A NEW EDDY DETECTION METHOD WITH OBJECT SEGMENTATION STRATEGIES FOR SATELLITE ALTIMETRY

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ABSTRACT

This paper introduces a new eddy detection method based on object segmentation strategies. It incorporates the advantages of the Okubo-Weiss (OW) method, and improves the algorithm robustness by using three different segmentation methods. First, by intersecting the OW mask with the positive and negative SLA masks, two separate initial eddy candidate segment masks for anticyclonic and cyclonic eddies are produced. Then the number of extrema inside the individual segments is calculated. If the number is two/greater than two, a histogram threshold/watershed method is applied to further divide the segments into sub-segments. If the number is one, the segment is tested by predefined eddy criteria. If the criteria are not fulfilled, the eddy boundary is repeatedly shrunk by one pixel inward until the segment meets all the criteria. In this case it is saved as an eddy. A segment is discarded if the number of extrema is zero. The eddy detection results of this method, of the OW method and of a geometric eddy detection method are displayed and analyzed statistically. The seasonal cycle of eddy number from the three eddy detection methods is discussed in comparison to the EKE.

Index Terms—Mesoscale eddy; automatic detection; object segmentation; Okubo-Weiss

1. INTRODUCTION

Mesoscale eddies are ubiquitous turbulent features in the ocean. They play an important role in ocean circulation, heat and mass transport, and atmospheric boundary phenomena [1]. Satellite altimetry, with unprecedented coverage of the ocean, is a powerful tool for the detection and analysis of eddies around the world's ocean [2].

Although many automatic eddy detection methods, such as Okubo-Weiss (OW) method [3], have been proposed in the past ten years, there are well-documented limitations in many circumstances and oceanic regions [4-6]. This makes researchers seek other methods, such as object segmentation to improve eddy detection [6]. One successful example is Wu [6], she combined a Non-Euclidean Voronoi segmentation technique (NEV) with the region-shrinking method to detect ocean eddies. However, the results of this method heavily depend on the initial segmentation results of NEV; if NEV does not work well, the eddy detection results deteriorate.

This paper introduces a new eddy detection method with object segmentation strategies. Similar to Wu, our method incorporate OW's indication of eddy vorticity, and use segmentation methods applied to Sea Level Anomaly (SLA) and SLA gradient data to mitigate the disadvantages of OW, such as the susceptibility to noise in SLA data and the OW threshold determination problem. Three different object segmentation methods are used to derive eddy candidate segments. In addition, a region-shrinking technique is used to modify the eddy boundaries.

2. METHODOLOGY

Mesoscale eddies are dome- or bowl-shaped structures [4, 6] in the SLA data. In this study, anticyclonic/cyclonic eddies (AE/CE) are defined to have only one maximum/minimum SLA value in its center. Although there is no general agreement among researchers about the eddy boundary definition, we apply the same strategy as Wu [6]: if the eddy candidate fulfills all the predefined eddy criteria, such as eddy amplitude, size, concave or convex shapes, it is saved as an eddy.

The new eddy detection method consists of two steps, including three segmentation methods. First, an OW mask (OM) is created with the same threshold value as Wu (-0.025 δ_w , δ_w is the spatial standard derivation of the OW parameter). Two other masks are calculated by applying a zero threshold to SLA data: a positive SLA mask (PM) for AE, and a negative SLA mask (NM) for CE. Then the 1st segmentation method, which intersects OM with PM and NM, respectively, produces two initial eddy candidate segment mask for AE and CE.

Next, the number of extrema within each obtained segment of both masks is derived. Four different procedures will be invoked corresponding to the number of extrema within the segments (0, 1, 2, and greater than 2):

1) If the number of extrema is 0, this component is not an eddy, and will be discarded.
2) If the number of extrema is 1, this component will be examined to see if it can meet all the predefined criteria of a true eddy, like amplitude, size, concave/convex shapes. If this component fulfills all the criteria, it is saved as an eddy; if the criteria are not met, the eddy boundary will be repeatedly shrunk by one pixel inward until this segment fulfills all the criteria or is discarded. In the first case, it is saved as an eddy.
3) If the number of extrema is 2, the 2nd segmentation is applied, which uses a histogram threshold to divide the component into two parts containing one extremum, respectively. And then return to (2) to identify eddies.
4) If the number of extrema is greater than 2, the 3rd segmentation method is applied that uses a watershed strategy (a method similar to NEV) to divide the segment. And then return to the step of checking extremum number in each segment.

The SLA field is composed of plateaus (AE) and basins (CE) [7]. The watershed algorithm is applied to a cost-distance surface based on SLA gradients. The cost of passing through a pixel A in a cardinal direction is calculated as the sum of the zonal and meridonal gradient vectors across A, and will increase by $\sqrt{2}$ in a diagonal direction. By following the steepest descending path, it is used to allocate each pixel to its closest extremum (the algorithm gives the pixel the same label as its closest extremum). The watershed method works very well when all the extrema are of the same type (maximum or minimum). But if the types of the extrema are different within one eddy candidate area, the watershed algorithm may confuse some boundaries between plateaus and basins [6]. So some pixels may be left unlabeled in some circumstances. In this case, an efficient eddy splitting method is used [8], which assigns the pixel to its nearest extremum by Euclidean distances. On the other hand, when the segment has two extrema, a histogram threshold is used based on one feature of the eddy candidate segment. The two most possible states of a segment with two extrema, which might emerge after the 1st segmentation procedure, are shown in Figure 1. Obviously, more pixels generally exist around the eddy centers (SLA local extrema in the algorithm), so we can apply a histogram threshold, i.e. count the number of pixels in rows and columns, and find the position that has the smallest number of pixels between the two extrema. This position is used to divide the segment into 2 parts. When the segment is rotated, the smallest number is expected to be larger than 1, and the watershed method is used instead to divide the segment.

The entire eddy detection flow chart is shown in Figure 2. The following eddy criteria are used to shrink the eddy candidate segment, which are similar parameters as used by Wu: amplitude > 1cm, size > 8 pixels, and the concave/convex shape criterion (for AE, the average SLA of all pixels at any given distance from the eddy center should decrease as this distance increases; while for CE, the average SLA should increase as the distance to the eddy center increases).

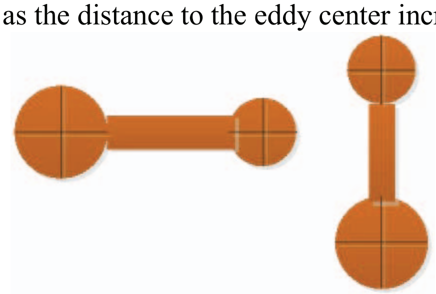

Figure 1 Two most likely states of a segment with two extrema. The crosses represent the eddy centers.

Table 1 Eddy properties obtained from the three automatic methods (only eddies with lifetime larger than 4 weeks are included). Seg represents our method, OW represents OW method, Fag represents the geometric eddy detection method proposed by Faghmous, Frenger, Yao, Warmka, Lindell and Kumar [9], and Chelton represents the method proposed by Chelton, Schlax and Samelson [4]. Amp represents eddy amplitude.

		Identified eddy number	Total observed eddies	Mean duration (days)	Max duration (days)	Mean radius (km)	Max radius (km)	Mean amp (m)	Max amp (m)
Seg	cyc	13295	107048	53.0588	460	64.2267	212.1534	0.0501	0.7838
	anticyc	13276	109202	58.4882	853	63.5898	220.0392	0.0532	0.8711
OW	cyc	10759	67691	54.9887	540	58.6537	152.2817	0.0496	0.6032

	anticyc	10053	68664	59.6777	854	57.8340	168.7686	0.0505	0.5655
Fag	cyc	18719	108157	45.7552	667	215.9647	859.6497	0.0512	1.1626
	anticyc	17557	103630	54.7979	805	223.4916	847.6210	0.0564	1.0956
Chelton	cyc	10263	-	93.4451	1288	91.2054	350.7940	0.0613	1.0261
	anticyc	9713	-	115.9227	1372	89.8088	390.8260	0.0641	0.7208

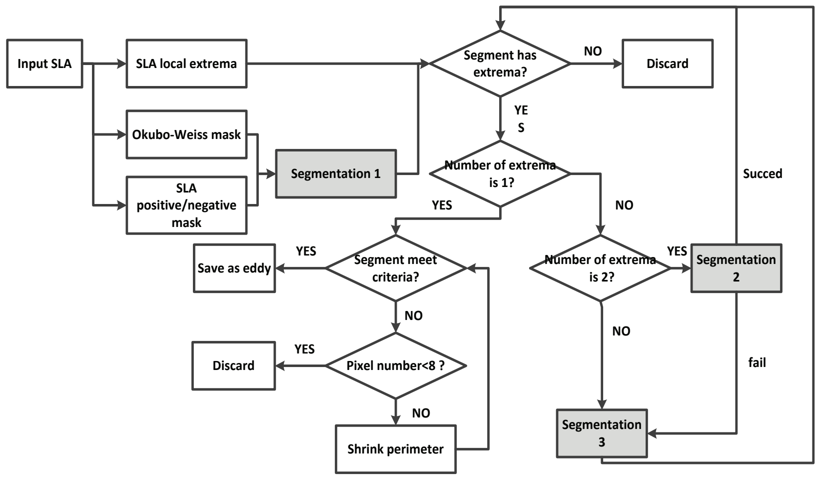

Figure 2 Eddy detection flow chart

3. RESULTS

In order to show the results of the new eddy detection method, the daily AVISO SLA global product (time delayed SSALTO/DUACS multi-mission altimeter product), which combined all available satellite data, and resampled on a 1/4˚x1/4˚ spatial resolution, is used. The SLA data of 11 years (1993-2003) in the North Pacific are processed by the three detection methods. Any eddies with lifetime shorter than 4 weeks are discarded. And the lifetime is determined by the automatic eddy tracking scheme from Faghmous, Frenger, Yao, Warmka, Lindell and Kumar [9].

The eddy detection results of our method (Seg), OW method (the threshold is -0.2 δ_w and -0.1 δ_w) and the geometric eddy detection method proposed by Faghmous, Frenger, Yao, Warmka, Lindell and Kumar [9] (Fag) on August 09, 2000 in the subtropical Pacific ocean are displayed in Figure 3. First, without considering the sizes and shapes of the detected eddies, the positions of CE and AE are mostly consistent in the three methods. And the size of the detected eddies from Fag tends to be larger than those of the other two. The reason might be that Fag defines the outmost SLA closed contour around an extremum as the eddy boundary. The OW method tends to divide larger segments identified as eddies in Fag into several smaller eddies. Reducing the OW threshold by a factor of two does not efficiently enlarge the eddy size, but results in a larger number of smaller eddies.

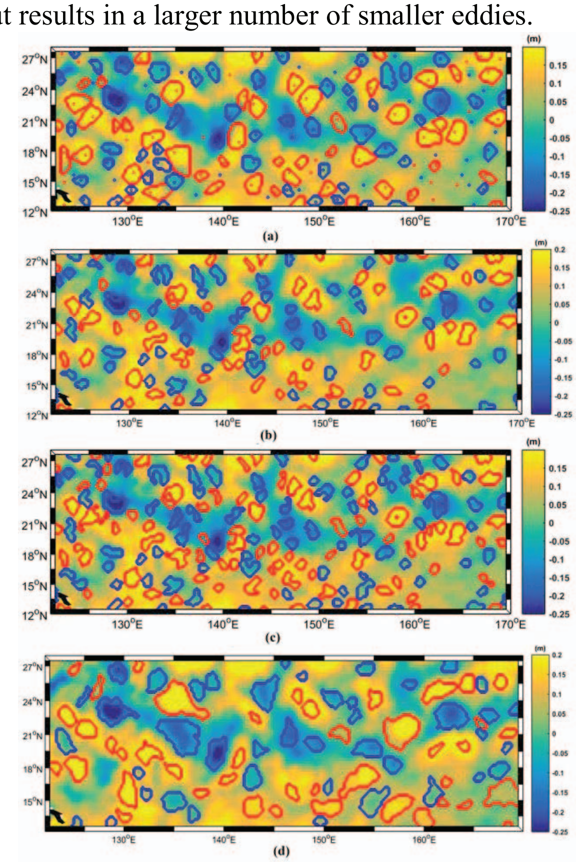

Figure 3 Eddy detection results (solid lines, blue for CE and red for AE) of Seg (a), OW with the threshold -0.2 δ_w (b) and -0.1 δ_w (c), and Fag (d) superimposed on the SLA field on August 09,

2000. The red and blue dots in (a) represent extrema of the SLA field.

Table 1 lists the eddy properties obtained from the three methods (OW threshold is -0.2 δ_w) and Chelton's results. Fag obtains the largest number of eddies, while OW gets the least. The eddy lifetime values of the three methods are consistent. Since [Chelton, Schlax and Samelson [4]] uses weekly SLA data and another eddy tracking algorithm based on a similarity parameter, the eddy lifetime values of the other three methods cannot be compared with Chelton. The mean values of the eddy amplitude of the four methods are similar. Differences in eddy radius and maximum amplitude among the 4 methods might result from eddy boundary definitions and the thresholds of the applied algorithms.

In addition, the seasonal cycle of eddy number from the three eddy detection methods and the eddy kinetic energy (EKE) is shown in Figure 4. We can see that the seasonal cycle of the eddy number from the different eddy detection methods are consistent, despite the different total number of eddies. We note a slight shift by less than a month between the seasonal cycle in EKE and the eddy numbers from the different eddy detection methods. The reason could be that more energetic eddies (with larger amplitudes or sizes) are found later contributing to the shift in the EKE seasonal cycle.

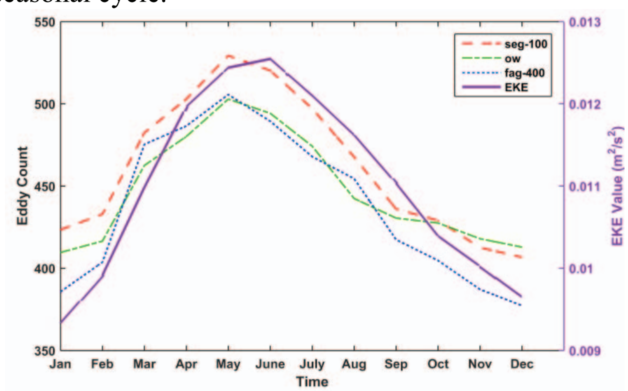

Figure 4 The seasonal cycle of eddy number from the two eddy detection methods and the EKE.

4. CONCLUSIONS AND OUTLOOK

This paper proposes a new eddy detection method which is based on different segmentation methods applied to SLA data combined with the initial use of the OW method to distinguish eddies dominated by high vorticity. Its advantages are: (1) object segmentation and more strict criteria are used so that small regions related to SLA data noise can be discarded; (2) a much smaller OW threshold (about 10 percent of the normal value used by most studies) is used to retain more and larger regions, and let the following object segmentation methods to identify the eddies. In this way, the final eddy detection results are not so susceptible to threshold value as the OW method. In the future, more verification work is needed to test the performances of our method in different marine circumstances, such as the near-coastal areas, regions with energetic currents, as well as the open ocean.

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