Segmentation and Tracking of Mesoscale Eddies in Numeric Ocean Models

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Abstract

An adequate understanding of climate variability and the eventual prediction of climate change are among the most urgent and far-reaching efforts of the scientific community.. Measurements done to-date have suggested that the mesoscale eddies and mesoscale features play a strong role in carrying heat poleward. Oceanographic visualizations may play a key role in unraveling these mysteries. In this paper we propose techniques for the automated detection, segmentation and tracking of these eddies. A structuring element based on velocity data is designed to detect centers of eddies. Best fitting ellipses/circular donuts are determined to outline and segment out the region of swirling currents around the detected centers. Segmented images from consecutive days of data are used to track eddies temporally. Small-motion assumption is used to track the full trajectory of the eddies. Visualizations resulting from this project will provide oceanographers an invaluable tool to assess mesoscale eddies and the Lagrangian characteristics of this mesoscale oceanic feature.

1. INTRODUCTION

MICOM is one of models, where the resolution of the numerical experiments is high enough to resolve the mesoscale eddies. The Miami Isopycnic Coordinate Ocean Model is a numeric data model of the North Atlantic Ocean that provides us high resolution data of ocean velocities, temperature etc. This data is available in both temporal and spatial scales. Mesoscale eddies are those vortices whose size varies from a few kilometers to a few hundred kilometers. These eddies contain large kinetic energy, comparable with that of the time averaged ocean circulation. They are crucial to the transport of heat, momentum, trace chemicals, biological communities, and the oxygen and nutrients relating to life in the sea. As a member of the huge family of turbulent motions, eddies contribute to the stirring and mixing of the oceans, to the creation of its basic, layered density field, and to its general circulation.

The enormity of a High resolution data makes it difficult and expensive in terms of power and time consumed for computations but a quantitative diagnostics on high-resolution numerical ocean models are necessary for testing and improving the fidelity of the numerical models. Here we will investigate six physical variables: temperature, salinity, layer depth, horizontal velocity components, and surface mixed layer. In addition to these basic variables we are also interested in other derived variables such as heat flux (velocity and temperature gradient), fresh water flux (velocity and salinity gradient), momentum flux (mechanical stress on layers), layer volume (change over time with respect to temperature, salinity and velocity, all of which can affect the layer volume).

For the purpose of our study we initially considered two metrics, namely the Poleward Heatflux and the EastWard Heatflux. The fluxes provide a measure for heat transport for each Latitude and Longitude and are an important metrics. The graphs produced with the help of these matrices were not very helpful for the purpose of visualization and thus in order to better Visualize, we break down the metrics down to their fundamental components and form a new metrics. Using this new metrics we propose to identify the mesoscale eddies in such models using visualization techniques, collect statistics on them and track their evolution temporally. While such diagnostics have been done manually in piecemeal fashion, this process has not been automated to-date with visualization methods.

2. PREVIOUS WORK

This section highlights some of the work in the general area of ocean-data visualization, recent research work on eddy detection and tracking techniques for oceanic datasets. Visualization techniques used for ocean data have included - trivariate (B-Splines) parametric representation of data [7], feature based visualization for tracking sea surface temperature [8], and measurement and analysis of feature velocities. Various visualization methods adopted for vortex detection and technique include - vortex detection in 2D velocity fields, based on the macroscopic geometric properties of streamlines [9], Structure approximation using an energy minimization process and tracking is modeled using the displacements of the control points and the variation of the radii of influence [10]. To assess the role of oceans in maintaining the global heat balance, three methods have been used in the recent years [3]. One of these is the direct method, which deals with the product of ocean velocity and temperature measured over the boundaries of a closed volume. These are integrated to determine the ocean heat transport divergence for the volume. One of the

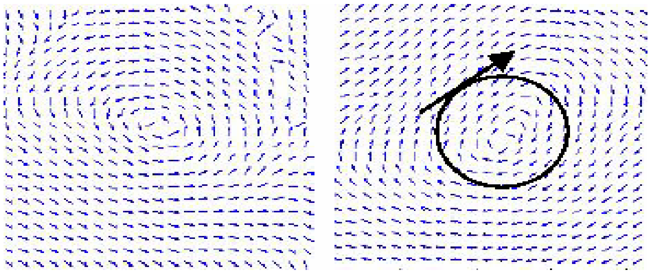


Figure 1 Observed flow field of an eddy

concerns while doing the direct estimates of the ocean heat transport is the role of eddy fluxes and the validity of the circulation scheme. Our ultimate goal is to be able to understand the role of eddies by detecting and following their motion. Here we summarize other recent studies that involve eddy detection, numerically as well as using remotely sensed data. In recent numerical studies, synthetic floats have been released in an ocean general circulation models. One such paper studies fluid pathways followed by the upper limb of the Atlantic Ocean meridional overturning circulation (MOC) [4]. Observationally, eddies are ubiquitous feature of the circulation in the ocean, e.g. southeastern Bering Sea [6]. Bering Sea eddies have been detected by the near-circular trajectories of satellite-tracked drifting buoys that were entrained within them or from radially symmetric geostrophic velocity cross sections inferred from water density as measured by CTD casts. Eddy detection is also frequently done for the remotely sensed data.

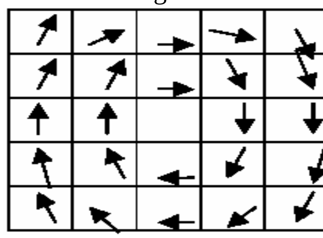
3. METHODOLOGY AND ALGORITHMS

Eddy detection using structuring elements were presented in [1,2] in the MICOM data. The issues of Eddy segmentation and motion trajectories were not discussed however. To establish continuity and context they are discussed briefly here. To build an algorithm that automatically locates an eddy in the ocean; we need to address an important question. What makes eddies different from other regions in the ocean? A pattern has to be established that is, first, consistent with all eddies in the ocean, and second, unique to regions belonging to those of eddies alone. Establishing this rigid pattern is essential in designing a successful search algorithm that generates minimal false positives and false negatives. The direction of the ocean current at any point is computable from the eastward and northward components of the velocities. The flux components were normalized to focus our attention to direction of currents, and not the magnitude of currents. The quiver plot of an eddy shows a pattern of swirling currents as expected from the center of an eddy and this pattern was noticed to be extremely consistent of all eddies in the MICOM simulations. It was decided to use direction of currents in designing the search pattern.

3.1 Designing the structuring element

To understand our structuring element matrix, consider a large circle drawn from the center of an eddy as shown in Figure 1. If a comparison were to be made with the direction of the tangent at any point on the imaginary circle, and the direction of the current at that particular point, the values of the angles were very close to each other, with an error of say *e*.

It was observed that irrespective of the shape of the eddy, if this circle was chosen to be drawn close to the center, the values of *e* at points on that circle would be quite low. This motivated building a structuring element to search for centers of eddies by examining a neighborhood of 5x5 grid points to determine how likely a center of an eddy would be present in that region. A synthetic eddy structure is shown in Figure 2a.



45	26	0	333	315
63	45	0	315	296
90	90		270	270
116	135	180	225	243
135	153	180	206	225

Figure 2a & b Eddy structure and Structuring Element.

The structuring element is in fact a numeric stencil of a circular clockwise eddy with the center of the eddy placed at the center of the matrix (shown in Figure 2b). The numbers around the center represent the direction of current (in degrees) of that location. A similar structuring element was developed for counter clockwise eddies. Error measurements from these 24 values were used to determine whether a point in the ocean was likely to be a center of an eddy. The eddy detection procedure was executed on several layers for many days of data and highly satisfactory results were obtained (verified manually and numerically). Table 1. provides statistics on a subset of the data tested for the accuracy of the Eddy detection process. Once the center of an eddy was known, an examination of the velocity vector fields around its vicinity was made using stream plots, quiver and cone plots. The streamline plots thus generated in the vector field provides confirmation that the region detected by our algorithm was actually those of eddies. Our detection procedure pinpoints centers of eddies. However it does not tell us how far from the center the eddy extends.

Days/Layers	Number of Eddies Present	Number of Eddies Detected	Percentage Accuracy
D 27/ L 4	140	130	93%
D 12/ L 12	118	107	91%
D 24/ L 4	1059	872	83%
D 33/ L 8	575	498	87%

Table 1 – Accuracy of the Eddy detection procedure on a subset of the data.

3.2 Eddy Segmentation

After identifying the points that are centers of eddies, the task of identifying the points that lie within this eddy and those outside need to be distinguished clearly. In an attempt to develop a technique to create this demarcation, pseudocolor plots of velocities and temperature were examined. As expected, the velocities are small at the center of an eddy and increases radially outward until a certain distance. The currents within this distance continue to flow around the center. Beyond this point currents are less influenced by the eddy and do not swirl around the center. Figure 6. illustrates the problem of segmenting the eddy.

Determining this distance may suffice in drawing the border of the eddy, for our purposes. Another approach would be to draw borders based on temperature variations. However this approach brought many challenges and do not always correspond to the velocity information, which is far more accurate for eddy segmentation.

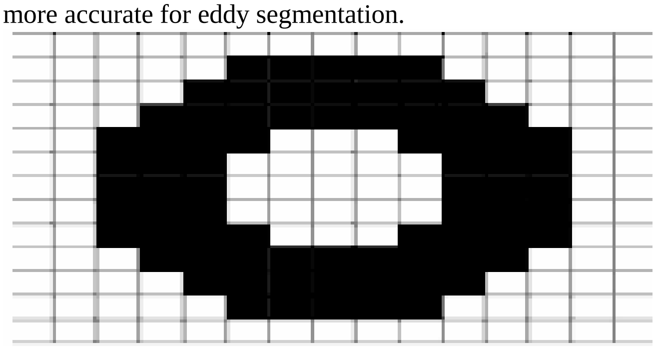


Figure 4 Donut shaped structuring element of radius 4 with 76 sample points

In the proposed approach, a mean radius of an eddy is estimated statistically from velocity direction information. The technique described here attempts to encompass the irregular shape of an eddy as much as possible, with a best fitting circle. To determine whether the eddy still extends beyond the distance say d from the center, three consecutive circles of radius d, d+1 and d-1 were used to form a ring on which current directions were sampled. Figure 4 shows a sample donut shape of the stencil used to determine the eddy boundaries.

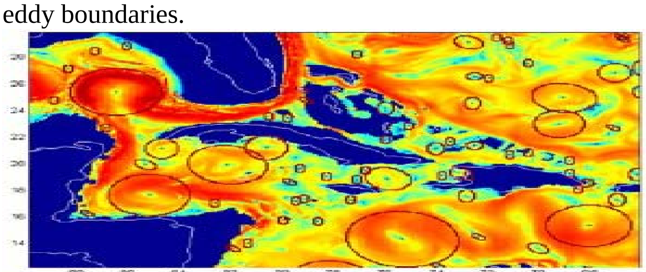


Figure 5 Eddy Bounded by the best fitting ellipse

The difference (in degrees) of the direction of ocean current at the point in the donut, and, the direction of the tangent to the donut is examined for all sample points within the donut. Histograms of the difference of these points were examined for each eddy, at different distances from the center. It was observed that at a distance where the mean difference were less than 45 degrees and the standard deviation of the errors were less than 29, the best fitting circle could be drawn. Figure 5 shows the detected and segmented eddies in a pseudocolor plot of the log-velocity of the ocean currents.

The red regions show areas of faster ocean currents, while the green and blue regions are those of slower or no ocean currents. The plot shows the eddies detected in layer 4 in the region south of Florida. The eddies are bounded by a best fitting circle.

3.3 Eddy tracking

Segmenting out areas in the ocean that belong to eddies gives a handle to our region of interest. To establish the

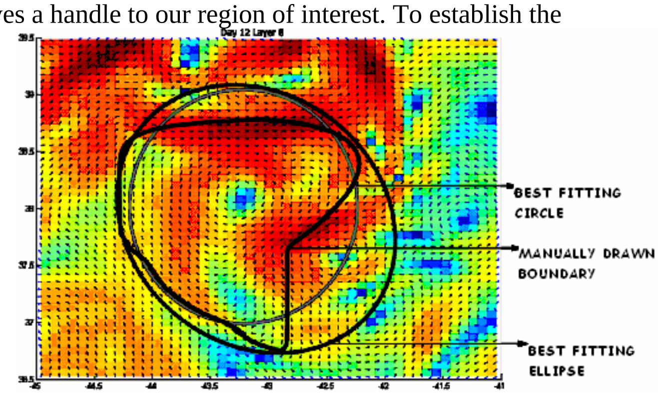


Figure 6 Pseudo color plot of different types of eddy segmentation.

correspondence between eddies in successive days; a *small motion* assumption was made. From the analysis of edidies in different frames, we concluded that we expected to find the eddy in close vicinity to the point it was observed in the previous day. A search window of 7 by 7 grid points was symmetrically placed around each of the points where eddy centers were located. The size of the window was computed from the maximum displacement an eddy would make in 2 consecutive frames. In subsequent frames, the closest eddy detected within this window was detected and marked as the corresponding eddy in the next day. Centers of both eddies were connected using a straight line to plot the trajectory. The biggest drawback of the above mentioned method was that it assumed that while tracking an eddy in a window of 7x7 there cannot be any other eddy center in that area. It assumes that all eddies move in the north-east direction and always corresponds to the first found eddy in the window. To improve upon the method a feature based mapping technique was developed. In the feature based tracking we try to characterize each eddy. This procedure requires finding out the characteristic feature of an eddy which prevail consistently for at least two consecutive frames. We manually tracked eddies for a period of 10 frames and found out that the two most consistent variables that could be used for this characterization are eddy-orientation and the eddy-area.

The process of tracking remains same as before where we use a window of 7x7 to track eddies. The segmented files for 2 concurrent days are loaded and for each eddy center in the first day the corresponding eddy center in the second day is searched using the small motion assumption. Once all the potential eddy centers (The centers where the eddy in the first day could have moved too) have been marked in the given window they are checked for the orientation. If the orientation of 2 or more matches the orientation of the eddy then the second test is done i.e. area is matched with acceptable difference of 2 Deltas* (*Delta is the resolution of the dataset along the Longitude and Latitude). If there still remains any ambiguity in the correspondence of eddies between frames the eddy closest to the eddy center in the earlier frame is chosen and a line is drawn between the eddy centers in two frames.

4. RESULTS

We are now able to plot the trajectory of the eddies in a video sequence of a layer of the ocean. Figure 7 shows the result of the eddy tracking. From the temporal data available, a frame similar to the above picture was made for every three days. A movie showing the motion of the eddies with their trajectories highlighted was generated using this tracking algorithm and is available for viewing upon request.

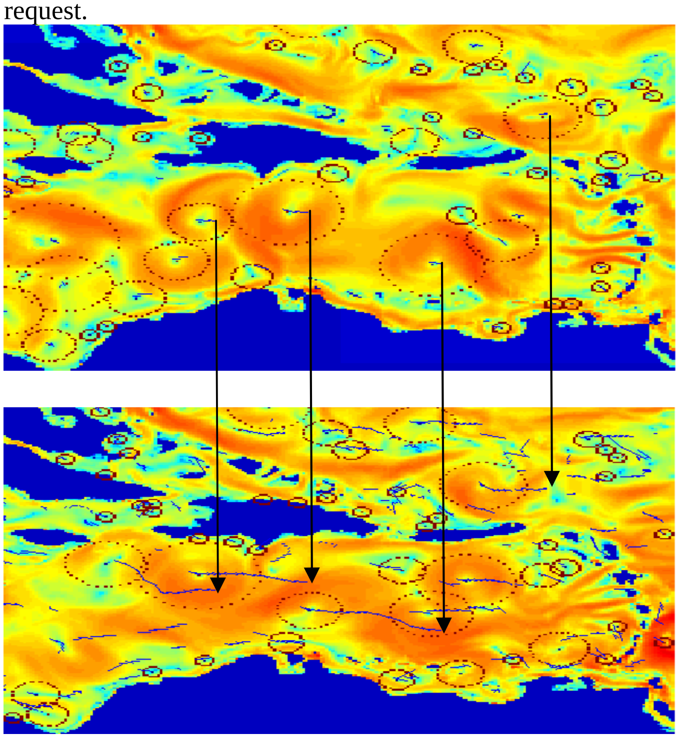


Figure 7 results of automated tracking

Window size	Type of Algorithm	Percentage accuracy
7 delta	Nearest Neighbor	85.84 %
7 delta	Feature Based	97.67 %
9 delta	Nearest Neighbor	82.34 %
9 delta	Feature Based	99.41 %

Table 2 comparison of results for nearest neighbor and feature based techniques for eddy tracking

A study was done where we tracked 120 eddies for 10 frames using the nearest neighbor and featured based algorithms and the results are shown in Table 2. As we increased the window size the efficiency of the nearest neighbor method decreased where as the feature based method improved. If we further increased the size of our search window the efficiency did not improve but the processing time increased by a great amount.

5. CONCLUSIONS AND FUTURE WORK

In this work we have demonstrated ways of segmenting and tracking mesoscale eddies in MICOM. Methods developed in this work for identifying, segmenting and tracking eddies will be extremely useful for Oceanographers in understanding the role of eddies in the transportation of heat Poleward. In the future, a motion description of the eddies, their lifespan and quantitative estimates of heat, from the visualization rather than numeric data are to be explored. Though the methods were developed using the MICOM data, they can be easily ported to many numeric ocean models.

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