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A case study of a Kuroshio main path cut-off event and impacts on the South China Sea in fall-winter 2013–2014

Quanan Zheng[1, 2], Chung-Ru Ho[3], Lingling Xie[2*], Mingming Li[2]

[1] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland 20742

[2] Guangdong Key Laboratory of Coastal Ocean Variability and Disaster Prediction, Guangdong Ocean University, Zhanjiang 524088

[3] Department of Marine Environmental Informatics, National Taiwan Ocean University, Keelung 20224

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Abstract

This study examines a Kuroshio main path (KMP) cut-off event east of Taiwan Island occurred in fall-winter 2013–2014 and its impacts on the South China Sea (SCS) by analyzing satellite altimetry and mooring observations. Satellite altimeter sea level anomaly (SLA) images reveal a complete process that a huge cyclonic eddy (CE) from the Pacific collided with the Kuroshio and the western boundary from 15 October 2013 to 15 January 2014. Mooring observations evidenced that the Kuroshio upper ocean volume transport was cut off more than 82% from 17×10^6 m^3/s in September to 3×10^6 m^3/s in November 2013. The KMP cut-off event caused the Kuroshio branching and intruding into the SCS and strengthened the eddy kinetic energy in the northern SCS west of the Luzon Strait. Using the total momentum as a dynamic criterion to determine the role of eddy collision with the Kuroshio reasonably explains the KMP cut-off event.

Key words: KMP cut-off event, eddy kinetic energy, dynamic criterion, South China Sea

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1 Introduction

A phenomenon that the Kuroshio current east of the Luzon Strait and Taiwan Island interacts with eddies propagating westward from the Pacific has attracted more and more attentions of the research community (Qiu and Chen, 2010; Lien et al., 2014; Zheng and Zheng, 2014; Tsai et al., 2015; Yin et al., 2017; Kuo et al., 2017). The reason is that more and more research results reveal that the phenomenon might be a key for understanding the spatial and temporal instabilities of the Kuroshio, such as the path deformation even cut-off (Miyazawa et al., 2010; Zheng et al., 2011; Nan et al., 2014; Tsai et al., 2015) and huge fluctuation of volume transport (Lien et al., 2014; Jan et al., 2015; Andres et al., 2017). Meanwhile, the Kuroshio main path (KMP) (i.e., the long-term mean path) cut-off, complete or partial, must have significant impacts on the circulation in upstream and downstream marginal seas (Hu et al., 2000; Qu et al., 2009; Lin et al., 2012; Yang et al., 2014; Xie et al., 2018; Xie and Zheng, 2017; Zheng et al., 2017).

This study examines a KMP cut-off event and its impacts on the South China Sea (SCS) occurred in fall-winter 2013–2014. The next section presents time series satellite altimetry images which show the complete process of the KMP cut-off caused by collision of a huge cyclonic eddy (CE) westward propagating from the Pacific with the western boundary. The event was further evidenced by the variability of Kuroshio volume transports that were concurrently mooring-observed along a section east of Taiwan Island with approaching of the CE to the western boundary (Andres et al., 2017). Section 3 analyzes impacts of the KMP cut-off event on the SCS. Section 4 proposes a physical criterion for determining a dominant role during the interaction of the Kuroshio with eddies. Section 5 gives conclusions.

2 KMP cut-off event in fall-winter 2013–2014

2.1 *Satellite altimetry observations*

Figure 1 shows time series of satellite sea level anomaly (SLA) images of the western boundary area of the North Pacific between 18° and 25°N, 115° and 130°E from 15 October 2013 to 15 January 2014 (SLA data are downloaded from http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global.html). One can see a complete process that a huge CE propagated westward from the Pacific and collided with the Kuroshio and the western boundary.

On 15 October 2013, the CE appeared as an ellipse-shaped, twin-core SLA pattern centered at about 22°N, 124°E (Fig. 1a). Its major and minor axes reached about 800 km and 450 km, respectively. The lowest SLA was as low as –30 cm, implying a strong cyclonic eddy. The CE moved westward and approached to the offshore flank of the Kuroshio on 1 November 2013 (Fig. 1b). Due to blockage of the western boundary, the moving speeds of

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*Corresponding author, E-mail: llingxie@163.com

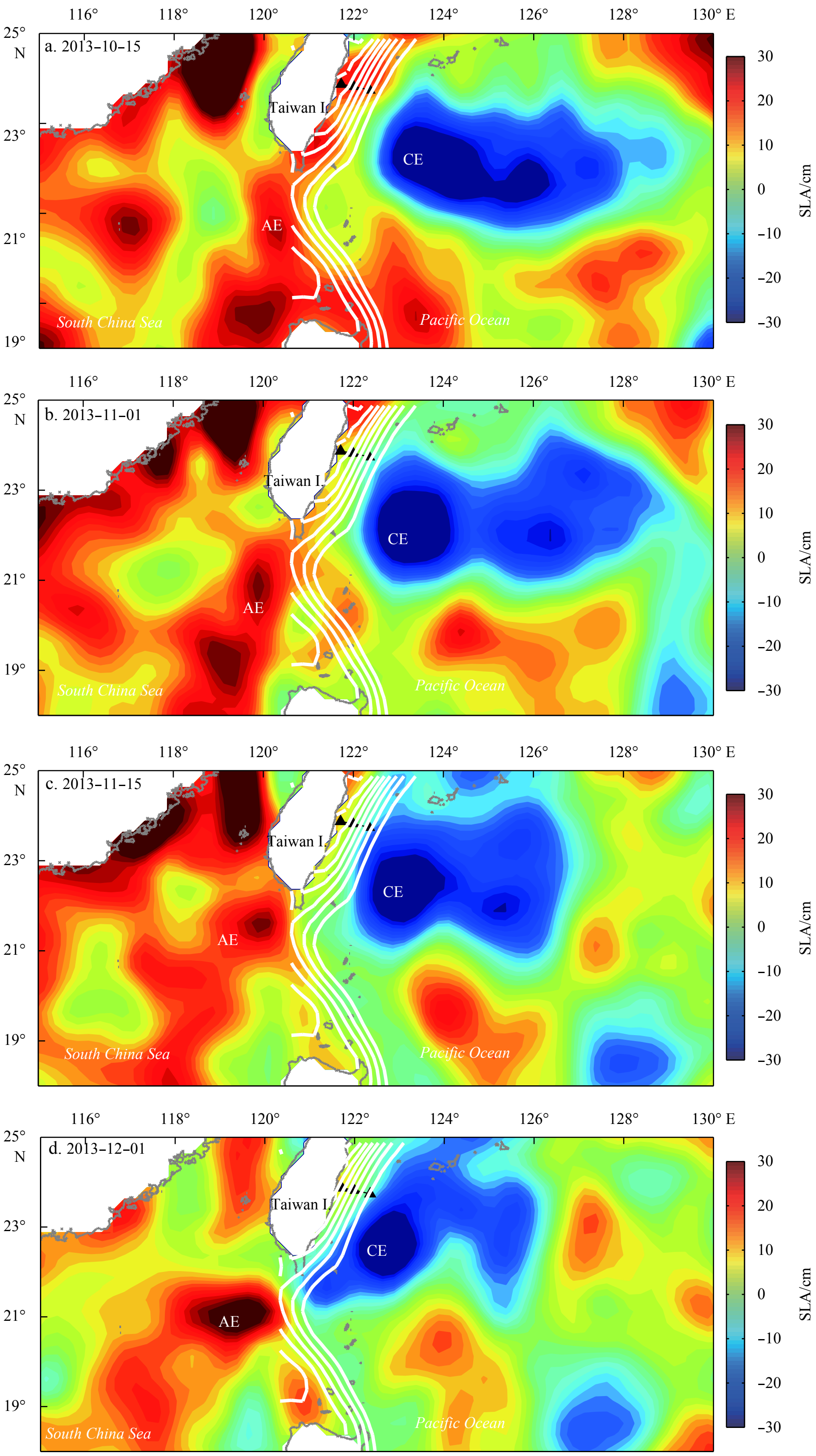
116°
118°
120°
122°
124°
126°
128°
130° E
25° N
23°
21°
19°
a. 2013-10-15
b. 2013-11-01
c. 2013-11-15
d. 2013-12-01
Taiwan I.
CE
AE
South China Sea
Pacific Ocean
30
20
10
0
−10
−20
−30
SLA/cm

Fig. 1.

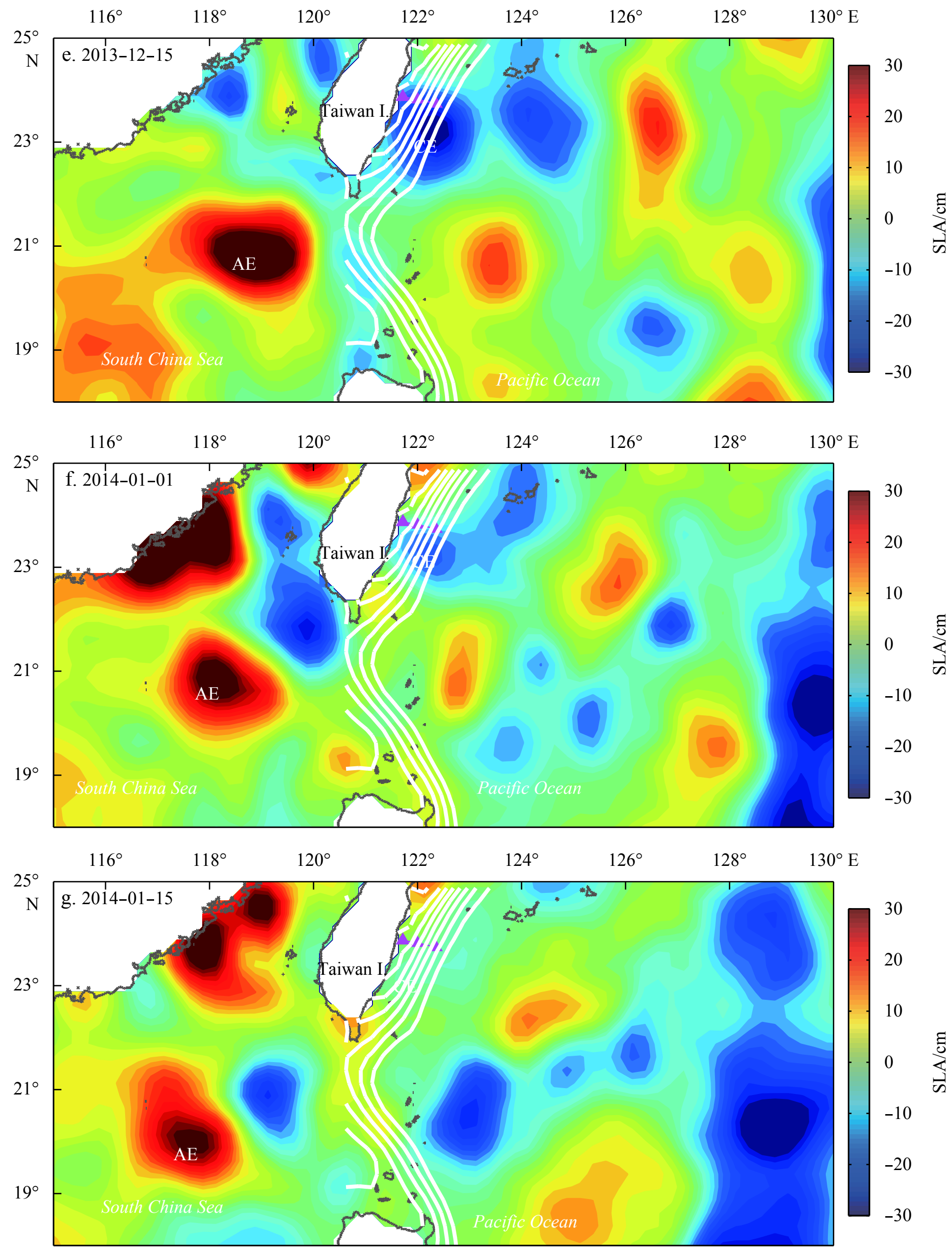

Fig. 1. Time series of satellite SLA images of the western boundary area of the North Pacific between 18° and 25°N, 115° and 130°E from 15 October 2013 to 15 January 2014. CE represents a cyclonic eddy propagating westward from the Pacific and finally colliding with the east coast of Taiwan Island. AE represents a pre-existing anticyclonic eddy in the SCS. White contour lines represent the Kuroshio main path derived from the 23-year (1993–2015) mean Absolute Dynamic Topography. Contour lines are from 90 cm to 125 cm with interval of 5 cm. Black/magenta lines with triangles east of Taiwan Island show the locations of mooring stations S1, S2 and S3. Grey line represents coastal line. Color codes of SLA are in cm.

the frontal front and the rear front of the CE were 4 cm/s and 8 cm/s averaged from 15 October to 15 November 2013, so that the CE was deformed, i.e., its major axis in the zonal direction decreased to about 650 km, while minor axis in the meridional direction increased to 500 km, respectively. Meanwhile, the lowest SLA kept as low as –30 cm. On 1 December 2013, the CE cut the KMP off completely at the northern Luzon Strait (Fig. 1d). On 15 December 2013, the eddy broke into two smaller cyclonic eddies with a radius of about 100 km (Fig. 1e), while the KMP was still cut off. On 1 January 2014, the horizontal size and the maximum SLA of the eddy decreased about 50% compared to that on 1 December (Fig. 1f), implying quick dissipation of the eddy momentum due to collision with the western boundary. On 15 January 2014, the KMP started recovery (Fig. 1g).

2.2 *Mooring observations*

For the above collision event of the CE with the western boundary, there are concurrently mooring-observed data available. The data we analyze were taken from a mooring array east of Taiwan Island deployed along a section at around 23.75°N from 121.7°E to 123.0°E spanning 135 km as shown in Figs 1a–g (black and magenta lines with triangles). One can see that the section just crosses the KMP. The array comprised three upward looking 75 kHz acoustic Doppler current profilers (ADCPs) at the depth of 500 m and four pressure-sensor equipped inverted echo sounders (PIESs) resting on the seafloor (see Andres et al. (2017) for details). Instruments were deployed from 14 November 2012 to 31 October 2014, just covering the event of interest occurred from October 2013 to January 2014.

Time series of 15-d low-pass filtered upper ocean (< 5×10^6 Pa) volume transports along the section at around 23.75°N from 121.7°E to 123.0°E, which are derived from the measurements by the ADCPs, PIESs and additional LADCPs, are shown in Fig. 5 in Andres et al. (2017). One can see that during the collision event of the CE with the western boundary from September 2013 to January 2014 as shown in Figs 1a–g, the Kuroshio upper ocean volume transport decreased 82% from 17×10^6 m³/s in September to 3×10^6 m³/s in November. In the other words, the westward moving CE gradually cut the KMP northward flow off. On 15 December 2013, the volume transport recovered to about 50% of the mean value (12.3×10^6 m³/s) as the eddy strength dissipated to about 50% of its peak value. After 15 January 2014, the volume transport recovered quickly to the normal level as the eddy disappeared.

To examine the KMP cut-off process caused by the CE collision with the western boundary, we plot the variability of the KMP upper ocean volume transport vs. the distance of the eddy front to the east coast of Taiwan Island. The results are shown in Fig. 2. One can see that the KMP upper ocean volume transport decreases linearly with the distance decrease of the CE front (defined as the most outside enclosed SLA isocline) to the coast. The KMP volume transport is cut off more than 80% as the eddy collides with the east coast of Taiwan Island. During this process, the CE continuously moved toward the coast and cut the whole KMP off.

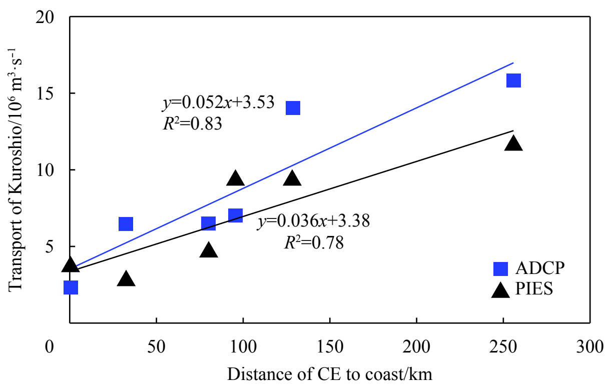

Fig. 2. Variability of the KMP volume transport vs. the distance of the eddy front to the east coast of Taiwan Island from September to December 2013. Squares and triangles represent data points taken from Fig. 5 in Andres et al. (2017), which are derived from measurements by ADCPs and PIESs, respectively. Lines represent the linear regression of the data points.

3 Impacts of the KMP cut-off event on the SCS

3.1 *Kuroshio branching and intruding into the SCS*

Figure 3 shows images of absolute dynamic topography (ADT) and absolute geostrophic velocity (AGV) of the study area during the KMP cut-off event east of Taiwan Island in November-December 2013 (ADT and AGV data are downloaded from http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global.html). On these images, dense northward current vectors along the western boundary show the KMP as marked by large white vectors. The high (low) sea level centers surrounding by anticyclonic (cyclonic) current vectors show anticyclonic (cyclonic) eddies, such as AE (CE) west (northeast) of the Luzon Strait. From image of 1 November 2013, one can see that the CE cut the KMP off east of Taiwan Island. Concurrently the Kuroshio in the Luzon Strait branched into two branches at 21.5°N, 121°E as marked by large white arrows. One branch flowed northward first and turned eastward at 22°N. The other branch flowed northwestward and entered the SCS. From image of 15 November 2013, one can see that the CE moved to the northern Luzon Strait and cut the KMP off completely. Meanwhile, the northward branch turned northeastward, and the northwestward branch turned westward and strengthened the AE centered at 21.5°N, 120°E west of the Luzon Strait on 1 November 2013, i .e., its major axis increased from about 200 km to 300 km and maximum tangent velocity increased from 0.5 m/s to 0.8 m/s from 1 to 15 November 2013. The image on 1 December 2013 shows that the CE, which entered the northern Luzon Strait, dissipated, but the KMP east of Taiwan Island was still cut off completely. The northeastward branch shifted closer to Taiwan Island, and the westward branch disappeared. Meanwhile, the AE separated from the Kuroshio, moved westward and further strengthened with the maximum tangent velocity increased to 1.0 m/s.

From the above case study, we find the following significant facts. (1) The KMP cut off by the CE east of Taiwan Island and in the Luzon Strait is a main cause for the Kuroshio branching and intruding into the SCS. Once the CE dissipates, the Kuroshio recovers its normal path. (2) The Kuroshio intrusion into the SCS strengthens pre-existing anticyclonic eddy AE west of the Luzon Strait.

3.2 *Variability of eddy kinetic energy (EKE)*

In order to estimate impact of the Kuroshio intrusion on the SCS, we calculate the EKE as defined as

$$\mathrm{EKE} = \frac{1}{2}\left(u_{ij}'^2 + v_{ij}'^2\right), \tag{1}$$

where (u_{ij}', v_{ij}') is the geostrophic velocity anomaly at grid i, j computed with respect to a twenty-year (1993–2012) mean (downloaded from https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/msla-uv.html). The test area is from 18° to 23°N and from 115° to 120.5°E, which is immediately connected to the Luzon Strait as marked in Fig. 3. The grid size is (1/4)° by (1/4)°.

Using Eq. (1), we calculate time series of averaged EKE in the test area from 1 June 2013 to 31 May 2014, which covers the KMP cut-off event in fall-winter 2013–2014. The results are shown in Fig. 4a. One can see a big EKE peak with a peak value of 0.08 m²/s², which occurred from 10 November 2013 to 1 February 2014, twice higher than the annual mean of 0.04 m²/s². Figures 4b–d shows the northward velocities $v1$, $v2$ and $v3$ at three mooring Stas S1, S2 and S3 from inshore to offshore east of Taiwan Island. Of three stations, S2 has the largest mean northward velocity of 0.8 m/s and maximum value of 1.5 m/s, indicating the central location of Kuroshio. It was cut off to zero in middle October 2013 and flowed much slower than annual mean velocity till late December 2014 (Fig. 4c). The average velocity in this period was 0.3 m/s, 80% off the maximum northward velocity. On the offshore side, $v3$ decreased significantly to zero in early October

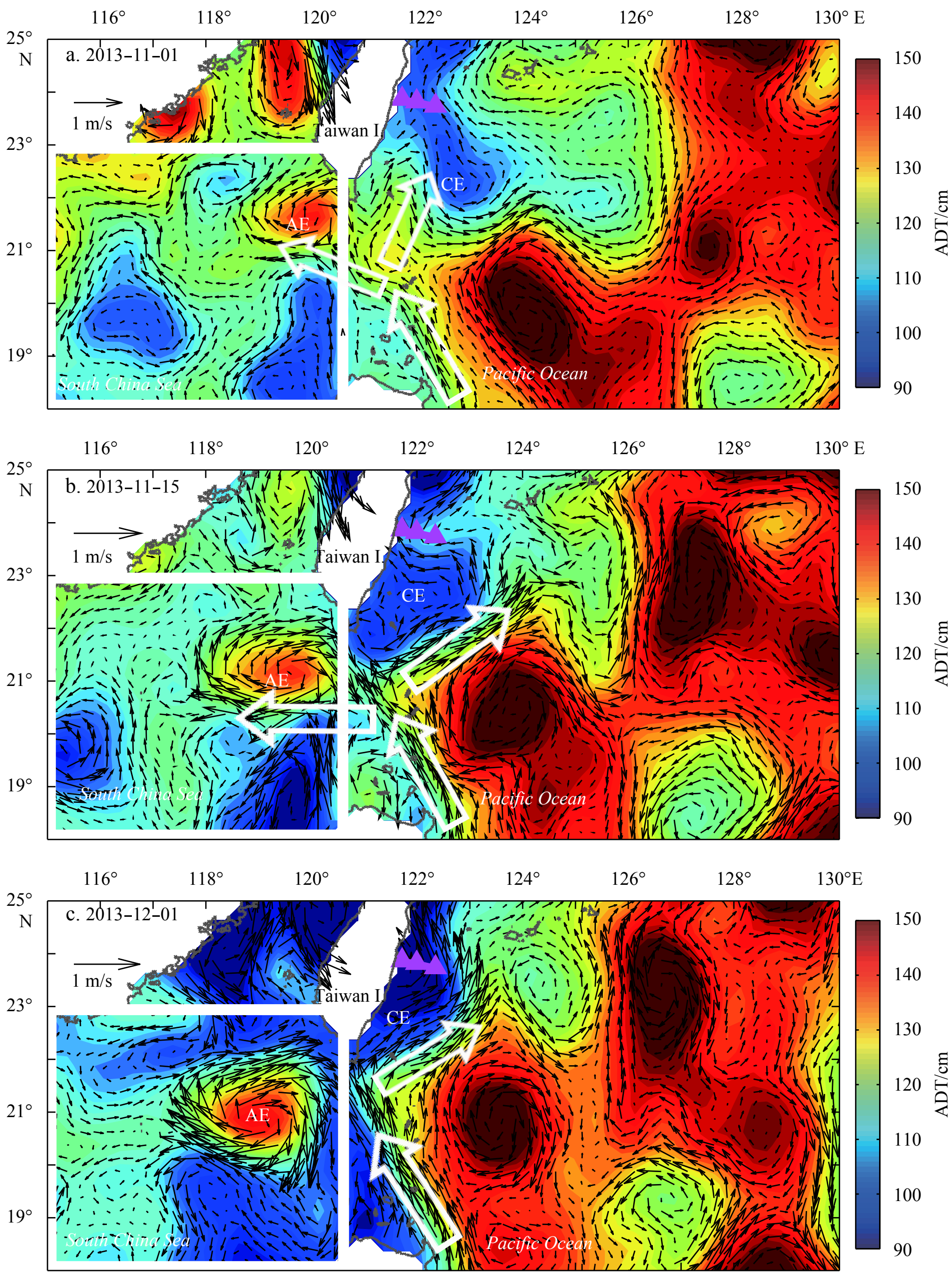

Fig. 3. Images of ADT during the period for the Kuroshio cut-off by the CE in November–December 2013. Small black arrows and large white arrows represent the geostrophic current vectors and the Kuroshio path, respectively. Magenta lines with triangles east of Taiwan Island show the locations of mooring Stas S1, S2 and S3. Area enclosed by white lines on the lower left side is used for calculating eddy kinetic energy (EKE). Grey line represents coastal line. Color codes are in cm.

2013, half month earlier than that at S2 (Fig. 4d). At the station nearest the shore, $v1$ decreased below the annual mean in late November 2013, and lasted till January 2014 (Fig. 4b). Compared the EKE curve with the curve of northward velocity at S2, one can see a very good one-month delayed correspondence between the two, i.e., the EKE increment occurred one month later than the Kuroshio cut-off east of Taiwan Island, implying that the Kuroshio cut-off event caused the upstream Kuroshio path branching and intruding into the SCS, so that strengthened the EKE in the northern SCS west of the Luzon Strait.

4 Discussion

For research of the Kuroshio-eddy interaction, there are two debatable problems: (1) which one plays a dominant role during the interaction, and (2) what dynamic parameter is more reasonable for determining the dominant role? Zheng et al. (2011) proposed to use the ratios of the total momentum and the total kinetic energy as dynamic criteria for determining the dominant role during the interaction. Tsai et al. (2015) suggested using the maximum velocity and the relative vorticity as dynamic criteria for determining the dominant role during interaction. They suggested that both the maximum orbital velocity and the relative vorticity of an impinging eddy were smaller or weaker than that of the Kuroshio, so that the eddy cannot induce significant influence on the Kuroshio, and the interaction between the two systems thus occurs mainly in the Kuroshio offshore flank.

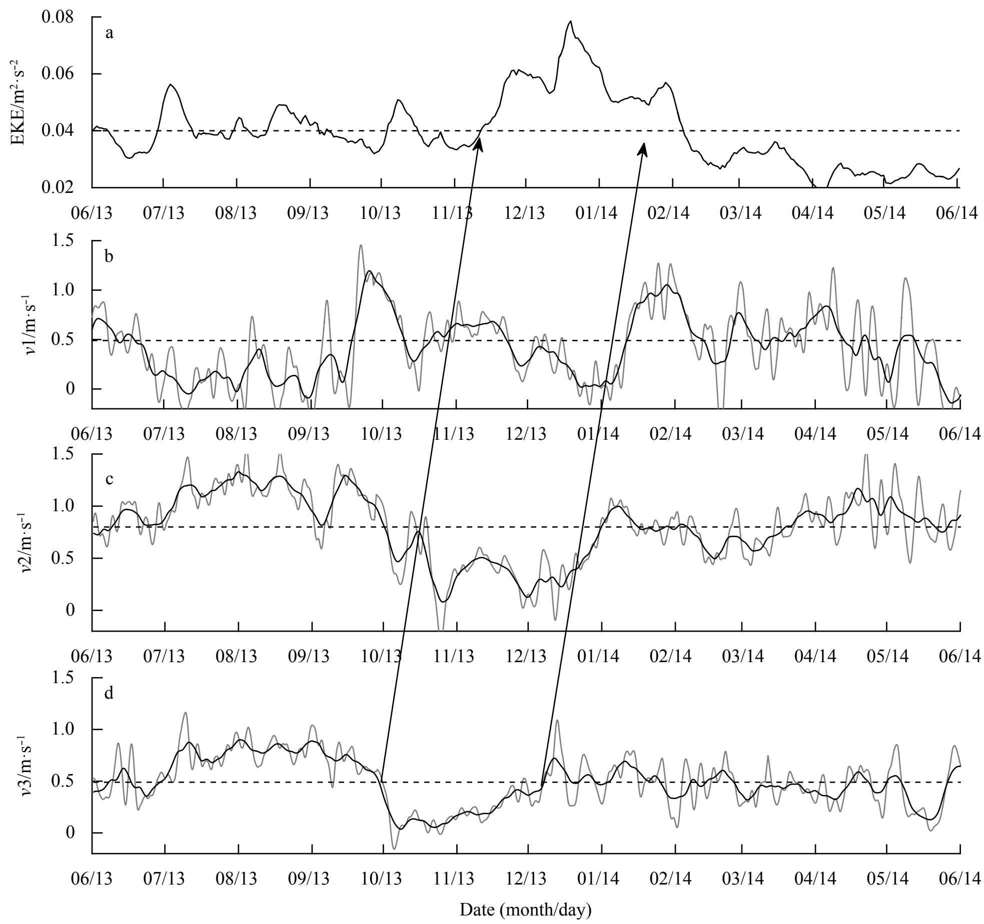

Fig. 4. Comparison of the time series of EKE in the test area from 1 June 2013 to 31 May 2014 (a) with the northward velocity components $v1$ (b), $v2$ (c) and $v3$ (d) at 50 m at three mooring Stas S1 (23.87°N, 121.72°E), S2 (23.82°N, 121.99°E) and S3 (23.74°N, 122.35°E), respectively.

We suggest that physically the interaction of the Kuroshio with the impinging eddy is a problem of collision of two moving water bodies in the same medium. Therefore, their behavior during and after collision should depend on the total momentum of individual water body, which count in both masses and velocities. Revisit Zheng et al. (2011), the amplitude of total momentum vector, carried by a segment of the Kuroshio with the same length as the impinging eddy diameter $2R$, can be calculated in a Cartesian coordinate system as

$$M_{\rm k} = \int_0^{L_{\rm k}} \int_0^{2R} \int_0^{D_{\rm k}} \rho\,(x,y,z)\, v_{\rm k}\,(x,y,z)\, {\rm d}x{\rm d}y{\rm d}z, \qquad (2)$$

where integral limits $L_{\rm k}$, $2R$, and $D_{\rm k}$ represent the width, the length, and the depth of the Kuroshio, $\rho(x, y, z)$ and $v_{\rm k}(x, y, z)$ are the water density and the velocity vector amplitude, respectively. Using the intermediate value theorem for integral calculation and assuming a homogeneous ocean (a constant density ρ) yields:

$$M_{\rm k} = 2\rho R L_{\rm k} D_{\rm k} V_{\rm k}, \qquad (3)$$

where $V_{\rm k}$ is the intermediate value of northward velocity vector amplitude.

For the eddy, the total momentum is a vector sum of the horizontal motion momentum and the rotation momentum. Using the same approach, the total momentum amplitude can be calculated in a cylindrical coordinate system as

$$\begin{aligned} {\rm M_e} &= \sqrt{M^2_{\rm horizontal} + M^2_{\rm rotation}} \\ &= \sqrt{(\pi\rho R^2 D_{\rm e} V_{\rm e})^2 + \left(\int_0^{D_{\rm e}} \int_0^{2\pi} \int_0^{R} \rho v_{\rm r}\,(r,\theta,z)\, r{\rm d}r{\rm d}\theta{\rm d}z\right)^2} \\ &= \pi\rho R^2 D_{\rm e}\left(V_{\rm e}^2 + V_{\rm r}^2\right)^{1/2}, \end{aligned} \qquad (4)$$

where R is the eddy radius, $D_{\rm e}$ is the eddy depth, $V_{\rm e}$ is the horizontal moving velocity amplitude, $v_{\rm r}\,(r, \theta, z)$ is the tangential velocity, r and θ are the radial distance and azimuth angle in cylindrical coordinate, and $V_{\rm r}$ is the intermediate value of tangential velocity amplitude.

From Eqs (3) and (4), we have the ratio of the total momentum amplitude of the Kuroshio to the eddy

$$\Gamma = \frac{2}{\pi}\left(\frac{D_{\rm k}}{D_{\rm e}}\right)\left(\frac{L_{\rm k}}{R}\right)\frac{V_{\rm k}}{(V_{\rm e}^2 + V_{\rm r}^2)^{1/2}}. \qquad (5)$$

One can see that Γ depends on not only the ratio of the eddy and the Kuroshio velocities, but also that of the horizontal and vertical scales. Figure 5 shows graphic expressions of Γ vs. R in summer and winter, respectively. Parameters are taken as fol-

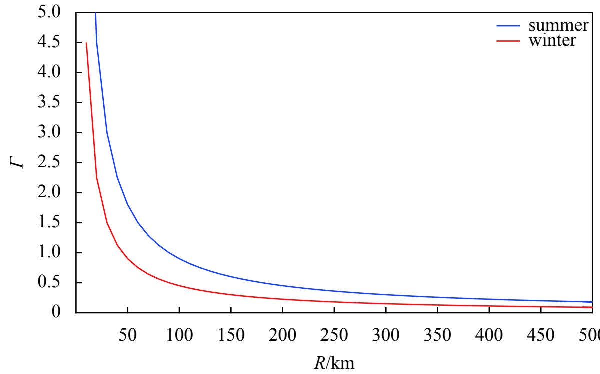

Fig. 5. Ratio of the total momentum amplitude of the Kuroshio to the CE Γ vs. the eddy radius R.

lows: D_k as 500 m in winter and 1 000 m in summer (Zheng et al., 2011), D_e as 2 000 m (Xie et al., 2016; Zhang et al., 2016), L_k as 100 km, V_k as 0.4 m/s (Lien et al., 2014; Tsai et al., 2015), V_e as 0.1 m/s and V_r as 0.1 m/s (Zhang et al., 2016; Zheng et al., 2017). One can see that the ratio of the total momentum amplitude of the Kuroshio to the eddy Γ decreases with the eddy radius. As R is greater than 200 km, Γ is smaller than 0.2 in winter and 0.4 in summer, implying that the Kuroshio is much weaker than the eddy. Therefore, the eddy plays a dominant role and could cut the Kuroshio off when they collide.

The collision event of the CE with the western boundary shown in Figs 1a–g verifies our analysis that the Kuroshio, no matter its offshore flank nor onshore flank, cannot absorb the CE or stop the CE westward propagation, but is cut off if the eddy is strong enough (radius>100 km and the lowest SLA<–30 cm). The Kuroshio would recover if and only if the total eddy momentum is much smaller than the Kuroshio.

5 Conclusions

This study examines the KMP cut-off event east of Taiwan Island occurred in fall-winter 2013–2014 and its impacts on the SCS using satellite altimetry and mooring observations. The major results are summarized as follows.

Time series of satellite SLA images reveal a complete process that a huge CE propagated westward from the Pacific and collided with the Kuroshio and the western boundary from 15 October 2013 to 15 January 2014. On 15 October 2013, the CE with major and minor axes of about 800 and 450 km and the lowest SLA of –30 cm moved westward, and approached to the offshore flank of the Kuroshio on 1 November. In December 2013, the KMP was cut off completely by the CE at the northern Luzon Strait and east of Taiwan Island till 15 January 2014 when the Kuroshio path started recovery.

Mooring observations along 23.8°N from 121.7°E to 122.3°E evidenced that the KMP upper ocean volume transport decreased linearly with the distance decrease of the CE front to the east coast of Taiwan Island and was cut off more than 82% from 17×10^6 m^3/s in September to 3×10^6 m^3/s in November 2013 as the eddy collided with the east coast of Taiwan Island.

The KMP event cut-off by the CE east of Taiwan Island and in the Luzon Strait has significant impacts on the SCS. This includes causing the Kuroshio branching and intruding into the SCS and strengthening the EKE in the northern SCS west of the Luzon Strait twice high lasting for 2.5 months from 15 November 2013 to 1 February 2014.

We suggest the use of the total momentum as a dynamic criterion to determine a dominant role during interaction of the Kuroshio with an eddy. Our theory gives reasonable explanations for the satellite altimetry and mooring observations for the studied KMP cut-off event.

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