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Multimodal structure of the internal tides on the continental shelf of the northwestern South China Sea

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ABSTRACT

Based on the moored current and temperature observations during the summer of 2005, the vertical structure of the internal tides on the continental shelf of the northwestern South China Sea (SCS) is studied. The vertical structure of the internal tides was found to differ greatly between semidiurnal and diurnal constituents. Generally, the diurnal constituents are dominated by the first-mode motions, which are consistent with the overwhelming first-mode signals in the northeastern SCS. In contrast, the semidiurnal internal tides, unlike the predomination of the first-mode variations in the northeastern area, exhibit a higher modal structure with dominate second-mode signals in the observational region. Moreover, although the diurnal internal tides are much stronger than the semidiurnal component, the shear caused by the latter over various scales was found to be significant compared to that induced by the diurnal tides, probably due to the superposition of the first-mode and higher-mode (smaller scale) semidiurnal variations. Further analysis demonstrates that the shear induced by the diurnal internal tides is larger than that induced by the semidiurnal variations around 45 m depth, where the first-mode current reversal in the vertical happens, while below 45 m depth higher-mode semidiurnal internal tides generally produce larger shear than that by the diurnal component. The northwest-propagating semidiurnal internal tides of higher-mode with small vertical scale, probably do not originate from a distant source like Luzon Strait, but were likely generated near the experiment site.

1. Introduction

Internal tides are internal gravity waves generated in stratified waters by the interaction of barotropic tidal currents with variable topography features (Helfrich and Melville, 2006; Garrett and Kunze, 2007). They are usually associated with large pycnocline fluctuations and strong currents, which play a significant role in affecting the offshore drilling operations and biology system in the ocean (Wolanski et al., 2004; Liu et al., 2008). Internal tides are also known to stimulate strong benthic dissipation and mixing, having an important influence on the decay of internal tidal energy and meridional circulation (Alford, 2003; Nash et al., 2004).

Low-mode internal tides may propagate for thousands of kilometers before dissipating (St. Laurent and Garrett, 2002; Alford et al., 2007), whereas high-mode (short vertical wavelength) internal tides usually break and dissipate near their source region, and thus lead to local ocean mixing (Moum et al., 2002). As a result, many studies suggested that small-scale baroclinic M_2-motions generally did not exist in the ocean except near their topography source (Rainville and Pinkel, 2006; van Haren, 2007). Furthermore, more recent studies have also revealed the evidence of rich multimodal internal tide field in many regions of the world seas (Park et al., 2006; Zhao et al., 2010).

The northern South China Sea (SCS) has been proposed to be an area with strong internal tides among the world seas. The internal tides mostly originate near the Luzon Strait (Jan et al., 2007; Shaw et al., 2009), propagate westward across the SCS basin (Duda et al., 2004; Liu and Hsu, 2004; Zhao et al., 2004; Farmer et al., 2009), and disintegrate into nonlinear waves (Liu et al., 1998; Lien et al., 2005). Most previous studies of the internal tides in the northern SCS were restricted to its east side (between Dongsha Plateau and Luzon Strait), and focused on the first-mode motions in this area (Duda et al., 2004; Yang et al., 2004). More recently, both in-situ measurements and numerical simulations also revealed the presence of higher-mode internal tides in the northeast region of the SCS (Vlasenko et al., 2010; Klymak et al., 2011). Nevertheless, all existing researches found that the first-mode motions predominated in the baroclinic wave field, though higher-mode signals may

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be significant during some specific cases within a short period (Wang et al., 2008).

Until recently, little attention has been devoted to the study of internal tides in the northwestern SCS, due to the shortage of high-resolution in-situ observations. Measurements by Liu et al. (2010) suggested that diurnal tides dominated the baroclinic energy in this area. However, modal structure of the internal tides in this region has not been considered yet. In this study, we use a high-resolution data set to provide the first observation of the modal structure of the internal tides on the continental shelf of the northwestern SCS. It is shown that the second-mode signals dominate the semidiurnal internal tides in this area, which is quite different from the predomination of the first-mode semidiurnal variations in the northeastern area. The rich multimodal structure of semidiurnal internal tides has been rarely reported in the SCS. The shear variations induced by the semidiurnal internal waves are also examined in relate to the modal structure and it is suggested that the small-scale baroclinic M_2-motions not only exist, but also contribute significantly to the shear field in our observational region.

2. Data and methods

The data reported here are composed of a two-month long (from the 22nd of July to 20th of September, 2005) time series obtained from an acoustic Doppler current profiler (ADCP) and a thermistor chain deployed at Wenchang Station on the northwestern shelf of the SCS. The water depth at the station is 117 m. The study area and mooring position are indicated in Fig. 1. The 190 kHz down-looking ADCP was positioned at a depth of 8 m. The depth of the available current data measured by ADCP ranged from 10 to 114 m, with a vertical interval of 2 m. Current measurements were recorded with a precision of 1×10^{-4} m/s at a time interval of 10 min. The temperature sensor information with a precision of 0.01 °C and a time interval of 1 min were collected at 23 layers. Most of the temperature sensors were placed between 4 and 40 m below the sea surface with a vertical separation of less than 4 m, whereas the bottom two sensors were located at depths of 50 and 75 m.

The barotropic current is defined here as the depth-averaged flow, and the baroclinic current as the residual once the barotropic current is removed. The barotropic tidal currents were estimated by applying a least-square fit method of harmonic analysis to the depth-averaged currents (Pawlowicz et al., 2002). Tidal harmonic analysis is also used to examine the vertical structure of the internal tidal currents. Additionally, due to the absence of temperature and density data covering the entire water column, we will use empirical orthogonal functions (EOF) method to investigate the detailed modal structure of the baroclinic signals. Furthermore, spectra properties of the shear current are calculated to examine the vertical scales of the multimodal tides, according to the method outlined by Emery and Thomson (2001).

3. Results

3.1. Barotropic tide

The M_2 is the largest barotropic tidal constituent, followed by the O_1 and S_2 with comparable magnitudes, and finally the K_1 (Table 1). Generally, all the major axises of the main constituents are aligned with the cross-isobath direction to within a few degrees, except for the K_1, with comparable cross-isobath and along-isobath components. The semidiurnal tidal currents are almost rectilinear, whereas the O_1 and K_1 tidal ellipses are a little circular, and the velocity vector rotates clockwise (Fig. 1). In the next section, we will use M_2 and K_1 to represent the semidiurnal and diurnal band motions, respectively, according to the focus of most previous studies in the northern SCS.

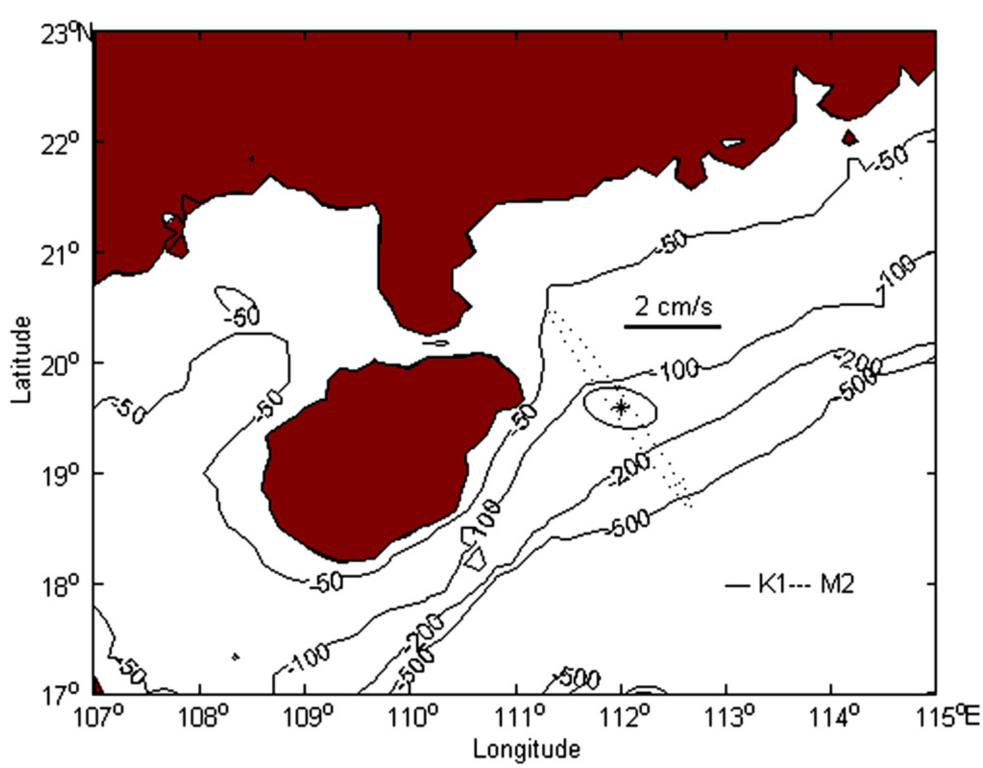

Fig. 1. Barotropic current ellipses for M_2 and K_1. Symbol * indicates the mooring position. Contours mark isobaths in meters.