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Detection of Mesoscale Eddies through Refined Winding-Angle Method

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***Abstract*—** Winding Angle method is the common eddy detection mode using geometric approach. It is based on the instantaneous streamlines' geometric properties. But the winding angle method works under the assumption, the mesoscale eddies are circular in shape, which is not the case in real time scenarios. In real time, eddies are elongated ones, as ocean flows are turbulent in nature. This restriction of shape may also result in excess/under detection of eddies. In this paper, a refined winding angle method is proposed, which to a great extent attempts to rectify the drawbacks of the original winding angle method. The experiments of the work are done using Sea Level Anomaly Data in the world's biggest bay, Bay of Bengal. The results are verified with the data from Argo float. A detailed comparison of the eddies which are detected using the original method and the refined approach points to the observation, that the eddies detected through the refined approach are elongated in shape. The Successful Detection Rate (SDR) and Excessive Detection Rate (EDR) values are high and low respectively for the proposed refined approach.

Index Terms— *Mesoscale Eddies, Winding Angle, eddy detection, Bay of Bengal*

Introduction

Oceanic currents known as mesoscale eddies are circular or spiral-shaped, occur over distances of tens to hundreds of kilometers, and last for several weeks to months[1]. These eddies are an essential part of ocean circulation and are crucial for the movement of heat, nutrients, and other essential elements throughout the ocean. Understanding how these eddies affect marine ecosystems, weather patterns, and climate change depends on being able to identify them [2]. There are several ways to recognise mesoscale eddies. The most popular techniques include in-person measurements, satellite observations, and numerical simulations. Each of these approaches has benefits and drawbacks of its own. The identification of mesoscale eddies frequently relies on satellite measurements. This approach makes use of altimetry readings to find a variation in sea surface height brought on by eddies. The eddies can be identified by their circular or spiral-like shape and their characteristic patterns of sea surface height anomalies. However, this is limited by the weather conditions of the atmosphere. There are three different eddy detection techniques:

(a) Dynamic approach: In this approach, eddies are found by using dynamic criteria that are based on how ocean currents behave, such as vorticity or divergence. The Okubo-Weiss method [3] and the velocity inversion approach [4] are two instances of dynamic methods.

(b) Geometric approach: Method that uses geometry to find eddies by looking for features like closed contours or spirals. The contour detection method [5] and the winding angle method [6] are two examples of geometric procedures.

(c) Hybrid approach: This approach combines geometric and dynamic criteria to find eddies. The thresholding method and the wavelet transform method are two examples of hybrid methods [7,8].

The Winding Angle (WA) method is regarded as the most accurate among the different types of automatic algorithms, and it has been employed by numerous studies for different sea areas. The WA method has certain inherent flaws despite its remarkable performance. In this work, an attempt is made to overcome the flaws/drawbacks associated with WA method by refining the algorithm to incorporate real time scenarios.

The paper is organized as follows. Section 2 describes a brief overview of the Winding angle methodology, its merits and demerits. The proposed refined winding angle methodology is explained in Section 3. The validation of the refined methodology as well as its comparison with original winding angle approach is detailed in Section 4. The conclusion of the paper is drawn in Section 5.

Winding Angle Method

A common method for finding mesoscale eddies in the water is the winding angle method. It is based on the idea that fluid molecules in an eddy rotate around its centre, causing a recognizable pattern of gradual changes in motion direction. The winding angle method tracks the movement of fluid particles, calculates the rate of rotation, and finds eddies as a result of satellite observations. The ocean surface is divided into small patches for the purpose of the winding angle method, which then tracks the movement of the fluid particles within each patch through time. The process determines the angle between each particle's velocity and a constant reference direction. Typically, a preferred direction is chosen as the reference direction, such as the mean of the flow.

The winding angle is the angle that changes over time. The winding angle will be zero, if the fluid molecule motion is linear. However, the winding angle will grow over time if the particles are rotating around a center. The rate of rotation of the eddy is inversely proportional to the rate of rise in the winding angle. The winding angle approach identifies rotational zones by applying a threshold value to the winding angle. By contrasting the measured winding angles with those anticipated for a completely random motion, this threshold value is typically established. The approach detects areas that are candidates for eddies when the observed winding angles are greater than the threshold value. When determining whether an eddy is cyclonic or anticyclonic, the approach additionally takes the fluid motion's curvature into account. Anticyclonic eddies rotate in the opposite direction as cyclonic eddies, which rotate clockwise in the Northern Hemisphere and anticlockwise in the Southern Hemisphere.

Compared to other eddy detection techniques, the winding angle method provides a number of benefits. It is more stable and trustworthy than techniques that rely on ad hoc criteria since it is based on the conservation of angular momentum, a fundamental physical property. Additionally, small-scale eddies that might be missed by other techniques can be detected. It can also be utilized with in situ and satellite data.

The winding angle method has certain drawbacks, including the assumption that fluid motion is two-dimensional and that each patch experiences a continuous, uniform flow of fluid. Oceanic flows are frequently highly three-dimensional and turbulent in nature, which can lead to variations from the method's idealized motion assumption. For instance, eddies with complicated shapes or those that are extended in the flow direction might not be detectable by the approach. This restriction may cause the size and quantity of eddies to be underestimated, especially in areas where the flow is very variable or where the eddies are not clearly characterized. The spatial and temporal resolution of the observational data using the winding angle method is similarly constrained. Finally, the winding angle method can have difficulties in distinguishing between eddies and other types of coherent structures in the ocean. There have been attempts in literature to improve different aspects of Winding Angle method as seen in [10, 11].

Refined Winding Angle Method

While refining the winding angle, the above mentioned drawbacks are studied in depth and solutions are proposed for the same. The algorithm for the improved winding angle method is a modification of the original winding angle method for identifying and characterizing mesoscale eddies in the ocean. The main modification is the use of an elongated path instead of a circular shape for eddy detection. This modification helps to capture more elongated eddies that would have been missed using the circular shape.

The algorithm starts by inputting the ocean surface current data at a given time and spatial resolution. The data are then divided into patches of the chosen shape and size, and the center streamline is identified for each patch by calculating the median position of all streamlines within the patch. The winding angle is then calculated along each streamline within the patch, using the same method as in the original winding angle method. The key improvement of this method is that the direction and angle in which each streamline crosses the center streamline is counted. If the streamline crosses the center streamline in clockwise direction/anticlockwise in Northern/Southern Hemishpere , it is considered to be part of an anticyclonic eddy. If it crosses an even number of times, it is considered to be part of a cyclonic eddy. This approach helps to avoid over-detection of eddies by only detecting well-defined eddies with a clear center.

The eddy radius, amplitude, and area are then calculated for each identified eddy. The eddy radius is calculated by taking the average distance between the center streamline and all streamlines that are part of the eddy. The eddy amplitude is calculated by taking the maximum value of vorticity within the eddy. The eddy area is calculated by summing the area of all grid cells within the eddy boundary. Once all patches have been analyzed, the locations, radii, amplitudes, and areas of all detected eddies are outputted. This information can be used to study the distribution and properties of mesoscale eddies in the ocean, which play an important role in ocean circulation and biogeochemical cycles.

The summary of the proposed refined algorithm is as follows.

Step1: Input the ocean surface current data at a given time and spatial resolution.

Step2: Choose a patch size and shape for eddy detection. The elongation shape is ensured by inputting an angle which is not equal to 360 degrees.

Step3: Divide the ocean surface into patches of the chosen shape and size.

Step4: For each patch, identify the center streamline by calculating the median position of all streamlines within the patch.

Step 5: Calculate the winding angle along each streamline within the patch, using the same method as in the original winding angle method.

Step 6: For each streamline, count the number of times it crosses the center streamline.

Step 7: If the streamline crosses the center streamline in clockwise direction/anticlockwise, it is considered to be part of an anticyclonic eddy in Northern/Southern Hemisphere. The viceversa is set for the cyclonic eddy.

Step 8: Calculate the eddy radius by taking the average distance between the center streamline and all streamlines that are part of the eddy.

Step 9: Calculate the eddy amplitude by taking the maximum value of vorticity within the eddy.

Step 10: Calculate the eddy area by summing the area of all grid cells within the eddy boundary.

Step 11: Repeat steps 4-10 for all patches in the ocean surface.

Step 12: Output the locations, radii, amplitudes, and areas of all detected eddies.

Table 1: Details of Data

Location- 0° N - 25° N and 75° E - 100° E				
Data	Data type	Spatial resolution	Temporal resolution	Variables
CMEMS reanalysis data	Re- analysis	0.08x0.08 (original grid) 3x3(averaged)	Daily 3 day mean. 2012-2021	SLA, Geostrophic currents (u &v)
ARGO- Float no 2901331	In-situ	BoB	Daily.2012	Float-track, Temperature

Validation

A. Data

The sea level anomaly (SLA) data utilised is gridded data from CMEMS (Copernicus Marine Environment Monitoring Services), which is based on the most recent global real-time forecasting system. The NEMO (Nucleus for European Modelling of Ocean) platform is the model component, and it is surface-driven by current ECMWF ERA-Interim and ERA5 reanalyses. A reduced-order Kalman filter is used to include the observations. Vertical profiles of in-situ temperature and salinity are combined with along track altimeter data (sea level anomaly), satellite sea surface temperature, sea ice concentration, and in-situ temperature and salinity. We employed the sea level anomaly (SLA) and geostrophic currents in 2012, which were spatially averaged into 1x1 regular grids and temporally into daily, for the eddy tracking and its mean parameters. The region of the study is Bay of Bengal [12] as given in Figure 1. The details of data used in the study are given in Table 1.

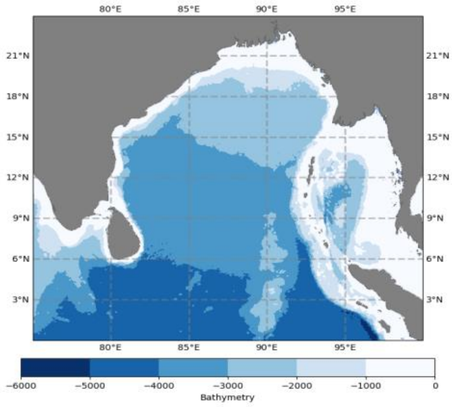

Figure 1: Region of Study overlaid with bathymetry

B. Comparison with Original WA method

In order to highlight the benefits of the refined WA approach, a thorough comparison of the old and new techniques is made in terms of the discovery of eddies.

The shape of eddies detected in the original method and the refined method are presented in Figure 2. The eddies detected by the original WA method as seen in Figure 2(a) are closed circles, which is far from the real time scenarios. However, in the refined method, the eddy shapes are in an elongated manner, as depicted in Figure 2(b), which is much closer to the real time situation. It is also observed in Figure 2(b) that eddies are detected more successfully than in the other scenario.

A selection of examples from the two strategies is shown in Figure 3. For the original method, various identifications with various thresholds are shown in Figure 3(a). Some of the eddies were correctly grouped when the threshold was set to above 50 km as radius. There are also instances of certain eddies being wrongly detected.

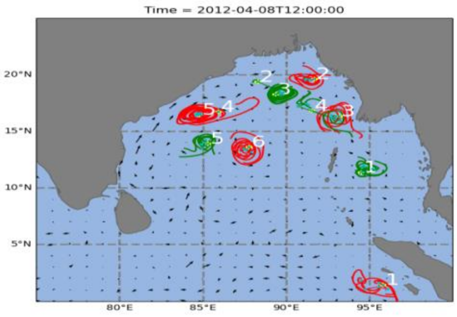

Figure 2(a): Eddy in Circuar shape using original winding angle method

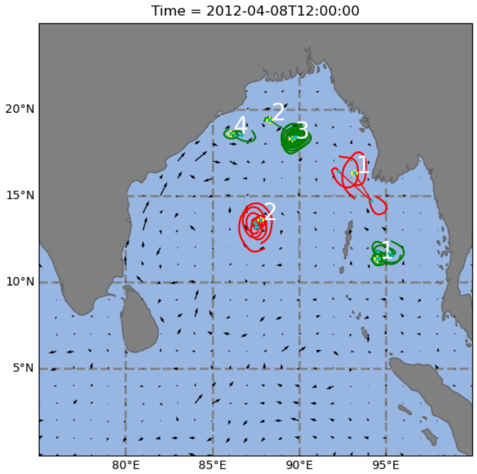

Figure 2(b): Eddy with elogated shape with using refined winding angle method

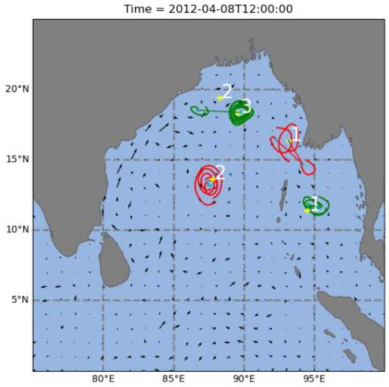

Figure 3(a): Eddy Radius > 50 km using WA method

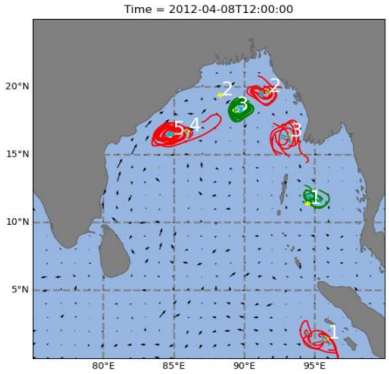

Figure 3(b): Eddy Radius > 50 km using refined WA method

The next experiment is based on the number of eddies which has been detected successfully and excessively, which is being defined as follows.

(i) Successful Detection Rate (SDR)= Number of successful eddies identified by the method/ Number of eddies identified by the experts.

(ii) Excess Detection Rate (EDR)= Number of excess eddies identified by the method/ Number of eddies identified by the experts.

The proposed refined WA (R-WA) method and the original WA method are compared in terms of the number of eddies detected and is described in Table 2. The number of eddies detected by the original WA method are 117 and that of the proposed R-WA method is 220. The highlight is in terms of the number of eddies detected in common and excess. The number of eddies detected in the original method is 77 and that of R-WA is 176, which is quite near to the actual number of eddy count(180). Another point worth noting is that the number of excess eddies detected is also less for R-WA method. To further analyze the results in details, the Successful Detection Rate (SDR) and the Excess Detection Rate (EDR) is studied. The results SDR and EDR [9] of the original WA and the refined WA are presented in Table 3. It is observed that the refined WA has high SDR and less EDR as compared to the original one.

Table 2: Comparison of number of eddies detected.

Method	*Total Eddies*	*Common*	*Excess*
WA	117	77	40
R-WA	220	176	44
Actual Eddies	180		

Table 3: Comparison of SDR and EDR

Method	*SDR*	*EDR*
WA	42.7%	22.2%
R-WA	97%	24%

To confirm the efficacy of the refined WA approach, the results are compared with compared with Argo float data and conclusions are drawn. The vertical profile of temperature and float track from the ARGO buoy for the months April and May 2012 is taken for analysis. The track of the Argo float is depicted in Figure 4(a). The eddies detected for 6th May 2012 using refined WA method is plotted in Figure 4(b). The figure shows that the distribution of ACEs (red contours) is in the track of the Argo float. Vertical profile of temperature from the ARGO shows the down sloping of isotherms during second half of April to first week of May, further confirmed the presence of ACEs as can be seen from Figure 4(c).

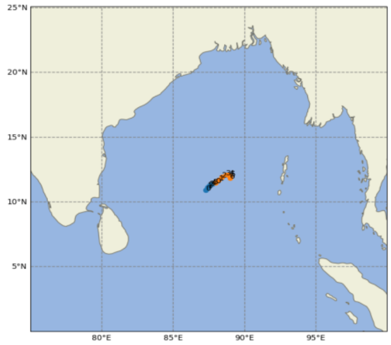

Figure 4(a): ARGO float no 2901331

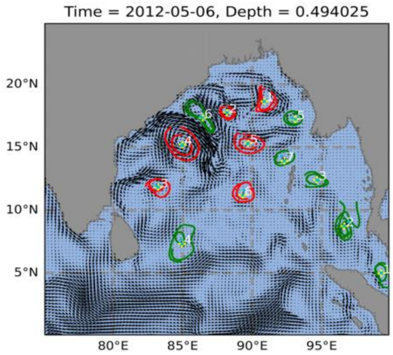

Figure 4(b): Eddies using Refined WA method

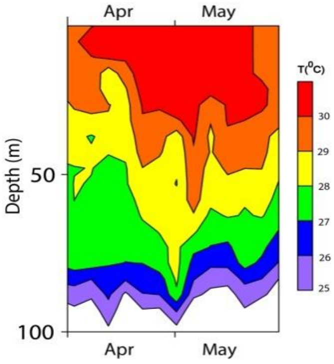

Figure 4(c): Vertical profile of temperature

II. Conclusion

In this paper, an algorithm is proposed to identify real time eddies by refining Winding Angle method. The algorithm proposes refinement in two concepts, ie, (a) eddies are not circular in shape, in real time scenarios, they are elongated, stretched and distorted and (b) the excess detection of eddies in the refined approach is minimized defining the closeness of the streamline centres. The experiments are conducted on the SLA data of Bay of Bengal. Validation of the experiments is performed by verifying the eddies detected using the track data of Argo float. A comparison of the results from the refined WA method with the original method is also summarized in the work. Results show that the proposed refined WA method outperforms the original WA method in terms of shape and has high SDR along with a low EDR. Future research directions include applying artificial intelligence techniques to detect eddies from the SLA data using automated techniques and also improve the accuracy of eddy detection.

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