The summer-fall anti-cyclonic eddy west of Luzon: Structure and evolution in 2012 and inter-annual variability

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Abstract

The structure and evolution of an anti-cyclonic eddy (AE) west of Luzon in the South China Sea (SCS) in summer-fall 2012 is investigated using in situ hydrographic and current observational data from a cruise in August 2012, together with satellite remote sensing data. The vertical structure of the AE along 18°N in August 2012 shows a trough located near 117.5°E, the affecting depth of eddy on temperature, salinity, density, sound velocity is ~ 200m. Seasonal variations of sea level anomalies show that the AE lasted for 5 months (June to early November), propagating westwards along 18°N with varying phase speeds and shapes to the continental slope off southeastern Hainan Island. Furthermore, T-S characteristics suggest that the AE was generated off west Luzon. Inter-annual variations of the summer (July-September) anti-cyclonic eddy presented by Empirical Orthogonal Function analysis, indicates that there were strong summer meso-scale eddy activities off west Luzon along 18 °N, in 2008, 2010, 2012 and 2013 during 1993-2014.

Keywords: mesoscale eddy, Structure and evolution, South China Sea

1. INTRODUCTION

The South China Sea (SCS) is the largest semi-enclosed marginal sea in the western Pacific Ocean. Its northeastern region connects with the East China Sea through Taiwan Strait to the northeast, and adjoins with the northwestern Pacific via the Luzon Strait to the east (Fig.1a). The SCS climate is part of the East Asian monsoon system (Wyrski, 1961). The upper layer circulation of the SCS is driven by seasonal monsoons, with significant impact of the Kuroshio on the northern part through the Luzon Strait (Fang et al., 1998; Qu, 2000, 2001). In summer, the basin scale circulation of the upper SCS is generally anti-cyclonic, in accordance with the southwesterly monsoon, while in winter the circulation reverses to cyclonic due to the monsoon reversal. The northern SCS is surrounded by Mainland China, Vietnam, Taiwan Island, Luzon Island and Hainan Island (Fig.1a). Under the combined influence of monsoon, 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). Mesoscale eddies are active in the northern SCS and have received much attention in the past

decades, and those off northwest Luzon were studied by a number of previous works (e.g., Li et al., 1998, 2002; Li et al., 2002; Yuan et al., 2007; Wang et al., 2008; Chen et al., 2010; Nan et al., 2012; Chu et al., 2014; Zhang et al., 2015). Previous studies showed that most of the northern SCS eddies originated in two areas: southwest of Taiwan and west of Luzon. Wang et al.(2008) examined the origins and evolutions of two anti-cyclonic 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. Based on oceanic surveys, a number of studies (e.g., Yang and Liu, 1998; Qu, 2000; He et al., 2015) reported that there exists a cyclonic eddy (Luzon Cold Eddy) west of Luzon in winter.

However, only a few studies focused on the summer-fall anti-cyclonic eddy off west Luzon. Li et al. (1998) reported that a warm-core anti-cyclonic eddy occurred off northwestern Luzon based on CTD (Conductivity-Temperature-Depth) profilers observations. They suggested that the anti-cyclonic 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 anti-cyclonic eddy generated northwest of Luzon Island, and named it Luzon Warm Eddy (LWE). Chen et al. (2010) investigated the vertical structure and temporal-spatial 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 that three long-lived seasonal anti-cyclonic eddies occurring along 18°N in the northern SCS in August 2007.

Although there were several previous works paying attention to the anti-cyclonic eddies west of Luzon as mentioned above, studies on their hydrographic features of vertical structures from in situ observation, as well as their variation, are still scarce. In August 2012, an anti-cyclonic eddy was captured during in situ observation along 18°N (see Fig.1b). In this work, based on in situ hydrographic and current observation from cruise in August 2012, together with multi-satellite remote sensing data, we investigate the vertical structure and temporal evolution, as well as the hydrographic characteristics of the anti-cyclonic eddy (AE) west of Luzon. We also present the inter-annual variability of the AE for the first time. This paper is organized as follows: Section 2 describes the data and analysis methods. Section 3 presents the observational results. Section 4 gives a discussion and section 5 is the summary.

Fig.1. (a) observational section and stations from curise August 2012 and bathymetry of the northern South China Sea (SCS), with the 50, 100, 200, 500, 1000, 2000, 3000, and 4000m contours plotted. We used 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). In situ observational stations are marked by white squares. The detailed information of in situ observation is on Table 1. (b) Means of sea level anomalies (SLAs, shaded, cm) and the corresponding surface geostrophic currents (vector, $\text{cm}\cdot\text{s}^{-1}$) during the in situ observations on 12-14 August 2012, white squares represent the in situ observational stations. (c) The climatological summer to early fall (July to September) means of SLAs (shaded, cm) and geostrophic current (vector, $\text{cm}\cdot\text{s}^{-1}$) during 1993-2014 in the northern SCS, showing a sub-basin scale anti-cyclonic circulation.

2. DATA AND METHODS

2.1 In situ Data and Calculation of Geostrophic Currents

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

Table 1. The detailed information of stations and section from cruise 2012.

Item	Date	Station number/section	Measuring instrument	Top/Bottom bin depth	Bin size	Sampling interval
CTD	Aug. 12-14	1-10	SBE911plus	3m/1500m	1m	1min
ADCP	Aug. 12-14	18°N	OS38 ADCP	38/278m	16m	5min

In order to calculate the geostrophic currents, the temperature and salinity data from the CTD were processed and interpolated to standard depths as by Levitus (1982). Applying the processed CTD data and selecting 1500m as the reference level, we calculated geostrophic velocities at each standard depth. Pressure gradients below 1500 m are 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).

2.2 Satellite Data and Identification of Eddies

To identify and track the eddy, daily multi-mission merged sea level anomaly (SLA) (1/4° resolution) and geostrophic velocity anomalies (also 1/4° resolution) from French Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) project (<http://www.aviso.altimetry.fr/duacs/>) were used. The dataset covers the period from 1993 to present. The climatological summer to early fall (July to September) means of SLAs and geostrophic current during 1993-2014 in the northern SCS are shown in Fig.1c.

The time evolution of the eddy was explored using the vector geometry-based detection algorithm (Nencioli et al., 2010). This scheme is a flow geometry-based method. The center of the eddy is determined by a local velocity minimum into an area where rotating flow has been detected. The eddy boundaries are defined as the outermost closed streamline around the center, across which velocity is still radially increasing. In order to improve the algorithm performance, the AVISO velocity field was linearly interpolated from a $1/4^\circ \times 1/4^\circ$ grid to $1/8^\circ \times 1/8^\circ$ grid, as it was performed in Liu et al. (2012).

3. RESULTS

3.1 Vertical Structure of the AE

Fig.2 shows the vertical structure of the AE, depicted by vertical sections of temperature, salinity, density, and sound velocity from the CTD measurements along 18°N from surface to 1500m depth. In order to reveal the characteristics of these vertical structures more clearly, we separated the vertical structure into two panels (0-300m and 300-1500m), note that each panel uses a different color scale. The structures of temperature, salinity, density, sound velocity are similar. There is a trough which can be seen in each of the temperature, salinity, density, and sound velocity contour maps. The troughs are located near 117.5°E (Station 6 and 5), corresponding to the center of the AE at 18°N . There is no significant trough in the deeper 300-1500m layer. The affecting depth of eddy on temperature, salinity, density, sound velocity is about 200m. There exists a salinity maximum (~ 34.55) at $\sim 150\text{m}$ depth and a salinity minimum (~ 34.42) at $\sim 500\text{m}$ depth (Fig.2b). The maximum sound velocity ($\sim 1540\text{m}\cdot\text{s}^{-1}$) is at surface. There exists sound velocity minimum (deep sound channel) at 1000-1200 m (Fig.2d). At the eddy center, vertical mean (0-1500m) temperature and sound velocity are 0.59°C and $1.14\text{m}\cdot\text{s}^{-1}$ larger than those in the surrounding areas (station 9 as the reference), while mean salinity and density are ~ 0.05 and $\sim 0.19\text{kg}\cdot\text{m}^{-3}$ smaller.

The profiles of thermocline, halocline, pycnocline, and sonic layer are shown in Fig.3. From surface to thermocline, the temperature, salinity, density, and sound velocity seem homogeneous due to mixing. Below the thermocline, temperature and sound velocity decrease gradually with depth (Figs.3a, 3b and 3d), while density increases below the pycnocline (Fig.3c). At the eddy center, the depths of thermocline, pycnocline, sonic layer can reach 100m.

Fig.4 shows the vertical distribution of geostrophic current. The velocity in the west is northward but southward in the east, implying that a distinctive AE existed. The position of the eddy center is basically consistent with that one identified in Fig.2. The maximum speed is at the surface. The maximum northward speed of the AE is $\sim 60\text{cm}\cdot\text{s}^{-1}$, while the maximum southward speed is $40\text{cm}\cdot\text{s}^{-1}$. The depth where the northward speed is over $10\text{cm}\cdot\text{s}^{-1}$ can reach nearly 300m, while that one with southward speed over $10\text{cm}\cdot\text{s}^{-1}$ can reach nearly 600m.

The currents were directly measured by the shipboard ADCP along the section during the cruise. The ADCP current data covering depth layers from 38m to 278m are presented in Fig.5. The maximum speed is at the surface, the current vectors at the section reveal an anti-cyclonic pattern with the maximum velocity of $0.6\sim 0.70\text{m}\cdot\text{s}^{-1}$, basically consistent with the geostrophic currents (Fig.4). In August 2012, corresponding to the anti-cyclonic circulation at 18°N , the flow was northeastward west of 117°E , whereas it was southward east of 117.5°E .

Fig.2. Vertical distributions of (a) temperature (in units of °C), (b) salinity (in units of psu), (c) density (σ_t ; in units of $\text{m}^3 \cdot \text{s}^{-1}$), and (d) sound velocity (in units of $\text{m} \cdot \text{s}^{-1}$), along the 18°N section in August 2012.

Fig.3. profiles of (a) temperature (in units of $^{\circ}\text{C}$), (b) salinity (in units of psu), (c) density (σ_t ; in units of $\text{m}^3 \cdot \text{s}^{-1}$), and (d) sound velocity (in units of $\text{m} \cdot \text{s}^{-1}$) at 10 stations.

Fig.4. vertical distribution of geostrophic current (in units of $\text{cm} \cdot \text{s}^{-1}$) along the 18°N section in

174 August 2012. Positive (negative) values represent northward (southward) currents,
 175 Data-Interpolating Variational Analysis (DIVA) (Troupin et al., 2012) is used for interpolation.

176
 177 Fig.5. Current vectors at different depth (as labeled) measured by ADCP for the 18°N section in
 178 August 2012. In units of $\text{m}\cdot\text{s}^{-1}$. The maximum speed is about $1.12 \text{ m}\cdot\text{s}^{-1}$, appears at the 38m and
 179 54m.

180 3.2 Surface Description of the AE

181 Fig.6 shows the temporal evolution of the AE delineated from the geostrophic velocity anomalies
 182 together with SLA data. The AE was first detected on 12 June west of Luzon, developed in June,
 183 intensified in July-August, split in September and then propagated westward to the eastern Hainan
 184 Island in early November. The eddy can be traced for nearly 5 months. The temporal evolution of
 185 the AE can be roughly divided into two stages: the growth period and westward propagation
 186 period. The migration speed of the AE in these two stages varies significantly. During the growth
 187 period from 12 June to 31 August, the AE started to form and intensify, its diameter increases
 188 from 27km to 220km and the maximum of SLAs is about 30 to 40cm, the westward migration at

189 this stage is very slow (less than $4\text{cm}\cdot\text{s}^{-1}$). From September to early November, the AE moves to
190 the second stage. The AE split into two anti-cyclonic eddies (marked as AE1 and AE2 in Fig.6) on
191 2 September. AE1 and AE2 lasted for about 2 months, AE2 had a faster western migration speed
192 up to $8\text{cm}\cdot\text{s}^{-1}$, and gradually weakened. The last day on which AE2 was detected by the automatic
193 scheme was 10 November. In contrast, AE1 only moved slowly, the last day on which AE1 was
194 detected was 22 October. The approximate pathway of the AE2 migrating westward is along
195 section 18°N .

Fig.6. Temporal evolution of anti-cyclonic circulation detected by altimeter SLA (color shading, units in cm) and geostrophic currents anomalies (vectors, units in $\text{m}\cdot\text{s}^{-1}$) from 20 May to 10 November 2012 west of Luzon. Closed black lines denote eddy cores of anti-cyclonic eddy.

3.3 Inter-annual variability of July-September SLA

a) sub-basin scale summer-fall anti-cyclonic circulation

To capture the dominant inter-annual variability signal of the summer (July to September) SLA from 1993 to 2014 west of Luzon, Empirical Orthogonal Function (EOF) analysis was performed. The first leading SLA EOF mode, explaining 73.9% of the variance This EOF mode has a positive spatial pattern mainly located west of Luzon between 16° N and 20° N with the maxima about 119° E (Fig.7a). The spatial pattern is similar to the climatological summer to early fall (July to September) means of sea level anomalies (Fig.1c). The time series of this EOF mode are always positive from 1993 to 2014. Combined with the spatial pattern, it shows the inter-annual variability of a sub-basin scale summer-fall anticyclonic circulation located west of Luzon. Note that the highest peaks appeared in 2010 and 2013, indicating that SLA was especially high west of Luzon during these time periods. The time series also shows three phase changes in 1998, 2003 and 2005, respectively. Three short term linear trends can be seen from the time series: an increase from 1998 to 2003, a decrease from 2003 to 2005, and a rapid rise from 2005 to 2014, which is similar to the results calculated by Fang et al. (2014), who suggested that the decadal variability of summer circulation in the SCS with three phase changes in 1998, 2001 and 2006, respectively. This implies that the strongest summer-fall anti-cyclonic circulation off northwest Luzon occurred during the years of 2010 and 2013.

b) Inter-annual variability of summer mesoscale eddies

In order to capture the inter-annual signals of SLA without the seasonal signal at summer-fall phase included, the climatology monthly means during 1993-2014 were removed from the climatologically monthly means, EOF analysis was performed. The first two leading EOF modes are presented in Fig.8. These two modes explain 42.6% and 10.4% of the total variance. Inter-annual variability of mesoscale signals is highlighted by removing the seasonal cycle. The dominant spatial pattern of mode one (Fig.8a) is characterized by two high positive SLA west of Luzon between 16° N and 20° N with the two maxima centered at 115°E and 118°E, showing a zonal eddy pattern along 18° N from western Luzon. The time series of this mode (Fig.8b) generally has four large peaks in years 2008, 2010, 2012 and 2013, respectively. Together with the spatial pattern, this indicates that anti-cyclonic eddies occurring in summer of those years were more active, consistent with the results from our in situ observation in August of 2012 as presented

above. In addition, the second mode shows a positive SLA over the southwest continental slope and a negative SLA southwest of Taiwan Island (Fig.8b), indicating that there existed another pathway: eddies propagating southwestward along the continental slope from southwestern Taiwan Island.

Fig.7. The first EOF mode of the summer to early fall, calculated from daily SLA, (a). spatial pattern of EOF1; (b) time coefficients of EOF1 (black solid line).

Fig.8. The first two leading EOF modes of the summer to early fall SLA, calculated from monthly SLAs with the seasonal signal at summer- early fall phase removed; a. spatial pattern of EOF1; b. spatial pattern of EOF2.; c. time coefficients of EOF1 (black solid line) and time coefficients of EOF2 (black dotted line).

4. DISCUSSION

4.1 The origin of the AE

The South China Sea is a semi-enclosed basin, its water masses differ from those of Pacific Ocean outside the Luzon Strait. In order to verify the origin of AE, Temperature-Salinity scatter diagrams for in situ data and August climatological data from WOA13 are shown in Fig.9. Black points represent data samples at 1-10 stations of in situ observation along 18°N section in August 2012, while blue, green, and red points denote data for August climatological T-S scatter diagrams at the eastern side of the Luzon Strait in the Kuroshio (from 19.625° N to 20.625° N, 122.125°E to 124.875°E), west of Luzon in the AE (range from 17.5°N to 18.5°N, from 116°E to 118°E) and northern SCS(range from 16.125°N to 18.875°N, from 112.125°E to 119.125°E), respectively. Fig.9 shows that the water mass characteristics at stations 1-10 were similar. The salinity reached a maximum of 34.6 at the 100-150m depth where the potential density is about 25. Major difference between the SCS and the Kuroshio T-S characteristics appears at the salinity maxima and minima.

255 Originated from North Pacific Tropical Water, the Kuroshio water is more saline with a maximum
256 of about 34.9 east of the Luzon Strait (Nitani, 1972). In the South China Sea, however, the
257 maximum salinity is usually lower than 34.7 (Yang et al., 1988). As we can see in Fig.9, the
258 maximum salinity of the Kuroshio water reaches 34.86~34.89 at 150-200m depth, and the
259 minimum salinity reaches 34.19~34.27 at the 550-650m depth, while the maximum salinity of the
260 northern SCS water is about 34.26~34.62 at 125-175m depth, and the minimum one reaches
261 34.44~34.47 at 550m. We found that the in situ water temperature and salinity are different from
262 those of the Kuroshio, the T-S characteristics of AE is much closer to northern SCS water whose
263 salinity was much lower than that of the Kuroshio (Fig. 9).

264 Li et al. (1998) found an anti-cyclonic eddy centered at about 21°N, 117.5°E just off the
265 continental slope with a horizontal scale of ~150km in the summer of 1994, and the water
266 characteristics in the eddy was between the SCS water and the Kuroshio at Luzon strait. The
267 chemical tracer analysis of Li and Pohlmann (2002) suggests that this eddy originated from the
268 Kuroshio. While based on the SLA and the geostrophic currents from satellite data, Yuan et
269 al.(2007) suggested that the AE west of Luzon originated from northwest of Luzon in early
270 summer. They argued that the anti-cyclonic eddy in late July of 1994 discovered by Li et al.(1998)
271 also originated from northwest of Luzon and carried primarily the SCS water.

272 Our results show that the T-S characteristics of the AE are much closer to those of the northern
273 SCS water (Fig.9). The salinity of the AE was much lower than that of the Kuroshio water, which
274 is consistent with Yuan et al. (2007). In addition, as shown in Fig.6, the AE west of Luzon was
275 quasi-steady at early stage, then propagated westward at varying phase speed and reached off the
276 Hainan island in early November, while during the entire process, the Kuroshio in the Luzon strait
277 stayed in a path from northeast of Luzon to southwest of Taiwan Island, no significant loop current
278 of the Kuroshio is indicated by the geostrophic currents (not shown). The dominant mode of
279 Kuroshio path fluctuations in the Luzon Strait consist of westward intrusion in fall and winter and
280 eastward meander anomalies in spring and summer (Lin et al., 2016), The results suggest that the
281 AE may be generated locally in the SCS.

Fig.9. Temperature-Salinity scatter diagrams for in situ section data in August 2012 and August climatological data from WOA13. Black points represent data samples at 1-10 stations of in situ data in August 2012. Blue, green and red points represent data samples in the Kuroshio, northern SCS, the area of AE, respectively (Temperature and salinity data from WOA2013). Gray contours show potential density.

4.2 Westward movement of the AE

As presented from the result of de-seasoned EOF analysis in section 3.3(b), the inter-annual modulation of mesoscale eddy was of two types: propagating westward from Luzon along 18°N; eddies propagating southwestward along the continental slope from southwestern Taiwan Island. The second type was less significant in summer but more dominant in winter as presented in previous studies (Zhuang et al., 2010; Lin et al., 2016). The westward propagation of the AE which belongs to the first type has been identified in Fig.6. We found that, during 12 June to 31 August the westward speed was less than $4\text{cm}\cdot\text{s}^{-1}$, while it was $8\text{cm}\cdot\text{s}^{-1}$ during 1 September to early November. Hu et al. (2001) suggested that the propagation of mesoscale eddy with $11\text{-}12\text{cm}\cdot\text{s}^{-1}$ phase speed in the northern SCS may be considered as the first-mode baroclinic Rossby wave. Based on 22-month temperature observations at a station in the northern SCS and other supporting data, Lin et al.(2016) estimated that the westward-propagating phase speed of the observed cyclonic eddy off west Luzon is about $5.8\text{cm}\cdot\text{s}^{-1}$. The calculated first-mode baroclinic

westward propagate speed by Yuan et al. (2007) was about $7.1\text{ cm}\cdot\text{s}^{-1}$. Chen et al. (2010) estimated that the migration speed of the LWE varies significantly. From July to September, the speed is slow (less than $3\text{ cm}\cdot\text{s}^{-1}$). Subsequently, the LWE has a faster migration speed of up to $14.3\text{ cm}\cdot\text{s}^{-1}$ in December. The mean westward propagation speed of the AE (their AE3) calculated by Nan et al. (2011) was $6.0\text{ cm}\cdot\text{s}^{-1}$, which is smaller than the speed of the first mode baroclinic Rossby wave. The westward propagation at a observed Rossby wave speed calculated by Xu et al. (2015) is $9\text{--}11\text{ cm}\cdot\text{s}^{-1}$ along 18° N using sea surface height anomalies (SSHA) obtained from AVISO. The westward propagating speed of the AE from our result is more similar to those estimated by Lin et al. (2016), Yuan et al. (2007) and Xu et al. (2015). The complicated westward propagation and splitting of the AEs in different years may suggest complex interactions between mesoscale eddy and ambient fluids during the westward movement and inter-annual variations.

5. SUMMARY

Based on CTD and ADCP in situ sectional measurements in 2012 and satellite altimeter data, we analyzed the vertical structure and evolution of the anti-cyclonic eddy west of Luzon during summer-fall 2012. The results show that the AE lasted for 5 months (June to early November), propagating westwards along the 18°N pathway with varying phase speeds and shapes to the continental slope off southeastern Hainan Island. The water mass characteristics revealed by the T-S diagram indicated that the AE may be generated locally in the SCS.

The vertical structure of the AE in August 2012 shows a trough located near 117.5°E , the affecting depth of eddy on temperature, salinity, density, and sound velocity is about 200m. Near the core of the eddy, vertical mean temperature and sound velocity are $\sim 0.59^\circ\text{C}$ and $\sim 1.14\text{ m}\cdot\text{s}^{-1}$ larger than those in the surrounding areas, respectively, while mean salinity and density are ~ 0.05 and $\sim 0.19\text{ kg}\cdot\text{m}^{-3}$ smaller.

Temporal evolution of the AE can be roughly divided into two stages: from June to August, the eddy started to develop and intensify. Its diameter increased from 27km to 220km and the maximum of sea level anomalies is about 30 to 40cm. The westward migration velocity was less than $4\text{ cm}\cdot\text{s}^{-1}$. From September on, the AE split into two anti-cyclonic eddies, one of them had a faster westward migration speed of up to $8\text{ cm}\cdot\text{s}^{-1}$, and gradually weakened.

For the first time, inter-annual variations of the summer (July-September) meso-scale eddies were

presented by Empirical Orthogonal Function analysis, indicating that there were strong summer meso-scale eddy activities off west Luzon along 18 °N, occurring in 2008, 2010, 2012 and 2013 during 1993-2014, which modulated the summer circulation in the northern SCS.

To date, the dynamics of the summer AE is unknown. Previous studies (e.g., Qu 2000; Xue et al. 2004; Wang et al. 2008) have extensively documented that eddies west of Luzon in winter can be generated by WSC. However, the WSC in summer northwest of Luzon is generally positive, it cannot produce the AE (Yuan et al., 2007). This paper focuses on the spatial and temporal structures and its evolution of the AE and its variability. Numerical modeling is necessary to explain the generation mechanism of the AE west of Luzon in future study.

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8. CAPTIONS

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 4000m contours plotted. We used 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). In situ observational stations are marked by white squares. The detailed information of in situ observation is on Table 1. (b) Means of sea level anomalies (SLAs, shaded, cm) and the corresponding surface geostrophic currents (vector, $\text{cm}\cdot\text{s}^{-1}$) during the in situ observations on 12-14 August 2012, white squares represent the in situ observational stations. (c) The climatological summer to early fall (July to September) means of SLAs, shaded, cm) and geostrophic current (vector, $\text{cm}\cdot\text{s}^{-1}$) during 1993-2014 in the northern SCS, showing a sub-basin scale anti-cyclonic circulation.

Fig.2. Vertical distributions of (a) temperature (in units of $^{\circ}\text{C}$), (b) salinity (in units of psu), (c) density (σ_t ; in units of $\text{m}^3\cdot\text{s}^{-1}$), and (d) sound velocity (in units of $\text{m}\cdot\text{s}^{-1}$), along the 18°N section in August 2012.

Fig.3. profiles of (a) temperature (in units of $^{\circ}\text{C}$), (b) salinity (in units of psu), (c) density (σ_t ; in units of $\text{m}^3\cdot\text{s}^{-1}$), and (d) sound velocity (in units of $\text{m}\cdot\text{s}^{-1}$) at 10 stations.

Fig.4. vertical distribution of geostrophic current (in units of $\text{cm}\cdot\text{s}^{-1}$) along the 18°N section in August 2012. Positive (negative) values represent northward (southward) currents, Data-Interpolating Variational Analysis (DIVA) (Troupin et al., 2012) is used for interpolation.

Fig.5. Current vectors at different depth (as labeled) measured by ADCP for the 18°N section in August 2012. In units of $\text{m}\cdot\text{s}^{-1}$.

Fig.6. Temporal evolution of anti-cyclonic circulation detected by altimeter SLA (color shading, units in cm) and geostrophic currents anomalies (vectors, units in $\text{m}\cdot\text{s}^{-1}$) from 20 May to 10 November 2012 west of Luzon. Closed black lines denote eddy cores of anti-cyclonic eddy.

Fig.7. The first EOF mode of the summer to early fall, calculated from daily SLA, (a) spatial pattern of EOF1; (b) time coefficients of EOF1 (black solid line).

Fig.8. The first two leading EOF modes of the summer to early fall SLA, calculated from monthly SLAs with the seasonal signal at summer- early fall phase removed; (a) spatial pattern of EOF1; (b) spatial pattern of EOF2; (c) time coefficients of EOF1 (black solid line) and time coefficients of EOF2 (black dotted line).

Fig.9. Temperature-Salinity scatter diagrams for in situ section data in August 2012 and August climatological data from WOA13. Black points represent data samples at 1-10 stations of in situ data in August 2012. Blue, green and red points represent data samples in the Kuroshio, northern SCS, the area of AE, respectively (Temperature and salinity data from WOA2013). Gray contours show potential density.