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Subsurface eddies in the southern South China Sea detected from in-situ observation in October 2011

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ABSTRACT

Two anticyclonic subsurface eddies (SSEs) are detected from the in-situ hydrography data of the southern South China Sea (SCS) during 15–25 October 2011. Both SSEs have the lens-shaped water bodies below the thermocline. Their maximum swirl speed appears at the depth of lens' core, which is also characterized by a dump in the *T–S* diagram. These eddies do not have an enclosed saline-water or warm-water body in its lens' core, which is different from those SSEs reported in other seas. These SSEs should be locally generated by the horizontal shear of the Southeast Vietnam Offshore Current. In the SSE generation site of the southern SCS, there is an upper-layer anticyclonic eddy (AE2) that is right above the SSE (SE2). After leaving its generation site, the eddy loses its energy source and starts to weaken. In this case, the eddy will decay quickly in the upper layer due to the restraint of the thermocline, and finally evolves into a pure subsurface eddy (i.e. SE4).

1. Introduction

The Mediterranean Eddies (Meddies) are well known subsurface mesoscale eddies in the Atlantic, which are represented by the warm salty anticyclonically rotating lenses of the modified Mediterranean Water, and have been studied extensively (e.g., Richardson et al., 2000; Bashmachnikov et al., 2009). Similarly, a subsurface eddy (SSE) was detected at the depth of about 300 dbar in the southeast of Okinawa, whose water mass was characterized as the North Pacific Subtropical Mode Water with salinity maximum and thick thermostad (Takikawa et al., 2005). Oka et al. (2009) also observed one SSE near 500 dbar depth in the western North Pacific southeast of Japan, containing the North Pacific central mode water. Moreover, off northern Baja California a SSE was observed propagating westward with the maximum swirl velocity of 3 $cm s^{-1}$ (Jerónimo and Gómez-Valdés, 2007). In the Bay of Bengal a cold core SSE was revealed below the mixed layer, with temperature drop of 4–5 °C at the eddy center as compared with the surroundings (Babu et al., 1991). However, except for the Atlantic, there are few investigations for the subsurface mesoscale eddies in other open oceans or marginal seas.

In the South China Sea (SCS), the surface circulation patterns are characterized by the cyclonic gyre in winter and anticyclonic circulation in summer (Liu et al., 2008), with multiple eddies. These mesoscale eddies have been extensively observed from both satellite altimeter (e.g., Hwang and Chen, 2000; Wang et al., 2003; Zhuang et al., 2010; Chen et al., 2011) and hydrographic data (e.g., Li et al., 1998; Liu et al., 2000). From the hydrographic observation, Fang et al. (1998, 2002) and Li (2002) showed the obvious season variation of the mesoscale eddies in the southern SCS. The characteristics of mesoscale eddies, such as eddy occurrence, eddy tracks, eddy structures, eddy formation mechanisms, and so on, have been investigated based on the satellite altimetry data and other data (e.g., Hwang and Chen, 2000; Wang et al., 2003; Zhuang et al., 2010; Xiu et al., 2010; Chen et al., 2011). A southern anticyclonic eddy and a northern cyclonic eddy off eastern Vietnam can be identified during the southwest monsoon (e.g., Chen et al., 2010; Wang et al., 2003). The biogeochemical impacts due to mesoscale eddies are also investigated (e.g. Xiu and Chai, 2011). However, to our knowledge, there is no publication on SSE in the SCS yet.

Since mesoscale eddies, including SSEs, carry specific water mass, so they play a crucial role in water mass transport and change of marine ecological environment in the southern SCS. The subsurface eddy is difficult to be detected because of its occurring uncertainty and the invisibility from the satellite. In this paper, we use the shipboard hydrographic and satellite altimetry data to describe the circulation and mesoscale eddies in the southern SCS

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in October 2011; in particular, we focus on detecting anticyclonic SSEs. We further analyze the main features and possible formation mechanism of these SSEs.

2. Data

During 15–25 October 2011, a survey aboard *R/V* Xiangyanghong 9 was carried out as part of the UNESCO-IOC/WESTPAC project "Response of marine hazards to climate change in the Western Pacific (ROSE)" in the southern SCS. We made the conductivity–temperature–depth (CTD) and current profiler measurements at 27 stations as shown in Fig. 2a. The CTD casts and current profile surveys were conducted using a tied SBE-911 and 300-kHz Lowered Acoustic Doppler Current Profiler (LADCP). We also collected the merged altimeter-based daily sea level anomaly (MSLA) and absolute geostrophic velocity products for the period of the survey, which are provided by the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO). The current profiles measured by the LADCP are processed on an 8 m depth grid with software developed at the Lamont–Doherty Earth Observatory, Columbia University by a linear inverse method (Visbeck, 2002).

3. Circulation and eddies in the southern SCS

Fig. 1 shows the MSLA map with the merged absolute geostrophic velocity on 21 October 2011. There are several noteworthy features as follows. There are two strong currents in the southern SCS. One is a monsoon current along the western boundary of the SCS. It flows southwestward in the area east and south of the Hainan Island, turns to south near 17°N and 110°E, and then flows southward along the Vietnam coast with strong velocity of 40–70 cm s^{-1}. The other is the Southeast Vietnam Offshore Current (SVOC), including its northward extension. The two currents link up at the region off the southeast Vietnam coast between 11°and 13°N and constitute a rather cyclonic circulation with a scale of 700 km. The SVOC flows eastward with a velocity of about 70 cm s^{-1} and has a meandering and varied path, especially for its northward extension. In addition, there is an anticyclonic circulation south of the SVOC, which is consistent with the Nansha Anticyclonic Circulation (NAC) observed in September 1994 (Li, 2002). This implies the circulation still keeps its summer pattern in the area south of 12°N.

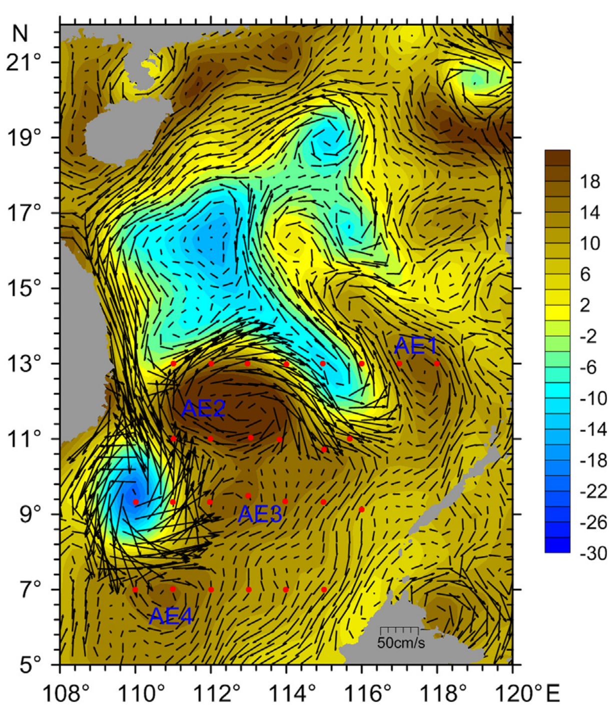

Fig. 1. Merged sea level anomaly (cm) with merged absolute geostrophic velocities from altimetry in the southern SCS on 21 October 2011. The survey stations are marked by red dots. AE1, AE2, AE3 and AE4 denote four anticyclonic eddies.

The cyclonic ring (cold-ring) centered at (9.5°N, 110°E) is very strong. In order to describe the rotational character of an eddy, the average velocity along a maximum velocity circle is defined as the swirl velocity of the eddy. The ring has a diameter of 200 km, a swirl velocity of 1.00 m s^{-1}, and a MSLA difference value of about 20 cm between its core and its outer-most surrounding area. A time series of the merged absolute geostrophic velocity maps in October 2011 (not shown) show that the cold ring was formed from a meandering part of the SVOC.

There are several weaker anticyclonic eddies closed to the east and south sides of the SVOC and the cold ring. Four observational transects just crossed the four anticyclonic eddies in the survey region (marked as AE1, AE2, AE3, and AE4 correspondingly), which allow us to analyze their structures. AE2 centered at (11.8°N, 112.5°E) is the strongest one, so it will be focused in this study. AE2 has a diameter of about 200 km, a sea level difference of 6 cm between its core and surrounding area, and a swirl velocity of 0.35 m s^{-1}. A similar warm-core anticyclonic eddy was observed in the same location with ship-board ADCP and CTD data in summer 1998 (Liu et al., 2000). Since AE1, AE3, and AE4 are relatively weak, we will not analyze them further in this paper.

4. Water mass characteristics of anticyclonic subsurface eddies

4.1. Eddies in the subsurface layer

Based on the in-situ CTD and LADCP data, the dynamic height and current covering the region of 7°–13°N are shown in Fig. 2a and b at the surface and 150 m depth, respectively. The observed currents shown in Fig. 2a are roughly consistent with those in Fig. 1, such as the SVOC along 13°N, the presence of the NAC, and an anticyclonic eddy (marked as AE2) construed by the SVOC and the westward flow along 11°N between stations B2 and B4, and the northward flow along 111.0°E. Meanwhile, two anticyclonic SSE (marked as SE2 and SE4) are distinct at 150 m depth (Fig. 2b). SE2 center shown by the dynamic height map is located at Station B3, which deviates to the south from the center of AE2. Noting the westward current between Stations B2 and B4, we can deduce that Station B3 is not an eddy center, and rather it is the southern part of the eddy due to the insufficient observed spatial resolution. Thus, we consider that AE2 and SE2 are the same eddy (marked as "AE2/SE2"), with a center at (11.8°N, 112.5°E), which are located at the surface and subsurface, respectively. Fig. 2a and b shows that SE2 is more distinct than AE2. The center of SE4 locates at Station D3, which is different from that of AE4 (shown in Fig. 1) near Station D2, and also different from that in Fig. 2a between Stations D2 and D3; so, SE4 appears only in the subsurface layer.

4.2. Vertical structure of subsurface eddies

In order to further investigate the vertical structures of SE2 and SE4, we show temperature, salinity and potential density along the two survey transects of B and D. The convex-lens shaped water bodies constituted by the isothermal, isohaline and isopycnic surfaces (named "lens" for short) appear in the subsurface layers along transects B and D, respectively. Fig. 3a shows clearly a lens of SE4 with a temperature of 13–21 °C and a diameter of 190 km.