We thank Prof. Bowers for your comments and suggestions. In general, we find there is something not clearly described and some figures are not well illuminated. We will modify these in our revision.

Comments For example, figure 2 illustrates how the process works: particles are imagined to roll down slopes into the regions of lowest sea level. In figure 2b, however, the particles don't seem to roll straight down hill. Is this just because the 'pixels' are not square?
Reply : After read your comments and suggestions, we think figure 2b should be redrawn especially by following your suggestions on presenting. The target of splitting algorithm is marking each pixel (grid) as part of proper eddies. Noting that each pixel is surrounded by 8 *discrete* neighbors, the paths are only the connections of the nearest pixels with approximation, when the particles roll straight down hill (in continuous field).
Comments Also, I'm not clear what happens at the 'watershed'. A particle placed on a watershed will not roll either way (unless given a nudge, presumably). Is this how the watershed is defined?
Reply : There are two kinds of 'watershed' in nature division (a ridge between basins / a valley between plateaus). A particle placed on a valley will not roll either way (unless along the valley), but a particle placed on a ridge will easily roll down (given a nudge, presumably) to basins (never along the ridge). In this paper, we do not try to find the exact location of the watershed, but only use the property of watershed (ridge): a particle can't roll across the ridge from one basin to another one.

Comments The figures are supplemented by text in the form of a flow diagram. That's potentially good idea but I don't think it works very well in this case. Perhaps MATLAB code would be clearer?
Reply : Our codes are totally written in Fortran and we do not familiar with MATLAB code. We will try to use flow diagram to show the algorithm more clearly.
Comments I therefore suggest that the authors think of a clearer way of presenting their method.
Reply : Thanks, we will follow your suggestions
Comments I would suggest presenting a two-dimensional grid of numbers with one or two eddies present and show how their strategy would proceed, explaining in terms of the numbers in the grid.
Reply : Thanks for this useful suggestion.

Comments page 1721 'reduce the contour of the SLA' doesn't make any sense. Do you mean reduce 'the number of contours'?
Reply : Yes
Comments page 1722 I don't know what you mean by a 'simply connected set of pixels'. This phrase appears again later in your paper.
Reply : 'simply connected set of pixels' is an objective requirement of eddy definition (e.g. Chelton et al, 2011). This condition assumes that all region of any eddy must be connected, which is something like that domain of a country.
Comments page 1724 line 1 in your steps: why do the eddies have to be cyclonic?

Reply : We are sorry for this unclear. The multi-nuclear problem occurs only when the close eddies have seem polarity (all in cyclonic or all in anti-cyclonic), because the cyclonic eddies can be easily identified from anti-cyclonic ones. We only take cyclonic eddies as examples. If the eddies are anti-cyclonic, the only different is that “fast descent” has to change to “fast ascent”, because the extremes are local maximums and the watershed is a valley now.

Comments figure 1 I’m afraid I don’t understand this diagram and I don’t see how it adds anything that is not covered by figure 2(b). You don’t label you axes. I think you should.

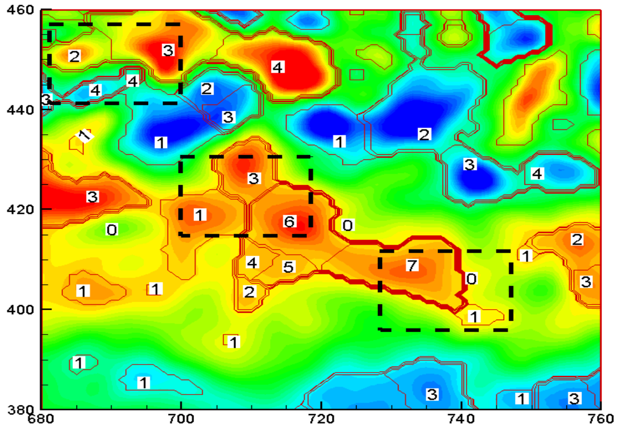
Reply : We are sorry for the unclear. Your suggestion about axes is useful, we will modify it accordingly. The main point of Figure 1 is that if we don’t use splitting method (Fig 1a), the identified eddies will be unexpectedly smaller and weaker than these in Fig 1b (these occurred in previous studies as mentioned in page 2, paragraph 2). However, we tried to explain how this splitting method works in Fig 2b. We are sorry for that the figure 2 is not as clear as we thought. But your above suggestion for presenting will sure be helpful.

We thank the anonymous referee for your comments and suggestions. In general, we find there is something not clearly described and some figures are not well illuminated. We now add some paragraphs and modify the figures in our revision by following your suggestions.

Comments 1 - The study presents a method to detect mesoscale eddies; however, the authors never provide a geophysical definition for such structures. They try to provide one in section 2.2; however, to me, that is rather a functional definition on which the detection method is then based on. All the other studies cited in the manuscript (e.g. Chelton, 2011; Chaigneau, 2008; Nencioli, 2010) first clearly identify what geophysically they consider an eddy (e.g. a coherent structure characterized by water rotating around a common center), and then develop their algorithm accordingly (minimum of OW parameter; spiraling streamlines; rotating velocity vectors around a velocity minimum). Without providing such definition it is hard to understand why this method would provide improved results in terms of eddy shapes and intensity than, for instance, the method by Chaigneau et sal., 2011 (pag. 1721, lines 6-13). More importantly, without such definition it is hard to understand why (for example) the area marked by 2 in Figure 4 should be considered all part of the same eddy. Based on the geophysical definition adopted in previous studies it should not: the area clearly crosses multiple isolines, thus encompassing water masses not rotating around the common center in 2. The same is valid for the area 3. It is important to notice that the study by Haller and Beron-Vera (2013) also cited multiple times in the manuscript, adopts an even more conservative definition: an eddy is not only a rotating structure, but also a structure that retains all its initial mass as it propagates (that's the reason why they are compared to black holes). The eddies identified in figure 4, do not correspond to this definition either. My impression is that the method could be used to identify the areas around single local minima. Then within those areas, one of the existing methods could be used to identify the portion corresponding to a mesoscale eddy.
Reply : Yes, this splitting strategy can be used to identify the areas around single local minima. For isolated mononuclear eddies, all kinds of eddy definitions are approximately similar regardless Geodesic eddy, SSH eddy, OW eddy and ME eddy (see Fig. 8 in Haller and Beron-Vera (2013)), although the Geodesic eddy by Haller and Beron-Vera may look better. We also emphasize that "*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.*" However, the strategy itself is not self-contained for eddy identification. It should be based on an eddy definition; this is what we described in section 2.2. As pointed out and suggested by the reviewer, we now follow the suggestion by providing a geophysical definition for eddies to clarify this.

Comments 2 - At the same time, I am not convinced that the method could work on realistic SLA fields, where local maxima and local minima of SLA coexist. (Note that the examples only show applications to SLA field characterized by negative values). In hydrology, watersheds identify the boundaries between different drainage basins. By definition, they correspond to mountain ridges. Therefore, for the way the method is currently presented, my suspect is that in the presence of local maxima of SLA the boundary of a cyclonic eddy would be identified across such maxima. As such, it is hard

to understand how the method would be capable to identify anticyclones, as well. A more realistic example with a SLA field including both cyclones and anticyclones at the same time should be provided.
Reply : This method works very well on realistic SLA, because local maxima and local minima of SLA are differently treated in the identification method. For example, the SLA of cyclonic eddies are negative below a threshold, and anticyclonic ones are positive above a threshold (e.g. pg 207, "Anticyclonic and cyclonic eddies are defined separately." in CH11). This makes the anticyclonic and cyclonic eddies being divided into different connection regions. We add a description for this at the end of Section 1. We also add a paragraph in section 3.4 to describe how to deal with anticyclonic eddies with this method. The following figure is an example of splitting of SLA on July 5th 2006 with this method.



This is an example of splitting for SLA on July 5th 2006, noting that there are lots of the anticyclonic eddies in the middle of the region.

Comments 3 - Finally, it is really hard to understand sections 3.2 and 3.3, which describe how the method works. I think that paragraphs with proper sentences (instead of the two bullet-lists provided) should be used to describe the algorithm. Please reduce the use of code notation (e.g. i = i+1; if i > n) to the minimum necessary.
Reply : Suggestion followed. We add some paragraphs before the algorithm to describe how it works. And the figures are also modified. We use number to mark the pixels to illuminate how we split the eddy with the algorithm. The algorithm is directly taken from our Fortran program, we hope the algorithm details will be helpful for those who want to write the programs.

Comments Also, the first sentence of section 3.2 says: "For any multinuclear eddy, the following...". Would that multinuclear eddy be detected by your method? If so, how? Or, should another method be applied before applying your method? If so, you should clearly state that your method of detection would not be completely independent/original but it would simply complement one of the existing detection methods.
Reply : The multinuclear eddy could be detected by any method (In fact, nearly all the existed methods can detect multinuclear eddy). In this study, the eddy is identified by only checking the eddy conditions (2) and (3) in section 2.2. A similar method and procedure can be found in CH11. As this paper mainly concerns the splitting method, we

omitted the multinuclear eddy detection. Now we add the detection procedure at the end of section 2.2.

Comments Similarly, point 1 (still on page 1724): "Label the extrema as cyclonic...". How are those extrema identified? No detail is provided.

Reply : We identify the extrema by using the definition in section 2.2 (A point within the region is a local extremum if it has an SLA greater or less than all of its nearest neighbours.). This is very common step in previous SLA based eddy identification methods, so we omitted it. Now we add some explanations both after the definition and at the method in section 2.2.

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; Wang et al., 2015); and 3) hybrid methods, which involve physical parameters and flow geometry characteristics (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; Wang et al., 2015).

A simple method to avoid the problem is to reduce the number of contours 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 eddy parameters (e.g., SLA) are similar to plateaus (anti-cyclonic eddies) and basins (cyclonic eddies) 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. For basins, the 'watershed' is a ridge between them, while it is a valley for plateaus.

In this paper, we do not try to find the exact location of the watersheds, but only use the property of watershed (ridge): a particle can't roll across the ridge from one basin to another one. We use the valley (ridge) to split the anti-cyclonic (cyclonic) multi-nuclear eddy into mononuclear ones. To simplify the descriptions, we use only cyclonic eddies as examples. The anti-cyclonic eddies can be split in a similar way.

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° × 0.25° 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. In general, an eddy is considered as a coherent structure characterized by water rotating around a common center (Chelton et al., 2011; Faghmous et al., 2013), and a structure that retains all its initial mass as it propagates (Haller and Beron-Vera, 2013). 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. We also use such definition of extremum in our following studies, in which the extrema are identified by checking each pixel in the map and the 8 pixels around them. 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 anti-cyclonic (cyclonic) eddies.

(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.

The eddy is identified by the following procedures. First, we find a simply-connected region with a given a threshold. Second, we check whether there is at least one extremum in the region. Then we check whether the region satisfies the eddy conditions (2) and (3). Finally, we check whether the eddy is multinuclear. As both conditions (2) and (3) allow that the eddy is multinuclear, we explicitly add condition (1) as a constraint. However, we need a splitting method to implement this.

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. Fig. 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.

3.2 Eddy splitting procedure

A simple example of the splitting procedure for cyclonic multinuclear eddy is illuminated in Fig. 2c. The procedure for anti-cyclonic one is similar but with a little bit difference in Section 3.4. At first, the extremes with the definition in section 2.2 are labelled as C1 and C2. Then, a path of steepest descent is found from the pixel p_{a1} to C1. Finally, the pixels in the path are marked as C1, i.e., the part of eddy C1. Similarly, the pixel p_{b1} has a path of steepest descent to p_{a3} (which is already marked as C1), thus it is also marked as C1. We descript the above procedure as following algorithm. For any cyclonic multinuclear eddy, the following steps are taken:

(1) Label the extremes 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 i-th 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 i-th 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.

The splitting procedure has two obvious advantages. 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

In the splitting procedure, we need to find a path of steepest descent. Noting that each pixel is surrounded by 8 *discrete* neighbors, the paths are only the connections of the nearest pixels with approximation, when the particles roll straight down hill (in continuous field). A simple example of such path is illuminated in Fig. 2c. The arrows indicate the path of steepest descents from pixel p_1 to the eddy centre C2. In algorithm, 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 m-th 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.

This procedure returns the path of steepest descent of a pixel to the eddy extremum. If a node of the path (e.g. p_{a3}) has already been marked as part of an eddy (e.g. C1), 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. Fig. 3a shows four cyclonic eddies that are difficult to split because they are very close to each other. Li et al. (2014) suggested re-identifying a multinuclear eddy if too many extremes 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.

When the eddies are anti-cyclonic like plateaus, the above method can't be directly used. One may transform the SLA values into negative ones by multiply -1. This data transform is only for eddy splitting. Then above method is valid for these modified data. Alternatively, we can also use the fast ascend method to split the anti-cyclonic eddies by noting that the extremes are local maximal, and that the watersheds are valleys now.

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, 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.

Acknowledgements

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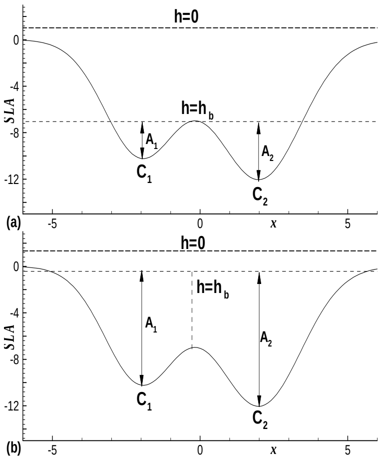

Figure 1. (a) Non-splitting mononuclear eddy identification. (b) Mononuclear eddy identification with splitting. Both the amplitude and the area are quite different in the two methods.

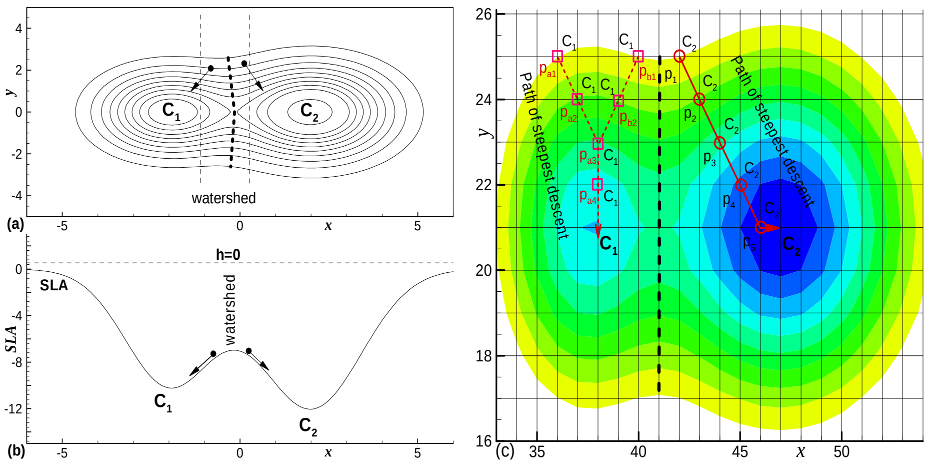

Figure 2. (a) The watershed as the natural division of eddies. (b) The particles on the watershed flow downward to the eddy centres. (c) Sketch map of the fast descent algorithm, where the dashed line indicates the watershed. The squires with arrows are paths to eddy C_1, while the circles with arrows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

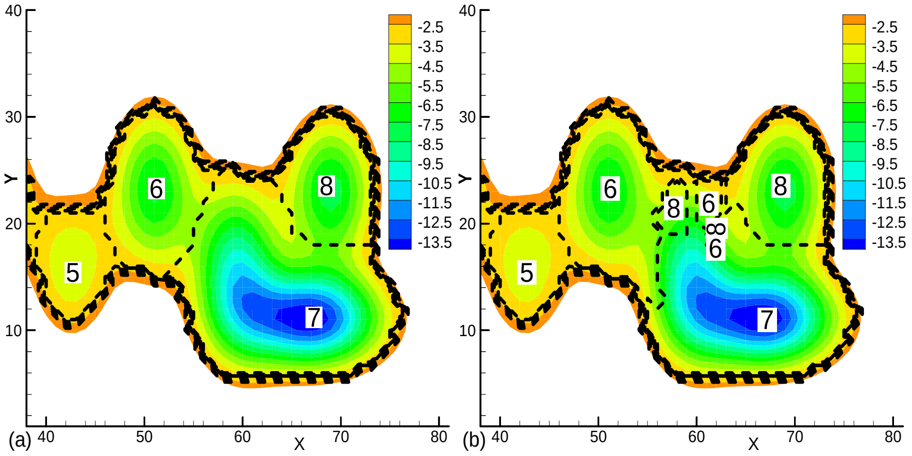

Figure 3. (a) Example of division of a multi-nuclear eddy by present algorithm, where the colour contours represent the SLA, and the numbers identify each eddy. (b) The same example as in (a) but by previous splitting strategies. The eddy boundaries are more zigzag in nature at the vicinity of eddies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

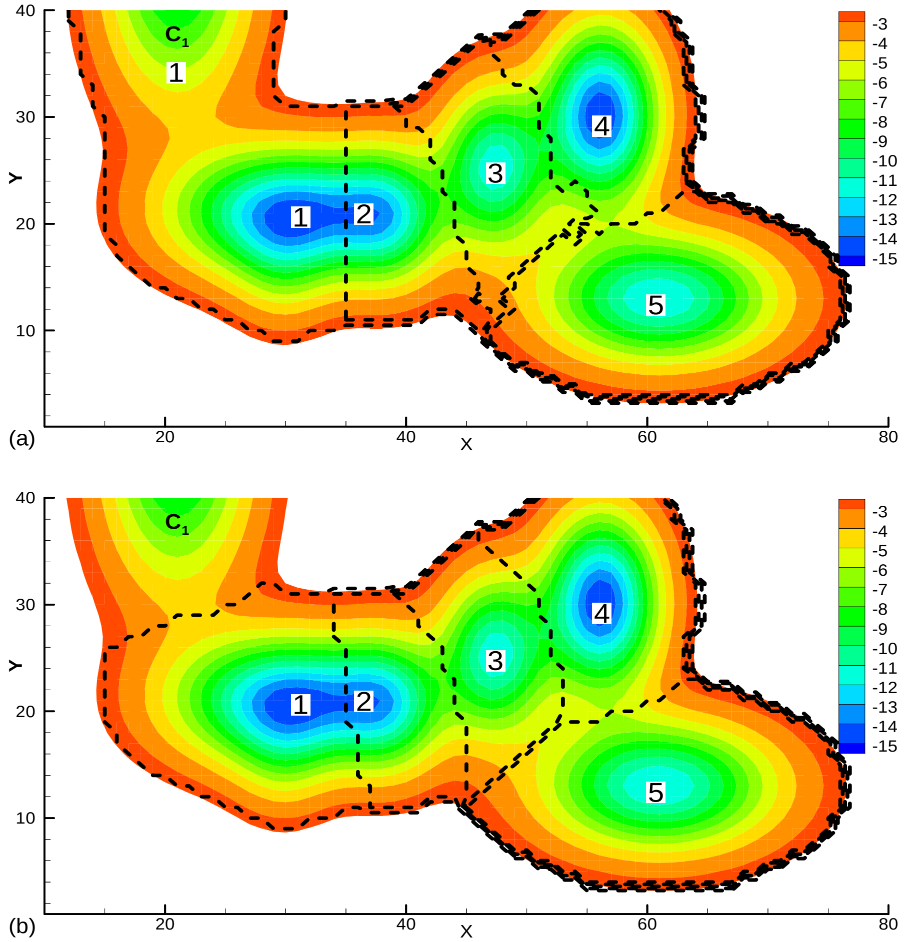

Figure 4. (a) Example of eddy splitting in simply-connected region, where the colour contours represent the SLA, and the numbers identify each eddy. Part of an eddy C_1 is located at $[10<x<30, 30<y<40]$ in this region. It was recognized as part of eddy 1 according to previous methods. (b) Same example 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).