A Gaussian-surface-based Approach to Identifying Oceanic Multi-eddy Structures from Satellite Altimeter Datasets

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***Abstract*—This study presents a Gaussian-surface-based approach to identifying multi-eddy structures from the sea level anomaly (SLA) maps. The SLA signals of an eddy are modeled by a two-dimensional anisotropic Gaussian surface. An identification criterion is introduced to determine whether to retain or split a multi-eddy structure. Detection result of a three-eddy structure from the SLA in the South China Sea (SCS) demonstrates the effectiveness of the identification approach. Comparison with a merger event previously reported about a multi-eddy structure in northern SCS reveals the advantage of this approach over simple splitting strategy, which may lose the eddy-eddy interaction details conveyed by real multi-eddy structures.**

Keywords: automated identification algorithm; ocean eddies; multi-eddy structure

I. INTRODUCTION

Mesoscale eddies (hereinafter eddies) are swirls of ocean currents (Fig. 1a) with spatial scales from tens to hundreds of kilometers and time scales from days to months, resembling the storms in the atmosphere [1, 2]. They are energetically dominant and pervasive in the ocean, and play a significant role in transporting heat, salt, and biochemical properties of sea water on a global scale [1, 3]. Advancements in remote sensing satellites in the last two decades not only provides the scientific community with a massive amount of long-term global altimeter data for observing the eddy dynamics [4], but also brings forth numerous studies about eddies' general dynamic characteristics and spatiotemporal variations in regional and global seas [5-11].

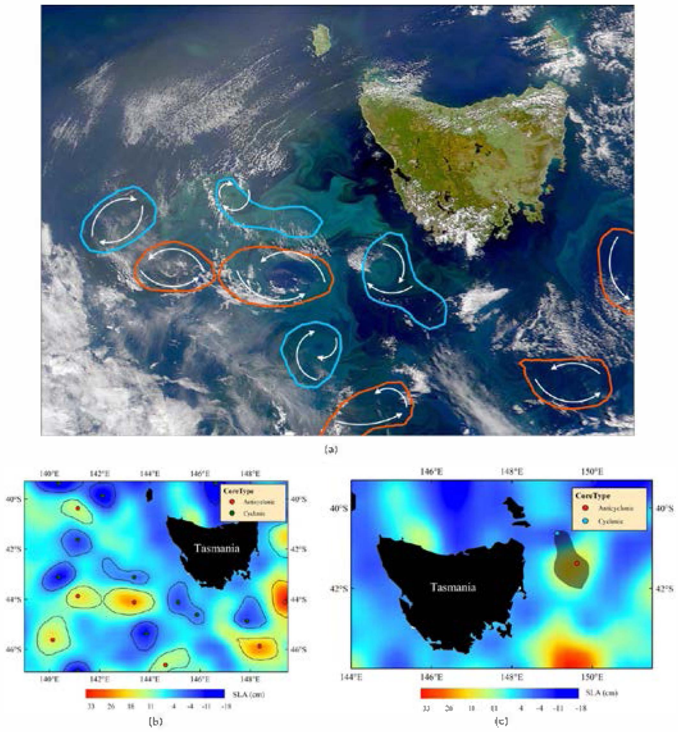

Figure 1. (a) The true-color SeaWiFS image of 7 November 2000 with identified ocean eddies superimposed (anticyclonic and cyclonic eddies are symbolized by orange and blue polygons, respectively). The phytoplankton blooms suggest the nutrients in deeper water are brought up to the surface by cyclonic eddies. (b) The eddy identification results superimposed on the sea level anomaly map. (c) a special case with two different types of eddies located in the same vorticity dominant region.

Automatic eddy identification algorithms are essential for helping scientists efficiently gain insights from large volumes of observation datasets, and are becoming a very important research topic in oceanography in recent years. Existing algorithms can be approximately divided into three groups: 1) physical parameter based [12-14], 2) flow geometry based [15-17], and 3) sea level anomaly (SLA) based [18-20]. Although various novel algorithms have been developed, few address the problem of identifying the multi-eddy structures (Fig. 1b), which can physically form when multiple eddies are closely located [21-24]. Chelton, et al. [8] proposed a SSH-based

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algorithm which may yield multi-eddy structures. The authors tried to split up these eddy composites but finally abandoned the effort, for it could introduce undesirable tracking errors. Li et al. [25] established two simple strategies to resolve the splitting problem. From a different standpoint that some multi-eddy structures may be potentially real phenomena that reveal complex eddy-eddy interactions and energy transfer, we in this study present a Gaussian-surface-based method to preserve the potential multi-eddy structures from being algorithmically separated. This work is a method improvement of our previously developed hybrid detection (HD) algorithm [26] in multi-eddy identification.

The rest of the paper is organized as follows: Sect. 2 describes the altimeter data used in this study and the specific procedures for identifying a multi-eddy structure; Sect. 3 presents the identification results and validation analysis of two real cases observed in the South China Sea (SCS); and Sect. 4 concludes the whole paper.

II. DATA AND METHODOLOGY

A. Altimeter dataset

The satellite altimeter datasets used in this study is the merged SLA datasets of delayed-time Reference Series product provided by the Archiving Validation and Interpretation of Satellite Data in Oceanography (AVISO, http://www.aviso.oceanobs.com). This merged altimeter datasets have combined different satellite missions to improve the estimation of mesoscale signals, and consist of weekly SLA maps computed with respect to a 7-year mean (1993-1999) and resampled on a ¼°×¼° Cartesian grid.

B. Identification methodology

It is common for existing identification algorithms to produce multi-eddies structures which encompass multiple eddy centers within a single boundary. The Okubo-Weiss (OW) method defines an eddy as a connected region satisfying $W < -0.2\delta$, (W is a physical parameter calculated from SLA, δ is the standard deviation of W). However, it occasionally happens that the regions of different eddies, even of different polarities, are connected when they are in close proximity (Fig. 1c). The SSH-based algorithm, which describes an eddy boundary by the outermost closed SSH contour, was also reported that a single boundary may contain more than one local SSH extremum probably because of irregular SSH contour structures. While some of these detected multi-eddy structures may reflect real eddy-eddy dynamic interactions in the ocean, some may be spurious structures that could bias the overall statistic characteristics of ocean eddies. So, quantitative restrictions for the identified multi-eddy structures are necessary for a more accurate and reliable detection result.

As the structure of an ideal ocean eddy is analogous to a mathematic Gaussian surface, many researchers have used Gaussian models to estimate the eddy scale and study the fluid dynamics [8, 27-31]. This study likewise adopts the Gaussian surface to fit the multi-eddy structures and estimate the eddy scale in the SLA field. Then, a splitting criterion based on the spatial distance and the scales of neighboring eddy pairs is applied to determine whether they compose a potential real multi-eddy structure or should be separated apart. The specific procedures are described as follows.

1) Gaussian surface fitting

For any given multi-eddy structure with n eddy centers, each component eddy i is modeled by an anisotropic two-dimensional Gaussian kernel expressed as

$$h_i(x,y) = b_i + G_i(x,y) \quad (2.1),$$

$$G_i(x,y) = A_i \exp\left\{-\frac{1}{2}\left[\frac{(x\cos\theta_i + y\sin\theta_i)^2}{\sigma_{iu}^2} + \frac{(y\cos\theta_i - x\sin\theta_i)^2}{\sigma_{iv}^2}\right]\right\} \quad (2.2),$$

where x, y denote the horizontal and vertical distance from the point to the eddy center, respectively. θ_i denotes the rotated angle of axes (Fig. 2a). σ_{iu} and σ_{iv} respectively denote the eddy scale along the rotated "horizontal" and "vertical" axis (Fig. 2a). b_i represents the basal SLA height and A_i denotes the eddy amplitude defined by the difference between the local SLA maximum or minimum at the eddy center and the basal height (Fig. 2b). So, A_i is a positive value for anticyclonic eddies, and negative for cyclonic eddies.

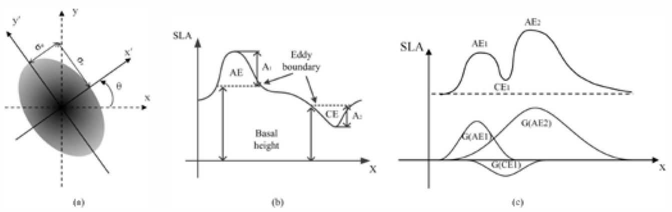

Figure 2. (a) illustration of an anisotropic two-dimensional Gaussian kernel. (b) Definition of eddy amplitude and basal SLA height. (c) Gaussian surface fitting result of a complex three-eddy composite.

The composite structure is then modeled by aggregating the Gaussian kernel of each contained eddy (Fig. 2c). The specific formulation of the model is defined as

$$H = B + \sum_{i=1}^{n} G_i(x,y) \quad (2.3),$$

where B is the basal SLA height of the multi-eddy structure. The nonlinear least square technique [32, 33] is used to fit the model to the SLA surface of multi-eddy structure. A, B, θ, σ_u, and σ_v are the unknown model coefficients being estimated for each component eddy.

2) Identification criterion and boundary delineation

For each eddy pair (e_1, e_2) in a multi-eddy structure (Fig. 3a), the Gaussian fitting scales are compared with the spatial distance between the eddy centers by the following criterion:

$$L(e_1, e_2) < \sigma_1' + \sigma_2' \quad (2.4),$$

where L is the length of the spatial connection line, σ_1' and σ_2' are the directional scales of the eddies along the connection line. For ideal Gaussian eddies, the horizontal scale σ is the radius at which the axial speed raises to maximum and hence the relative vorticity reduces to zero [8]. So, if an eddy pair satisfies the criterion expressed by inequality (2.4), the vorticity of the two eddies is possibly mixed, forming a real multi-eddy structure. If not, their connection may be just caused by the irregularity of SLA contours, and a split-up procedure should be performed.

This identification criterion is able to differentiate which group of eddies in a composite structure forms a real multi-eddy structure, and which of them should be separated apart. Modifying the boundary of contained eddy is a simple way to divide up a multi-eddy structure. After all eddy pairs are examined by the identification criterion, the boundaries of resultant isolated single eddies or sub-composite structures are redefined by the outermost SLA contour of their governing areas (Fig. 3b).

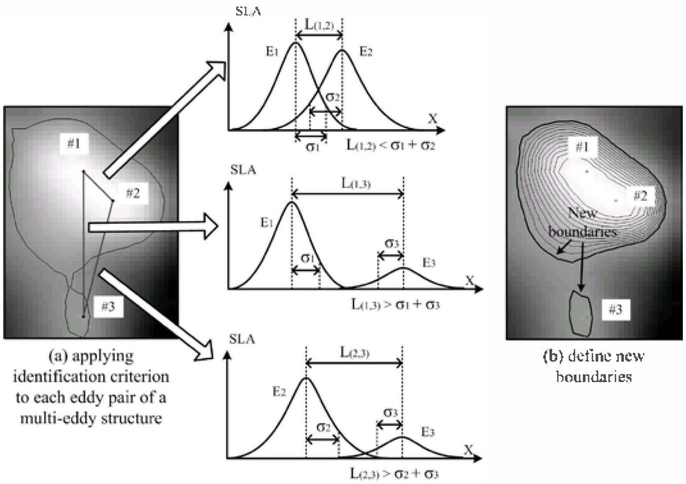

Figure 3. (a) illustration of applying identification criterion to each eddy pair of a multi-eddy structure. (b) define new boundaries of the resultant single eddy and new composite structure.

III. RESULTS AND DISCUSSION

The multi-eddy identification approach has been implemented and integrated into the HD method. Experiments were conducted on the SLA maps of the South China Sea to test the identification capability.

Figure 4a shows a composite structure of three cyclonic eddies (CEs) identified in the central part of SCS on 2 December 1992 by the HD algorithm. CE1 is located near (15°N, 113°E) with an amplitude about -21.9 cm. CE2 and CE3 are located west of CE1 near the Luzon Island and also show very high eddy intensity (-22 and -20.4 cm, respectively). The fitting results with Gaussian surfaces (Fig. 4a) demonstrate that all CEs are elliptically shaped with the long axis oriented northeast-southwest, which agree with the geometry of SLA contours. The distance between CE1 and CE2, CE1 and CE3 (401.3 and 373.8 km, respectively) is much larger than the sum of eddy scales, resulting in the separation of CE1 from the composite structure (Fig. 4b). CE2 and CE3, however, satisfy the criterion expressed in inequality (2.4), and are thus preserved as a potential multi-eddy structure in this case (Fig. 4b). This three-cyclonic-eddy case demonstrated the ability of the proposed approach to split spurious multi-eddy structures and retain the real ones.

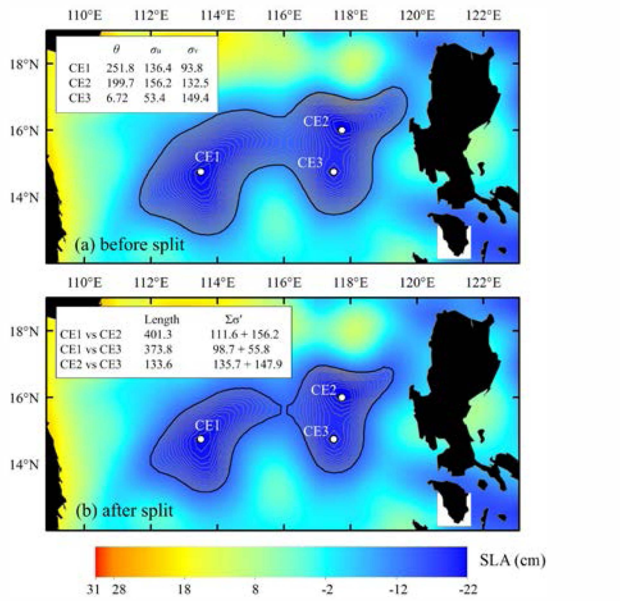

Figure 4. The identification results before and after splitting a three-eddy structure in the SCS on December 2, 1992.

Further, an eddy merger event which was previously reported with in situ observations [22] was also examined to validate the method's advantage over the splitting strategy [25]. Figure 5a-c are the detection results of applying the multi-eddy structure identification criterion. AE1 and AE2 formed a two-eddy structure to the west of Luzon on August 8, 2007. With two weeks' growth in eddy intensity, they finally merged into a strong coherent single eddy near Luzon on August 22. The result is consistent with the observation in Nan et al. [22] and reveals a detailed evolution process and interactions of AE1 and AE2. But by using simple splitting algorithm, the merger event would probably be missed if the composite structure of AE1 and AE2 was split up. So, the detection of multi-eddy structure can contribute to understanding how eddies interact during their lifespan.

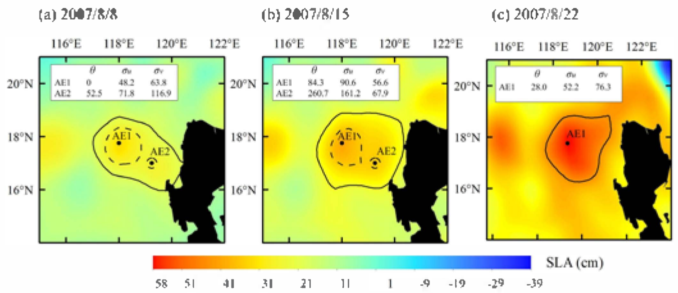

Figure 5. identification results of the eddy merger events in northern SCS.

IV. CONCLUSION

This study developed a Gaussian-surface-based approach to identifying multi-eddy structures from the SLA maps. This approach involved two major procedures: 1) the SLA signals of an eddy were approximated by a two-dimensional anisotropic Gaussian surface; then 2) an identification criterion based on the spatial proximity and the estimated eddy scale of each contained eddy was applied to determine whether a multi-eddy structure should be retained as a potentially real one or should be split up.

The algorithm has been integrated with our previously developed eddy detection method to improve the ability of capturing potential multi-eddy structures. Using the SLA maps of SCS, we examined the utility of method on real eddy cases. Detection of a three-cyclonic-eddy structure in central SCS on 2 December 1992 illustrated the effectiveness of method on preserving potential multi-eddy structures. Comparison with a previously reported two-anticyclonic-eddy structure in northern SCS demonstrated the advantage of revealing eddy-eddy interactions during the evolution process.

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