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Asymmetry of internal waves and its effects on the ecological environment observed in the northern South China Sea

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ABSTRACT

Ecological parameters, including current velocity, water temperature, and nutrient and chlorophyll *a* concentrations, accompanied by two internal solitary waves, were observed in the South China Sea deep basin from 2 October to 4 October, 2012. Both solitons belonged to the mode-1 category, which were characterized by a westward velocity exceeding 1 m s^{-1} above 500 m and an eastward velocity up to 0.1 m s^{-1} below 500 m. The observed structure of the vertical current was asymmetrical. For the first soliton, the downwelling region had a temporal scale of 32 min and an average vertical velocity of 3 cm s^{-1}, whereas the upwelling region had a temporal scale of 24 min and an average vertical velocity of 2 cm s^{-1}. For the second soliton, the temporal scale and average velocity were 36 min and 2 cm s^{-1} in the downwelling, compared with 26 min and 2 cm s^{-1} in the upwelling. On the basis of the convection equation, the downward net vertical displacements of water particles ranged from nearly zero to tens of meters with the maximum value in excess of 50 m. Such asymmetry caused changes in temperature as high as 2.3 °C, nutrient concentrations up to 12.04 μmol L^{-1}, and chlorophyll *a* concentration up to 0.12 μg L^{-1} before and after the passage of the solitons.

1. Introduction

Internal solitary waves (ISWs), with amplitudes of as high as 200 m and horizontal velocities exceeding 2 m s^{-1}, are observed in the northern South China Sea (SCS) (Zhao et al., 2004, 2012; Klymak et al., 2006; Zheng et al., 2007; Ramp et al., 2010; Huang et al., 2014). ISWs are believed to be generated by tide-topography interactions in the Luzon Strait, and propagate across the SCS deep basin to the continental shelf (Zheng et al., 2007; Alford et al., 2010; Ramp et al., 2010; Lien et al., 2012; Lien et al., 2014).

ISWs on the continental shelf enhance vertical mixing because of strong vertical shear or wave breaking, which leads to vertical heat and substance flux (Moum et al., 2003; Shroyer et al., 2010; Lien et al., 2012). Wang et al. (2007) reported that ISWs were capable of bringing organic matter up via enhanced mixing around the Dongsha Atoll in the SCS, affecting the local ecological environment. Leichter et al. (2003) noted that internal bores induced upwelling accompanied by strong vertical heat and substance transport when internal bores ran up a continental slope. Moreover, trapped cores are formed along with strong water transport when the shoaling ISWs break (Farmer et al., 2011; Lien et al., 2012). The upwelling in the rear portion of trapped cores may also entrain fish, plankton, and nutrients as whales exploit prey following the waves (Moore and Lien, 2007).

The effect of ISWs on water transport, including heat and nutrients, has been studied, but the role of the vertical convection has not drawn as much attention. In this paper, we aim to analyze the asymmetry of the vertical velocity field induced by ISWs by cruise observation in the northern SCS deep basin from 2 October to 4 October 2012. Section 2 describes the cruise observation program. Section 3 presents the observed velocity and temperature structures of the ISWs. The effects of the ISWs on the water temperature fields and the changes of nutrients and chlorophyll *a* are analyzed in Sections 4 and 5, respectively. Section 6 presents the discussion and conclusions.

2. Data

2.1. Cruise observation

A mooring was deployed at 20° 59.911' N, 118° 24.622' E in the northern SCS deep basin with a water depth of 2460 m as shown

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by the red star in Fig. 1(b). A schematic diagram of the mooring configuration is shown in Fig. 1(a). The mooring was equipped with an upward-looking Teledyne RD Instruments 75 KHz Acoustic Doppler Current Profiler (ADCP) and a downward-looking ADCP, mounted in a specially designed cage. Three Seaguard Recording Current Meters (RCMs) were attached every 400 m below 1550 m. In the upper 1000 m, five SBE 37SM conductivity-temperature-depth recorders (CTDs) and ninety-five SBE 56 temperature loggers were placed every 10 m, and three more CTDs were placed at 5 m below the RCMs. The ADCPs measured the velocity every 2 min with a 16 m bin size in 37 bins, and the RCMs recorded the velocity using the same sampling technique. The sampling rate of the temperature and salinity was 20 s. The configurations provided full-depth velocity and temperature fields from 2 October to 4 October 2012, which constituted the baseline for the ISW analysis.

Hydrographic casts were repeatedly made four times before and after ISWs aboard R/V Dongfang Hong 2 in order to examine the ISW effects on the vertical distribution of nutrients and chlorophyll *a*. Water samples were taken from the surface down to 500 m using 12 L Niskin bottles deployed via a CTD rosette (Table 1). The water samples were filtered immediately on board. Nutrient concentrations were measured by spectrophotometry (Grasshoff et al., 1999) and chlorophyll *a* concentration was measured by a Turner Designs model II fluorometer. The accuracies for nutrient concentrations were 5–10% from 1 μmol L^{-1} to 10 μmol L^{-1} and 1–5% from 10 μmol L^{-1} to 100 μmol L^{-1} (Zhang et al., 1997). To maintain the sampling repeatability, the R/V was repositioned to the same original location, which was near the west of the mooring, before each experiment.

2.2. Data processing

The ADCP performed four tests on velocity data: correlation, a fish rejection algorithm, error velocity and percent good. The test results were well for the ADCP measurements. The recorded instrument attitude indicated that the ADCP tilt did not exceed the functional angle range of $\pm 15^\circ$ from the vertical direction. Details about data quality can be found in RD Instruments (1998).

The depth variation from the ADCP pressure sensor allowed the correction of the vertical velocity by adding the moving velocity of the ADCP in the vertical direction. Fig. 2(a) shows the depth variations of the two ADCPs. The depth variations were coherent in time; hence, the vertical velocity derived from the upward-looking ADCP was used for the correction. As shown in Fig. 2(b), the vertical velocity of the ADCPs was approximately zero except during the ISW passage. During the ISW intrusion, the vertical velocity reached up to 1.7 cm s^{-1}.

Using the error velocity was another way to evaluate the ADCP measurements. We contoured the vertical and error velocities of one of the observed solitons in Fig. 2(c) and (d). The error velocity was larger (less than 3 cm s^{-1}) near the surface, because the bins near the surface were far away from the ADCP transducers. Nevertheless, in addition to these bins, the magnitude of the error velocity was less than 1.5 cm s^{-1} and decreased as depth increased. Such error velocity was one order of magnitude smaller than the observed vertical velocity during ISWs, thereby implying the confidence in the measured vertical velocity. We calculated the correlation coefficients between vertical velocity and error velocity, which were 0.28, 0.26, 0.19, at depths of 150 m, 250 m and 500 m. Thus, the ADCP tilt that was caused by the ISWs barely impacted the instrument measurements in light of the error velocity.

3. Velocity and temperature structures of the ISWs

Two internal waves, W1 and W2, were observed to propagate westward (Fig. 3(a)–(d)). From the amplitude and current field structures, the two waves propagated as solitons. The largest isotherm displacement was accompanied by a horizontal velocity peak during the passage of the two ISWs. The maximum westward velocity was 1 m s^{-1} near the surface, coincident in time with the maximum amplitude. The meridional velocity was not shown here, because it was one order smaller than the zonal velocity.

Table 1
Hydrographic casts and depths of water samples.

Cast	Time	Depth (m)
LX01	18:12, October 2, 2012	0, 50, 100, 150, 200, 250, 300, 500
LX02	03:32, October 3, 2012	Same
LX03	23:51, October 3, 2012	Same
LX04	04:13, October 4, 2012	Same

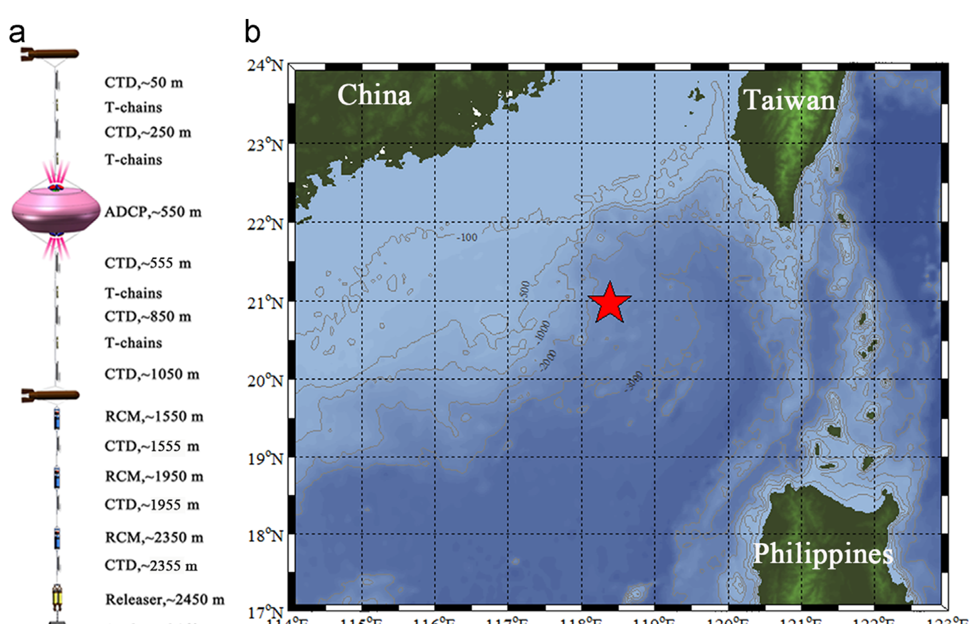

Fig. 1. (a) A schematic diagram of the mooring configuration. (b) The mooring location is depicted as a red pentagram. The base map is the topography of the northern South China Sea.