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The summer-fall anticyclonic eddy west of Luzon: Structure and evolution in 2012 and interannual variability

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ABSTRACT

The Conductivity–Temperature–Depth (CTD) and acoustic Doppler current profiler (ADCP) measurements along 18°N off the western Luzon in the South China Sea (SCS), collected during a cruise from August 12–14, 2012, were used to explore the vertical structure of an anticyclonic eddy (AE) during the observational period. Further, the French Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) sea level anomaly (SLA) and corresponding anomalous surface geostrophic velocity were used to study the temporal evolution of the AE. The vertical structure of the AE along 18°N in August 2012 showed a trough located near 117.5°E. The AE extended vertically downward and its distinct feature was identifiable to 200 m depth. Seasonal variations of SLA indicate that the AE lasted for 5 months (June to early November), going through the growth and nearly stationary period from mid-June to late August and then propagating westward along 18°N with varying phase speeds and shapes to the continental slope off the southeastern Hainan Island during late September to November. Furthermore, T–S characteristics suggest that the AE was generated off the western Luzon. Interannual variations of the summer (July–September) SLA presented by Empirical Orthogonal Function analysis, indicates that the local circulation was enhanced by the anomalous anticyclonic eddy along 18°N in the years of 2008, 2010, 2012 and 2013 during the period from1993 to 2014.

1. Introduction

The South China Sea (SCS) is the largest semi-enclosed marginal sea in the western Pacific Ocean. Its northeastern region connects to the East China Sea through the Taiwan Strait, and adjoins with the northwestern Pacific via the Luzon Strait (Fig. 1a). The SCS climate is a component of the East Asian monsoon system (Wyrtki, 1961). The upper layer ocean circulation is forced by seasonal monsoon winds, with significant impact of the Kuroshio on the northern region through the Luzon Strait (Fang et al., 1998; Qu, 2000; Qu et al., 2000; Qu, 2001; Xue et al., 2004; Hu et al., 2012). Influenced by the Asian monsoon system, the SCS experiences the northeasterly monsoon in winter and the southwesterly monsoon in summer. In response to the winter monsoon, the upper layer ocean circulation is characterized by a cyclonic gyre. In summer, there are a cyclonic gyre north of about 12°N and an anticyclonic gyre south of about 12°N (Wyrtki, 1961; Qu, 2000; Gan et al., 2006).

The northern SCS is surrounded by Mainland China, Vietnam, Taiwan Island, Luzon Island and Hainan Island (Fig. 1a). Under the combined influence of monsoon winds, the Kuroshio intrusion, complex topography, and tidal forcing, the general circulation is more intricate (e.g., Xue et al., 2004; Fang et al., 2005; Gan et al., 2006). An ocean eddy which is quasi-geostrophic and with horizontal scales of 50–500 km is defined as synoptic eddy (Woods, 1980). Synoptic eddies are relatively active in the northern SCS. They have been receiving more and more attention since the 1990s. Those off the northwestern Luzon have been investigated by a number of previous works (e.g., Li et al., 1998, 2002; Li and Pohlmann, 2002; Yuan et al., 2007; Wang et al., 2008; Chen et al., 2010; Hu et al., 2012; Nan et al., 2011; Zhang et al., 2015). Previous studies showed that most of the northern SCS eddies originated in two areas: one off the southwestern Taiwan and the other off the western Luzon. Wang et al. (2008) examined the origin and evolution of two anticyclonic eddies in the northeastern SCS using multi-satellite remote sensing data, trajectory data of surface drifting buoys, and in situ hydrographic data during winter 2003/2004. Several studies (e.g., Qu, 2000; Yang and Liu, 2003; He et al., 2016) reported that there is a cyclonic eddy (Luzon Cold Eddy) off the western Luzon in winter.

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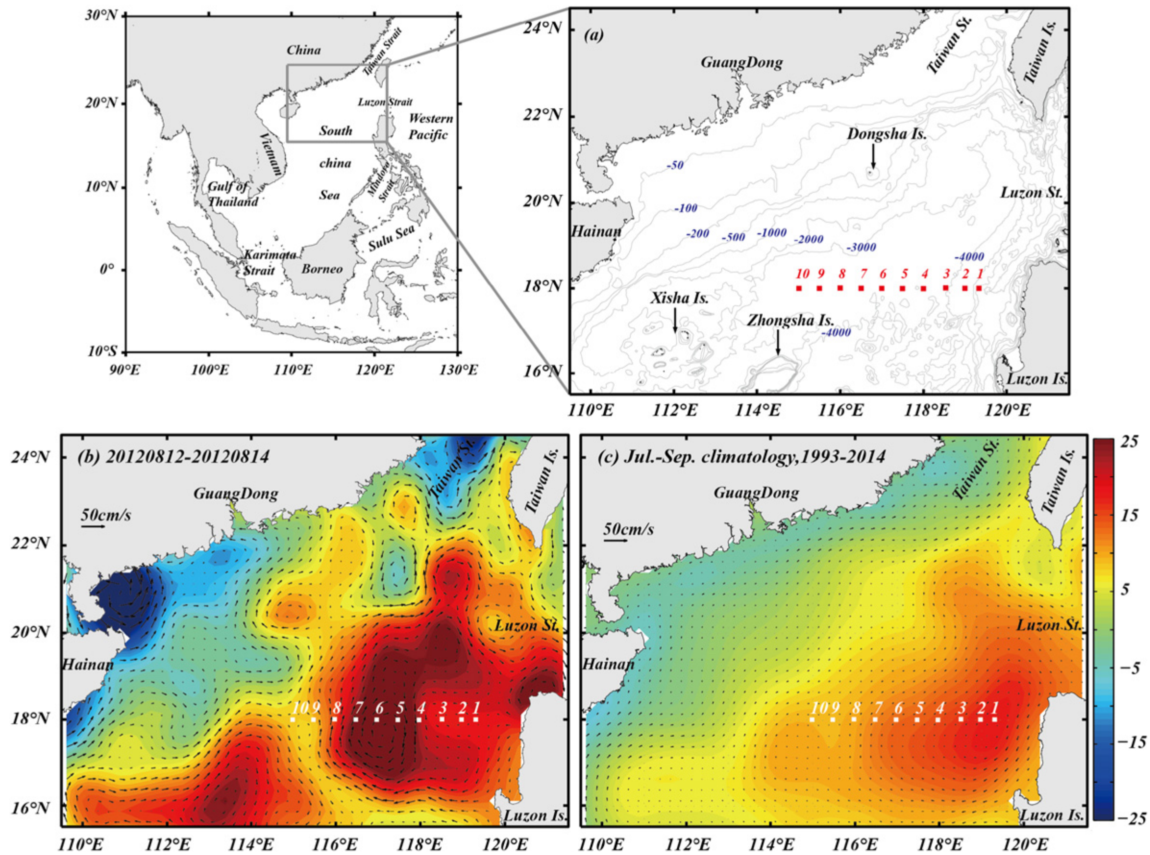

Fig. 1. (a) Observational section and stations from cruise August 2012 and bathymetry of the northern South China Sea (SCS), with the 50, 100, 200, 500, 1000, 2000, 3000, and 4000 m contours plotted. The bathymetry from the ETOPO5 global relief (http://www.ngdc.noaa.gov/mgg/global/etopo5.html) supplied by the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC) were used. In situ observational stations are marked by red squares. The detailed information of in situ observation is listed on Table 1. (b) Mean sea level anomaly (SLA, shaded, cm) and the corresponding anomalous surface geostrophic currents (vector, $cm \cdot s^{-1}$) during the in situ observations from August 12–14, 2012; white squares represent the in situ observational stations. (c) The climatological summer to early fall (July to September) mean SLA (shaded, cm) and anomalous surface geostrophic current (vector, $cm \cdot s^{-1}$) during 1993–2014 in the northern SCS, showing a sub-basin scale anomalous anticyclonic circulation.

However, to date only a few studies have focused on the summer–fall anticyclonic eddy off the western Luzon. Li et al. (1998) reported that a warm-core anticyclonic eddy occurred off the northwestern Luzon based on CTD (Conductivity–Temperature–Depth) profilers observations. According to that study, the anticyclonic ring originated from Kuroshio meander at the Luzon Strait and shed into the northern SCS. Using satellite altimeter data, Yuan et al. (2007) identified a seasonal anticyclonic eddy generated off the northwest of Luzon, and named it Luzon Warm Eddy (LWE). Chen et al. (2010) investigated the vertical structure and spatiotemporal evolution of the LWE using Argo float data and satellite altimeter data. Based on in situ measurements and satellite sea level anomaly (SLA), Nan et al. (2011) reported three long-lived seasonal anticyclonic eddies occurring along 18°N in August 2007.

Although there are several previous works focused on the anticyclonic eddies off the northwestern Luzon, studies on their hydrographic and current structures from in situ observation, as well as their variation, are still quite scarce. Therefore, this study aims to address the following questions: what is the vertical structure of the anticyclonic eddy? and what is its seasonal evolution and interannual variability? In August 2012, an anticyclonic eddy was captured during the in situ observation along 18°N (see Fig. 1b). In this work, the CTD and acoustic Doppler current profiler (ADCP) measurements along 18°N off the western Luzon in the SCS are used to explore the vertical structure of an anticyclonic eddy (AE) during the observational period of August 12–14, 2012. Further, the AVISO sea level anomaly and corresponding anomalous surface geostrophic currents were employed to study the temporal evolution of the AE. The interannual variability of the eddy activities along 18°N are presented for the first time. Following this introduction, Section 2 describes the data and analysis methods. Section 3 presents the observational results. Section 4 gives a discussion. Finally, Section 5 is the summary.

2. Data and methods

2.1. In situ data and calculation of geostrophic currents

The in situ observation was conducted in August 12–14, 2012 from the R/V Shiyan 3 cruise. Temperature, salinity, density, and sound velocity data were observed using SBE 911plus CTD. There were 10 observational stations along 18°N between 115°E and 119.5°E (Fig. 1a, b). The vertical resolution of the data was 1 m. The observational depths were all greater than 1500 m (Fig. 1a). A vessel–mounted ADCP, made by Teledyne RD Instruments, was used for underway current measurements along the transect. The ADCP current data are available at depths ranging between 38 and 278 m with a vertical interval of 16 m. More detailed information on sampling station and section is listed on Table 1.

In order to calculate the geostrophic currents, the temperature and salinity data from the CTD were processed and interpolated to standard depths consistent with Levitus (1983). By applying the processed CTD data and selecting 1500 m as the reference level, we calculated geostrophic velocities at each standard depth. Pressure gradients below 1500 m are typically weak and the geostrophic currents can be negligible. The validity and effectiveness of such a method to calculate geostrophic currents in the SCS have been demonstrated by previous studies (Fang et al., 2002; Xiang et al., 2016).