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MESOSCALE EDDIES: A CASE STUDY IN THE NORTHERN SOUTH CHINA SEA**

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ABSTRACT

The paper presents a Geographical Information System (GIS)-based method for depicting the characteristics, particularly the internal structures and evolutionary processes, of mesoscale eddies. This was done by examining topologic relations among closed Sea Surface Height (SSH) contours which were reconstructed from the Naval Research Laboratory (NRL) Layered Ocean Model (NLOM). Different scenarios of the topological relations among the contour lines permitted the identification of the outermost outline of eddies and the depiction of the number of cores in each mesoscale oceanic eddy. With full consideration of the internal structure of the eddies, we then reconstructed the evolutionary processes of these eddies and the results were compared with empirical observations on three long-lived mesoscale eddies in the northern South China Sea (SCS). Tracking results were similar, thereby validating our method as being efficient and robust in reconstructing mesoscale ocean eddies, especially their evolutionary processes based on their internal structures.

Key Words: Mesoscale Eddies; GIS; Topology; Naval Research Laboratory Layered Ocean Model (NLOM); Northern South China Sea

INTRODUCTION

Different methods have been developed to investigate the characteristics, dynamics and role of eddies in the various oceans, among them the Pacific (Penven et al. 2005; Chaigneau et al. 2008), the Indian, the southeast Atlantic, and the northeast Pacific (Morrow et al. 2004), and also oceans on a global basis (Chelton et al. 2007; Chelton et al. 2011). The Okubo-Weiss (O-W) parameter method (Okubo 1970; Weiss 1991) was firstly applied by Isern-Fontanet et al. (2003) to detect marine eddies from observational data. Morrow et al. (2004) and Penven et al. (2005) applied the O-W method systematically to altimeter data and numerical model output data, respectively. In brief, this method defines an eddy as an object having a vorticity-dominated core surrounded by strain-dominated circulation cells.

Chaigneau et al. (2008) applied a threshold-free winding-angle method which characterized an eddy structure by a point that defines its center, and by a closed streamlined contour corresponding to the edge of the eddy. This method traces the closed streamlined contour based on the geostrophic velocities that are obtained from derivatives of the Sea Surface Height (SSH) field. A limitation occurs with this method because the geostrophic velocity is susceptible to noise in the SSH data, though it is less problematic than the O-W technique that relies on products of doubly differentiated SSH. A new algorithm developed by Nencioli et al. (2010) was exclusively based on the geometry of velocity vectors (VG). Four constraints were considered to characterize the spatial distribution of the VG around eddy centers. The centers were derived from the general features that were associated with the velocity field in the presence of eddies.

This method permitted identification of eddies in the Southern California Bight. Chelton et al. (2011) reviewed the threshold-free winding-angle method and also tested the O-W method. It was concluded that both methods were inappropriate for the identification of mesoscale eddies from SSH data. It was mentioned that a specific threshold value for the Weiss parameter used in the O-W method must be specified for eddy identification, and that there was no single optimal value for the global oceans. Essentially, the numerical estimates of the Weiss parameter were susceptible to noise in the SSH fields. Chelton et al. (2011) then proposed a SSH-based and threshold-free method to identify eddies in the global oceans.

Other research efforts concentrated on understanding eddies in the various seas, among them the Mediterranean Sea (Isern-Fontanet et al. 2003; Isern-Fontanet et al. 2004; Isern-Fontanet et al. 2006), and the South China Sea (SCS) (Li 2002; Wang et al. 2003; Wang 2004; Cheng et al. 2005; Guan and Yuan 2006; Lin et al. 2007; Xiu et al. 2010; Nan et al. 2011). Investigations in the Mediterranean Sea by Isern-Fontanet et al. (2006) revealed the presence of vortices in several parts of the basin. In the Algerian basin the vortices contributed to the redistribution of water masses and also produced meridionally smooth gradients of mean temperature and salinity. Findings from the SCS indicated that mesoscale eddies had an average horizontal scale from 50-200 km, with an average life span of between 20-200 days. Nan et al. (2011), using the O-W method, reported three long-lived eddies in the northern South China Sea (SCS).

While the aforementioned researchers have identified eddies and vortices in oceans and seas it is, nevertheless, worthwhile to note that Chelton et al. (2011) emphasized that better methods must be made available to extract information on the dynamics of eddies in the oceans and seas. In this

respect this research presented a GIS-based method to identify, track, and investigate the evolutionary characteristics of mesoscale eddies. As far as could be ascertained, this is the first study to identify mesoscale eddies and analyze their evolutionary processes with a GIS; an efficient computerized system, functioning to facilitate the storage, manipulation, analysis, and modeling of spatially referenced data (Lakhan 1996). The identification and tracking results were validated by a comparison with the empirical observations of mesoscale eddies in the northern SCS.

STUDY AREA

We chose the SCS to test our method and validate the identification and tracking results (Figure 1). The northern SCS was chosen because of the availability of field data from various researchers (for example, Li 2002; Wang et al. 2003; Wang 2004; Cheng et al. 2005; Lin et al. 2007; Xiu et al. 2010) who studied this area to track the evolution of mesoscale eddies. The SCS is the largest semi-enclosed marginal sea in the northwest Pacific Ocean. Its total area is approximately $3.5 \times 10^6 \text{ km}^2$ with a mean depth of 1,212 m. The SCS has a large NE–SW oriented abyssal basin with the greatest depth being 5,567 m.

The general upper-circulation pattern of the northern SCS exhibits seasonal variability (Wyrski 1961; Xu et al. 1982; Qu 2000). It develops as a basin-wide cyclonic gyre in winter and a dipole structure in summer with a cyclonic gyre in the northern SCS, and an anticyclonic gyre in the summer in the southern portion (Su 2004). This circulation pattern results from the seasonally reversing winds that typically blow strongly from the northeast during the boreal winter

(October-March) and from the southwest during the boreal summer (June-August) (e.g., Dale 1956; Wyrski 1961; Metzger and Hurlburt 2001; Su 2004; Wang et al. 2006). Under the confluence of wind forcing, Kuroshio intrusion, and complex topography, the northern SCS is characterized as an area with strong mesoscale activities (Su 2001; He et al. 2002; Yang et al. 2014).

The SCS could be divided into four zones (Figure 1, Z_1 - Z_4) in terms of the generating mechanisms of mesoscale eddies (Wang et al. 2003). In zone Z_1 , there are warm eddies which shed from the intruding Kuroshio on the west of the Luzon Strait (Li et al. 1998; Su et al. 2002; Wang et al. 2003; Yuan et al. 2006) due to the frontal instability (Wang et al. 2000). Cold eddies are induced to the southwest Taiwan Island due to orographic winds of the winter monsoon (Wang et al. 2008). In zone Z_2 , mesoscale eddies are induced by curled wind stress (Yang and Liu 2003) and vorticity that advected westward from the Kuroshio front (Liu and Su 1992). Eddies in zone Z_3 are generated by the interaction between strong barotropic shelf currents and local topography (Cai et al. 2001; Gan and Qu 2008). An eddy pair usually develops in zone Z_4 in the summer offshore from Vietnam, and is influenced by the eastward baroclinic wind jet around 12° N (Wang et al. 2003).

DATA

Two different datasets were used in this study. The first dataset was the merged-and-gridded satellite altimeter data provided by AVISO (<http://www.aviso.oceanobs.com>) based on TOPEX/Poseidon, Jason 1, ERS-1, and ERS-2 data (Ducet et al. 2000). This Sea Level Anomaly

(SLA) product has a $(1/4)^{\circ}$ spatial resolution in both latitude and longitude and a 7-day temporal resolution.

The second dataset was the daily Sea Surface Height (SSH) outputs of the $(1/32)^{\circ} \times (1/32)^{\circ}$ global Naval Research Laboratory Layered Ocean Model (NLOM). This is a multi-layer, free surface, and hydrodynamic primitive equation ocean model with full-scale bottom topography in the lowest layer. This dataset was acquired from NRL (<http://apdrc.soest.hawaii.edu/data/data.php>). The NLOM SSH field has the capability of tracking the eddy process (Rhodes et al. 2002) finely enough due to its high temporal and spatial resolution.

METHODS

In this study, we developed a method to identify mesoscale ocean eddies from the SSH outputs from the NLOM. The gridded SSH outputs were first vectorized into contour lines at a one cm contour interval. For an individual eddy it was specified that there should be at least one closed contour line to represent its outermost perimeter, i.e., its outline. All other contour lines within the outline should have SSH values higher or lower than the outline's SSH value. The SSH difference between the maximum/minimum SSH values within a specified outline should be no less than 2 cm, i.e., there should be at least three contour lines to represent an eddy. Furthermore, the eddies should also meet the following criteria. Minimum size of an eddy should be no less than the area of a circle with a radius of 45 km, but no more than the area of a circle with a radius of 250 km. The distance between any pair of points within an eddy at a specific latitude should be less than a linearly interpolated value between two end numbers: 400 km at 25° latitude and

1200 km at the equator. This permitted erasing eddies having complex structures while retaining those eddies which were compact.

Each individual closed contour line was represented either by a root, middle, leaf, or a branch node, depending upon their location relative to other closed contours (Figure 2). The outermost closed contour, which was not contained by any other closed contours but contained at least one closed contour, was represented by a root node. The innermost closed contour, which was contained by at least one other closed contour line, but contained no other closed contours, was deemed as a leaf node. A leaf node thus had no further child node. For a node that was neither a root nor a leaf node, if it had at least two child nodes it would be defined as a branch node. Otherwise, it was a middle node. A cyclic graph was then built with nodes representing the closed contours (Figure 2). Within each connected acyclic graph, there was only one root node, but this may have more than one leaf node, branch, and middle nodes. The connections between nodes on the graph thus show the topological relationships among the closed contours, from which the internal structures of mesoscale ocean eddies would be identified as described in the section to follow.

All root nodes were first examined to check whether the aforementioned criteria were met to delineate an eddy. If all criteria were met, the root node would be retained and accepted as a potential candidate of mesoscale ocean eddies. The nodes that were connected to a retained root node would then be further scrutinized to determine whether it actually represented an eddy.

Scenario 1: The acyclic graph had no branch nodes but only one leaf node that was connected to the root node (Figure 2a). If there was at least one middle node between the root node and the leaf node, it would represent a single core eddy. For this case, the outermost closed contour would be accepted as the outline of this eddy while the geometric center of the closed contour line represented by the leaf node would be deemed as the core of this eddy.

Scenario 2: The acyclic graph had more than one leaf node which was connected to either a branch node or to a root node directly (Figure 2b). The algorithm first checked the number of middle nodes between the leaf nodes and the branch or root nodes. The branches without any middle nodes would be deleted and other branches with at least one middle node would be retained. In Figure 2b, the right two branches were deleted while the left one was retained. The acyclic graph was thus trimmed and became similar to the one shown in Figure 2a, which represented a single-core eddy as described in Scenario 1.

Scenario 3: The acyclic graph had no branch nodes but at least two leaf nodes which were connected to the root node. If there was at least one middle node on each branch (Figure 2c), it would represent a multi-core eddy. Again, the outermost closed contour would be accepted as the edge of this eddy. The geometric centers of the leaf nodes were accepted as the cores of this eddy.

Scenario 4: The acyclic graph had more than one leaf node which was connected to the root nodes through a common branch node. If there was at least one middle node between the branch and the leaf nodes (Figure 2d), the graph would represent a multi-core eddy as in Scenario 3.

However, if there was no middle node between the branch and the leaf nodes, the corresponding branch would be deleted as in Scenario 2.

The method outlined above was capable of identifying the internal structure of each individual eddy by examining the topological relations between the nodes (i.e., the closed contour lines). This method has a major advantage because it could distinguish a multi-core eddy from a couple of individual eddies that cluster together in space (Wang et al., 2013). Furthermore, the eddy boundary and the location of its core(s) could be anchored much better than with the method proposed by Chelton et al. (2011) who simply used the extreme SLA values within an eddy as its core regardless of whether the eddy has one or multi-cores.

EDDY TRACKING

The generalized nondimensional distance (Penven et al. 2005) and geometrical distance (Isern-Fontanet et al. 2006) were used together to reconstruct the trajectory of a specific eddy in time once all eddies were automatically identified from each SSH map (Figure 3). The generalized nondimensional distance (X) between two eddies (e_1, e_2) that were identified from two successive maps measured the dissimilarity between these two eddies, and was calculated by Penven et al. (2005) with:

$$X_{e_1, e_2} = \sqrt{\left(\frac{\Delta X}{X_0}\right)^2 + \left(\frac{\Delta R}{R_0}\right)^2 + \left(\frac{\Delta \xi}{\xi_0}\right)^2}$$

where, ΔX , ΔR , and $\Delta \zeta$ are the spatial distance, variation of diameter, and variation of vorticity between eddies e_1 and e_2 , respectively. X_0 , R_0 , and ζ_0 are a characteristic length scale (100 km), a characteristic radius (50 km), and a characteristic vorticity (10^{-6} s^{-1}) respectively. The geometrical distance (Isern-Fontanet et al. 2006) is exactly the same as ΔX , i.e., the spatial distance between eddies e_1 and e_2 .

For the purpose of illustration, the eddies that were identified on the SSH maps at time step t and $t+n$ ($n=1, 2, \dots, 7$) were named as e_t and e_{t+n} , respectively. The procedure utilized started to track the eddy from the SSH map at the next time step, i.e., $t+1$. If no successor was found at time step $t+1$, the procedure would study the eddy at time step $t+2$. The procedure will stop if no successor was found at time step $t+7$.

In each iteration, the geometrical distance (ΔX) between eddies e_t and e_{t+n} was first calculated. If the distance was less than $n \times 2$ km, the eddies at the next time step were considered to split from the one in the previous time step and this eddy was accepted as the successor at the next time step. If there was more than one eddy at time step t and there was only one eddy at time step $t+n$, and the spatial distance between e_t and e_{t+n} was less than $n \times 2$ km, the process was defined as a coalescence process, i.e., two eddies at time step t merged into one at time step $t+n$. In this paper 2 km was used as a threshold to identify the coalescence and partition processes from the daily NLOM outputs. By contrast Isern-Fontanet et al. (2006) used 20 km, about one-half of the average radius of intense eddies, to track eddies from the 7-day resolved SLA data. Considering the different temporal resolution between the NLOM outputs and the SLA data, the threshold value used in this study was about 1 km less than that used by Isern-Fontanet et al. (2006).

However, the 2 km threshold value proved to be the most suitable in this study after we conducted multiple experimental tests in tracking eddies in the SCS from SSH maps.

If the geometrical distance between the eddies on two consecutive SSH maps was more than $n \times 2$ km and less than $n \times 10$ km, the generalized nondimensional distance (Penven et al. 2005) between these eddies was calculated. The eddy with the shortest generalized nondimensional distance was accepted as the successor.

If the geometrical distance between eddies on two consecutive SSH maps was more than $n \times 10$ km, they were then considered as not being the same, and no successor was identified at this time step. For this situation, the procedure was applied to the next step time SSH map. If no successor was identified in a 7-day window step time, the eddy was considered to have disappeared. This procedure was used to examine all eddies that were identified from the NLOM outputs, and the trajectory of each specific eddy in time was reconstructed.

TRACKING RESULTS STORED IN A GIS DATABASE

A Topology-based Eddy Process (TEP) data model was created to store and organize the mesoscale eddy processes (Yi et al., 2014). In simple terms, an eddy process is considered as a collection of all the eddy states from that of the first generated state to the final state. The TEP used the Eddy State Object (ESO) to represent the characteristic state of an eddy at any given time. The ESO was comprised of two parts; one for spatial features, and the other for the attribute features. The spatial feature was represented by the centre of the eddy and was referred

to as the Eddy Centre Point (ECP). Associated with the ECP was the Eddy Boundary Area (EBA). The ECP's were symbolized as points while the EBA's were represented by polygons. The attribute features stored the physical characteristics of the eddies; namely the vorticity, the amplitude, horizontal scale, and speed of propagation. The spatial features and the attribute features were linked by a unique eddy State ID (SID). To account for dynamic eddy processes an Eddy Process Object (EPO) was also used. The EPO recorded all of the information for each eddy process that was generated by the ESO. Each eddy process was assigned a unique process ID (PID) which was a combination of the date that the eddy was generated and its associated serial number. The spatial features of each eddy process were stored as a collection of all the spatial features of each eddy state that belonged to that process. The attribute features kept the average value or change rates of eddy characteristics such as intensity, duration, and frequency, etc. The spatial features and attribute features of the same eddy process were linked by the PID.

The ArcGIS 10.1 (ESRI 2012) geodatabase was used to implement the TEP data model. The spatial features of ESO were represented by a point feature layer which symbolized the eddy centre whereas the polygon feature layers of ESO represented the coverage area of each of the eddies. The attribute features of ESO were recorded in a relational table. The spatial and attribute features were linked by the SID. The causal relationships between the eddy states were examined in the relational table by considering each of the ESOs. Since each EPO was a collection of ESO's that shared the same PID the data model operated at maximum computational efficiency.

RESULTS

The method proposed in this study succeeded in identifying three long-lived mesoscale eddies in the northern SCS. These eddies were also detected by Nan et al. (2011) using SLA data and *in situ* measurements. The eddies developed at around 20°N latitude. The distance between any pair of points within each of these eddies was less than 1040 km; a linearly interpolated value between 400 km for 25° N and 1200 km at the Equator (Chelton et al., 2011). Following Nan et al. (2011) the three eddies were labelled as ACE1, ACE2, and ACE3. The general characteristics and evolutionary processes of these three eddies are described below.

General Characteristics of Eddies

The duration of the three eddies (ACE1, ACE2 and ACE3) was 76, 125, and 199 days, respectively. A time series of the daily SSH, absolute vorticity at the eddy core, and horizontal scale of the three eddies could be seen in Figure 4. The averaged SSH value was slightly lower for ACE1 (79.63 ± 3.09 cm) than ACE2 ($84.07.63 \pm 3.25$ cm) and ACE3 (86.31 ± 4.14 cm). ACE1 ($(-4.68 \pm 1.08) \times 10^{-6} S^{-1}$) had almost the same averaged vorticity ($(-4.69 \pm 1.34) \times 10^{-6} S^{-1}$) as ACE3, which was somewhat lower than that of ACE2 ($(-4.71 \pm 1.30) \times 10^{-6} S^{-1}$). The averaged horizontal diameters of three eddies were 174.95 ± 24.69 km, 175.99 ± 28.88 km and 170.50 ± 28.40 km, respectively.

Evolutionary Processes

Of the three eddies, ACE1 was the least complicated in terms of its evolutionary process. The ACE1 eddy emerged on 19 May with its center at 112°E and 15°N as a single core eddy and lasted until 2 August 2007 (Figure 4). This eddy strengthened on a gradual basis as demonstrated

by its increasing horizontal scale (Figures 4 and 5), but culminated on 30 June at a scale of about 210k m. Its horizontal scale started to shrink and the eddy disappeared rather suddenly on 11 August. During its lifetime, no other eddy was detected as being split from or merged into ACE1 (Figure 4). In terms of its geometric structures, ACE1 appeared as a mono-core eddy during most of its lifetime, with the exceptions of its appearance as a double-core eddy on 27, 30 May; 17, 19 June; 3, 10, 12 July, and 2 August, and also as a tri-core eddy on 25 May, and 4, 29 July (Figures 4 and 5).

The evolutionary process of ACE2 was more complicated than that of ACE1 (Figures 4 & 6). It developed on 6 June as a mono-core eddy. The core split into two on 9 June, then coalesced on 16 June, and then split into two again on 19 June. This two-core eddy lasted until 28 June, at which time it separated into two independent eddies. The western eddy existed only one day and disappeared on 29 June while the eastern eddy continued to strengthen as a mono-core eddy until 3 July. Based on the NLOM outputs, no eddy was detected from 4 July to 10 July. This eddy appeared again on 10 July with two cores. Another eddy developed to the north of ACE2 on 12 July and intruded into ACE2 on 13 July. A two-core eddy then developed and lasted until 15 July after which time the southern core disappeared. Thereafter, ACE2 turned into a mono-core eddy and lasted until 8 October, when it finally dissipated.

The ACE3 eddy was first identified on 16 June from the NLOM outputs and it lasted until 31 December. At the beginning of its evolutionary process, ACE3 had only one core. However, it evolved into an eddy with two cores between 22-24 June, four cores on 25 June, and three cores on 28 June. ACE3 existed as a mono-core eddy for most of the time from 29 June to 3 August,

except as a two-core eddy on 5 July (Figures 4 and 7). Here it should be noted that a water mass developed on 3 August to the west of ACE3, and then moved eastward and eventually intruded into ACE3 on 4 August. However, it split from ACE3 and moved westward after 9 August. Another eddy then developed to the north of ACE3 on 3 August and it lasted until 6 September, though at times it became a warm eddy. This eddy coalesced with ACE3 on 11 August. ACE3 then evolved as an eddy with three cores from 15-17 August. The total number of cores in ACE3 was generally reduced to either two or one after 18 August, though ACE3 had three cores on 13, 24, 25 October, and 26 November, and four cores on 23 October (Figures 4 and 7). ACE3 started to move northwestward from 25 October, and westward from 29 November before it finally disappeared at around 112°E 18°N on 31 December.

COMPARISON WITH RESULTS DERIVED FROM SLA AND NLOM OUTPUTS USING DIFFERENT IDENTIFICATION METHODS

We compared the identification results that were derived from SLA data and NLOM SSH outputs using the O-W method, the SSH-based method (Chelton et al., 2011), and the method proposed in this study. We mainly focused on the three long-lived eddies that were reported by Nan et al. (2011) as their observation of these eddies was further validated by *in-situ* measurements. Emphasis will be placed on highlighting those areas where the results were reasonably similar to the empirical findings from the northern SCS.

Identification results of the three long-lived eddies from the NLOM SSH output using our method visually agreed with variations in the altimeter data. Figure 8 shows the edges of ACE1

on 13 June, ACE2 on 11 July, and ACE3 on 24 October 2007. These edges were overlapped atop the altimeter data for the aforementioned three dates. All pixels within the edges had higher SLA values than the pixels along the edges. Hence, a potential eddy could be detected, thereby suggesting that the proposed identification method could detect mesoscale eddies in the SCS from the NLOM outputs.

The identification results were further compared against those identified from the NLOM outputs of 22 August 2007 using the SSH-based method (Chelton et al. 2011) and the O-W methods. We particularly chose this date because it is the same date that the three eddies were also identified and elaborated by Nan et al. (2011, see Figure 2). Figure 9 shows that the O-W method better depicts the core areas of the eddies from the NLOM SSH outputs. However, it fails to accurately present their boundaries. Furthermore, many more small eddy-like structures, particularly in the southern SCS were identified by the O-W method mainly due to the high spatial resolution of the NLOM outputs. By contrast, the eddies identified by Chelton's SSH method (2011) are generally bigger as they used the outmost closed SSH contour line to depict the boundaries of the eddies. In addition, Chelton's SSH method (2011) failed to provide any information on core number of eddies. From the same NLOM SSH outputs, our method showed much better performance in delineating eddies' boundary and internal structures.

Both eddies ACE2 and ACE3 had approximately the same duration as observed by Nan et al. (2011). The duration of ACE1 was somewhat shorter than that identified from the SLA data, but this could be due to the presence of noise in the altimeter data. Other general characteristics

(average SSH, average horizontal diameter, and vorticity) of the three eddies were generally the same, with only minor differences (Figure 4).

In addition to eddy duration this research also observed that ACE2 separated into two eddies on 28 June. The west eddy disappeared on 30 June. On 12 July, an independent eddy intruded into ACE2 from the north. While both studies found only one small eddy split from ACE2 on 11 July, it was determined that the new eddy lasted only one day while the other investigation reported that the eddy lasted at least one week. It was also evident from the NLOM outputs that an eddy emerged on 3 August, and lasted until 29 August. This small eddy (water mass) was located northeast of ACE3 and then moved southwest until finally merging into ACE3 on 29 August. On the other hand, the previous investigation reported that for ACE3 a two-week long small eddy merged into ACE3 on 22 August. Similar coalescence processes were also reported by Nan et al. (2011), although there was a slight difference in the timing. This could be attributed to the differences in temporal resolutions of the NLOM outputs and the SLA data, as well as to the different methods and criteria that were used to identify the eddies.

Further comparisons were made by reconstructing the trajectories of the three eddies (see Figure 10). The trajectories that were derived from the SLA data and the NLOM outputs were then compared to those reported by Nan et al. (2011). The similarities/dissimilarities could now be observed. As illustrated, ACE1 was moving toward north while the other two eddies moved toward the west. Evidently, both the O-W method and this study revealed the general evolutionary processes of the three eddies, though different criteria were used to identify and track them. There was, however, a noticeable discrepancy in the spatial locations of the eddy

centers that were identified from the NLOM outputs and SLA data. This discrepancy could be attributed to the data because both the NLOM outputs and the SLA data have different spatial and temporal resolutions.

There was also a noticeable difference, particularly in terms of the spatial location of eddy centers. Figure 11 highlights the variation of the center SLA, mean vorticity and average horizontal diameter of the three eddies that were identified from the SLA data. The variation pattern was similar to that was reported by Nan et al. (2011), particularly the center SLA. However, it should be noted that it was not possible to identify the successor of ACE2 during July, while the previous investigation reported on the existence of this eddy. This could be attributed to the fact that the two methods identified eddies at varying levels of detail from the same SLA data.

Additional comparisons were done on the center of the SLA, the average vorticity, and the horizontal scale of the three eddies that were identified from the SLA data. As demonstrated in Figure 11 similarities exist, especially on eddy vorticity. For instance, the vorticity of ACE3 gradually increased in the NLOM outputs after 13 October while a totally opposite trend was observed from the SLA data. The NLOM outputs also showed a general decreasing horizontal scale for ACE2 after 22 September while the SLA data displayed a more or less constant scale.

DISCUSSION AND CONCLUSION

The GIS-based method proposed in this research proved to be valid and functionally useful for identifying and tracking mesoscale eddies in the northern SCS from daily-resolved NLOM outputs. Evidently, the identification and tracking results were in close similarity to those obtained from the empirical observations as reported by Nan et al. (2011). Discrepancies of the duration and the spatial location of the eddy centers occurred because of the dissimilarities in data sources and differences in methodological approaches.

Given the fact that our method permitted determination of the centroid location and edges of eddies, it could be considered as operationally useful to investigate eddies in the other oceans. Here it should be noted that the contour interval used to construct the contour lines would be an important factor in determining the location of the eddies. For instance, the core of an eddy could be missed if the contour interval is too large. By contrast, more than one core would be identified if the contour interval was set too small. In this study, the SSH contour lines were set at an interval of 1 cm. It is, however, worthwhile to note that in some situations, the sea water surface might slightly increase or decrease over a large area due to circulation of warm (or cold) current though no eddies would develop. To eliminate these pseudo eddies a threshold value was set. This threshold could be the maximum depth or height of an eddy. For this study, a 2 cm value was used as the threshold for the SCS, because Wang (2004) claimed that the general variation in surface water height was usually less than 1 cm in the SCS. This threshold value would require adjustment if the proposed method is applied to examine eddies in other locations.

Another significant aspect of this study is that it highlighted the usefulness of NLOM outputs for obtaining insights on the evolutionary processes of mesoscale eddies. It is already established

that NLOM outputs have high spatial and temporal resolutions. It is worthwhile to emphasize that the NLOM outputs have the advantage of providing a daily record of eddy propagation (Figures 4 & 8), which is not achievable from the 7-day resolved altimeter data. In addition, the NLOM outputs could also effectively record the splitting and merging of adjacent eddies since the change could be detected on two or more consecutive maps if the split and merge lasted for more than one day (see Figure 4).

Without doubt, the proposed approach is valid and applicable for detecting mesoscale eddies from the NLOM SSH field. Utilization of data from the daily resolved NLOM outputs would be practically useful for all oceanic environments. Researchers would, therefore, be able to accurately track the partition and coalescence of mesoscale eddy processes on a timely basis. Incorporation of small-scale temporal-and-spatially resolved NLOM outputs into the GIS would certainly provide more detailed information which could then be used to reasonably reconstruct the evolutionary processes of mesoscale oceanic eddies.

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Figure 11. Time series of SLA (top panel), vorticity (middle panel) at the center of eddy core, and horizontal scale (bottom panel) of these three eddies that were identified from the SLA data using the method proposed in this study.

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