Impacts of a Mesoscale Eddy Pair on Internal Solitary Waves in the Northern South China Sea revealed by Mooring Array Observations

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ABSTRACT

Both internal solitary waves (ISWs) and mesoscale eddies are ubiquitous in the northern South China Sea (SCS). In this study, the authors examine the impacts of mesoscale eddies on the ISWs transiting the northern SCS deep basin that evolve from the steepening internal tide generated in the Luzon Strait, using in situ data collected from a specifically designed mooring array. From November 2013 to January 2014, an energetic mesoscale eddy pair consisting of one anticyclonic eddy (AE) and one cyclonic eddy (CE) propagated across the mooring array. Observations revealed that the amplitude, propagation direction, and speed of the transbasin ISWs were significantly modulated by the eddy pair. When the moorings were covered by the southern portion of the AE, the ISW amplitudes decreased by as much as 67% because of the thermocline deepening along the wave direction and the energy divergence along the wave front. When the moorings were covered by the northern portions of both eddies, the amplitude of ISWs also decreased but to a relatively smaller degree. ISWs propagated the fastest inside the southern portion of the AE, where both the thermocline deepening and eddy currents enhanced the propagation speed of ISWs. Under the influence of the AE (CE) core, ISWs propagated more northward (southward) than usual. The observational results reported here highlight the importance of resolving mesoscale eddies in circulation–internal wave coupled models to accurately predict kinematic characteristics of ISWs.

1. Introduction

Internal solitary waves (ISWs), characterized by short periods and strong nonlinearity, are widely distributed in the world’s oceans, especially near rough topography regions in marginal seas and coastal zones (Helfrich and Melville 2006; Jackson 2007). Among the world’s oceans, ISWs are the most active in the northern South China Sea (SCS; Alford et al. 2015), where their amplitudes and current velocities can reach 150 m and 2 m s$^{-1}$, respectively (Alford et al. 2010; Huang et al. 2014; Klymak et al. 2006; Ramp et al. 2010, 2004; Yang et al. 2004; Zhao et al. 2012), and their crest lengths are longer than 100 km (Hsu et al. 2000; Liu et al. 1998; Zhao et al. 2004; Zhao et al. 2014; Zheng et al. 2007). Most recently, the study of Huang et al. (2016) reported an extreme ISW in the northern SCS with maximum amplitude and horizontal velocity of 240 m and 2.55 m s$^{-1}$, respectively; this extreme ISW is believed to be the strongest ISW ever observed in the world’s oceans. Because of their large amplitudes and strong current velocities, ISWs in the northern SCS have been demonstrated to be effective in...
modulating the ocean ecosystem (Dong et al. 2015; Wang et al. 2007), transporting energy and materials (Klymak et al. 2006), and triggering diapycnal mixing (Laurent et al. 2011; Lien et al. 2011). In addition, they are considered to be a major hazard to submarine navigation and marine engineering (Cai et al. 2012).

ISWs in the northern SCS are remotely generated in the Luzon Strait (LS) through energetic surface tide–topography interaction (Alford et al. 2015; Li and Farmer 2011; Lien et al. 2005; Zhao et al. 2004). During spring tide, large-amplitude ISWs are radiated out from the LS every day (Alford et al. 2010; Ramp et al. 2004; Ramp et al. 2010; Zhao and Alford 2006). Based on statistical results from satellite images, Zhao et al. (2004) proposed that ISWs in the northern SCS are developed by nonlinear steepening of the baroclinic tides. This viewpoint was further corroborated by mooring measurements (Alford et al. 2010; Li and Farmer 2011; Lien et al. 2005) and numerical simulations (Buïjsman et al. 2010a; Zhang et al. 2011). Alford et al. (2010) showed that ISWs begin as broad internal tides in the Luzon Strait; then they steepen into ISWs in the deep basin and become narrower as they enter shallower water. In addition to ISWs, there are abundant energetic mesoscale eddies in the northern SCS (Wang et al. 2008; Wu et al. 2005; Zhang et al. 2013, 2016, 2017). Statistical analysis of satellite altimeter data has revealed that mesoscale eddies in the northern SCS are present 35%–60% of the time, and they have a mean diameter as large as 200 km (Chen et al. 2011). Because mesoscale eddies are often present on the propagation path of ISWs in the northern SCS, their frequent encounters are inevitable.

Mesoscale eddies are dynamically important in modulating current and temperature in the northern SCS. Field observations show that the current velocities associated with mesoscale eddies in the northern SCS are up to 1 m s$^{-1}$ near the surface and can reach 0.1 m s$^{-1}$ at 1000-m depth, and the temperature anomalies associated with anticyclonic eddies (AEs) and cyclonic eddies (CEs) can be as large as 7.9°C and −3.0°C, respectively, near the main thermocline (Zhang et al. 2013). In the absence of mesoscale eddies, internal tides in the northern SCS remain largely intact at diurnal frequency as they propagate due to the balance between the rotational dispersion and nonlinearity (Farmer et al. 2009; Helfrich and Grimshaw 2008; Li and Farmer 2011). With respect to high-frequency ISWs in the northern SCS, they maintain their shape as they propagate due to the balance between nonhydstatic dispersion and nonlinearity (Klymak et al. 2006). However, previous studies have shown that if strong background currents are present, wave shape, vertical structure, and propagation speed of ISWs may be significantly modified (Alford et al. 2010; Cai et al. 2008; Stastna and Lamb 2002). In addition, numerical simulations suggested that the growth of ISWs is sensitive to changes in stratification, and a deeper thermocline depth would suppress the development of ISWs (Buïjsman et al. 2010b; Chen et al. 2014; Shaw et al. 2009; Zheng et al. 2007). Based on these previous results, we anticipate that the current and temperature changes associated with mesoscale eddies may potentially affect ISWs in the northern SCS.

Recently, a numerical study of Dunphy and Lamb (2014) showed that the energy flux of mode-1 internal tide was in a beamlike pattern in the x–y plane after interacting with a barotropic eddy and that the mode-1 internal tide passing through a mode-1 baroclinic eddy could give rise to higher-mode internal tides. Numerical simulations conducted by Xie et al. (2015) showed that mesoscale eddies can redistribute the energy of ISWs along their wave front. In the energy focusing and spreading regions associated with eddies, the amplitudes of ISWs tended to increase and decrease, respectively (Xie et al. 2015). In addition, observational studies of Park and Farmer (2013) and Li et al. (2016) suggested that mesoscale structures in the LS and northern SCS can result in substantial distortion of the propagation path of ISWs and that the amplitude of ISWs at a fixed location was thus dramatically changed.

Investigating the impacts of mesoscale eddies on ISWs is important for better understanding the variability of ISWs in the northern SCS. Although previous studies have recognized the potential role of mesoscale eddies in modulating ISWs, the impacts of mesoscale eddies on the characteristics of ISWs have never been directly quantified based on in situ observations. To investigate interactions between mesoscale eddies and internal waves, a specifically designed mooring array was deployed in the deep basin of the northern SCS from late October 2013 to early June 2014 (Fig. 1). An energetic mesoscale eddy pair consisting of one AE and one CE was well captured by the mooring array between November 2013 and January 2014 (Fig. 2). At the same time, a number of well-developed, high-frequency ISWs were captured by the easternmost mooring near the LS (see supplemental information), which corresponded to the type-a ISWs, as demonstrated by previous studies (Alford et al. 2010; Ramp et al. 2004, 2010). Those well-developed ISWs transited across the deep basin where their evolution processes were monitored by the mooring array. Based on the mooring data, we diagnose the responses of those transbasin ISWs to the eddy pair. Note that the transbasin ISWs are called ISWs for short hereafter. We also investigate the possible mechanisms by which the mesoscale eddies affect the ISWs through the synergetic use of mooring data and a data assimilation modeling product.
This paper is organized as follows: We introduce the data used in this study in section 2. We show the primary results of the observed eddies and ISWs in section 3. We discuss the possible mechanisms regarding how eddies affected ISWs in section 4. Finally, a summary is given in section 5.

2. Data

a. In situ mooring data

The northern SCS has been a hot spot for studying strong multiscale dynamical processes, including energetic internal waves and mesoscale eddies. To investigate the 3D structure and life cycle of mesoscale eddies and their interaction with internal waves, the South China Sea Mesoscale Eddy Experiment (S-MEE) was designed and successfully conducted in the northern SCS during 2013–14 (Zhang et al. 2016). The in situ data used here are from a mooring array of the S-MEE. The array consisted of six subsurface moorings, which were approximately along the main orientation of ISWs in the synthetic aperture radar (SAR) images (Zhao et al. 2004), extending from 117.87° to 120.20°E (Fig. 1). The moorings were deployed in late October 2013 and successfully recovered in early June 2014.

To measure current velocity in the upper 1000 m, two Long Ranger 75-kHz acoustic Doppler current profilers (ADCPs) were mounted on each mooring at a nominal depth of ~500 m, with one looking upward and the other downward. The ADCPs had a sampling interval and vertical bin size of 3 min and 16 m, respectively. In addition to the ADCPs, all the moorings except M6 were equipped with temperature–salinity (T–S) chains consisting of dozens of temperature loggers and several conductivity–temperature–depth (CTD) recorders to monitor upper-layer T–S. The sampling intervals of T–S chains were set to 2 or 3 min. The moorings in the deep water at M2-M10 were also equipped with several Aanderaa SEAGUARD current meters (RCMs; Aanderaa Data Instruments) and CTDs below ~1500 m to monitor current velocity and T–S in the deep layer. Detailed information of the moorings, including their locations, instrument settings, and working time are summarized in Table 1.

b. Satellite data

To identify mesoscale eddies, the simultaneous altimeter sea level anomaly (SLA) data and surface geostrophic velocity field from the Archiving, Validation, and Interpretation of Satellite Oceanographic Data (AVISO) are also used in this study. The altimeter data used here are from a multisatellite merged dataset that has spatial and temporal resolutions of 1/4° and 1 day, respectively.

c. HYCOM assimilation product

In addition to the observational data, we also employ the product of the Hybrid Coordinate Ocean Model (HYCOM), which assimilates satellite altimeter and sea surface temperature data together with available T–S profiles from XBTs, Argo floats, and moored buoys (http://hycom.org/). The HYCOM product provides daily variables and fields with a fine horizontal resolution (1/12° by 1/12°), which can resolve mesoscale eddy variability. In the vertical, the model outputs of temperature, salinity, and velocities have 33 levels with a resolution of 10 m near the surface and 500 m near the maximum depth of 5500 m.

In a previous study, our moored observations demonstrated that the HYCOM assimilation product accurately reproduced the mesoscale variation caused by the eddies in the winter of 2011/12 in terms of both velocity and temperature in the northern SCS (Zhang et al. 2013). Moreover, Park and Farmer (2013) reported that the HYCOM-simulated sea surface height differences (ΔSSH) between their two pressure-sensor-equipped inverted echo sounders (PIES) were moderately well correlated with the PIES-measured ΔSSH induced by mesoscale dynamics in the northern SCS. In the present study, we compare the HYCOM product...
with the mooring observations from late November 2013 to early June 2014 (see supplemental information). It shows that HYCOM can accurately simulate the trends of observed temperature and velocity associated with the eddy pair, although there are some slight differences in details.

3. Observation results

a. The mesoscale eddy pair

The AVISO altimeter data showed that a mesoscale eddy pair consisting of one AE and one CE was generated in the region southwest of Taiwan in November–December 2013 (Fig. 2). This type of eddy pair is a common phenomenon found in the northeastern SCS and is demonstrated to be associated with the Kuroshio Loop Current sheddings (Zhang et al. 2017). After their generation, the eddies propagated southwestward and successively crossed the mooring array. As revealed by the observations at mooring M2, the eddy pair gave rise to significant temperature changes in the upper 400 m (Fig. 3a). Here, we define the thermocline depth using the depth of the 15°C isotherm following Zheng et al. (2007). When the AE passed, the 2-day, low-pass filtered thermocline depth (white curve) at M2 increased from 235 m on 11 November to 295 m on 10 December and then gradually returned to its original depth around 3 January. The influence of the CE on temperature was weaker due to its weaker strength (Figs. 2, 3a). When the CE passed, the thermocline was slightly elevated, with a minimum depth of 203 m on 8 January. The thermocline

![Fig. 2. The AVISO SLA (shadings) and absolute geostrophic currents (vectors) in the experimental area during the winter of 2013/14. Black dots denote the mooring locations. Date is marked on each panel.](https://example.com/figure2.png)
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finally returned to its original depth after 20 January when the eddy pair propagated away from the mooring array.

In addition to temperature, the AE and the CE also caused remarkable changes in the ocean current (Fig. 3b). Under the influence of the eddy pair, the current velocity was greatly enhanced, with the maximum magnitude reaching 0.78 and 0.66 m s$^{-1}$ during the AE and the CE passage, respectively. Because of the propagation of the eddy pair, the currents changed direction with time. Although the velocity associated with the eddy pair sharply decreased with depth, its magnitude was still 0.18 m s$^{-1}$ at a depth of 400 m. Mesoscale eddies in the northern SCS have been found to extend from the surface to the bottom with depth deeper than 2000 m (Zhang et al. 2013, 2016). The 3D structure, generation, and dissipation of the eddy pair reported here are described in detail in Zhang et al. (2016).

b. Amplitude of ISWs

Figure 3a shows that ISWs produced many significant high-frequency fluctuations at the thermocline represented by the 15°C isotherm (black curve), which was smoothly modulated by the eddy pair (white curve). Figure 3c presents the time-depth variation of temperature observed at M2 between 14 and 18 December, when the AE core was near the mooring. During this period, the surface mixed layer became thicker, and sharp depressions of isotherms caused by ISWs were not noticeable until below 150 m. Because of the superimposed influence of eddies and ISWs, the thermocline depth varied significantly, and only
the 15°C isotherm was continuously captured by moorings M10, M9, M3, M2, and M1. To investigate the evolution of an ISW's amplitude along the mooring array, we define the amplitude of ISWs as the maximum displacement of the 15°C isotherm. Figure 4 presents the temporal evolution of ISW amplitudes observed at M10, M9, M3, M2, and M1. Note that the amplitude of ISWs at M6 was not obtained due to the lack of a $T$–$S$ chain. As can be seen in Fig. 4, ISWs emerged in clusters every 14 days, in accordance with the period of the spring–neap tidal cycle.

Given the contrasting features of the two eddies, we investigate their impacts on the amplitude of ISWs separately. Figure 5a shows the thermocline depth (15°C isotherm) at the moorings 1 h prior to the arrival of ISWs when the mooring array was covered by the AE (between 11 November and 21 December). On average, the thermocline depth showed a concave pattern (black dashed curve) in the east–west direction during this period. The deepest thermocline appeared at M3, where the thermocline depth was 52 m deeper than that at M10. As the dashed curve in Fig. 5b shows, the mean amplitude of ISWs exhibited a decreasing trend from M10 to M2 when they propagated across the AE’s center. The reverse was true from M2 to M1 when the ISWs propagated away from the AE.

To remove the influences of barotropic tides and the Kuroshio over the generation sites in LS, we normalize the mean amplitude of ISWs at each mooring using the mean amplitude of ISWs at the easternmost mooring (M10), which was close to LS. Besides the eddies, the shoaling continental slope (Lien et al. 2005; Alford et al. 2010), the radiation of long trailing inertia–gravity waves (Lamb and Warn-Varnas 2015), and dissipation (Laurent et al. 2011) are expected to change the ISW amplitudes as they propagate across the northern SCS. To provide a reference to quantify the impacts of the eddy pair on the amplitude of ISWs, we calculate the normalized mean amplitude of ISWs (gray triangles in Fig. 5c) when the moorings were not affected by eddies during the periods between 20 January and 4 March and 3 May and 2 June (in addition to the eddy pair analyzed in this study, another AE with moderate strength was present between 5 March and 2 May; see the supplemental information). The gray triangles in Fig. 5c reveal a notable increase in the wave amplitude as ISWs shoal from M10 to M1 in the absence of eddies.

The normalized mean amplitude of ISWs when the mooring array was covered by the AE (between 11 November and 21 December) is shown by the black circles with white filling in Fig. 5c. By comparing the black circles with white filling to the gray triangles in Fig. 5c, we find that the mean amplitude of ISWs during the AE period decreased by a mean percentage of 31%, 53%, 59%, and 52%, respectively, at M9, M3, M2, and M1. The normalized mean amplitude of ISWs when the mooring array was covered by the AE’s southern portion (between 11 November and 8 December) and northern portion (between 15 and 21 December) is shown by the black circles with yellow and cyan fillings in Fig. 5c, respectively. When the moorings were covered by the AE’s southern portion (between 11 November and 8 December), the mean amplitude of ISWs decreased by 39%, 63%, 67%, and 57% at M9, M3, M2, and M1, respectively. The decrease was much less (14%, 26%, 40%, and 38%) when the moorings were covered by the north portion of the AE (between 15 and 21 December). We can see that the decrease in the amplitude of ISWs was more significant when the mooring array was covered by the AE’s southern portion than its northern portion.

Following the AE, the CE began to affect mooring M9 after 21 December 2013. Figure 2 shows that the southern portion of the CE moved rapidly across the mooring array. Note that only very few ISWs were observed by the moorings during the short duration of the CE’s southern portion (Fig. 4), and hence the analysis here primarily focuses on the ISWs when the CE’s northern portion affected the moorings (between 4 and...
14 January 2014). During this period, the thermocline depth from M10 to M1 showed a slightly convex pattern (dashed curve in Fig. 5e) with the shallowest thermocline at M3. The amplitude of ISWs tended to decrease when they propagated across the CE’s northern portion from M10 to M3, while it tended to increase as the ISWs approached M2 (black circles with cyan filling in Fig. 5f). In comparison with the reference level (gray triangles in Fig. 5g), the normalized mean amplitude of ISWs (black circles with cyan filling in Fig. 5g) decreased by 21%, 39%, 22%, and 28% at M9, M3, M2, and M1, respectively, when the mooring array was covered by the northern portions of AE. The gray triangles indicate the mean value when the mooring array was covered by the northern portions of AE.

c. Propagation direction of ISWs

For mode-1 depression ISWs, their propagation direction is the same as the direction of the ISW-induced current in the upper layer. Here, the propagation direction of ISWs was obtained using the main axis of high-pass filtered (with cutoff period of 5 h) current velocities in the upper layer when ISWs passed by (Ramp et al. 2010). Figure 6 presents the propagation direction of ISWs at moorings M10, M6, M3, M, and M1. In the eastern deep basin where M10 was located, ISWs had a mean propagation direction of 275.7°N (0° pointing north) during the entire experimental period. From November 2013 to January 2014, mooring M10 was only slightly affected by the periphery of the eddies, where the mean propagation direction of ISWs showed relatively small variation. To the west of the middle deep basin where M6, M3, M2, and M1 were located, the propagation direction of ISWs varied significantly when the eddy pair was present (Figs. 6b–e). Within the AE’s...
core (defined as the part of the eddy within the circle of maximum rotational velocity), ISWs propagated more toward the north (enclosed by the dashed black lines in Figs. 6b–e) than the reference level (gray triangles) during the period without eddies. The changes of propagation direction of ISWs inside the AE’s core were up to 23°, 36°, 41°, and 32° at M6, M3, M2, and M1, respectively. In contrast, ISWs propagated more toward the south under the influence of the CE’s core, with the direction change up to 9° at M3.

d. Propagation speed of ISWs

Along the mooring array, the propagation speed of ISWs \(C_p\) can be obtained using the following equation:

\[
C_p = D \cos(\theta)/T_m, \tag{1}
\]

where \(D\) and \(T_m\) denote the distance and traveling time of ISWs between two moorings, respectively; \(\theta\) is the angle between the mooring line and the propagation direction of ISWs. As demonstrated in Fig. 7, the propagation speed of ISWs (black dots) varied significantly in the presence of the CE’s core, with the direction change up to 9° at M3.

M9 and M3 (Fig. 7b) reached a maximum of 3.58 m s\(^{-1}\) on 21 November, which was 0.65 m s\(^{-1}\) faster than the reference speed (2.93 m s\(^{-1}\), which was the mean propagation speed during the period without eddies, gray dot in Fig. 7b). As the northern portion of the AE approached, the propagation speed of ISWs decreased. ISWs propagated the slowest within the southern portion of the CE; for example, ISWs propagated at a speed of 2.53 m s\(^{-1}\) from M9 to M3 on 23 December (Fig. 7b), which was 0.4 m s\(^{-1}\) slower than the reference speed. As the northern portion of the CE approached, the propagation speed of ISWs generally started to increase and reached another peak. The propagation speed of ISWs between M10 and M9 and M3 and M1 (Figs. 7a,c) showed similar responses to the eddy pair as that between M9 and M3, although these moorings were closer to the boundaries of the eddies.

When moorings were inside the AE, ISWs had a mean propagation speed of 3.56, 3.26, and 2.98 m s\(^{-1}\), respectively, between M10 and M9, M9 and M3, and M3...
and M1. Inside the CE, the mean propagation speed of ISWs decreased to 3.33, 2.80, and 2.84 m s\(^{-1}\), respectively. We can see that the ISWs propagated faster on average when encountering the AE than encountering the CE. In addition, inside the AE, ISWs propagated faster within its southern portion than within its northern portion. For example, the mean propagation speed of ISWs between M9 and M3 was 3.34 and 3.10 m s\(^{-1}\), respectively, within the AE’s southern and northern portions. The reverse occurred as the ISWs encountered the CE, when the ISWs propagated more slowly within the southern portion of the CE than within its northern portion on average.

4. Mechanisms of ISW modulation

a. On the propagation speed of ISWs

According to the Korteweg–de Vries (KdV) equation, the propagation speed of ISWs \(C_p = C_a + C_{\text{non}}\). Here, \(C_a\) is the mode-1 linear phase speed along the ISW direction, and the nonlinear contribution part

\[
C_{\text{non}} = \frac{1}{3} \alpha \eta_0, \tag{2}
\]

where \(\alpha\) is the nonlinear parameter, and \(\eta_0\) is the maximum isotherm displacement. As shown in Fig. 3, the mesoscale eddy pair caused significant anomalies in both thermal and current structures. To quantify the role of the eddy-induced temperature and velocity anomalies in modulating the propagation speed of ISWs, we obtain \(C_a\) through solving the Taylor–Goldstein equation (Apel et al. 2006)

\[
\frac{d}{dz} \left( [C_a - U_o(z)]^2 \frac{df_1}{dz} \right) + N^2(z)f_1 = 0 \tag{3}
\]

with boundary conditions \(f_1(0) = f_1(H) = 0\). In Eq. (3), \(f_1\) is the eigenfunction of vertical displacement of the mode-1 internal wave. The term \(U_o(z)\) is the component of the background current in the wave direction as defined in Smyth et al. (2011), which is calculated from the daily averaged velocity profile measured by the ADCPs and RCMs. The term \(N(z)\) is the Brunt–Väisälä frequency profile calculated using the moored \(T–S\) data. The lack of stratification information near the surface and in the lower layer below the deepest CTD is made up using the normal-mode analysis method (Chiang et al. 2006). Here, we focus on the impacts of eddies on the propagation speed of transbasin ISWs that are high frequency at all six moorings, and therefore the effect of Earth rotation is not considered.

The black curves in Fig. 7 show the variations of \(C_a\) caused by the eddy-induced temperature and velocity anomalies. It can be seen that \(C_a\) generally reached its maximum inside the southern portion of the AE, in agreement with the fastest propagation speed of ISWs. Between M10 and M9 and between M9 and M3, the minimum \(C_a\) appeared when those moorings were covered by the southern portion of the CE; between M3 and M1, where the southern portion of the CE did not reach, \(C_a\) showed a minimum under the northern portion of the AE. Generally, the mean propagation speed of ISWs \(\overline{C_p}\) over each spring–neap tidal cycle (red dots in Fig. 7) varied following \(C_a\). The correlation between \(\overline{C_p}\) and \(C_a\) was 0.90, 0.89, and 0.85, respectively, between M10 and M9, M9 and M3, and M3 and M1. This result indicates that the change of \(C_a\) caused by the eddy pair was one of the primary factors modulating the propagation speed of ISWs.

For a simple two-layer system, the linear phase speed \(C_a = \{g(\Delta \rho/\rho)((b_1b_2)/(b_1 + b_2))\}^{1/2}\), where \(g\) is the gravity acceleration, \(\rho\) is the average density, \(\Delta \rho\) is the density difference, and \(b_1\) and \(b_2\) represent the upper- and deep-layer thicknesses, respectively. From the above equation, we can infer that linear phase speed in the deep ocean will be amplified (reduced) during the AE (CE) period because of the depressed (elevated) thermocline. To quantify the role of varying stratification in modulating the propagation speed of ISWs, we solve the Taylor–Goldstein equation using the observed continuous \(N(z)\) without \(U_o(z)\). The calculated results are shown as cyan curves in Fig. 7. It was shown that the mean \(C_a\) values between M10 and M9, M9 and M3, and M3 and M1 decreased by 0.19, 0.15, and 0.13 m s\(^{-1}\), respectively, from the AE period to the CE period due to the variations in stratification. This result indicates that the changes of stratification characterized by the varying thermocline depth were one important reason for the faster propagation speed of ISWs inside the AE than inside the CE, as described in section 3d. On the other hand, through solving Eq. (3) using the time-mean \(N(z)\) with the realistic \(U_o(z)\), we find that the mean \(C_a\) (magenta curves in Fig. 7) values during the AE period between M10 and M9 and M9 and M3 were 0.19 and 0.18 m s\(^{-1}\) faster than those during the CE period, respectively. This result suggests that the advection effect of eddy current on the propagation speed of ISWs was more significant inside the AE than inside the CE.

Comparing the cyan curves with the gray triangles [mean \(C_a\) with realistic \(N(z)\) during the period without eddies] in Fig. 7, we can see that the variation of \(N(z)\) enhanced the propagation speed of ISWs during the AE period. Comparing the magenta curves with the gray triangles in Fig. 7 reveals that, inside the southern portion of the AE, the eddy current in the direction of ISW propagation also enhanced the propagation speed of ISWs. The
combined positive effects of \( N(z) \) and \( U_d(z) \) anomalies associated with the AE explained why the ISWs propagated the fastest inside the southern portion of the AE.

To examine the contribution of the wave nonlinearity to the propagation speed of ISWs, we compute the nonlinear parameter \( \alpha \), following Grimshaw et al. (2002):

\[
\alpha = \frac{3}{2} \int_{-H}^{0} \rho_0(z)[C_a - U_a(z)]^2 \frac{df}{dz} dz \int_{-H}^{0} \rho_0(z)[C_a - U_a(z)] (df/dz)^2 dz. \tag{4}
\]

Under the influence of the AE, the mean \( \alpha \) value was \(-9.9 \times 10^{-3} \) s\(^{-1}\) between M9 and M3. The AE reduced the \( \eta_0 \) of ISWs by 41 and 68 m at M9 and M3, respectively. According to Eq. (2), the corresponding decrease in the propagation speed of ISWs is 0.18 m s\(^{-1}\) due to the decrease in nonlinearity. Under the influence of the CE’s northern portion, the mean \( \alpha \) value was \(-7.7 \times 10^{-3} \) s\(^{-1}\) between M9 and M3. During this period, the \( \eta_0 \) of ISWs decreased by 24 and 50 m at M9 and M3, respectively, which would reduce the propagation speed of ISWs by 0.09 m s\(^{-1}\). These results suggest that variations in the propagation speed of ISWs associated with the eddy-induced amplitude decay should also not be neglected.

b. On the propagation path of ISWs

As described in section 4a, the propagation speed of ISWs was sensitive to the changes in current and density fields. Because of the spatial variation in current and density fields associated with the eddy pair, the propagation speed of ISWs was expected to vary along the wave front, which could lead to distortion of the ISW front and modification of their propagation path. To investigate how the mesoscale eddy pair affected the propagation path of ISWs, we adopt the horizontal ray-tracing method (Park and Farmer 2013; Sherwin et al. 2002) to calculate the position of the ISW front. The initial ISW front is set to be located near 120.7°E (west of LS) with the initial propagation angle set to 275.7°N, the mean propagation direction of ISWs is 0.18 m s\(^{-1}\). During this period, the \( \eta_0 \) of ISWs decreased by 24 and 50 m at M9 and M3, respectively, which would reduce the propagation speed of ISWs by 0.09 m s\(^{-1}\). These results suggest that variations in the propagation speed of ISWs associated with the eddy-induced amplitude decay should also not be neglected.

The ray direction at each mooring is obtained from the ray-tracing calculation, as indicated by the open circles in Fig. 6. Although the predicted ray direction at M3, M2, and M1 varied remarkably, it well describes the general variation trends of the observed ISW propagation direction (black dots). Given that the propagation path of ISWs is determined by the predicted ray direction, the good agreement between the ray direction and the observed ISW propagation direction indicates that it is appropriate here to use Eq. (5) to examine the impacts of eddies on the propagation path of ISWs. As seen from Fig. 8, because of the change of ray direction, the propagation path of ISWs varied significantly under the influence of the eddy pair, which could be divided into four main stages:

- The first stage was the broadening of the propagation path (Figs. 8a–d) when the central portion of the ISW front was inside the southern portion of the AE. In section 3d, we demonstrated that ISWs propagated the fastest inside the southern portion of the AE. In the zonal direction, we assume \( \eta_0 \) varies linearly between moorings, and beyond the experimental area to the west and east of the mooring array, the amplitudes of ISWs are set constant equal to the amplitudes at the westernmost and easternmost moorings, respectively. In the meridional direction, \( \eta_0 \) is assumed to be uniform.

- For the second stage, as shown in Fig. 8e, the refraction of the ISW front was much less than that during the first stage. During this stage, the entire ISW front was rotated clockwise by the AE core and the ISW front propagated toward the north part of the northern SCS. This result explains why ISWs propagated more northward within the AE’s core, as revealed in Fig. 6c.
The third stage was the shortening of the ISW front around 24 December when the ISWs propagated across the AE’s northern portion and the CE’s southern portion (Fig. 8f). During this stage, the central portion of the ISW front encountered the connection zone between the AE and the CE, where the $U_a(z)$ was opposite the ISW’s propagation direction and reduced the propagation speed of ISWs. Hence, the central portion of ISW front propagated more slowly than its two edges, making the two edges converge toward its central portion. Thus, the wave front became shorter during this stage.

During the fourth stage (Fig. 8h), the central portion of the ISW front encountered the northern portion of the ISW front due to the positive effect of the eddy current in the direction of ISW propagation. Similar to the first stage, the northern and southern portions of ISW front were refracted toward the northern and southern parts of the northern SCS, respectively, and the propagation path of ISWs was extended.

c. On the amplitude of ISWs

Along the propagation direction of ISWs, the growth rate of ISW amplitudes is sensitive to the horizontally inhomogeneous thermocline (Buijsman et al. 2010b; Li 2014; Zheng et al. 2007). Perpendicular to the propagation direction of ISWs along the wave front, the energy convergence/divergence caused by the distortion of
the wave front could also give rise to changes in amplitude of ISWs (Park and Farmer 2013; Xie et al. 2015). In this subsection, we will explain the observed variation of ISW’s amplitude associated with the eddy pair by quantifying the effects of the inhomogeneous thermocline along the wave direction and the energy convergence/divergence along the wave front on the amplitude of ISWs.

To evaluate the effects of the horizontally inhomogeneous thermocline on the amplitude of ISWs, we calculate the solitary wave amplitude growth ratio (SAGR) as defined in Zheng et al. (2007):

$$\text{SAGR} = \left( \frac{h_0}{d} \right)^{3/2},$$

where $h_0$ represents the thermocline depth prior to the arrival of ISWs at M10, and $d$ represents the thermocline depth at the other four moorings. As shown by the gray curve in Fig. 5a, the mean thermocline depth varied from M10 to M1, even during the period without eddies. Hence, we also calculate the SAGR during the no eddy period and take it as a reference to estimate the effects of horizontally inhomogeneous thermocline caused by the eddies on the amplitude of ISWs.

As shown in Fig. 8, all six moorings in the array captured the ISW front, although the propagation path varied significantly during the period of the eddy pair. Li et al. (2016) reported that the ISW front was refracted away from their observation sites by the eddies. This case did not appear in our observations. Assuming that the energy of ISWs was conserved when transiting across the mooring array, the focusing and scattering of rays would give rise to an increase and decrease of energy and amplitude of ISWs, respectively. Based on the ray-tracing calculation, we evaluate the change in the amplitude of ISWs associated with the distortion of the ISW front by calculating the ratio of the distance between the rays around the moorings to its initial distance near LS.

When the mooring array was covered by the southern portion of the AE, the calculated SAGR shows that the deepened thermocline suppressed ISW amplitudes by 27%, 26%, 12%, and 17% on average, respectively, at moorings M9, M3, M2, and M1. On the other hand, the broadening of the ISW front led to energy divergence along the wave front during this period (Figs. 8a–d), and the amplitude of ISW was thus reduced by 20%, 33%, 27%, 26%, 12%, and 17% on average, respectively, at M9, M3, M2, and M1. The above results indicate that not only the effects of deepened thermocline but also energy divergence along the wave front decreased the amplitude of ISWs.

When the mooring array was covered by the northern portion of the AE, the calculated SAGR showed that the amplitude of ISWs decayed by 24%, 40%, 39%, and 39%, respectively, at M9, M3, M2, and M1 due to the deepened thermocline. Because of the distortion of the wave front, the amplitude of ISWs increased by 1% and 10% at M3 and M1, respectively, but decreased by 2% and 1% at M9 and M2, respectively. The above results suggest that the effect of thermocline deepening played a dominant role, and hence the observed amplitude of ISWs was reduced during this period (Table 2).

When the mooring array was covered by the northern portion of the CE, the calculated SAGR showed that the

### Table 2. Variation of amplitude of ISWs when the array was covered by the AE and the CE at M9, M3, M2, and M1. The estimated effects of zonal inhomogeneity of thermocline and wave energy redistribution along the wave front on the amplitude of ISWs are also listed.

<table>
<thead>
<tr>
<th></th>
<th>Mooring</th>
<th>M9</th>
<th>M3</th>
<th>M2</th>
<th>M1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AE</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The entire AE</td>
<td>Observed variation</td>
<td>−31%</td>
<td>−53%</td>
<td>−59%</td>
<td>−52%</td>
</tr>
<tr>
<td>(between 11 Nov and 21 Dec)</td>
<td>Effects of deepened thermocline</td>
<td>−24%</td>
<td>−32%</td>
<td>−21%</td>
<td>−23%</td>
</tr>
<tr>
<td></td>
<td>Effects of energy convergence</td>
<td>−12%</td>
<td>−28%</td>
<td>−38%</td>
<td>−41%</td>
</tr>
<tr>
<td>Southern portion of the AE (between 11 Nov and 8 Dec)</td>
<td>Observed variation</td>
<td>−39%</td>
<td>−63%</td>
<td>−67%</td>
<td>−57%</td>
</tr>
<tr>
<td></td>
<td>Effects of deepened thermocline</td>
<td>−27%</td>
<td>−26%</td>
<td>−12%</td>
<td>−17%</td>
</tr>
<tr>
<td></td>
<td>Effects of energy divergence</td>
<td>−20%</td>
<td>−33%</td>
<td>−45%</td>
<td>−49%</td>
</tr>
<tr>
<td>Northern portion of the AE (between 15 and 21 Dec)</td>
<td>Observed variation</td>
<td>−14%</td>
<td>−26%</td>
<td>−40%</td>
<td>−38%</td>
</tr>
<tr>
<td></td>
<td>Effects of deepened thermocline</td>
<td>−24%</td>
<td>−40%</td>
<td>−39%</td>
<td>−39%</td>
</tr>
<tr>
<td></td>
<td>Effects of energy convergence/divergence</td>
<td>−2%</td>
<td>1%</td>
<td>−1%</td>
<td>10%</td>
</tr>
<tr>
<td>CE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern portion of the CE (between 4 and 14 Jan)</td>
<td>Observed variation</td>
<td>−21%</td>
<td>−39%</td>
<td>−22%</td>
<td>−28%</td>
</tr>
<tr>
<td></td>
<td>Effects of elevated thermocline</td>
<td>+5%</td>
<td>−3%</td>
<td>+2%</td>
<td>+10%</td>
</tr>
<tr>
<td></td>
<td>Effects of energy divergence</td>
<td>−13%</td>
<td>−24%</td>
<td>−29%</td>
<td>−35%</td>
</tr>
</tbody>
</table>
elevated thermocline amplified the ISWs’ amplitude by 5%, 2%, and 10% at M9, M2, and M1, respectively, but decreased the ISWs amplitude by 3% at M3. The divergence of ISW energy along the wave front resulted in a drop in wave amplitude by 13% at M9, by 24% at M3, by 29% at M2, and by 35% at M1. It was shown that the effect of the energy divergence on ISW amplitude was predominant over the amplifying effect of elevated thermocline during this period, and thus the observed amplitude of ISWs decreased (Table 2).

As can be seen in Table 2, the observed varying trends of ISW amplitudes could be well predicted by assessing the effects of the deepened/elevated thermocline along the wave direction and of the energy convergence/divergence along the wave front on the amplitude of ISWs. Quantitatively, the predicted changes in the ISW amplitudes are in good agreement with the observation for most cases. As Fig. 6 shows, although the general varying trend of the predicted ray direction in the ray-tracing calculation agreed well with the observations, there exist case-to-case discrepancies between the predicted ray direction and the observed ISW direction, which may be due to the differences between the HYCOM product and the mooring data in details, and that the ray-tracing calculation is not perfect under the assumption that the ISW amplitude is uniform in the meridional direction. Those factors may result in departures when we qualitatively assess the effects of energy divergence/convergence of ISWs along the wave front on the amplitude of ISWs.

5. Summary

In this study, the impacts of mesoscale eddies on the ISWs in the northern SCS were investigated based on in situ observations from a specifically designed mooring array spanning the deep basin deployed from late October 2013 to early June 2014. Between November 2013 and January 2014, an energetic mesoscale eddy pair consisting of one AE and one CE was captured by the mooring array. At the same time, a number of well-developed, high-frequency ISWs transiting the deep basin were observed. The variations of amplitude, propagation speed, and direction of these transbasin ISWs caused by the eddy pair were directly quantified. Possible mechanisms through which the eddy pair affected the transbasin ISWs were discussed. The main points are summarized as follows:

- The ISW amplitudes were significantly modulated by the eddy pair. When the mooring array was covered by the southern portion of the AE, the ISW amplitudes decreased by as much as 67% compared to the reference level in the absence of eddies. When the mooring array was covered by the northern portion of both the AE and the CE, the amplitude of ISWs decreased by up to 40% and 39%, respectively. The solitary wave amplitude growth ratio (SAGR) was calculated to assess the effects of the deepened/elevated thermocline along the wave direction on the ISW amplitudes. The ray-tracing calculation was performed to assess the effects of the energy convergence/divergence along the wave front on the ISW amplitudes. The observed varying trends of ISW amplitudes were generally well predicted by assessing the above two factors. When the mooring array was covered by the southern portion of the AE, in addition to the energy divergence effect associated with the ISW front distortion as reported by Park and Farmer (2013) and Xie et al. (2015), the deepened thermocline also decreased the amplitude of ISWs. As a result, ISWs during this period had the largest drop in amplitude.

- Propagation speed of ISWs reached the maximum when encountering the southern portion of the AE because both the deepened thermocline and eddy currents accelerated the propagation of ISWs. ISWs propagated the slowest under the influence of the southern portion of the CE. Because of the opposite changing tendencies of thermocline depth during the AE and the CE, ISWs propagated faster when encountering the AE than when encountering the CE, on average. Moreover, ISWs propagated at faster speeds within the AE’s southern portion (CE’s northern portion) than within its northern (southern) portion.

- ISWs propagated more northward within the AE’s core by up to 41°. In contrast, under the influence of the CE’s core, ISWs propagated more southward. The ray-tracing calculation revealed that the propagation path of ISWs varied significantly under the influence of the eddy pair. After penetrating the AE core, the ISW front was rotated clockwise, causing the ISWs to propagate more toward the north.

Statistical analysis of satellite altimeter data has revealed that mesoscale eddies in the northern SCS exhibited notable variations from seasonal to interannual time scales (Chen et al. 2011; Zhang et al. 2017). Given that the amplitude of ISWs is sensitive to eddies, as demonstrated in this study, we can infer that the seasonal to interannual variation of mesoscale eddies probably play an important role in the long-term variation of ISWs. We leave this topic for future studies when more in situ data become available.

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