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Extracting, Visualizing and Tracking Mesoscale Ocean Eddies in Two-dimensional Image Sequences Using Contours and Moments

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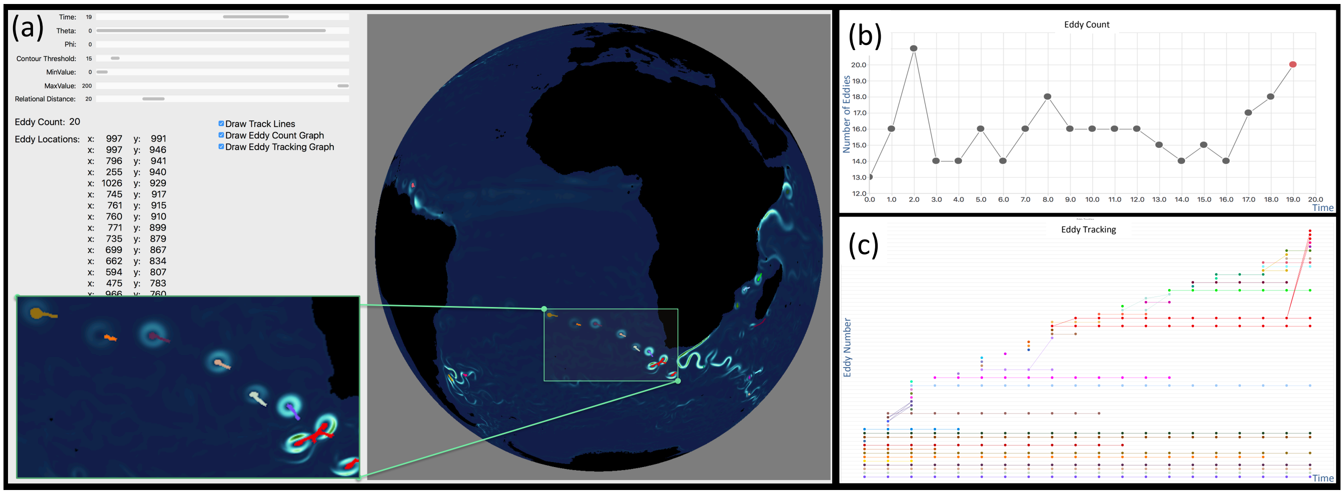
Time: 19
Theta: 0
Phi: 0
Contour Threshold: 15
MinValue: 0
MaxValue: 200
Relational Distance: 20

Eddy Count: 20

Eddy Locations:				
	x:	997	y:	991
	x:	997	y:	946
	x:	796	y:	941
	x:	255	y:	940
	x:	1026	y:	929
	x:	745	y:	917
	x:	761	y:	915
	x:	760	y:	910
	x:	771	y:	899
	x:	735	y:	879
	x:	699	y:	867
	x:	662	y:	834
	x:	594	y:	807
	x:	475	y:	783
	x:	966	y:	760

☑ Draw Track Lines
☑ Draw Eddy Count Graph
☑ Draw Eddy Tracking Graph

Figure 1: *The three Analysis Interface Viewers (a,b,c) show the various aspects of the eddy analysis system, using the kinetic energy parameter of an ocean simulation. In the Main View (a), a user can select values for Time, Theta and Phi (to select a camera angle of the simulation) and display a particular image selected from the Cinema database. The user sets the parameter values needed for feature detection and moment computations to select the desired eddy structures. Detailed information about the number of eddies located in the image and their positions is provided. A closeup of the eddies being tracked, with a trail of their last five locations is shown here. The Eddy Count Graph View (b) provides a line plot showing the number of eddies for all timesteps, from timestep zero to the current timestep (in red). As the Time scrollbar is moved in The Main View, the Eddy Count Graph is updated accordingly. The Eddy Tracking Graph View (c) is also updated following changes to parameter values in the Main View. This view shows the history of all detected and tracked eddies.*

Abstract

We introduce a system to extract and track mesoscale eddies captured in massive global ocean simulations. The major strength and contribution of our system is its design, which is based on two-dimensional image data processing. The Cinema database [CD] enables the generation and storage of two-dimensional image data taken in-situ, i.e., the creation of images via a virtual camera generating images during the ongoing simulation. The problem of eddy extraction and tracking is simplified by our approach to the problem of finding, matching and tracking eddies in two-dimensional images, thus eliminating the task of processing the original three-dimensional data set. Our system can be used on a simple desktop computer and provides an intuitive interface allowing a scientist to perform an eddy analysis for global ocean data in real-time. We demonstrate the effectiveness of our implementation for a specific simulated data set.

Categories and Subject Descriptors (according to ACM CCS): Image Processing and Computer Vision [I.4.8]: Scene Analysis—Object recognition, Time-varying imagery, Tracking Information Interfaces and Presentation [H.5.2]: User Interfaces—Graphical user interfaces (GUI); Artificial Intelligence [I.2.10]: Vision and Scene Understanding—Modeling and recovery of physical attributes Database management [H.2.8]: Database Applications—Image Databases

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1. Introduction and Background

Mesoscale eddies are vortices of water in the ocean, up to 150km in diameter, that can travel hundreds of miles over hundreds of days [WPS*16]. Observations and modeling of ocean eddies have shown that they have impact on the marine biosphere [CGS*11, GCSB13, MPM08], modulate exchanges between ocean basins [WDRSD02,BDRB*11], significantly contribute to equator-to-pole heat transport variability [VLF08], and interact with topography to catalyze the dissipation of ocean energy [DH10, HDBW11]. Eddies also play a significant role in transporting pollutants from man-made disasters, e.g., the Fukushima Nuclear Power Plant accident [BGK*15] or the Deep Water Horizon oil spill [WPR*11]. Eddies play a role in processes on a broad range of space and time scales, and are relevant to several scientific disciplines.

A mathematically rigorous, universally accepted definition of and methodology for extracting ocean eddies from data does not exist, though several successful strategies have been devised [FFY*15]. Mason et al. [MPM14] summarized commonly used approaches. Early applications of automated eddy detection focused on following closed contours resulting from the Okubo-Weiss parameter [IFGLF03,WHP*11,WPB*11,PWM*13], which measures rotational behavior in a turbulent fluid. This method is quite sensitive to noise due to use of discrete, finite difference approximations for derivatives. Chelton et al. [CGS*11] applied a geometrical approach based directly on the sea-surface height field, eliminating the need for such approximations. Further, wavelet analysis has provided an efficient approach for identifying localized coherent structures [DBSL07]. All these methods have proven to be successful for detecting eddies. However, they are typically applied to regional data or coarse-resolution global data, limiting their general applicability. Furthermore, eddy detection can be labor-intensive and time-consuming, often requiring high-performance computing support in addition to significant in-person time [WPS*16]. As numerical simulations of the global ocean are using increasingly higher resolutions in space and time, they produce ever larger amounts of data, ranging from several gigabytes to terabytes of data. Extracting eddies from such simulated data sets can require hours to days of data processing time when using traditional numerical analysis approaches. Clearly, there exists a need for robust and efficient tools to obtain the desired and valuable information captured in such simulations.

We present a system that uses in-situ visualization and computer vision techniques to overcome the disk-space and processing-time restrictions that limit most common approaches. During an ongoing simulation, ParaView Catalyst [FMT*11, Par], an in-situ visualization API, extracts important information and stores it in a Cinema image database [CD]. This reduces a simulation of disk-space 10^{15} to a data set of 10^6 [AJO*14]. Our eddy detection method, in contrast to many standard tools, uses an effective combination of computer vision techniques, i.e., contour detection and image moments, to extract and track features of interest, eddies in our case. Our implementation generates analysis results in real-time and can be performed on a personal computer. We describe the design of our interactive analysis system, driven by the goal to detect and track eddies captured in large time-varying ocean simulations. Previous techniques to extract and track regions from time-varying data [PVH*03, PVH*03, AMST11, RPS01, SSZC94] generally rely on vector-field or gridded data, while we apply our technique to scalar-field data from 2D images.

2. System Design

The Eddy Analysis System has two main components, the Data Generation and an Analysis Interface.

2.1. Data Generation

Catalyst is an in-situ tool to extract a Cinema database as a simulation runs. Our database is of an MPAS-Ocean [MD] model, an earth-system simulation for ocean and climate studies. As eddies have high rotational and translational velocity, they are particularly well-defined by the kinetic energy field [WMZ07]. Therefore, we use a Cinema database of this parameter, though any parameter where eddies are well-defined could be utilized. This particular ocean simulation is 15km resolution, consists of 29 timesteps, each five days apart and contains only the uppermost sea-surface layer of MPAS. The parameters used for this MPAS-Ocean simulation are typical of simulations commonly used by oceanographers.

To generate a Cinema Database for the provided simulation, Catalyst places a camera at evenly distributed points on a bounding sphere around the simulation domain. The coordinates of the cameras are defined by angles theta and phi. From each point, a 'snapshot image' is taken for each timestep [KY14], see Figure 2(a). Each image is generated as a 2D perspective projection of the simulation, with each pixel storing the corresponding value of the simulation data, see Figure 2(b). Since each image is tagged with the corresponding theta, phi and time values, they can be easily parsed and analyzed in the Analysis Interface.

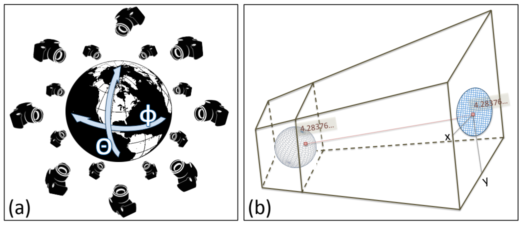

Figure 2: *Cameras are placed at evenly spaced theta and phi angle locations to capture the simulation (a). For each image, the simulation is projected into the 2D image plane, where every pixel in the image stores the corresponding data value (b).*

2.2. Analysis Interface

The Cinema database is loaded into the Analysis Interface, consisting of three main components: the Main View, the Eddy Count Graph View and the Eddy Tracking Graph View (see Figure 1). A supplementary video of the various components is also provided.

2.2.1. The Main View

Eddies are detected in each Cinema image by using a combination of contour extraction/thresholding and image moment computation [FZS16]. Using the scrollbars, a user first determines Theta,

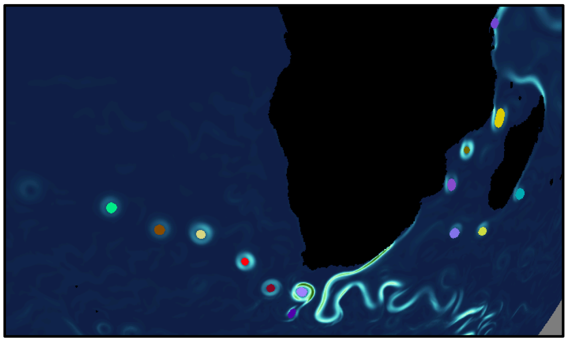

Figure 3: *A closeup view of regions with relatively high kinetic energy, often indicating eddy structures. Each colored region is a contour corresponding to an eddy that has been detected. Each contour is given a unique random color to distinguish it from other eddy contours and to track it in the Eddy Tracking Graph View. As eddies have high rotational and translational velocity, they are prominently defined in the kinetic energy field.*

Phi and Time values to select an image containing the area of interest. In Figure 1(a), the image showing the eddies from the Agulhas Retroflection and East Madagascar Current is selected at timestep zero. By manipulating the Contour Threshold, MinValue and MaxValue parameters, we can extract the desired structures that are eddies in this region. A closeup view is shown in Figure 3.

In our setting, a contour is defined as a closed curve, here a connected set of pixels, which have a similar value at the eddy enclose. This characteristic is suitable for eddy detection as eddies are rotating regions of water, defining closed or almost closed bodies of water. To find closed contours in an image, a threshold value is used to convert it to a binary image. Any value below the threshold is set to zero, and a value above the threshold is set to one. At this point, a contour is any closed shape that is white on a black background [FP11, ope]. Mathematically, a contour refers to an isoline defined by a specific isovalue; we use the term contour less rigorously as often done in computer vision. We can manipulate the threshold value until we find one that captures the desired eddies in the image. This process effectively culls high-velocity currents in the image from the list of features detected, since they are typically not closed features. We can refine our search by defining image moments for each contour. Moments are weighted averages of the contour region's pixel intensities that describe various properties such as shape, size, location and orientation [FZS16]. Using the MinValue and MaxValue parameters and the contour moment information, we can remove shapes that are too small or too large.

Once eddies are detected, we can determine their locations and count for each image. The (x,y) center of mass of a contour is defined by the 0th (M_{00}) and 1st (M_{01}, M_{10}) order elements of the moment matrix:

$$x = M_{10}/M_{00}$$

$$y = M_{01}/M_{00}$$

When eddy contours are detected and tracked, each eddy that is born is assigned a new random color and the interior of the contour filled with the corresponding color. As eddies move, they leave behind a trail connecting their last five locations (see Figure 1(a) closeup). The trail is also colored correspondingly. By studying the trail behavior one can see how fast eddies are moving across the ocean. If an eddy merges with another or splits into two eddies, the tail shows this relational movement; as shown in red in the eddy split in the bottom-right corner of Figure 1(a) closeup. As eddies die, their tails linger for a few more timesteps, to inform the user where past eddies were, in relation to new eddies that might be approaching the same region (as shown in orange in the top-left area of Figure 1(a) closeup).

2.2.2. The Eddy Count Graph View

The Eddy Count Graph View displays a line graph to compare the number of eddies detected at each timestep. The x-axis represents time and the y-axis lists the corresponding eddy count. Both axes are re-sized based on the movement of the Time scrollbar and the min and max count of eddies. An example is shown in Figure 1(b).

2.2.3. The Eddy Tracking Graph View

The Eddy Tracking Graph View shows the births, lives and deaths of eddies from timestep zero to the current timestep. Tracking is performed using a simple location-based technique. For any eddy 'a' at timestep 't', and any eddy 'b' at timestep 't-1', we perform this test: if the distance between a and b is less than or equal to the relationalDistance parameter value (set by the user), then we consider 'a' and 'b' to be the same eddy or interpret them as being the result of an eddy split. By keeping a bi-directional list of all such relations, we expand this analysis to capture the behavior of multiple eddies colliding into a few or one eddy splitting into many.

Referring to Figure 1(c), each unit along the x-axis represents a timestep, and each row shows the life of a particular eddy. For any particular timestep, there are five cases to consider: the birth of an eddy; the death of an eddy; one eddy moving to another location; one eddy splitting into multiple pieces with each of those pieces moving; and multiple eddies converging into one or more eddies with the resulting eddies moving away. When an eddy is born and assigned a random color in the Main View, a dot of the same color is placed on the Eddy Tracking Graph for the current timestep, and on a new row of the graph. If the eddy is only alive for that one timestep, the dot will remain but there will be no connecting lines. If the eddy lives for more than one timestep, there will be lines connecting the dot of its birth to the last dot of its death. Examples of the birth, life and death of an eddy are shown in Figure 4.

The two interesting cases arise when one eddy splits into many eddies or when many eddies merge into a few. As shown in Figure 5, when one eddy splits into more than one piece, the initial line is maintained for the first piece, and additional lines are created for all additional pieces. A line is drawn from the last point of the original eddy to each new piece to show that they all originate from the same eddy. Similarly, when many eddies merge into one, lines are drawn from the last point of individual eddies to an entirely new eddy on the graph. When many eddies merge to form one, the new eddy is not interpreted as being the continuation of any old eddy, but viewed as an entirely new one (see Figure 6).

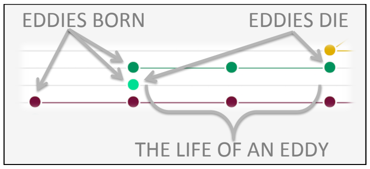

Figure 4: *Closeup view of Eddy Tracking Graph. The first three cases of eddy analysis are highlighted: eddy birth, eddy death, and an eddy moving from one location to another with no changes.*

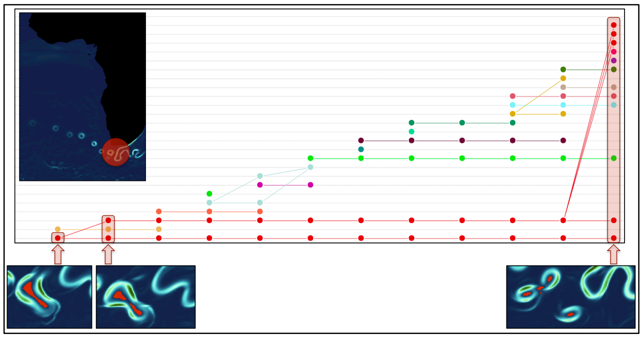

Figure 5: *Closeup view of Eddy Tracking Graph from Figure 1(c) showing various cases where one eddy splits into many eddies. The reference image shown in the top-left highlights the area of interest, and the smaller images are smaller regions within the area of interest. In the tracking graph, we see that the eddy formed by the Agulhas Retroflection splits into two eddies. These two eddies travel for nine timesteps before the top eddy splits into four smaller pieces.*

3. Discussion

The examples presented in this paper focus on the South Atlantic Ocean as this is a region of high concentration of eddies, and it is therefore of great interest to ocean scientists. A major advantage of our method is the fact that it operates on the much smaller image data provided by the Cinema database, thus drastically reducing processing time required for contour detection and image moment computation. It is possible to perform image processing operations on a global scale and analyze large portions of the global ocean in real-time, on a local, personal computer. In contrast, other commonly used methods require a user to focus on small ocean regions to keep processing times acceptable. From the original 20 gigabyte MPAS-Ocean simulation data, we created a Cinema database of 32 megabytes for 29 timesteps (kinetic energy). We performed the tests of our method using this dataset with the OSX El Capitan desktop operation system, using an Intel i7 4 GHz processor, with 40GB of DDR3 memory, and an AMD Radeon 4GB graphics card. The average time to apply a set of parametric values was 0.033 seconds, well within the limits of real-time [BW09].

Through our ongoing collaboration with ocean scientists from Los Alamos National Laboratory during the development of this system, we were able to focus on implementation details that are of particular importance to the scientist. The Eddy Tracking Graph View allows domain scientists to analyze the history of all eddies over many timesteps, in the context of a single image. Furthermore, as the tracking lines of an eddy's past positions are limited to five timesteps instead of every timestep from zero, it reduces occlusion while preserving information about eddy movements relative to one other. Additionally, as we are able to maintain the spatial resolution and temporal frequency of the MPAS-Ocean simulation by using a Cinema database, the scientist can track even the smallest of eddies and detect eddy splits and merges at maximum temporal frequency of the simulation. Ocean scientist Joseph Schoonover commented that "This eddy detection and tracking software is a practical and computationally efficient tool for extracting important details of ocean eddy statistics. The graphical display of results is both intuitive and incredibly informative."

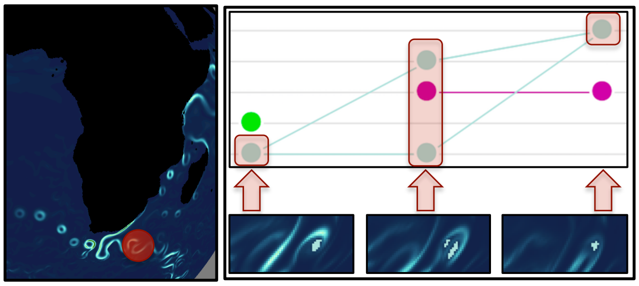

Figure 6: *Closeup view of Eddy Tracking Graph from Figure 1(c) shows the light blue eddy splitting into two, and merging back into one. Eddy merges are more rare than eddy splits in the South Atlantic Ocean, due to the turbulent nature of the currents in the region. In this example, a small eddy splits into two, then merges back into one in the region of the Aghulas Return Current.*

4. Conclusion and Future Work

We have introduced an effective, highly efficient and simple-to-use method to extract and track eddies in large global ocean simulations. The use of in-situ 2D images provided by the Cinema database drastically reduces the amount of data from gigabytes to megabytes and analysis processing time from hours or days to real-time. Further, using contour detection and image moments for finding, matching and tracking eddies represents a unique and novel combination of concepts. The major strength of our system is the possibility of real-time data exploration resulting in scientifically meaningful interpretations. Since an eddy generally cannot be defined mathematically, an oceanographer can use our system as part of an initial exploratory process, to identify areas of interest, prior to utilizing more complicated or time-consuming analysis methods.

In the future, we plan to explore other advanced contour detection and matching methods [KWT88] used in computer vision and more complex, location-based tracking that consider geometrical shape and size of eddies [Hu62].

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