and incoherent features, seasonal behaviors and spatial variations of internal tides in the northern South China Sea

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ABSTRACT

Based on observations of the currents at six moorings from March 2010 to April 2011, the coherent and incoherent features, seasonal behaviors and spatial variations of internal tides (ITs) in the northern South China Sea (SCS) are investigated. Measurements of the currents indicate that both diurnal and semidiurnal ITs contain stronger coherent signals than incoherent ones at all moorings. In the measuring range, coherent internal tidal current variances explain ~70% of the semidiurnal motion at most moorings. However, the proportion of coherent signals in the diurnal motion shows a non-monotonically decreasing trend with the westward propagation of diurnal ITs. Coherent signals of diurnal and semidiurnal ITs exhibit different seasonal variability at the six moorings: Diurnal ITs are stronger in winter (December to February) and summer (June to August) than in spring (March to May) and autumn (September to November), whereas stronger semidiurnal ITs always appear in spring and autumn. Combining these results with the temporal variation of barotropic tidal currents at the Luzon Strait (LS), it can be concluded that the seasonal variability of ITs at the six moorings are determined by the barotropic tides at the LS. In addition, this study shows that there are asymmetric features of ITs to the east and west of the LS.

1. Introduction

The Luzon Strait (LS) connects the western Pacific and South China Sea (SCS) between Taiwan and the Philippines (Fig. 1). When barotropic tidal currents flow over the LS, strong internal tides (ITs) are generated, making the SCS one of the most significant generation regions of ITs around the world (Niwa and Hibiya, 2004; Jan et al., 2007, 2008; Miao et al., 2011; Buijsman et al., 2014; Li et al., 2015). According to Alford et al. (2011), baroclinic currents exceeding 2 m/s and vertical displacements exceeding 300 m were observed near the LS. Alford et al. (2015) further estimated that the time-averaged westward energy fluxes in the SCS could reach 40 ± 8 kW/m, which were approximately 100 times greater than the typical open-ocean values and exceeded any other known generation site around the world. As an important intermediate step of the tides-to-turbulence cascade (Rudnick et al., 2003), ITs play an important role in dissipating surface tidal energy (Munk, 1997; Egbert and Ray, 2001; Niwa and Hibiya, 2001, 2004) and enhancing mixing (Tian et al., 2006, 2009) to contribute to deep-water circulation in the SCS (Lan et al., 2013; Zhao et al., 2014; Zhou et al., 2014).

Previous studies have indicated that ITs generated at the LS could propagate over 1000 km in the SCS (Miao et al., 2011; Zhao, 2014; Xu et al., 2016). During their long-range propagation, ITs exhibit intermittency and part of the internal tidal energy is transferred to frequencies outside the deterministic tidal frequencies due to the modulation of varying background conditions and stratification (Eich et al., 2004; van Haren, 2004; van Aken et al., 2007; Xu et al., 2014; Liu et al., 2016). In other words, ITs lose coherence to astronomical forcing and show incoherent features. In recent years, measurement variances have been used to examine the coherent and incoherent features of ITs in the SCS. Based on eight-month-long moored acoustic Doppler current profiler (ADCP) observations, Lee et al. (2012) highlighted the importance of incoherent internal tidal motion on the continental slope near Dongsha Island, which explained three-quarters of the total observed tidal energy. Xu et al. (2013) found that the semidiurnal ITs were more incoherent than the diurnal ones in this area. By analyzing two nine-month-long moored current observations, Xu et al. (2014) showed that ITs and their incoherent features had apparent south-north asymmetry in the SCS Basin. Liu et al. (2016) investigated the coherent and incoherent ITs in the southern SCS and showed their modal decomposition results. The results suggested that coherent ITs were dominated by mode-1, whereas mode-1 and higher-mode signals were comparable in incoherent ITs.

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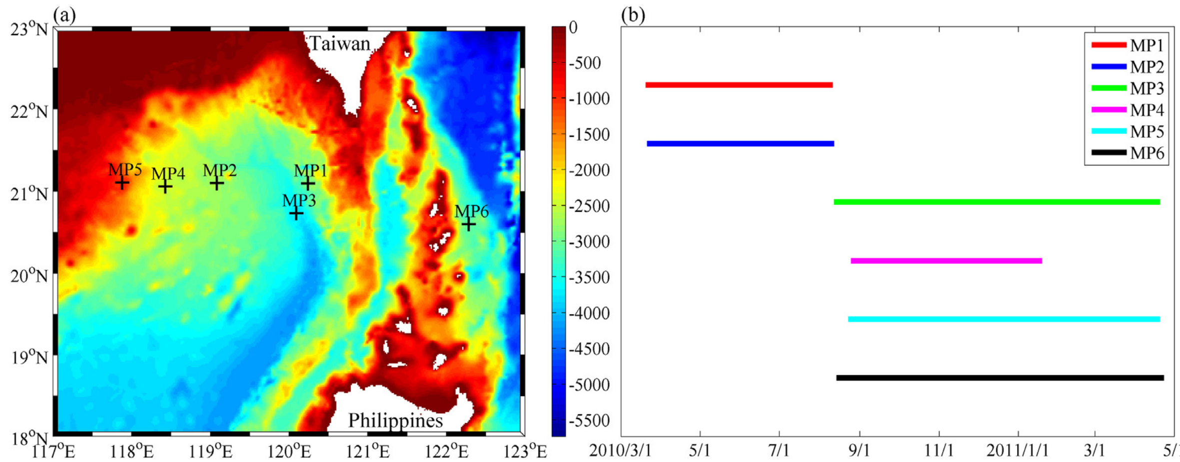

Fig. 1. (a) Bathymetry (color, unit: m) of the northern SCS. The six black pluses denote the mooring positions (MP1–MP6). (b) Observation periods of the six moorings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Because of scanty in situ observations, the aforementioned previous studies examined ITs in the SCS based on observations from one or two moorings. However, ITs in the SCS have temporal and spatial variations (Guo et al., 2012; Lee et al., 2012; Wu et al., 2013; Xu et al., 2013, 2014; Cao et al., 2015; Shang et al., 2015) due to the complicated topographical condition and varying stratification. The SCS Internal Wave Experiment deployed several moorings in the northern SCS from March 2010 to April 2011 and offered a chance to better understand ITs in this area. By analyzing current observations of six subsurface moorings in the northern SCS, this study examines the coherent and incoherent features of ITs as well as their temporal and spatial variations in the near field of IT propagation (Zhao, 2014; Xu et al., 2016). This paper is organized as follows. The mooring observations and data analysis methodology are introduced in Section 2. The aforementioned characteristics of the ITs in the northern SCS are described in Section 3. Finally, the discussion and conclusion are presented in Section 4.

2. Data and methodology

2.1. Mooring observations

As part of the SCS Internal Wave Experiment, six subsurface moorings (MP1–MP6) were deployed around the LS and in the northern SCS from March 2010 to April 2011 (Fig. 1). Water depths at moorings MP1–MP6 were 2895 m, 2719 m, 3745 m, 2480 m, 968 m and 3116 m, respectively. Each mooring was equipped with a 75-kHz up-looking ADCP at an approximately 400–650 m depth to measure the currents in the upper ocean. Detailed information about these moorings is displayed in Table 1.

2.2. Data processing

First, the data of currents at each mooring were averaged on an hourly basis and linearly interpolated at uniform 5-m interval levels. Due to the influence of background currents, mesoscale eddies and other marine dynamic processes, the moorings occasionally had a vertical excursion, which resulted in gaps in current observations (Fig. 2). Therefore, linear interpolation was used to fill in the gaps in the temporal domain if raw observations covered more than 95% of the total observation period at the corresponding depth. Fig. 2 compares the raw east-west currents and interpolated currents at moorings MP3 and MP6. As seen, the interpolated currents reserved principal features of the raw currents. After preprocessing, the effective vertical ranges of the currents at moorings MP1–MP6 were 85–405 m, 50–535 m, 125–455 m, 80–355 m, 50–420 m and 55–490 m, respectively.

Because of the limited range covered by ADCP measurements, it is difficult to separate barotropic currents directly from observations. According to Ramp et al. (2004) and Alford et al. (2011), barotropic currents derived from the Oregon State University Tidal Inversion Software (OTIS, Egbert and Erofeeva, 2002) agreed well with in situ observations around the LS. Therefore, the barotropic currents used in this study are predictions from OTIS, similar to Xu et al. (2014).The baroclinic currents at each mooring were obtained by removing the barotropic currents from the current observations.

Based on the least squares method, harmonic analysis (Pawlowicz et al., 2002) was used to separate the internal tidal currents of the K_1, O_1, P_1, Q_1,M_2, S_2, N_2 and K_2 constituents, which were tested to be coherent with the barotropic tidal currents on the east ridge of the LS, a process explained in the next section. Then, a fourth-order Butterworth filter was applied to the baroclinic current time series at each depth to extract the baroclinic currents at diurnal (0.80–1.20 cpd) and semidiurnal (1.73–2.13 cpd) frequency bands (Zhao et al., 2010; Guo et al., 2012). The incoherent internal tidal currents were obtained by subtracting the coherent internal tidal currents from the band-pass filtered baroclinic currents. To quantify the coherent and incoherent features at each mooring, current variances ($\mathrm{Var} = u^2 + v^2$, u and v are the east-west and south-north currents, respectively) were calculated for both the coherent and incoherent internal tidal currents.

Table 1
Detailed information of moorings MP1–MP6.

Mooring	Position	Water depth (m)	Instrument	Instrument depth (m)	Sample interval (min)	Bin size (m)
MP1	120°15′E, 21°05′N	2895	75 kHz ADCP	~650	5	8
MP2	119°05′E, 21°06′N	2719	75 kHz ADCP	~650	5	8
MP3	120°06′E, 20°44′N	3745	75 kHz ADCP	~515	5	8
MP4	118°26′E, 21°04′N	2480	75 kHz ADCP	~408	5	8
MP5	117°53′E, 21°06′N	968	75 kHz ADCP	~442	5	8
MP6	122°17′E, 20°36′N	3116	75 kHz ADCP	~517	5	8