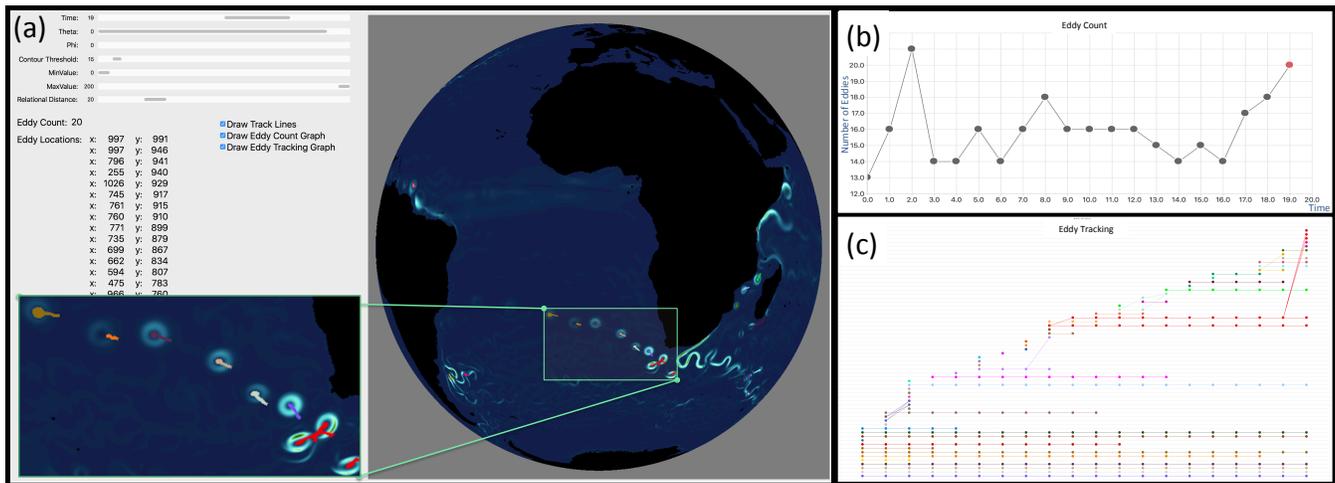


# Extracting, Visualizing and Tracking Mesoscale Ocean Eddies in Two-dimensional Image Sequences Using Contours and Moments

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**Figure 1:** The three Analysis Interface Viewers (a,b,c) show the various aspects of the eddy analysis system. In the Main View (a), a user can select values for Time, Theta and Phi to 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 also 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. As the Time scroll bar 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 for the extraction and tracking of 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] makes possible 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 massive 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

## 1. Introduction and Background

Mesoscale eddies in the global ocean transport large amounts of chemical and biological tracers over large distances. In addition, they greatly influence the ocean's temperature structure since they also transport heat along their trajectories. 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. More and better tools for the detection and tracking of ocean eddies and characterization of their properties are necessary for understanding their roles in a multitude of ocean processes.

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. [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 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 space and processing-time restrictions that limit most common approaches. During an ongoing simulation, ParaView Catalyst [FMT\*11, Par], an in-situ tool, extracts important information and stores it in a Cinema image database [CD]. The Cinema database approach makes possible the reduction of a data set of size  $10^{15}$  to size  $10^6$  [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 of detecting and tracking eddies captured in massive time-dependent ocean simulations.

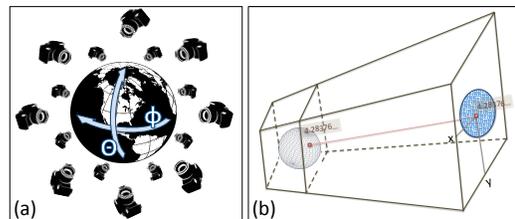
## 2. System Design

The Eddy Analysis System has two main components: Data Generation and Analysis Interface.

### 2.1. Data Generation

The Data Generation component creates a Cinema image database using ParaView Catalyst. Catalyst is an in-situ tool to extract information and generate a Cinema database as a simulation runs. We use MPAS-Ocean [MD], an earth-system simulation model 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 consists of 29 timesteps, each five days apart. The parameters used for and variables computed by this MPAS-Ocean simulation are typical of simulations commonly used by oceanographers.

From a given simulation, Catalyst generates a Cinema database by placing a camera at various points on a bounding sphere around the simulation's domain, using theta and phi angles as the points' coordinates for the sphere's parametrization. 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.



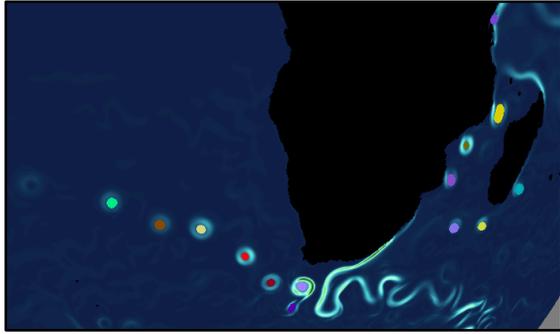
**Figure 2:** Cameras are placed at evenly spaced theta and phi angle locations to capture the simulation (a). For each image, the simulation is projected into the 2D image plane, where every pixel in the image stores the corresponding data value (b).

### 2.2. Analysis Interface

Once the Cinema database is created, it is loaded into the Analysis Interface, consisting of three main components, see Figure 1.

#### 2.2.1. The Main View

Eddies are detected in each image by using a combination of contour extraction/thresholding and image moment computation. Using the scroll bars, a user first determines Theta, Phi and Time values to select an image containing the area of interest. In Figure 1(a),



**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 in the Eddy Tracking Graph View.

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 of eddy selection is shown in Figure 3.

In our setting, a contour is defined as a closed curve, here a connected set of pixels, that 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 all the 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. Once the shapes corresponding to eddies are determined, we can refine the search further to extract eddies of interest. For each contour, we define an image moment to extract its properties. Moments are weighted averages of the contour region's pixel intensities that describe various properties of the contour, 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 0<sup>th</sup> ( $M_{00}$ ) and 1<sup>st</sup> ( $M_{01}$ ,  $M_{10}$ ) 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 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). This is especially obvious for eddies that cross the Atlantic Ocean from the Agulhas Retroflection and approach South America, generally dying or fading in kinetic energy along the way.

### 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 scroll bar and the min and max count of eddies. An example is shown in Figure 1(b).

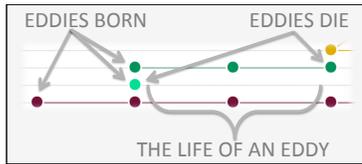
### 2.2.3. The Eddy Tracking Graph View

The Eddy Tracking Graph View shows the births, lives and deaths of eddies from timestep zero to the current timestep. Tracking is performed by 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.

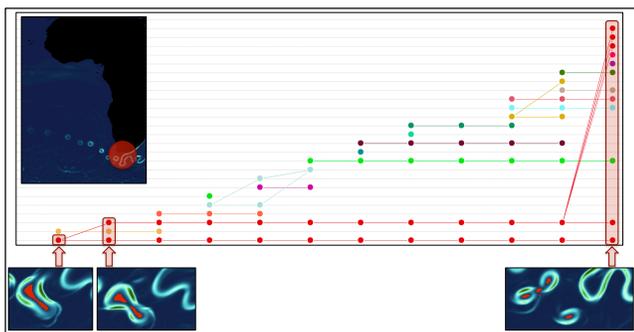
Referring to Figure 1(c), each unit along the x-axis represents a timestep, and each row shows the life of a particular eddy. For any particular timestep, there are five cases to consider: the birth of an eddy; the death of an eddy; one eddy moving to another location; one eddy splitting into multiple 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.

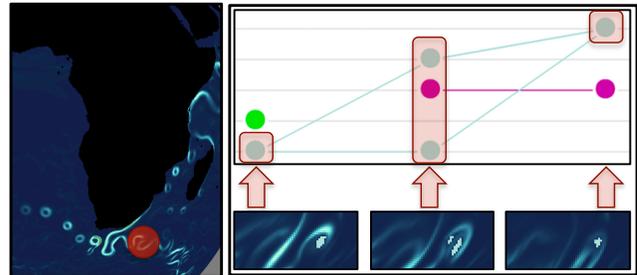


**Figure 5:** Closeup view of Eddy Tracking Graph from Figure 1(c) showing various cases where one eddy splits into many eddies. The reference image shown in the top-left corner highlights the area of interest, and the smaller images are smaller regions within the area of interest. When one follows the tracking graph, one sees 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. Case Study

The examples presented in this paper focus on the South Atlantic Ocean and eddies generated by the Agulhas Retroflection and the East Madagascar Current. 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. The entire Analysis Interface can be displayed on a local, personal computer. It is possible to perform image processing operations on a global scale and analyze large portions of the global ocean in real-time. 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 generated 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.

Through our ongoing collaboration with ocean scientists during



**Figure 6:** Closeup view of Eddy Tracking Graph from Figure 1(c) showing an 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 Agulhas Return Current.

the development of this system, we were able to focus on implementation details which 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. We have virtually condensed 20 gigabytes of data into a single image, extracting only the information that is necessary. 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. One ocean scientist collaborator 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."

### 4. Conclusions and Future Work

We have introduced an effective, highly efficient and simple-to-use method for extracting and tracking 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. Our system makes possible real-time data exploration producing scientifically meaningful results, being its major strength. 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 and time-consuming analysis methods.

In the future, we plan to explore other advanced contour detection and matching methods used in computer vision. One goal will be to achieve a higher degree of precision in our analysis results. We also plan to explore complex, location-based tracking techniques that consider geometrical shape and size of eddies.

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