Submesoscale Eddies in the Taiwan Strait Observed by High-Frequency Radars: Detection Algorithms and Eddy Properties

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ABSTRACT

This study compared the efficiencies of two widely used automatic eddy detection algorithms—that is, the winding-angle (WA) method and the vector geometry (VG) method—and investigated the submesoscale eddy properties using surface current observations derived from high-frequency radars (HFRs) in the Taiwan Strait. The results showed that the WA method using the streamline and the VG method based on the streamfunction field have almost the same capacity for identifying eddies, but the former is more competent than the latter in capturing the eddy size. The two algorithms simultaneously identified 1080 submesoscale eddies, with the centers and boundaries determined only by the WA method, and they were further used to investigate the eddy properties. In general, no significant difference was observed between the cyclonic and anticyclonic eddies in terms of radius, life span, and kinematics, as well as the evolution during their life cycles. The typical radius of the eddy in this region was 3–18 km. And a strong correlation was observed between the life span and the radius. The spatial distribution of the eddies indicated that topography played a significant role in the generation of the eddies. And the trajectories of the eddies suggested that all the eddies in this area mostly tended to move southeastward. Statistically, three different stages of the eddy’s life span could be identified by the significant growth and decay of the radius and the mean kinetic energy. This study shows the great capability of HFRs in oceanography research and applications, especially for observing the submesoscale dynamics.

1. Introduction

A lateral current structure with the velocity vectors rotating clockwise or counterclockwise around a center is referred to as an eddy or a vortex appearing in the upper ocean frequently and ubiquitously. It is generally more energetic than the surrounding currents. The diameters of such eddies vary substantially from a few hundred meters to hundreds or thousands of kilometers. These eddies, characterized by an $O(1)$ Rossby number, are largely formed over the shelf and coastal slope depending much on the bottom topography and the coastal orography (Zatsepin et al. 2011). Eddies are an important component of dynamical oceanography, making a significant contribution to the transportation of heat, mass, momentum, and biogeochemical properties (Mewhilells 2008; Wang et al. 2012; Simons et al. 2015).

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and they are an important cross-isobath transport mechanism for nutrients, particles, and larvae (Bassin et al. 2005). Moreover, eddies can have a profound influence on offshore advection, dispersion of river plumes (Corredor et al. 2004), buoyant substances, and pollutants (Chérubin and Richardson 2007). In addition, increasing coastal activities, such as fisheries, pollution monitoring, and offshore industry, also raise the need for studying eddy properties as well as the interactions between eddies and inshore circulation to produce reliable hydrodynamic forecasts of littoral water.

The study area is located in the southern Taiwan Strait (Fig. 1), which has a quite uneven topography. The water depth is less than 30 m along Fujian coast, about 40–60 m in the offshore, and greater than 1000 m in the southeastern area. The current pattern in this area is also quite complicated. Hu et al. (2010) has summarized the evolution of the investigation about the current circulation in this area as well as its surroundings. There are three flows coexisting in the Taiwan Strait: the extension of the South China Sea warm current (SCSWCe) flowing northeastward, the Zhemin Coastal Current (ZCC)
coming from the northeast, and the Kuroshio intruding from the Pacific (Fig. 1). Moreover, the SCSWc and the ZCC flow through the Taiwan Strait with the opposite current directions. Therefore, with complex topography and intricate flow, the southern Taiwan Strait is an area with strong eddy activities.

In the past decades, several eddies have been captured by in situ observations in our study region and its surroundings, including an anticyclonic eddy located at 21°N, 117.5°E with a scale of some 150 km and a vertical extension as deep as 1000 m (Li et al. 1998), and three long-lived anticyclonic eddies (Nan et al. 2011). Undoubtedly, in situ measurements have made tremendous contributions for oceanographers to understand the formation mechanisms of eddies. However, statistical characteristics of eddies are quite difficult to gain from in situ instruments owing to the limited coverage. Fortunately, in recent years high-precision satellite altimeters coming into use have essentially revolutionized our capacity for observing ocean processes, which has made striking progresses in our understanding and modeling of ocean circulations. Satellite altimeter data for sea surface height anomalies (SSHA) or sea level anomalies (SLA) have been extensively applied to study the statistical characteristics of surface eddies (Liu et al. 2012; Chelton et al. 2011; Chen et al. 2011; Chaigneau et al. 2008; Wang et al. 2003). Properties like radius, lifetime, vorticity, and spatial distribution have also been discussed in these studies.

The satellite altimeters have made a great contribution toward oceanographers’ study of ocean processes. However, some researchers argued that submesoscale eddies with a radius smaller than 30 km cannot be identified and extracted from satellite altimetry but can be captured by high-frequency radars (HFRs), which can measure ocean surface current over a large horizontal extent with a high spatial–temporal resolution. Chavanne and Klein (2010) compared sea level anomalies obtained from satellite altimeter with those derived from HFRs, and they suggested that satellite altimeter cannot observe the submesoscale process due to the signal contamination from high-frequency motions, incoherent internal tides, and cross-track currents measurement noise. Pomales-Velázquez et al. (2015) studied the characteristics of mesoscale and submesoscale eddies in southwestern Puerto Rico using satellite imagery (i.e., sea surface height anomalies, chlorophyll-a, and floating algae index images) and surface currents sensed by HFRs. They found that a submesoscale eddy lasting for 3 days was not resolved by satellite altimetry products but captured by HFRs. In this study, we used two shore-based HFRs to investigate the characteristics of the submesoscale eddies in the southern Taiwan Strait (Fig. 1). Although the HFR technology has been used to study the current characteristics in the southern Taiwan Strait (Shen et al. 2014; Lai et al. 2017), this is the first time for it to be used to study the submesoscale eddy properties in this region. The results showed the great capability of the HFR in oceanographic researches and applications, especially for the observation of submesoscale dynamics.

Besides the observation tool, competitive eddy detection algorithm is also vital for eddy characteristics analysis. Numerous schemes for automatic eddy detection have been proposed, based on either physical or geometric properties of the flow field (Jeong and Hussain 1995; Portela 1997; Sadarjoen and Post 1999). Schemes based on physical properties compare the values of a specified physical parameter with a preset threshold, including pressure and sea level anomaly magnitude (Jeong and Hussain 1995; Fang and Morrow 2003; Chaigneau and Pizarro 2005), vorticity (Mcwilliams 1990), and various quantities derived from the velocity gradient tensor (Morrow et al. 2004; Isern-Fontanet et al. 2003). On the other hand, techniques based on the geometric criteria are also numerous: the winding-angle (WA) method (Sadarjoen and Post 2000, 1999; Sadarjoen et al. 1998),
the vector geometry (VG) method (Nencioli et al. 2010), the vector pattern matching (Heiberg et al. 2003), the Clifford convolution (Ebling and Scheuermann 2003), and the feature extraction (Guo 2004). A comparison between the physical-parameter-based methods and the geometry-based methods suggested some limitations of the former, which failed to detect some obvious eddies and tended toward regarding a nonvortical structure as an eddy (Chaigneau et al. 2008; Sadarjoen and Post 2000).

Among all the geometry-based methods, the WA method and the VG method are considered to be the primary and the most widely used geometrical techniques for eddy detection in oceanography. Unfortunately, there is no literature providing a comparison of them. Thus, another goal of this study is to compare these two geometrical eddy detection methods.

For the above-mentioned goals, we first compared the WA and VG methods. After establishing the suitability of the WA method to extract eddies from a flow field, we applied it to investigate eddy activities in the southern Taiwan Strait using the current fields observed by two shore-based HFRs. The paper is organized as follows. In section 2, we describe the HFR dataset, the two eddy identification algorithms, the eddy attribute determination, and the tracking algorithms. Section 3 compares the eddy detection results from both eddy detection schemes. The mean eddy properties in the study region are dealt with in section 4. And a summary of the results is provided in section 5.

2. Data and method

a. HFR data

From 11 January to 31 March 2013, two HFRs named Ocean State Measuring and Analyzing Radar, type S (OSMAR-S), were deployed at SHLI (24°09’5”N, 117°59’0”E) and XIAN (23°44’3”N, 117°36’1”E) in Fujian Province, China, to observe the surface current of the southern Taiwan Strait, as shown in Fig. 1. The OSMAR-S, a direction-finding HFR, is equipped with a compact cross-loop–monopole antenna for receiving. A linear frequency-modulated interrupted continuous wave (FMICW)-type waveform is adopted with a center frequency of 13 MHz and a bandwidth of 60 kHz. The range resolution is correspondingly 2.5 km. Table 1 provides the specific settings of the OSMAR-S. During the observation period, the two radars were 60.5 km apart. A raw radial current velocity map is obtained every 6.5 min, and three successive sparse radial maps are combined to achieve a final radial map with an interval of 20 min. Then, the final radial current maps from the two sites at the same time were synthesized to give total vector current maps on a Cartesian grid. In this study, 20-min total vector current maps were achieved on a 32×34 longitude–latitude grid covering from 23.25° to 24.18°N and from 117.63° to 118.62°E with a spacing of 0.03° in both dimensions.

A series of experiments have proved the accuracy and reliability of the current and wave products extracted by the OSMAR-S system (Wen et al. 2009; Zhou et al. 2014, 2015; Wei et al. 2016). Here, the temporal coverage rate of the dataset, as shown in Fig. 2, was calculated at every cell as the proportion of time instants when there is a valid vector current measurement (invalid solutions were mainly caused by interruptions, system calibrations, and short-duration system malfunctions). It shows that most cells, except for a very small number of cells at the edge of the radars’ detection area, have a temporal coverage rate greater than 0.8. An intercomparison of
this dataset with current vectors measured by two moored acoustic Doppler current profilers (ADCPs) was conducted. The locations of the radar sites and the two ADCPs can be seen in Fig. 2, and the comparison results are shown in Fig. 3. It can be seen that the $u-y$ components of the currents measured by the HFRs coincide well with those by the ADCPs (Fig. 3). The correlation coefficients reach up to 0.92 and the root-mean-square errors (RMSEs) are smaller than 0.18 m s$^{-1}$. These correlation coefficients indicate a comparable performance between OSMAR-S and the Coastal Ocean Dynamics Applications Radar (CODAR; Liu et al. 2014), but the RMSE values are slightly higher than the recent CODAR’s comparison result (Liu et al. 2014), which is mainly attributed to different external noise (Merz et al. 2015). Thus, these intercomparison results show the high quality of the radar measurements, indicating that the dataset is suitable for further applications. In particular, this dataset has been used to study the regional tidal and residual current characteristics (Lai et al. 2017).

According to the existing literature, only a very small number of submesoscale eddies observed by HFRs can survive longer than a day (Pomales-Velázquez et al. 2015; Kim 2010). This means that we should reserve the high-frequency components of the currents measured by the HFRs and take full advantage of the high temporal resolution of the HFRs. Therefore, within the eddy detection procedure, no time averaging or smoothing was imposed on the 20-min interval vector current maps.

b. Eddy detection schemes

Among all the documented eddy detection schemes, two methods are counted as the primary geometrical techniques for eddy identification in oceanography, which are independent of physical parameters and exclusively based on the geometry properties of the flow field: one is the WA method developed by Sadarjoen and Post (2000) and the other one is the VG method proposed by Nencioli et al. (2010).

1) VG METHOD

When the VG method was developed, it was confirmed that it can be applied to detect eddies for HFR-derived velocity fields (Nencioli et al. 2010). The VG method was purely based on the geometry features of velocity vectors that depict the vector current field related to eddy patterns. For example, there is a minimum velocity near the eddy center, and the tangential velocity increases approximately linearly with distance from the center before reaching a maximum value and then decaying (Nencioli et al. 2010, 2008).

There are only two steps for the VG method to determine an eddy structure. The first step is to identify the eddy center, which follows four constraints: 1) along the
east–west section, the north–south component of the current velocity reverses in sign across the eddy center and its magnitude increases away from the center; 2) along the north–south section, the east–west component of the current velocity reverses in sign across the eddy center and its magnitude increases away from the center; 3) there is a local minimum of the velocity magnitude at the eddy center; and 4) the direction of the vector current around the eddy center changes with the same trend and two neighboring vectors lie within the same or two adjacent quadrants (which are defined by the north–south and west–east axes). Two parameters need to be specified to implement these constraints. The first parameter, for the first, second, and fourth constraints, is referred to as \( a \), defining the positions where the magnitudes of the north–south (east–west) component along the east–west (north–south) axes are checked, and also determining the curve around the eddy center along which the change in direction of the velocity vectors is inspected. The second parameter, for the third constraint, is referred to as \( b \), defining the dimension (in grid points) of the area used to search for the local minimum of velocity. The sensitivity tests of the detection algorithm for different values of these two parameters can be found in Nencioli et al. (2010), which reported \( a = 3 \) and \( b = 2 \), which can offer a relatively higher success of detection rate (SDR) and a lower excess of detection rate (EDR). Furthermore, the values of \( a = 3 \) and \( b = 2 \) were also adopted by other researchers to identify the eddy structures, such as Liu et al. (2012), Pomales-Velázquez et al. (2015), and Lin et al. (2015). Therefore, we also used these values in this study.

The second step is to compute the eddy boundary, which is defined as the outermost closed contour line of the streamfunction field around the center. The streamfunction at a given position \((i, j)\) is computed as

\[
\psi(i, j) = \int_{(0,0)}^{(i,j)} (-v \, dx + u \, dy),
\]

where \( u \) and \( v \) are the Cartesian velocity components of the vector currents observed by the HFRs. For more implementation details, one can refer to Nencioli et al. (2010).

2) WA METHOD

The WA method is motivated by the concrete definition of a vortex provided by Robinson (1991), which is described as instantaneous streamlines exhibiting a roughly circular or spiral pattern around a center. In fact, this definition is consistent with the one assumed by the VG method. The WA method tries to determine an eddy structure by a point, which defines its center, and looped streamlines, which correspond to the eddy edge. The center of the looped streamlines is approximated to the eddy center for this method (Sadarjoen and Post 2000).

Thus, the process of detecting eddies with the WA method for each flow field observed by the HFRs consists of three main stages: computing streamlines, selecting streamlines associated with eddies, and clustering the distinct streamlines corresponding to the same eddy. Considering the high spatial resolution of our dataset, there were no more spatial interpolations and the streamlines were computed on every \( 0.03^\circ \times 0.03^\circ \) grid point. For each streamline, the step size used was 0.1 (corresponding approximately to 0.35 km) and the maximum number of vertices was 10 000. Thus, the maximum length of a streamline was set at 3500 km, which allows for circling around the observation region boundary 10 times and guarantees enough length for a streamline with an outward expansion spiral pattern. After the streamlines for a flow field have been computed, they were selected according to the criterion of the winding angle being greater than or equal to \( 2\pi \). The winding angle is defined as the cumulative change of the directions for the segments on each streamline [a schematic representation of the winding angle can be found in Sadarjoen and Post (2000) and Chaigneau et al. (2008)]. Then, the selected streamlines were grouped and combined into a distinct number of clusters. Streamlines belonging to the same cluster were considered to be part of the same eddy. To determine the eddy boundary, the ellipse fitting was done on all streamlines within an eddy. And the fitting procedure is similar to the one used in Sadarjoen and Post (2000), but some modifications were conducted (see the appendix for more details).

c. Specific eddy attributes determination

The two eddy identification algorithms described above were applied to the entire HFR dataset to detect eddy structures. After an eddy was identified, several eddy properties were computed. The eddy radius \( R \) was calculated as the mean distance from the center to every point on the boundary. The eddy area \( A \) corresponding to the area delimited by the eddy boundary was approximated to a circular area with an equivalent radius equal to \( R \). In addition, the eddy kinetic energy (EKE) was calculated by the classical relation

\[
\text{EKE} = \frac{1}{2} (u^2 + v^2),
\]

where \( u \) and \( v \) are the velocity components derived directly from the HFRs. The mean eddy kinetic energy...
(MEKE) was defined as the average kinetic energy within an eddy area,

\[ \text{MEKE} = \frac{\text{EKE}}{A}. \]

To investigate the principal eddy kinematic properties, we also computed their vorticity and deformation rates. First, in the local Cartesian coordinate system, the gradients of the velocity components were

\[ g_{11} = \frac{\partial u}{\partial x}, \quad g_{12} = \frac{\partial u}{\partial y}, \quad g_{21} = \frac{\partial v}{\partial x}, \quad \text{and} \quad g_{22} = \frac{\partial v}{\partial y}. \]

By these gradients, we can denote the vorticity

\[ \zeta = g_{21} - g_{12}, \]

the shearing deformation rate

\[ s_s = g_{21} + g_{12}, \]

the stretching deformation rate

\[ s_n = g_{11} - g_{22}, \]

the total deformation rate

\[ s = \sqrt{s_s^2 + s_n^2}, \]

and the divergence

\[ \psi = g_{11} + g_{22}. \]

d. Eddy-tracking algorithm

After eddies were identified during the entire period of the observation, eddies were tracked by comparing the eddy centers at successive time intervals, starting from the first sampling time. An eddy track usually lasts more than one observation interval (20 min in this study); hence, the number of eddy tracks is much smaller than the amount of eddies. The eddy-tracking algorithm employed in this study is adapted from that introduced by Nencioli et al. (2010). The track of a given eddy at time step \( t \) was updated by searching eddy centers of the same type (cyclonic or anticyclonic) at time \( t + 1 \). And a searching radius of 12 km was chosen for HFRs that generally have a bearing offset of about 10° (Liu et al. 2010; Paduan et al. 2006), which corresponds to a 12-km spatial offset at a detection range of 70 km (the detection range of the HFRs used here is 60–80 km, which was determined by the external noise). If any center was not discovered within the searching area at \( t + 1 \), then a second search was performed at \( t + 2 \) with a searching radius being 1.5 times as large as the search radius at \( t + 1 \). The current eddy was supposed to vanish when there was no update at \( t + 2 \). In addition, if an eddy was not connected to any center identified in the previous two time steps, then it was considered to be a new eddy.

3. Comparison between the VG and WA eddy detection methods

It is not a trivial task to make an objective assessment of the eddy detection algorithms due to the absence of a dataset in which the eddy distribution is definitely known. Moreover, manual eddy detection, even by experts, shows a varying number of results (Chaigneau et al. 2008) due to the challenges in identifying the relatively small features. Therefore, we compared those two detection methods by means of eddy detection results (eddy positions and radii) from the same dataset rather than evaluating the SDR or EDR.

During the observation period, 1275 and 1350 eddies were identified by the VG method and the WA method, respectively, and the total number of eddies identified by both methods was 1080 with 546 cyclones and 534 anticyclones. They were confirmed by the type, time instant, and location. Figure 4 shows two eddies identified by the two algorithms. Unfortunately, the eddies observed by the HFRs are unable to be verified by observations from other sensors due to the absence of a measurement, whose temporal–spatial resolution is comparable with the HFR dataset.

Figure 5 exhibits the separation distance of the eddy centers determined by the VG method and the WA method. The histogram has a peak located at 1 km, and a steep decrease for a distance greater than 1 km can be seen clearly. The average separation distance between the results from these two eddy detection methods was 2.6 km, which was less than the spatial resolution (the spatial resolution is about 3 km for the data used in this study). Thus, the offset of eddy locations determined by the two methods was insignificant. And this can also be seen in Fig. 4, in which the centers determined by the two methods are close. On the other hand, it is well known that vorticity within an eddy varies from its center to its boundary. Furthermore, the magnitude of the vorticity is maximum at the center and reaches zero at its boundary theoretically. Thus, we checked the distance between the eddy center’s position and the maximum magnitude of the vorticity within a minimum rectangular region exactly covering both eddy boundaries determined by the VG and WA methods. The distributions of the distance shown in Fig. 6a are close to a Gaussian distribution with a subtle slant on the large
FIG. 4. Two examples of eddy detection. Current velocity field observed by the HFRs at (a) 0600 UTC 12 Jan 2013 and (b) 0320 UTC 17 Jan 2013. (c),(d) Contour lines of the streamfunction (thin lines) and eddy boundary (thick circle) derived from the VG method associated with the flow fields in (a),(b). (e),(f) Instantaneous streamlines (thin lines) and eddy boundary (thick circle) derived from the WA method corresponding to the flow fields in (a),(b). Stars in (c)–(f) indicate the eddy center computed by the relative algorithms.
values for both the VG method and the WA method. The agreement between the two eddy identification methods also verifies that the eddy centers determined by the two methods were very close. The average distances between the maximum magnitude of vorticity and the eddy centers ascertained by the two schemes were almost equal to 22 km, which is up to 7 times as large as the spatial resolution. Even more amazingly, the distance variation as a function of the eddy radius was increasing, as shown in Fig. 6b. It indicated that a maximum of vorticity was located outside of the eddy boundaries. Therefore, the adoption of vorticities as a criterion for eddy centers is inadvisable. In summary, the idea of estimating an eddy center by vorticity is unwise, and the number of detected eddies and its center determined by the two methods suggest that the VG and WA methods have almost the same capacity for identifying eddies.

The eddy boundary is another necessity for depicting an eddy that combines the center defining the eddy within a flow field. Thus, it is necessary to inspect the boundary for the same eddy picked out by both the VG method and the WA method. However, it is rather inconvenient to compare the veritable boundaries. Fortunately, the eddy size corresponding to its radius is a quantitative property that can be a substitute for the boundary and is easy to compare. The distribution of the radius difference (radius derived from the WA method minus that computed by the VG method) shown in Fig. 7 indicates that the radius difference varied on a large scale with a ratio of 20% when it is larger than 5 km and 32% when it is larger than 3.5 km. Given the relatively small size of the eddy in this study (see the radius distribution in Fig. 10), such a radius difference was significant. This distinction of the radius mainly stemmed from the boundary definition in the VG method, which calculates the largest closed curve of the streamfunction field (Nencioli et al. 2010). However, there may be no closed contour line of the streamfunction field around the eddy center, which leads to the incapability of this scheme to capture the eddy boundary. In the case of no closed contour line of the streamfunction field (e.g., Fig. 4c), Nencioli et al. (2010) proposed the VG method and adopted $a - 1$ (see section 2b for the definition of $a$) as the eddy radius (the eddy boundary shown in Fig. 4c was exactly calculated as $a - 1$); and no exiting literature has so far proposed a new solution to this problem. Thus, the physical radius of eddies varied with the value of $a$. Moreover, the case of no closed contour line embracing the eddy center was not scarce. The proportion of such eddies identified by the VG method was 49% for $a = 3$.
only the 1080 eddies mentioned above have been taken into account). And this proportion increased to 52% for \( a = 4 \) [all the detected eddies (1185 eddies actually) have been taken into account]. Figure 8 shows the histograms of the eddy radius for \( a = 3 \) and \( a = 4 \). Figure 8a suggests a radius distribution for \( a = 3 \) centered around 6 km and stood extremely out for both the cyclonic and anticyclonic eddies. In contrast, the outstanding peak for \( a = 4 \) was at 9 km. They were exactly corresponding to the production value of \( a - 1 \) and the spatial resolution. Thus, the VG method is often incapable of capturing the eddy size. In contrast, the WA method employs the feature of the streamlines, which guarantees their presence and reflects the eddy size. Therefore, we adopted the eddy attributes derived from the WA method for studying the eddy statistics properties.

4. Mean eddy properties

a. Eddy frequency, radius, and life span

The submesoscale eddies covered a large proportion of the observed region, and their frequency is shown in Fig. 9. The interpretation for this is straightforward because it corresponds for every grid to the percentage of time instants when the grid was located within eddies. It indicates that the occurrence of eddies was more preferential in the southern part (Fig. 9). Moreover, the eddies most frequently appeared in the region where the topography varies sharply with a distinct arc outline (the −30- and −40-m isobaths reveal an obvious arc). Therefore, the topography played an important role in the formation of the eddies. Moreover, the results of the eddy-frequency contour lines were also influenced by the limited observation area. For example, the contour lines in Fig. 9 with a value of zero are approximated to the radars’ coverage area (Fig. 2) and the relative low frequency in the southern part was also observed due to those areas being close to the edge of the HFR coverage. Thus, it is necessary to establish a radar network to expand the observation area and then obtain an accurate eddy spatial distribution.

The distribution of the radius shown in Fig. 10a deviates from a Gaussian distribution with a slight skew toward the larger size, and a peak at 6 km for both the cyclonic and anticyclonic eddies. No distinct difference was observed between the size of the cyclones and that of the anticyclones. The mean radius values were 10.1 and 9.2 km for the cyclones and the anticyclones, respectively. Moreover, the histograms also show that eddies with a radius larger than 20 km were quite infrequent. In addition, there were 290 and 271 trajectories for the cyclones and the anticyclones, respectively.

(a)  

![Histogram of eddy radius distribution for a = 3](image1)

(b)  

![Histogram of eddy radius distribution for a = 4](image2)
The histogram of their life spans is shown in Fig. 10b. There were no significant differences between the life span of the two eddy types. The mean life span was about 0.7 h. An overwhelming majority of the eddies survived for less than 1 h, and only a few eddies lasted more than 3 h. To assess the relationship between the life span and the radius, we took the maximum radius of the eddies, composing a trajectory, as the trajectory radius. And the variation of the life span versus the trajectory radius is shown in Fig. 11. On average, the eddy life span increased from less than 0.5 h for a very weak eddy with a near-zero radius to 2 h for a strong eddy with a radius larger than 20 km. This monotonic relationship implies that an eddy with a larger scale usually subsisted for a longer time.

b. Eddy kinematics

The cyclonic and anticyclonic eddies have similar average vorticities with an order of $2.4 \times 10^{-5} \text{s}^{-1}$ in absolute value, as listed in Table 2. And the probability density function of the normalized vorticity ($\zeta/f$), shown in Fig. 12a, also indicates that the vorticity of the cyclonic eddies seemed to be the same as that of the anticyclonic eddies. The dominant Rossby number of the eddies observed in this study was 0.3–0.4 (Fig. 12a). Furthermore, the joint probability density for the radius and the normalized vorticity presented an overview of the submesoscale eddies, as shown in Fig. 12b. The eddies had an effective radius about 3–18 km and a Rossby number about 0.1–1.

The statistics of the eddy kinematic parameters are listed in Table 2. The vorticities for both the cyclonic and anticyclonic eddies are similar in absolute value, indicating that the eddies are spinning in a consistent direction.
anticyclonic eddies had an order of $2.4 \times 10^{-5} \text{s}^{-1}$. In contrast, other kinematic parameters, such as the shearing, stretching deformations rates, and the divergences, were smaller than the vorticities even to several orders of magnitude for both types of the eddies on average. In addition, a total deformation rate of $10^{-6} \text{s}^{-1}$ indicates that eddies tend to be deformed and are not perfectly circular. Figure 13a shows the variation of the total deformation rate versus the radius. The total deformation decreased over all of the radius scope. It suggests that the smaller eddies were less deformed and more circular. To confirm this result and to better investigate the eddy shape, we checked the eccentricities of the eddies. As expected, the mean ellipse eccentricity decreased with the radius, as shown in Fig. 13b. Furthermore, almost the same trend can be clearly seen between the eccentricity and the total deformation rate. These solid evidences adequately disclose that the smaller eddies were more circular.

c. Eddy life cycle

Figure 14a shows the trajectories of the eddies with a life span no less than 1.5 h. The total number of such eddy trajectories was 30 for the cyclonic eddies and 32 for the anticyclones. The eddies mainly appeared at $23.5^\circ \pm 10^\circ \text{N}$, where the eddies arose most frequently (Fig. 9). Moreover, the distribution of the trajectories' direction is also displayed in Fig. 14b. In this study, the direction for each trajectory was defined as the azimuth of the ending position to the starting position calculated clockwise from north. The distribution shown in Fig. 14b suggests that the eddies predominantly moved southeastward.

Besides the position, other parameters of each eddy also varied during each eddy's life span. In this study, we investigated the evolution of the radius and the MEKE. We analyzed their average temporal values throughout the eddies’ lifetime with the eddies surviving no less than 1.5 h (whose trajectories are shown in Fig. 14a). To compare the eddies with different life spans, we normalized each eddy age by its life span. Similarly, the radius and the MEKE also have been normalized by their maximum value within each eddy’s life span. The normalized temporal evolutions are shown in Fig. 15. Both eddy types exhibited similar variation trend in terms of the radius and the kinetic energy during the whole eddy life cycle. The eddy size and the mean kinetic energy increased in the first 30% of an eddy life cycle and then fluctuated in a small scope for next 40% of the life cycle. In the last 30% of the mean life cycle, these parameters decreased to a value similar to the initial level.

5. Summary

This study compared the efficiencies of two widely used automatic eddy detection methods and investigated the

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<th>Table 2. Mean statistics of the eddy kinematics.</th>
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<tr>
<td>Cyclonic eddies ($10^{-5} \text{s}^{-1}$)</td>
</tr>
<tr>
<td>Vorticity</td>
</tr>
<tr>
<td>Mean: 2.42</td>
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<tr>
<td>Std dev: 1.40</td>
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<tr>
<td>Min: 0.19</td>
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<tr>
<td>Max: 9.41</td>
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<td>Divergence</td>
</tr>
<tr>
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<tr>
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<tr>
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<tr>
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</tr>
<tr>
<td>Shearing deformation</td>
</tr>
<tr>
<td>Mean: −0.09</td>
</tr>
<tr>
<td>Std dev: 0.66</td>
</tr>
<tr>
<td>Min: −2.81</td>
</tr>
<tr>
<td>Max: 4.31</td>
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<tr>
<td>Stretching deformation</td>
</tr>
<tr>
<td>Mean: 0.52</td>
</tr>
<tr>
<td>Std dev: 0.66</td>
</tr>
<tr>
<td>Min: −4.06</td>
</tr>
<tr>
<td>Max: 3.81</td>
</tr>
<tr>
<td>Total deformation</td>
</tr>
<tr>
<td>Mean: 0.86</td>
</tr>
<tr>
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</tr>
<tr>
<td>Min: 0.01</td>
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<tr>
<td>Anticyclonic eddies ($10^{-5} \text{s}^{-1}$)</td>
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<tr>
<td>Vorticity</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>Divergence</td>
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<tr>
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<tr>
<td>Min: 0.06</td>
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<tr>
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(a)

Fig. 12. (a) Probability density function of $\zeta/f$. (b) Joint probability density of radius and normalized vorticity.
submesoscale eddy properties using the 80-day-long HFR measurements with a high spatial–temporal resolution. Both of the eddy detection methods are exclusively based on the geometry properties of flow field and originate from the same definition of an eddy. The total number of eddies identified by the winding-angle method was almost equal to that of the eddy recognized by the vector geometry algorithm. Moreover, the eddy centers for the same eddies picked out by the two different methods were also close. This proved that the two automatic detection methods have almost the same capacities in identifying eddies. However, the distributions of the eddy sizes derived from the two algorithms differed greatly on account of the incapability of the vector geometry algorithm to capture the eddy boundary. This incapability, which will affect the eddy properties analysis greatly, results from the absence of a closed contour line of the streamfunction field around eddy centers. Therefore, the study revealed that the winding-angle method appeared to be more competent than the vector geometry algorithm. We strongly recommend the use of the winding-angle method for determination of the eddy boundary.

Then, 1080 eddies, identified by both the winding-angle method and the vector geometry method, were

![Graphs showing variations in total deformation rate and eccentricity as functions of radius.](http://journals.ametsoc.org/jtech/article-pdf/34/4/939/3392122/jtech-d-16-0160_1.pdf)

**FIG. 13.** (a) Variation of the total deformation rate as a function of the radius. Solid line shows a third-order polynomial fit with a correlation coefficient of 0.91 and a root-mean-square difference of $13.08 \times 10^{-3}$ s$^{-1}$.

**FIG. 14.** (a) Eddy trajectories: red (blue) lines are trajectories of the cyclonic eddies (anticyclones); solid circles indicate the starting positions of an eddy track, and asterisks denote the ending positions. (b) Statistics of the trajectory direction. Trajectory direction was defined as the bearing angle of the ending position (stars in Fig. 14a) to the starting position (solid circles in Fig. 14a) calculated clockwise from north.
selected to analyze the mean eddy properties in the southern Taiwan Strait. In general, no significant difference was observed between the cyclonic and anticyclonic eddies in terms of the radius, life span, kinematics, and evolution during their life cycle. The typical radius of the eddy in this region was 3–18 km with a Rossby number of 0.1–1. However, the mean radius of all eddies was about 10 km and their mean lifetime was roughly 0.7 h. Moreover, the eddies could survive longer if they had a larger size. They were more frequently observed within 23.5° ± 10°N. And the general occurrence frequency exhibits a strong correlation with the topography. The observed eddies were more circular with a smaller size, since the eccentricity and the total deformation rate decrease with increasing radius. And they lived through three phases during their life cycle with remarkable radius and kinetic energy growth and decay.

The results may be useful for selecting and developing an efficient eddy detection algorithm and validating high-resolution regional models, and they could even be of interest to the biological community to investigate links between ecosystems and eddy activities. Moreover, it demonstrates the great capability of the high-frequency radars in oceanographic research and applications, especially for observing submesocale dynamics, which can fill the gap of the temporal–spatial resolution between the in situ and satellite measurements.

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APPENDIX

Ellipse Fitting

As explained in section 2b, the winding-angle algorithm attempts to recognize an eddy by selecting and clustering closed streamlines. Let us consider clustered streamlines. We denote the coordinates of all the points on these clustered streamlines as $M$. Then, the cluster covariance $C$ can be easily obtained. Sadarjoen et al. (1998) and Sadarjoen and Post (1999, 2000) provide the same approach to fit the streamlines to an ellipse (i.e., regarding the eigenvalues $r$ of $C$ as the ellipse axis lengths). This is inaccurate and needs to be revised. Let us consider a cluster with only one streamline and this streamline is a perfect ellipse with a semimajor axis of $l_1$ and a semiminor axis of $l_2$. Moreover, for simplification, we assume the angle of the inclination to be zero. Thus, the coordinates of all the points on the streamline can be denoted as

\[
\begin{align*}
  x &= l_1 \sin \theta \\
  y &= l_2 \cos \theta
\end{align*}
\]

where $\theta$ is evenly distributed in the 0 to $2\pi$ range. Thus, the cluster covariance can be expressed as

\[
C = \begin{bmatrix}
  D(x) & 0 \\
  0 & D(y)
\end{bmatrix},
\]
where the $D(\cdot)$ denotes the variance. The eigenvalues of the cluster covariance can be expressed as

$$\mathbf{r} = \begin{bmatrix} D(x) \\ D(y) \end{bmatrix}.$$ 

Distinctly, the elements of $\mathbf{r}$ are not the semimajor axis and the semiminor axis. But the following relational expression can be illuminated:

$$
\begin{bmatrix} D(x) \\ D(y) \end{bmatrix} = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} D(\sin \theta) \\ D(\cos \theta) \end{bmatrix}.
$$

Since $\theta$ is evenly distributed in the $0$ to $2\pi$ range, then $D(\sin \theta) = D(\cos \theta) = 1/2$. Thus, we can derive the relation as

$$\sqrt{2}\mathbf{r} = \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix}.$$ 

We thought this should be the correct relation between the eigenvalues of the cluster covariance and the ellipse axis lengths. And this relation has been adopted in this study.

REFERENCES


