Counter-rotating eddy pair in the Luzon Strait—

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Abstract: Based on satellite remote-sensing observation data and Hybrid Coordinate Ocean Model (HYCOM) reanalysis data, we studied the counter-rotating eddy pair in the Luzon Strait (LS). Statistical analysis revealed that when an anticyclonic mesoscale eddy (AE) in the Northwest Pacific (NWP) gradually approaches the east side of the LS, a CE (an AE) gradually forms on the west side of the LS, and it was defined as the AE (CE) mode of the counter-rotating eddy pair in the LS. The counter-rotating eddy pair exhibited obvious seasonal variation: the AE mode mainly occurred in the summer half of the year, while the CE mode mainly occurred in the winter half of the year. The mean durations of the AE mode and CE mode were both approximately 70 days. Based on energy analysis and the vorticity budget equation and...
energy analysis, the dynamic mechanism of the counter-rotating eddy-pair occurrence was determined to be as follows: the AE (CE) on the east side of the LS causes a positive (negative) vorticity anomaly through horizontal velocity shear on the west side of the LS, and the positive (negative) vorticity anomaly is transported westward by the zonal advection of the vorticity, finally leading to the formation of the CE (AE) on the west side of the LS.

**Keywords:** counter-rotating eddy pair; Luzon Strait; vorticity budget equation; barotropic instability.

**1 Introduction**

The Luzon Strait (LS), located between the island of Taiwan Island and the Luzon Island, is an important gap for material and energy exchange between the South China Sea (SCS) and the Northwest Pacific (NWP). The topography around the LS is very complicated. The LS comprises three straits from north to south: the Bashi Strait, the Balintang Strait, and the Babuyan Strait. The Batanes Islands and Babuyan Islands are located in these straights (Figure 1). These complex topographic features can significantly affect the topography, leading to the generation and aggregation of a large number of mesoscale eddies, which then play an important role in the dynamic ocean process around the LS and play an important role in the material and energy exchange between the SCS and the NWP (Liu et al., 2017; Lu and Liu, 2013; Sun et al., 2016a; Sun et al., 2016b). It pointed out that the Kuroshio bifurcates into west and east branches when it encounters the Batanes Islands in the LS. The bifurcation of the Kuroshio can significantly alter the transport of the Kuroshio’s main axis, and therefore, it has a potential impact on the intrusion of the Kuroshio into the SCS. The bifurcation of the Kuroshio is also affected by mesoscale eddies (Sun et al., 2016a, 2020).
Mesoscale eddies widely exist in the vicinity of the LS, and many of them come from the NWP. These mesoscale eddies from the NWP can carry an enormous amount of kinetic energy and can alter the local circulation, including the Kuroshio. Some of them cross the LS into the SCS, thus contributing to the material and energy exchange between the SCS and the NWP. However, in addition to their method of entering the SCS, interaction is an important determinant if the mesoscale eddies from the NWP affect the material and energy exchange between the SCS and WNP in other ways? For example, mesoscale eddies from the NWP do not have to enter into the SCS, and they can affect the SCS circulation through eddy-eddy interactions.

Numerous focus of previous studies have been conducted on the eddy-eddy interaction, mesoscale eddies in the vicinity of the LS. Jing and Li (2003) used satellite remote sensing observation data to discover a cyclonic mesoscale cold eddy around the Lanyu Island to the northeast of the LS, and they speculated. They pointed out that the overshooting formation of the Lanyu cold eddy was the result of the joint action of the meandering Kuroshio when it leaves the SCS and the effects of the overshooting and conservation of the potential vorticity may be the formation mechanism of the Lanyu cold eddy. Using a neural network and satellite remote sensing observation data, Yin et al. Sun et al. (2014) statistically demonstrated that a CE (AE) from the NWP can decrease (increase) the velocity of the Kuroshio, thus causing the Kuroshio to intrude into the East China Sea (ECS) in a stronger (weaker) cyclonic manner. This showed that mesoscale eddies from the NWP can alter the ECS circulation without entering the ECS. Sun et al. (2016b) believed that the formation of the Lanyu cold eddy was a process of eddies-eddies interaction. They used updated satellite remote sensing observation data and composition analysis to determine the Lanyu cold-eddy phenomenon, and pointed out that the combined action of the Kuroshio loop...
(cyclonic circulation) and an AE from the NWP led to the formation of the Lanyu cold eddy to the northeast of the LS. However, none of these studies determined the dynamic mechanism of eddy-eddy interactions. Based on satellite observation data, in situ observation data and numerical modelling data, Zhang et al. (2007, 2017) studied mesoscale eddies-eddies interaction to the northwest of the LS. They analyzed the energy budget of the Kuroshio invading the SCS, and determined that the northern branch of the anticyclonic circulation caused by the Kuroshio loop leads to the formation of a CE southwest of the Taiwan Island through the barotropic instability, which proposed a dynamic mechanism for eddy-eddy interactions around the LS.

Although some research related to eddy-eddy interactions in the vicinity of the LS has been conducted, and it has been discovered that mesoscale eddies are widely distributed on the west and east sides of the LS (Figure 2), it is not clear whether the mesoscale eddies on the west and east sides of the LS can interact and exchange energy between the SCS and the NWP. In order to explore this issue, we compared sea-surface height anomaly (SSHA) distributions in the SCS when a CE occurs and when an AE occurs on the east side of the LS (Figure 3). The specific process will be described in detail in Section 3.1. Figure 3 shows that when an AE (a CE) occurs on the east side of
the LS, a CE (an AE) formed on the west side of the LS, which was observed in the in situ observation data (Huang et al., 2019). This is referred to in this article as the counter-rotating eddy pair phenomenon in this paper. This counter-rotating eddy pair process inevitably led to energy exchange between the SCS and the NWP. To the best of our knowledge, it is not only a new phenomenon proposed for the first time, but it is also a new mechanism, a counter-rotating eddy-pair phenomenon in the LS has been proposed for the first time, i.e., that which creates a new form of particle and energy exchange between the SCS and the NWP. The present study will supplement and perfect the theory of particle and energy exchange between the SCS and NWP. We analyze the statistical characteristics and dynamic mechanism of this phenomenon herein. The rest of this paper is organized as follows. Section 2 briefly introduces the data and methods., Section 3 presents the research results, and Section 4 presents the provides a discussion and conclusion.
Figure 1. Spatial climate state of spatial distribution of the RSS SST (℃, shading) and CMEMS geostrophic current (m/s; vectors) from 2003 to 2020. SCS: South China Sea; BIS: Batanes Islands; TWI: Taiwan Island; LZI: Luzon Island; BBYI: Babuyan Islands. The white; LYI, Lanyu Island. White box borders 20.2–22.2°N, 122–124°E. The extent of the main map is shown as a black-bordered box in the inset.
Figure 2. Spatial distribution of the CMEMS SSHA and locations of centers of the eddies on (a) September 10, 1993 and (b) June 15, 1994. The colors and contours represent the SSHA. The blue star and red star denote the locations of the AE and CE, respectively.
Figure 3. Spatial distribution of the counter-rotating eddy pair in the LS. (a) Spatial pattern of the AE mode; (b) Spatial pattern of the CE mode. The contour corresponds to average state when an AE (a CE) occurred in area marked by red box on east side of LS from 1993 to 2020. Contours represent SSHA (units of m). Colors represent the sea temperature anomaly (unit: °C) at a depth of 300 m. The interval of the SSHA is 0.03 m. The red boxes on the west side and east sides of the LS border mark 20.5–21.8°N, 119.4–120.7°E and 20.9–22°N, and 122–124°E, respectively. This figure is similar to Figure 3 in Sun et al. (2018), and is based on HYCOM data.

2 Data and methods

2.1 Data

Satellite remote-sensing SSHA, geostrophic current, and geostrophic current anomaly data are provided by the Copernicus Marine Environment Monitoring Service (CMEMS) website: https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=...
The data set was generated by the processing system including data from all altimeter missions: Sentinel-3A/B, Jason-3, HY-2A, Cryosat-2, OSTM/Jason-2, Jason-1, Topex/Poseidon, Envisat, GFO, and ERS-1/2. The data set provides global coverage data from 1 January 1993 to present August 2021, with a spatial resolution of 0.25°×0.25° and temporal sampling frequency of 1 day. It also provides one near-real-time component and one delayed-time component. The delayed-time component has been inter-calibrated and provides a homogeneous and highly accurate, long time series of all altimeter data (Pujol and Francoise, 2019), and is chosen for use in this paper.

Model data are obtained from the Hybrid Coordinate Ocean Model (HYCOM) organization provided the HYCOM reanalysis data (model output by the download website: https://www.hycom.org/dataerver/gofs-3pt0/reanalysis). The data set is based on ocean prediction system output, and the product with the longest time span from 2 October 1992 to 31 December 2012 is chosen among all HYCOM data-assimilation products provided by the HYCOM organization. The data set is based on ocean prediction system output with a spatial resolution of 0.08°×0.08° and 40 standard z-levels between 80.48°S and 80.48°N. It provides temperature, salinity, sea-surface height, zonal flow, and meridional flow (Wallcraft et al., 2003).

The data set of wind was provided by the National Climate Data Center (NCDC) (https://www.ncdc.noaa.gov/data-access/marine-ocean-data/blended-global/blended-sea-winds). Centers for Environmental Information (NCEI). The data set merges multiple satellite observation observations with in-situ instrument and related individual products. It provides for: daily and monthly wind and climate data with a spatial resolution of 0.25°×0.25°. The data
contains globally gridded ocean surface vector winds and wind stresses (Zhang et al., 2006).

Sea surface temperature (SST) data are derived from Remote Sensing Systems (RSS). The dataset merges the near-coastal capability and high spatial resolution of the infrared SST data with through-cloud capabilities of the microwave SST data, and has applied atmospheric corrections. It provides daily data with a spatial resolution of 9 km × 9 km from July 1, 2002 to the present.

2.2 Methods

2.2.1 Eddy energetic and hydrodynamic instability formula

The formation mechanisms of mesoscale eddies in the ocean are commonly attributed to baroclinic and barotropic instabilities (Pedlosky, 1987; Zhang et al., 2015; Zhang et al., 2017). The barotropic conversion (BT) and the baroclinic conversion (BC) are manifestations of the baroclinic and barotropic instabilities, respectively, and they are the major eddy energy sources around the LS (Yang et al., 2013; Zhang et al., 2013, 2015, 2017). In addition, the wind-stress work (WW) can also contribute to the formation of eddies (Ivchenko, 1997; Sun et al., 2015). The BT, BC, and WW can be expressed as follows (Ivchenko, 1997; Oey, 2008):

\[ BT = -\int \left( \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} + u' \frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y} \right) dx, \]  

\[ BC = -\int \left( \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} + u' \frac{\partial \theta}{\partial x} + \frac{\partial \theta}{\partial y} \right) dx, \]  

\[ WW = \frac{1}{2} \left( \frac{\partial \tau_n}{\partial x} + \frac{\partial \tau_v}{\partial y} \right), \]

where \( f \) is the Coriolis parameter; \( u', v', w' \) are the zonal, meridional, and vertical velocity, respectively, and their positive directions are east, north, and up, respectively. \( g \) is the acceleration due to gravity; \( N \) is the buoyancy frequency; \( \rho \) is the density of sea water; \( \rho_0 \) is thedensity of water at the freezing point; \( \theta \) is the potential temperature; \( \sigma \) is the density anomaly; \( \tau_n \) and \( \tau_v \) are the zonal and meridional wind stress components.
The mean seawater density; \( p \) is the sea pressure; and \( \tau_x \) and \( \tau_y \) are the zonal and meridional components of the wind stress, respectively. \( x, y, \) and \( z \) are the conventional east-west, north-south, and up-down Cartesian coordinates, respectively. The depth integrals for BT and BC are from 400m to the sea surface. The overbar denotes a time average over an \( n \)-day period, the primes denote deviations from the average value of 35 days before and after this day, and the other symbols and notations are standard. The \( n \)-day period was chosen to be 70 days according to the period of the counter-rotating eddy-pair phenomenon occurring, developing, and disappearing from \( t = -36 \) to \( t = 36 \), i.e., approximately 70 days. Therefore, the period is chosen to be 70 days. We have made several attempts to set the period between 65 and 80 days, and they will not affect our basic conclusion. BT and BC were calculated from the HYCOM data. CMEMS surface-current velocity data and NCDC wind data were used to calculate the WW.

**2.2.2 Vorticity budget equation**

To examine the influence of the vorticity change, we applied the vorticity budget equation:

\[ \frac{\partial \zeta}{\partial t} = -u \frac{\partial \zeta}{\partial x} - v \frac{\partial \zeta}{\partial y} - (\zeta + f) \frac{\partial u}{\partial x} - v \frac{\partial v}{\partial y} + \frac{1}{\rho} \frac{\partial (\rho v \zeta)}{\partial x} - \frac{\partial (\rho f \zeta)}{\partial y}, \quad (4) \]

Where \( \zeta = \frac{\partial v}{\partial y} - \frac{\partial u}{\partial x} \) is the relative vorticity, \( t \) is the time, \( u \) and \( v \) is the zonal velocity, meridional velocity, respectively. \( x, y, \) and \( z \) are the conventional east-west, north-south, and up-down cartesian coordinates, respectively; \( f \) is the Coriolis parameter; \( \rho \) is the sea water density; \( P \) is the sea-water pressure; and \( \nu = 1.004 \times 10^{-6} \) is the kinematic viscosity coefficient. \( x, y, z, u, v, \) and \( \rho \) in formula (4) are as defined in formulas (1)-(3). The items on the right-hand side of the equation are, from left to right, the zonal advection term, the meridional advection term,
the, stretching term, the, beta term, the, baroclinic term, and the diffusion term from left to right.

2.2.3 Definition of modes and intensity index of counter-rotating eddy-pair phenomenon

When an AE (a CE) in the NWP gradually approaches the northern LS, a CE (an AE) gradually forms on the west side of the LS, and we define it as an AE (a CE) mode of the counter-rotating eddy-pair phenomenon, as shown in Figures 2a, 3a, and 6 (Figures 2b, 3b, and 8).

To reflect the intensity of counter-rotating eddy-pair phenomenon, we must construct an intensity index. As this phenomenon mainly involves the difference of SSHA between the east and west sides of the LS, the index is defined as the time series of the SSHA in the east red box of Figure 2 (expressed as $SSHA_{east}$) minus that in the west red box of Figure 2 (expressed as $SSHA_{west}$), which is shown in Figure 3a and can be expressed as $Index = SSHA_{east} - SSHA_{west}$.

3 Results

3.1 Identification of and temporal variation in the counter-rotating eddy pair in the LS

Based on cluster analysis, which is the same as the clustering method used by Sun et al. (2018), we determined the SSHA and sea-temperature anomaly (STA) are determined based on the days when an AE and a CE exist on the east side and west side of the LS (shown in the white box in Figure 1), respectively. Figure 2 shows that when an AE (a CE) occurred on the east side of the LS, a CE (an AE) formed on the west side of the LS, which is defined as a counter-rotating eddy pair in the LS in this paper. Figure 3a shows that the SSHA in the red box on the east side of the LS increases from the outside to the inside, which means that there was an AE. Due to the geostrophic balance and mass conservation, the AE causes convergence of the sea water, leading to downwelling in its center, subsequently leading to an increase in the
temperature in the deep ocean. This is verified by the fact that the STA in the red box on the east side of the LS is gradually increases from outside to inside and the value is the highest in the center. In addition, the SSHA in the red box on the west side of the LS decreases from outside to inside and the STA is negative, indicating the presence of a weak CE. Figure 3b is similar to Figure 3a, but for a CE and an AE on the east and west sides of the LS, respectively. According to the definition of modes of the counter-rotating eddy pair given in Section 2.2.3, the SSHA pattern in Figure 2a can be identified as an AE mode of the counter-rotating eddy pair. In order to better reflect the Figure 2a, but for a CE and an AE on the east and west sides of the LS, respectively, its SSHA pattern can be identified as an AE mode of the counter-rotating eddy pair. According to the intensity of this phenomenon, we index defined in Section 2.2.3, the SSHA is constructed an index which is defined as the time series of the SSHA in the red box on the east side of the LS minus that on the west side of the LS, in order to obtain a time series (Figure 4a). We constructed the SSHA based on the days when the positive and negative intensity index values are more than one standard deviation away from the mean. As shown in Figures 3b and 3c, Figure 3b (3c) shows that an AE (a CE) on the east side of the LS and corresponds well to a CE (an AE) on the west side of the LS are shown in Figure 4b (Figure 4c) for the days with, and can well reflect the AE (CE) mode of a counter-rotating eddy pair in the LS. It also shows that we can well identify this phenomenon according to the intensity index, and, furthermore, that the positive (and negative) intensity index values, which reflects the indexes correspond to AE and CE modes, respectively, of this phenomenon of a counter-rotating eddy pair in the LS well. The pattern in...
Figure 4b (Figure 4c) is defined as the AE (CE) mode of the counter-rotating eddy pair in this paper.
Figure 4 (a) Time series of the intensity index of the counter-rotating eddy pair in the LS. The red dotted line above (below) represents the sum (difference) of one time the standard deviation and the average value of the time series. Composition of the SSHA for (b) the positive and (c) the negative intensity index days and (c) the negative intensity index days. The SSHA interval of the SSHA is 0.02 m. This figure is based on HYCOM data.

3.2 Seasonal variation of counter-rotating eddy pair in LS

We counted the temporal distribution of the positive and negative intensity index values. In a statistical sense, Figure 5a (Figure 5b, In 4b) shows that most of the AE (CE) mode of the instances of the counter-rotating eddy pair occurred in the summer (winter) half of the year. The first two months with the highest incidences of the AE (CE) mode were May and June (December and January), and their occurrence rates were 17.01% and 15.47% (19.69% and 15.57%), respectively. We constructed the geostrophic current in May and June (Figure 6a, 6c) and
in December and January (Figure 6b). The patterns of the Kuroshio Current in Figures 6a and 6b exhibit as the “Leap” and “Loop” patterns of the Kuroshio in the LS, which illustrates that the Leap and Loop patterns of the Kuroshio contribute to the occurrence of the AE mode and the CE mode, respectively, of the counter-rotating eddy pair, respectively. Figure 6c (Figure 6d) shows that the geostrophic current anomaly in the northern LS is northward (southward). It produces positive (negative) vorticity through horizontal velocity shear on the west side of the LS, and then contributes to the formation of a CE (an AE) on the west side of the LS. We will discuss the dynamic mechanism of the counter-rotating eddy pair phenomenon in detail in Section 3.3.

Figure 5. Seasonal distribution of the occurrence rate for (a) the positive intensity index and (b) the negative intensity index.
Figure 65. Climatic distribution of the geostrophic current in (a) May and June, (b) and December and January; Climatic distribution of the (c) May and June, (d) and (d) December and January. The red boxes in (c) and (d) outline 20.5–21.8°N, 119.4–120.7°E, which represent the position of the mesoscale eddies on the west side of the LS. The figure is based on CMEMS data.

3.2.3 Evolution of the counter-rotating eddy pair in the LS

Figure 76 shows the spatial evolution of the AE mode of the counter-rotating eddy pair in the LS. It shows that at the beginning, for example, at \( t = -24 \), there was a weak AE far away from the east side of the LS, but there was no CE on the west side of the LS. From \( t = -20 \) to \( t = 0 \),
as the AE in the NWP approached the northern LS, a CE gradually formed on the west side of the LS. At t = 0, the AE mode reached its maximum. Then, from t = 4 to t = 36, as the AE in the NWP gradually moved away from the northern LS, the CE on the west side of the LS gradually weakened until it finally died out.

The growth and weakening of a mesoscale eddy must be accompanied by a change in its relative vorticity. Figure 8a shows that as the AE on the east side of the LS approached and then moved away from the northern LS, its relative vorticity initially decreased and then increased, while the relative vorticity of the corresponding CE on the west side of the LS initially increased and then decreased. The maximum negative (positive) value of the time series of the AE (CE) on the east (west) side of the LS reached $-4.2 \times 10^{-6}$ s$^{-1}$ ($3.6 \times 10^{-6}$ s$^{-1}$). These time series had a good correspondence, and their correlation coefficient was $-0.97$ at the 95% confidence level. Therefore, the temporal variations in the relative vorticity in Figure 8a verify the evolution of the AE mode of the counter-rotating eddy pair in the LS.
Figure 76: Evolution of the AE mode of the counter-rotating eddy pair in the LS based on HYCOM data. The contour and shading both represent the SSHA (units: m). The contour interval of the SSHA is 0.02 m. The value in the top-left corner of each panel denotes the days before (negative value) or after (positive value) the AE mode of the counter-rotating eddy pair reached the maximum. $t = 0$ corresponds to the time of Figure 4b, 3b.
Figure 8. The distribution of the relative vorticity surrounded by the area bordered by the red boxes in Figure 3. (Panel a) Relative vorticity of the AE mode over time. The blue line represents the time series of the relative vorticity of the AE on the east (west) side of the LS, which corresponds to Figure 7; (Panel b) Relative vorticity of the CE mode over time. The blue line represents the time series of the relative vorticity of the CE on the east (west) side of the LS, which corresponds to Figure 9. This figure is based on HYCOM data.

Figure 9 is the same as Figure 7 but for the CE mode of the counter-rotating eddy pair in the LS. It shows that at the beginning, for example, at $t = -32$, there was a weak CE far away from the east side of the LS, but there was no AE on the west side of the LS. From $t = -28$ to $t = -22$...
as the CE in NWP approached the northern LS, an AE gradually formed on the west side of the LS. At $t = 0$, the CE mode of the evolution of the counter-rotating eddy pair reached the pinnacle maximum. Then, from $t = 4$ to $t = 36$, as the CE in the NWP gradually moved away from the northern LS, the AE in the west side of the LS gradually weakened until it finally died out. Figure 8b is the same as Figure 8a but for plots of the CE mode. It shows that as the CE on the east side of the LS approached and moved away from the northern LS, its relative vorticity initially increased and then decreased, while the relative vorticity of the corresponding AE on the west side of the LS initially decreased and then increased. The maximum positive (negative) value of the time series of the CE (AE) on the east (west) side of the LS can reach $0.48 \times 10^{-6} \text{s}^{-1}$ ($-6.7 \times 10^{-6} \text{s}^{-1}$). These time series have good correspondence and their correlation coefficient was $-0.96$ at the 95% confidence level. Therefore, the temporal variations in the relative vorticity in Figure 8b verify the evolution of the AE mode of the counter-rotating eddy pair in the LS. The evolution of the AE (and CE) modes of the counter-rotating eddy pair in the LS is also reflected by the satellite observations (Figures 10 and 11).
Figure 9 is the same as Figure 7 but for the CE mode of the counter-rotating eddy pair in the LS.
Figure 10 is the same as Figure 7, but it is based on the CMEMS data.
Figure 11 is the same as Figure 9, but it is based on the CMEMS data.

Figure 8. Evolution of CE mode of counter-rotating eddy pair in LS based on HYCOM data. Contours and shading both represent SSHA (units of m). SSHA interval is 0.02 m. t in the top left-hand corner of each panel denotes the days before (negative value) or after (positive value) the CE mode of the counter-rotating eddy pair reached the maximum (t=0). t = 0 corresponds to time of Figure 3b.
Figure 9 Evolution of AE mode of counter-rotating eddy pair in LS based on CMEMS data. Contours and shading both represent SSHA (units of m). SSHA interval is 0.02 m. $t$ in the top left corner of each panel denotes days before (negative value) or after (positive value) the AE mode of counter-rotating eddy pair reached the maximum ($t=0$). $t=0$ corresponds to time of Figure 3b.
Figure 10 Evolution of CE mode of counter-rotating eddy pair in LS based on CMEMS data.

Contours and shading both represent SSHA (units of m). SSHA interval is 0.02 m. $t$ in the top left-hand corner of each panel denotes days before (negative value) or after (positive value) the CE mode of counter-rotating eddy pair reached the maximum ($t=0$). $t = 0$ corresponds to time of Figure 3b.

3.3.4 Formation mechanism of the counter-rotating eddy pair in the LS

Zhang et al. (2017) reported that CEs mainly formed due to the barotropic instability caused by horizontal velocity shear of the Kuroshio Loop current southwest of the Taiwan Island. Huang et al. (2019) discovered that an AE from the NWP caused a CE to form on the west side of the LS via horizontal velocity shear. In addition, Figures 4b and 4c show that the dense contour of the SSHA means that there were strong current anomalies and thus strong horizontal velocity shear at the junction of the AE and CE. Therefore, we investigated the role of horizontal velocity...
shear in the formation of a counter-rotating eddy in the LS.

Because meridional horizontal velocity shear is weak, we only show the zonal velocity shear.

Figure 12 shows that from $t = -40$ to $t = 0$, as the AE on the east side of the NWP gradually approaches the northern LS, the absolute value of the zonal horizontal velocity shear $\left( \frac{\partial v}{\partial x} \right)$ gradually increases, and a CE gradually forms and strengthens on the west side of the LS. From $t = 0$ to $t = 36$, as the AE gradually moves away from the northern LS, the absolute value of the zonal horizontal velocity shear $\left( \frac{\partial v}{\partial x} \right)$ gradually decreases, and the CE on the west side of the LS gradually weakens. Figure 13 is the same as Figure 12, but for the CE mode of the counter-rotating eddy pair in the LS. It shows a similar corresponding evolution process. This demonstrates that there is a good correspondence between the zonal horizontal velocity shear and the evolution process of the counter-rotating eddy pair.
Figure 1211 Evolution process of the absolute value of the zonal horizontal velocity shear ($\frac{\partial v}{\partial x}$) for the AE mode of the counter-rotating eddy pair in the LS based on HYCOM data. The shading represents the zonal horizontal velocity shear (unit: $10^{-6}$ units of $10^{-6} \text{ s}^{-2}$). The vector represents the current anomaly. The $t$ in the top-left-hand corner of each panel denotes the days before (negative value) or after (positive value) the AE mode of the counter-rotating eddy pair reached the pinnacle maximum ($t = 0$). Time $t = 0$ corresponds to the time of Figure 4b. The red boxes on the west side of the LS cover $20.5^\circ - 21.8^\circ \text{N}$, $119.4^\circ - 120.7^\circ \text{E}$ and represent the location of the CE on the west side of the LS.
Figure 13 is the same as Figure 12 but for the CE mode of the counter-rotating eddy pair in the LS. Figure 12: Evolution process of absolute value of zonal horizontal velocity shear ($|\partial v/\partial x|$) for CE mode of counter-rotating eddy pair in LS based on HYCOM data. Shading represents zonal horizontal velocity shear (units of $10^{-6}$ s$^{-2}$). Vector represents current anomaly. t in top left-hand corner of each panel denotes days before (negative value) or after (positive value) the AE mode of counter-rotating eddy pair reached the maximum ($t = 0$). Time $t = 0$ corresponds to time of Figure 3b. Red boxes on west side of LS cover 20.5-21.8°N, 119.4-120.7°E and represent the location of CE on west side of LS. However, Figure 11 (12—Figure 13) shows that zonal horizontal velocity shear only occurred on the right-hand side of the red box, that is, on the right-hand side of the CE (AE).
How does the horizontal velocity shear pass to the entire CE (AE)? To answer this question, we used the vorticity budget equation. Figures 14 (a1 - f1) are for plotting the AE mode of the counter-rotating eddy pair and show the respective contributions of the zonal advection term, meridional advection term, stretching term, beta term, baroclinic term, and diffusion terms of the vorticity budget equation, respectively. Compared to the stretching term, beta term, baroclinic term, and diffusion terms, the values of the zonal advection term and meridional advection terms in the red box are large. However, most of the values of the meridional advection term in the red box are negative. Only positive vorticity advection can lead to CE formation of a CE, which suggests that the zonal advection term is the main cause of the CE formation in the red box. To further test this conclusion, Figure 15a shows the correspondence between the relative vorticity anomaly and the zonal advection of vorticity in the red box in Figure 14. It shows a good correspondence and their correlation coefficient is as high as 0.96 at the 95% confidence level. Therefore, we conclude that the zonal advection term plays the most important role in the vorticity transport and contributes to the formation of the CE on the west side of the LS.

Figures 14 (a2 - f2) are the same as Figures 14 (a1 - f1), but for plotting the CE mode of the counter-rotating eddy pair. Figures 14 (a2 - f2) also show and shows that compared to the stretching term, beta term, baroclinic term, and diffusion terms, the values of the zonal advection term and the meridional advection terms in the red box are large. However, most of the values of the meridional advection term in the red box are positive. Only negative vorticity advection can lead to AE formation of an AE, which implies that the zonal advection term is the main cause of the AE formation in the red box. To further test this conclusion, Figure 15b shows the correspondence between the relative vorticity anomaly and the zonal advection of vorticity. It shows illustrating...
that there is a good correspondence and their correlation coefficient is as high as 0.84 at the 95% confidence level. Therefore, we conclude that the zonal advection term plays the most important role in the vorticity transport and contributes to the formation of the AE on the west side of the LS.

Figure 14. Vorticity budget equation for (a1 – f1) the AE mode of counter-rotating eddy pair and (a2 – f2) the CE mode of the counter-rotating eddy pair. a1 and a2 represent the zonal advection term, b1 and b2 represent the meridional advection term, c1 and c2 represent the stretching term, d1 and d2 represent the beta term, e1 and e2 represent the baroclinic term, and f1 and f2 represent...
the diffusion term. The unit is \(10^{-10}\) units and \(10^{-10} \text{s}^{-2}\). The red boxes on the west side of the LS border cover 20.5–21.8°N, 119.4–120.7°E, and they represent the location of the CE or AE on the west side of the LS. The black solid line represents the zero contour. This figure is based on the HYCOM data.

Figure 15. The distribution of the relative vorticity anomaly and the zonal advection of vorticity surrounded by the red boxes in Figure 14 for AE (a) is for the AE mode and CE (b) modes of the counter-rotating eddy pair in the LS, and (b) is for the CE mode of the counter-rotating eddy pair in the LS.

Above, we have proposed that the horizontal velocity shear caused by the mesoscale eddy on the east side of the LS is transported westward through zonal advection, resulting in the formation of a counter-rotating mesoscale eddy on the west side of the LS. Horizontal velocity shear
will inevitably lead to barotropic instability. Now, we will verify our conclusion from the perspective of energy. Figures 16a, 16b, 15a, 15b, and 15c show that, compared to the BC and WW values, the BT values in the LS are large and most of the values are positive, especially in the area surrounded by the red box in Figure 16a, which is the junction of the AE and CE. This means that the BT plays the most important role in the formation of the AE on the west side of the LS.

Figures 16d, 16e, 15d, 15e, and 15f show the BT, BC, and WW, respectively, corresponding to the AE mode of the counter-rotating eddy pair in the LS, respectively. The description and dynamic mechanism of the AE mode are similar to those of the CE mode of the counter-rotating eddy pair in the LS, so we will discuss the details in this paper and will not be discussed here.
the counter-rotating eddy pair in the LS. d, e and f are for the AE mode of the counter-rotating eddy pair in the LS.

4 Discussion and conclusions

In this study, based on satellite observation data and HYCOM reanalysis data, the counter-rotating eddy pair in the LS was investigated. The phenomenon of counter-rotating eddy pair was defined as the stage when an AE (a CE) in the NWP gradually approached the northern LS, and a CE (an AE) formed on the west side of the LS. This phenomenon exhibited obvious seasonal variation, that is, the AE mode mainly occurred in the summer half of the year, while the CE mode mainly occurred in the winter half of the year. The mean durations of the AE mode and CE mode were both approximately 70 days. The Leap and Loop patterns of the Kuroshio contribute to the occurrence of the AE mode and CE mode of the counter-rotating eddy pair, respectively. Based on energy analysis and the vorticity budget equation, the dynamic mechanism of the occurrence of a counter-rotating eddy pair is as follows. The AE (CE) in the NWP causes a positive (negative) vorticity anomaly through horizontal velocity shear on the west side of the LS, and the positive (negative) vorticity anomaly is transported westward by the zonal advection of the vorticity, finally leading to the formation of a CE (an AE) on the west side of the LS. This conclusion is also verified by barotropic instability based on the energy analysis.

When we investigated the question of how the horizontal velocity shear passes to the entire CE or AE in Section 3.4, we found that the magnitudes of the meridional and zonal advection terms are roughly the same. Because the meridional advection term has the opposite effect of CE (AE)
formation in the west side of the LS for the AE (CE) mode of the counter-rotating eddy pair, we
confirmed that the zonal advection term plays a main role in horizontal velocity shear transportation.

However, the research since the magnitude of the meridional advection term is very large, it may
play a role in the ocean dynamic process of the LS, which deserves further study.

The results presented in this paper are preliminary and some problems require
further study. The occurrence probability of a counter-rotating eddy pair in the LS needs
to be determined. The counter-rotating eddy pair phenomenon involves temporal-
spatial variations in two mesoscale eddies on both sides of the LS, and it is difficult
to provide a quantifiable definition of this phenomenon for a single event. For example, how far
apart defined the mesoscale eddies on the east and west sides of the LS need to be in order to define
them as a counter-rotating eddy pair. We preliminarily calculated that the incidence of this
phenomenon was about 5%.

Another problem to solve involves threshold of the NWP mesoscale eddies entering the SCS,
and what role does the Kuroshio Current plays in the counter-rotating eddy-pair phenomenon in the
LS. When we illustrated in this study, our illustration of the counter-rotating eddy pair phenomenon
in this study, we eliminated the mean current field, which means that the influence
of the Kuroshio was eliminated. Current is not considered. However, the role of the Kuroshio in the
energy transfer is still worthy of further study. Numerical simulations can be useful to address this
issue. Our study provides a new perspective on particle and energy exchange, and further perfects
the theory of particle and energy exchange between the SCS and the NWP.

Acknowledges
The authors would like to acknowledge several data sets used in this paper. Satellite remote sensing
geostrophic current data and sea level anomaly were obtained from the CMEMS
(https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SEALEVE
L_GLO_PHY_L4_REP_OBSERVATIONS_008_047), the HYCOM reanalysis data were
downloaded from HYCOM organization (https://www.hycom.org/dataserver/gofs-3pt0/
reanalysis), the data set of wind was provided by National Climate Data Center (https://www.
temperature data comes from Remote Sensing System (http://www.remss.com/measurements/sea-
surface-temperature/). This study was supported by National Natural Science Foundation of China
(grant number 41806019), National Key R&D Program of China (2019YFD0901305), Key R&D
projection of Zhejiang Province (2020C03012), National Natural Science Foundation of China
(No.41776012), State Key Laboratory of Tropical Oceanography (South China Sea Institute of Oceanology Chinese Academy of Sciences) open topics
(grant number LTO2011), Key R&D project of Guangdong Province (2020B1111030002), Major science and technology project of Sanya YZBSTC (SKJC-KJ-2019KY03). We thank LetPub (www.letpub.com) for its linguistic assistance during the
preparation of this manuscript.

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