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Technical Note: Watershed strategy for oceanic mesoscale eddy splitting

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Abstract

To identify oceanic mononuclear mesoscale eddies, a threshold-free splitting method was developed based on the watershed. Because oceanic eddies are similar to plateaus and basins in the map of the sea level anomaly (SLA) data, the natural divisions of the basins are the watersheds between them. The splitting algorithm is based on identifying these watersheds by finding the path of steepest descent. Compared to previous splitting methods, the proposed splitting algorithm has some advantages. First, there are no artificial parameters. Second, the algorithm is robust; the splitting strategy is independent of the algorithm and procedure and automatically guarantees that the split mononuclear eddies are simply-connected pixel sets. Third, the new method is very fast, and the time complexity is $O(N)$, where N is the number of multinuclear eddy pixels; each pixel is scanned only once for splitting, regardless of how many extremes there are. Fourth, the algorithm is independent of parameters; the strategy can potentially be applied to any possible physical parameters (e.g., SLA, geostrophic potential vorticity, Okubo–Weiss parameter, etc.). Besides, the present strategy can also be applied to automatic identification of troughs and ridges from weather charts. Because this general method can be applied to a variety of eddy parameter fields, we denoted it the Universal Splitting Technology for Circulations (USTC) method.

1 Introduction

To investigate the dynamics and roles of oceanic eddies in the environment, these eddies must first be automatically identified and tracked, especially when they are close to each other. In general, the automated eddy detection algorithms are categorised into three types: (1) physical parameter-based algorithms, e.g., Okubo–Weiss (O–W) (Isern-Fontanet et al., 2003; Chaigneau et al., 2008), (2) flow geometry-based algorithms (Fang and Morrow, 2003; Chaigneau et al., 2011; Chelton et al., 2011); and (3) hybrid methods, which involve physical parameters and flow geometry characteristics

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(Nencioli et al., 2010; Xiu et al., 2011; Dong et al., 2011; Yi et al., 2014). However, each identification method poses a multinuclear eddy identification problem, e.g., multiple SLA extremes (Chelton et al., 2011). This problem can occur when multiple eddies are physically close together. Note that such multiple eddies are very common in SLA data (Li et al., 2014).

A simple method to avoid the problem is to reduce the contour of the SLA until there is only one extreme in the contour (Chaigneau et al., 2011). Thus, only one extreme is located in the eddy, as shown in Fig. 1a. However, reducing this contour will lead to reductions in both the area and the amplitude of the eddy. The identified eddies are much smaller and weaker. For example, the amplitudes of the identified eddies were only approximately 2–3 cm (Chaigneau et al., 2008), whereas they could be in the range of 20 to 30 cm in other eddy identifications (Chelton et al., 2011; Xiu et al., 2011).

The best approach to solve the multinuclear eddy identification problem is by directly splitting multinuclear eddies, as shown in Fig. 1b. This splitting is not easily achieved. Chelton et al. (2011) attempted to split multinuclear eddies using various methods. However, their splitting process often resulted in some track problems, and it was finally abandoned. Subsequently, Yi et al. (2014) applied a hybrid detection approach by integrating the ideas of the O–W method and the SLA-based method. Li et al. (2014), following the approach proposed by Chelton et al. (2011), attempted to split multiple eddies according to SLA with two simple strategies and a threshold for strategy choice.

Note that Yi's hybrid method does not include any splitting strategy or method. As a result, Yi's hybrid method simply identifies the boundary of the multinuclear eddy using one parameter and identifies the centres of multinuclear eddies using another parameter but cannot actually split multinuclear eddies into single ones. Li's method, which includes the splitting method, requires an additional threshold. In addition, these splitting methods have difficulty in identifying very close multinuclear eddies.

The goal of this study was to establish a splitting strategy that could separate multinuclear eddies into mononuclear eddies. The idea is based on the fact that the values of

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eddy parameters (e.g., SLA) are similar to plateaus and basins in a map and that the vortex is similar to a funnel like a black hole (Haller and Beron-Vera, 2013). The natural divisions of the basins are the watersheds between them. Using these watersheds, the multi-nuclear eddy could be split into mononuclear ones.

2 Definition of a mononuclear eddy

2.1 Data

The SLA data used in this study were from the MSLA (maps of sea level anomalies), a merged and gridded satellite product, which is produced and distributed by AVISO (archiving, validation, and interpretation of satellite oceanographic data at http://www.aviso.oceanobs.com/) and based on TOPEX/Poseidon, Jason 1, and the European remote sensing (ERS) satellites (i.e., ERS-1 and ERS-2 data) (Ducet et al., 2000). Currently, the products are available on a daily scale at a resolution of $0.25^\circ \times 0.25^\circ$ over the global ocean. The data were corrected for all geophysical errors.

2.2 Mononuclear eddy identification

To identify eddies, a physical definition of an eddy is required. Because this study focuses mainly on the splitting strategy, the choice of parameters is not of concern, and we simply use SLA as an example. The following mononuclear eddy definition is from previous studies (Li et al., 2014). Each pixel has eight nearby neighbours. A point within the region is a local extremum if it has an SLA greater or less than all of its nearest neighbours. An eddy is defined as a simply-connected set of pixels that satisfies the following criteria:

1. Only *one* SLA extremum exists in the set.
2. The SLA values of the eddy are above (below) a given SLA threshold associated with data error e.g., 3 cm (e.g., −3 cm) for anticyclonic (cyclonic) eddies.

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3. The amplitude of the eddy is larger than the data error (e.g., 3 cm).

Conditions (2) and (3) provide lower bounds for the eddy size and amplitude. Moreover, we increase the amplitude criterion from 1 cm, as proposed by Chelton et al. (2011), to 3 cm because the SLA data error is approximately 3 cm (Ponte et al., 2007). The above criterions remove the constraints of eddy pixel number and distance between eddy pixels (e.g., Chelton et al., 2011). So they are simpler and more consistent.

3 Eddy splitting method

3.1 Eddy splitting strategy

In this study, an eddy is split based on the fact that the negative gradient vector of the SLA points toward the eddy centre of an ideal circular-shaped eddy (Li et al., 2014) and the fact that the vortex is similar to a funnel (Haller and Beron-Vera, 2013). Because oceanic cyclonic eddies are similar to basins in the map of the SLA data, the natural divisions of the basins are the watersheds between them.

Figure 2 illustrates this eddy splitting strategy. Figure 2a shows two individual but close eddies. The pixels between the two dashed lines are naturally divided by the watershed. As shown in Fig. 2b, the cross-section of the eddy clearly shows that two closely located particles on the left and right sides of watershed slide along their ways to different eddy centres. The shape of SLA can provide sufficient information to split the multinuclear eddy into mononuclear ones.

To make the strategy more effective, we assume that all of the particles fall only along the path of steepest descent. This assumption ensures that the particle at each pixel has one and only path to the eddy centre. As the path to the centre is mathematically well defined, it is obvious that such a path does not depend on the search method or procedure.

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3.2 Eddy splitting procedure

For any multinuclear eddy, the following steps are taken:

1. Label the extrema as cyclonic eddies of C1, C2, C3, etc.
2. Mark the pixels in the multinuclear eddy as 1, 2, 3, . . . , n.
3. Let the index $i = 1$.
4. Take the ith pixel from the list.
5. It is marked as part of any eddy? If yes, go to (8). If no, go to (6).
6. Find the path and eddy label "Cx" for the ith pixel using the fast descent method.
7. Mark all of the pixels in the path as cyclonic eddy "Cx".
8. Let the index $i = i + 1$; if $i > n$, go to (9), else go to (5).
9. Stop.

First, this procedure automatically guarantees that the split mononuclear eddies are simply-connected pixel sets because all the pixels in the eddy are connected to the central extremum. In contrast, the previous splitting methods cannot guarantee this connected nature, and some further procedure is needed to delete the unconnected parts (Li et al., 2014).

Second, the algorithm is linear and very fast. Each pixel is scanned only once; thus, the time complexity is $O(N)$, where N is the number of multinuclear eddy pixels. However, the split method is not completely finished. In step (6), we require a procedure to return the path from pixel "i" to eddy "Cx".

3.3 Path of steepest descent

The path of steepest descent from pixel "i" can be obtained through the following steps:

1. Let $m = 1$.
2. Take pixel "i" as the mth element of the path.
3. Find the pixel "j" with the lowest value amongst "i" and the surrounding eight pixels.
4. Check whether "j" is already marked as "Cx". If yes, go to (6). If no, go to (5).
5. $m = m + 1$, $i = j$, go to (2)
6. Return along the path of m pixels and label those pixels as parts of eddy "Cx".
7. Stop.

A simple example of this procedure is illuminated in Fig. 2c. The arrows indicate the path of steepest descents to the eddy centres. This procedure returns the path of steepest descent of a pixel to the eddy extremum. If a node of the path has already been marked as part of an eddy, it will return the result immediately. As a result, this procedure is very efficient and fast. In step (3), the pixel with the lowest value is well defined. Therefore, the path of steepest descent to the eddy extremum is also well defined. There is only one path of steepest descent for any pixel, and this path is independent of the search procedure. As a result, the procedure is independent to the scan order and is thus robust.

3.4 The example

We apply this method to some examples. Figure 3a shows four cyclonic eddies that are difficult to split because they are very close to each other. Li et al. (2014) suggested

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re-identifying a multinuclear eddy if too many extrema exist ($n > 3$). The present algorithm can simply split the multinuclear eddy into individual ones, using the watersheds between each eddy as the eddy boundaries. We also used Li's method to split the multinuclear eddy, and the result is shown in Fig. 3b. Compared with the present algorithm, the previous method can also split the multinuclear eddy into four individual ones, but the result is quite different from that obtained with the proposed algorithm except for eddy 5. First, eddies 6 and 8 have disconnected areas, and eddy 7 exhibits multiple connection after the splitting procedure; as a result, some additional procedure is required to eliminate this issue. Second, the eddy boundaries are more zigzag in appearance than those shown in Fig. 3a. The twisted eddy shape will introduce some difficulties in further applications. For example, the eddy composition must initially find similarly shaped eddies.

Besides, this new method can also avoid another problem in many SLA-based identification methods. As shown in Fig. 4a, the colour contours show a simply-connected region above a critical value. Part of an eddy C_1 is located at ($10 < x < 30$, $30 < y < 40$) in this region. It is recognized as part of eddy 1 according to previous methods. However, the present method can automatically recognize it as part of another eddy (Fig. 4b) because there is a watershed between eddy C_1 and eddy 1.

In general, the splitting strategy should meet the following requirements. First, the strategy should be threshold-free. Any artificial threshold might be unphysical and controversial. Second, the strategy should be robust, i.e., the splitting strategy should be independent of the numbers of extremes and independent of the algorithm and procedure. Third, the strategy should be independent of the parameter(s) usable. Because there are many eddy parameters (e.g., SLA, geostrophic potential vorticity, Okubo–Weiss parameter, etc.), the best parameter for the physical definition of an eddy remains unknown. The present algorithm satisfies all of these requirements. Besides, the present strategy can also be applied to automatic identification of troughs and ridges from weather charts. Due to the potential general applications of eddy splitting,

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we denoted the proposed algorithm the Universal Splitting Technology for Circulations (USTC) method.

4 Conclusions

In this study, a watershed splitting strategy was used for mononuclear eddy identification. The splitting strategy has the following advantages. First, the strategy is threshold-free. No artificial threshold was required in the proposed procedure. Second, the strategy is robust and independent of the algorithm and procedure used. Third, the strategy is very fast, regardless of how many extremes there are. Fourth, the strategy is independent of the parameter used (e.g., SLA, geostrophic potential vorticity, Okubo–Weiss parameter, etc.). Besides, the present strategy can also be applied to automatic identification of troughs and ridges from weather charts. Due to the potential general applications of eddy splitting, we denoted it the Universal Splitting Technology for Circulations (USTC) method.

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References

Chaigneau, A., Gizolme, A., and Grados, C.: Mesoscale eddies off Peru in altimeter records: identification algorithms and eddy spatio-temporal patterns, Progr. Oceanogr., 79, 106–119, 2008.

Chaigneau, A., Le Texier, M., Eldin, G., Grados, C., and Pizarro, O.: Vertical structure of mesoscale eddies in the eastern South Pacific Ocean: a composite analysis from altimetry and Argo profiling floats, J. Geophys. Res.-Oceans, 116, C11025, doi:10.1029/2011JC007134, 2011.

Chelton, D. B., Schlax, M. G., Samelson, R. M., and de Szoeke, R. A.: Global observations of large oceanic eddies, Geophys. Res. Lett., 34, L15606, doi:10.1029/2007GL030812, 2007.

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Chelton, D.B, Schlax, M. G., and Samelson, R. M.: Global observations of nonlinear mesoscale eddies, Progr. Oceanogr., 91, 167–216, 2011.
Dong, C., Nencioli, F., Liu, Y., and McWilliams, J.: An automated approach to detect oceanic eddies from satellite remotely sensed sea surface temperature data, IEEE T. Geosci. Remote, 99, 1–5, 2011.
Ducet, N., Le Traon, P. Y., and Reverdin, G.: Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2, J. Geophys. Res., 105, 19477–19478, doi:10.1029/2000JC900063, 2000.
Fang, F. and Morrow, R.: Evolution, movement and decay of warm-core Leeuwin Current eddies, Deep-Sea Res. Pt. II 50, 2245–2261, 2003.
Haller, G. and Beron-Vera, F. J.: Coherent Lagrangian vortices: the black holes of turbulence, J. Fluid Mech., 731, 10 pp., doi:10.1017/jfm.2013.391, 2013.
Isern-Fontanet, J., Garcia-Ladona, E., and Font, J.: Identification of marine eddies from altimetric maps, J. Atmos. Ocean. Technol., 20, 772–778, 2003.
Li, Q. Y., Sun, L., Liu, S. S., Xian, T., and Yan, Y. F.: A new mononuclear eddy identification method with simple splitting strategies, Rem. Sens. Lett., 5, 65–72, 2014.
Nencioli, F., Dong, C., Dickey, T., Washburn, L., and McWilliams, J. C.: A vector geometry–based eddy detection algorithm and its application to a high-resolution numerical model product and high-frequency radar surface velocities in the Southern California Bight, J. Atmos. Ocean. Technol., 27, 564–579, 2010.
Petersen, M. R., Williams, S. J., Maltrud, M. E., Hecht, M. W., and Hamann, B.: A three-dimensional eddy census of a high-resolution global ocean simulation, J. Geophys. Res.-Oceans, 118, 1759–1774, 2013.
Ponte, R. M., Wunsch, C., and Stammer, D.: Spatial mapping of time-variable errors in Jason-1 and TOPEX/Poseidon sea surface height measurements, J. Atmos. Ocean. Technol., 24, 1078–1085, 2007.
Xiu, P., Chai, F., Shi, L., Xue, H., and Chao, Y.: A census of eddy activities in the South China Sea during 1993–2007, J. Geophys. Res.-Oceans, 115, C03012, doi:10.1029/2009JC005657, 2010.
Yi, J., Du, Y., He, Z., and Zhou, C.: Enhancing the accuracy of automatic eddy detection and the capability of recognizing the multi-core structures from maps of sea level anomaly, Ocean Sci., 10, 39–48, doi:10.5194/os-10-39-2014, 2014.

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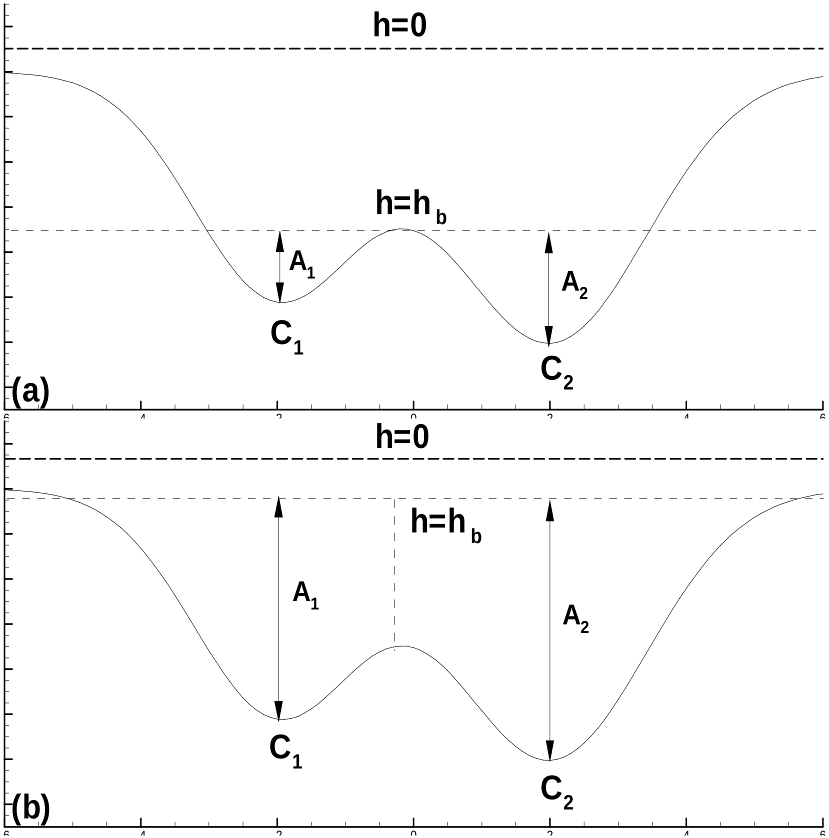

Figure 1. (a) Non-splitting mononuclear eddy identification. **(b)** Mononuclear eddy identification with splitting. Both the amplitude and the area are quite different in the two methods.

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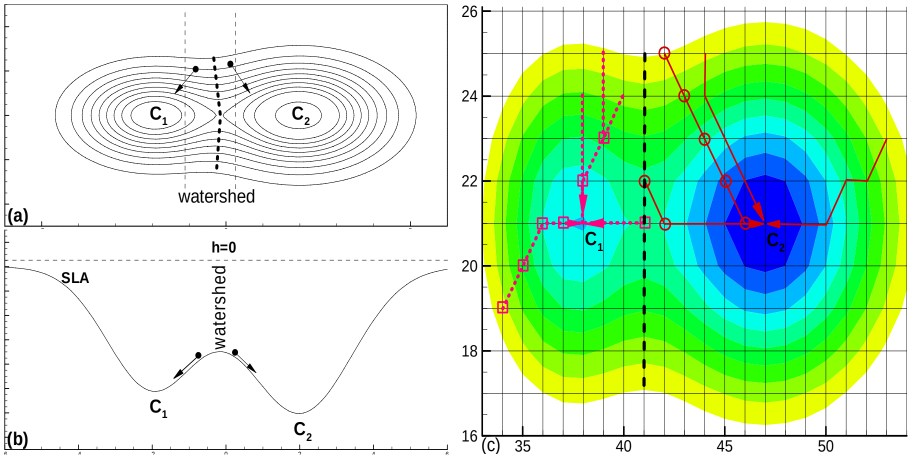

Figure 2. (a) The watershed as the natural division of eddies. **(b)** The particles on the watershed flow downward to the eddy centres. **(c)** Sketch map of the fast descent algorithm, where the dashed line indicates the watershed. The squires with arrows are paths to eddy C_1, while the circles with arrows are paths to eddy C_2.

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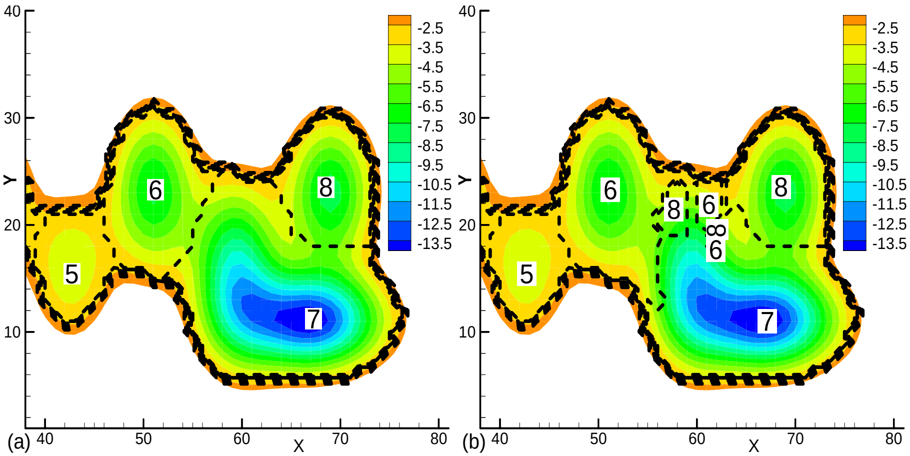

Figure 3. (a) Example of division of a multi-nuclear eddy by present algorithm, where the colour contours represent the SLA, and the numbers identify each eddy. **(b)** The same example as in **(a)** but by previous splitting strategies. The eddy boundaries are more zigzag in nature at the vicinity of eddies 6, 7 and 8 than these in **(a)**. Besides, both eddies 6 and 8 have disconnected areas after splitting.

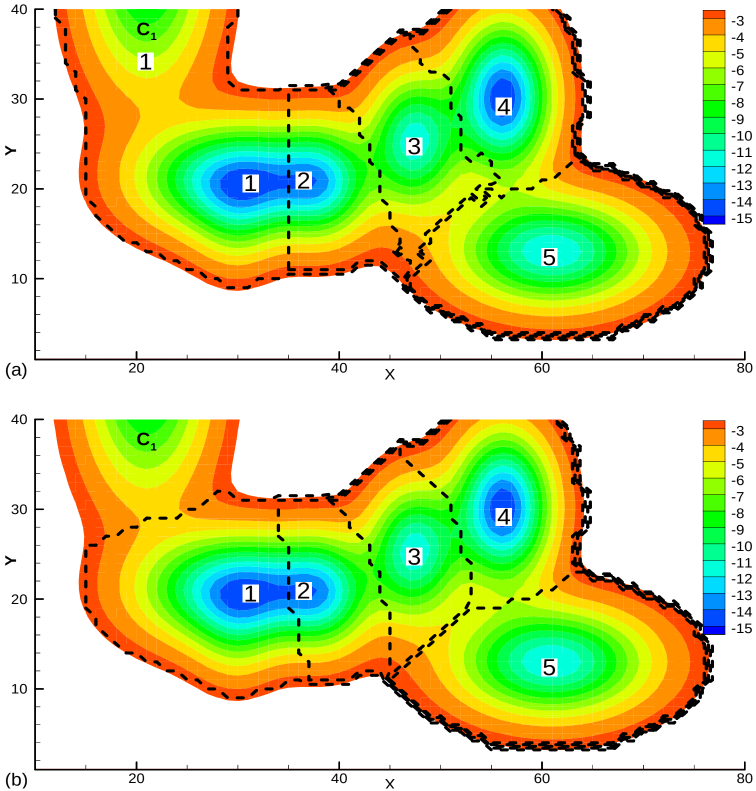

Figure 4. (a) Example of eddy splitting in simply-connected region, where the colour contours represent the SLA, and the numbers identify each eddy. Part of an eddy C_1 is located at ($10 < x < 30$, $30 < y < 40$) in this region. It was recognized as part of eddy 1 according to previous methods. **(b)** Same example as in **(a)** but by present splitting strategy. The new algorithm automatically eliminates eddy C_1 from the present region. The eddy boundaries are smoother in nature than those in **(a)**.

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