Title: Visualization and Analysis of Eddies in a Global Ocean Simulation

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ABSTRACT

Eddies at a scale of approximately one hundred kilometers have been shown to be surprisingly important to understanding large-scale transport of heat and nutrients in the ocean. Due to difficulties in observing the ocean directly, the behavior of eddies below the surface is not very well understood. To fill this gap, we employ a high-resolution simulation of the ocean developed at Los Alamos National Laboratory. Using large-scale parallel visualization and analysis tools, we produce three-dimensional images of ocean eddies, and also generate a census of eddy distribution and shape averaged over multiple simulation time steps, resulting in a world map of eddy characteristics. As expected from observational studies, our census reveals a higher concentration of eddies at the mid-latitudes than the equator. Our analysis further shows that mid-latitude eddies are thicker, within a range of 1000-2000m, while equatorial eddies are less than 100m thick.

Index Terms: I.3.8 [Computer Graphics]: Applications—Oceanography I.6.6 [Simulation and Modeling]: Simulation Output Analysis—Ocean General Circulation Models

1 INTRODUCTION

Oceanography in the early and mid-20th Century was focused on the description and analysis of the mean circulation. This changed in the later decades of the century as new observations produced evidence of a surprisingly vigorous field of often long-lived and deeply penetrating vortices, referred to as mesoscale eddies. Satellite-based sea surface height altimetry soon produced nearly global maps on which the surface signature of these vortices was clearly evident. Spectral analysis indicated that a large fraction of the total estimate of oceanic kinetic energy is associated with these mesoscale eddies, transforming our understanding of the fluid dynamics of ocean circulation.

Around the time that satellite-borne altimeters began producing near-global observations of sea surface height, ocean general circulation models (OGCMs) crossed into a higher resolution regime in which the mesoscale eddies began to be resolved. These models are closely related to those used in numerical weather prediction and atmospheric modeling in general, and the ancestry of the first OGCM [4] owed a great deal to earlier work on numerical modeling of geophysical fluid dynamics for atmospheric science.

The first realistic eddying ocean model simulations focused regionally on the Southern Ocean [7] and on the North Atlantic [2, 3]. A spectral analysis of an approximately $\frac{1}{4}$ resolution model, based on the average horizontal spacing between grid points, showed a model sea surface height variability that was lower than that derived from the altimeter by approximately a factor of two [8]. As computing power increased, first regional and then global models could be configured and run at horizontal grid resolutions of around $\frac{1}{16}$, and their mesoscale variability was found to come into much better agreement with observations [18, 14]. The mean currents also came into much better agreement with observations in terms of width, speed and depth. The Gulf Stream, running from the Florida Straits and departing from the continental shelf at Cape Hatteras, then feeding into the northward-turning North Atlantic Current, showed great improvement in path, an indication of the essential role of eddy-mean flow feedbacks in determining the large scale circulation.

Computer modeling of ocean circulation and modern observing programs together have produced major advances in physical oceanography. Ocean models save full three-dimensional data fields, but publications in oceanography typically show simple two-dimensional plots of variables on the surface and in vertical sections. This is partly because oceanographers are familiar with these views from observational studies, and partly due to the limitations of the standard set of visualization tools. Horizontal velocities in the ocean are 1000 times larger than vertical velocities, so 2D horizontal sections are often the best way to display the ocean’s currents. A notable exception is the vertical structure of eddies. Questions about their vertical extent, tilt, and tapering require three-dimensional analysis and visualization.

To this end, we performed extensive analysis of high-resolution ocean simulation data on a local supercomputer, generating imagery of eddies in the vicinity of the world's strongest ocean currents. Furthermore, by computing the radius and thickness (distance from top to bottom) of every eddy across several time steps of the simulation, we created histograms of eddy distribution and shape upon the two dimensions of a world map. These novel analyses are expected to contribute to our understanding of how eddies affect large-scale ocean circulation, and by extension, how they affect the global climate.

2 RELATED WORK

Numerous studies of satellite data have quantified the size and distribution of eddies in regions including the Mediterranean Sea [12], the Tasman Sea [21], the Gulf of Alaska [10] and globally [5]. An eddy census from satellite data is limited to surface features, while data from vertical ship-deployed profiles and fixed moorings can only capture a very incomplete picture. Eddies in the Arctic, which are hidden from satellites’ view below the ice, are very poorly understood, even though they may play an important role in heat and nutrient transport. Thus ocean models provide a way to study oceanic features that are not directly observable at this time. Previous studies of eddies in model data include [6] in the Cape Basin and [15] in the South California Bight, but these were both limited to surface features. The methods we present will form the basis for more thorough investigation of the vertical structure of ocean eddies.

Extracting and visualizing turbulence in vector fields has long been of interest to the visualization community. Methods generally focus on either extracting specific structures (e.g. vortices) and drawing a bounding volume [17], or extracting the overall topology and visualizing it through glyphs or other proxies [9, 19]. For extracting vortex-like structures in particular, popular methods include finding regions of high vorticity [20] or, if the data are available, by looking for regions of low pressure at the center of a vortex [1]. We employ the Okubo-Weiss parameter [16, 22], which is extremely similar to the $k_\theta$ parameter [13] often used in three-dimensional flow analysis.

3 EDDY IDENTIFICATION AND VISUALIZATION

Our analysis of eddies focuses on data generated by Los Alamos National Laboratory’s Parallel Ocean Program (POP) in the context of a global ocean simulation with grid resolution of $\frac{1}{16}$. The resulting output is a rectilinear grid with dimensions of $3600 \times 2400 \times 42$. These data comprise approximately 1.4 GB per floating-point variable per time step, so all our visualization and analysis was done on...
The Okubo-Weiss parameter at the ocean surface in the North Atlantic. While we generated this image, it is typical of visualizations currently used by the oceanography community. Because Okubo-Weiss is difficult to interpret directly, it has been normalized to its standard deviation and colored based on the oceanographic rule of thumb that the significant activity is 0.2 standard deviations from 0. Red regions are those dominated by vorticity, while blue regions are those dominated by strain. Okubo-Weiss easily identifies several eddies as red circles, but the Gulf Stream itself is also shown as a distinctly red, meandering line from the Gulf of Mexico running toward the British Isles.

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We focus on one of the ocean community’s canonical methods for identifying eddies: the Okubo-Weiss parameter. In general, this parameter divides the ocean into regions dominated by vorticity, regions dominated by strain or deformation, and a background where neither effect is dominant. Regions dominated by vorticity are potentially eddies, though vorticity dominance can be caused by other effects, such as sharp turns in the mean flow. Mathematically, the Okubo-Weiss parameter is defined as:

\[ OW = s_n^2 + s_s^2 - \omega^2 \]  

Here, \( s_n \) is normal strain (currents pushing against each other), \( s_s \) is shear strain (currents running in opposite directions past each other), and \( \omega \) is vorticity (currents moving in circles). These three variables can be expressed in terms of velocity gradients:

\[ s_n = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \]  
\[ s_s = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \]  
\[ \omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \]  

Substituting these gradients into the original Okubo-Weiss expression provides an equation that can be implemented solely from ocean velocity:

\[ OW = \left( \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right)^2 - \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)^2 \]  

Being defined only in terms of velocity gradients, the Okubo-Weiss parameter has the advantage of being fast and easy to compute. However, the parameter can vary greatly in different situations, and so can be difficult to interpret. A first approach might...
be to consider the parameter solely in terms of positive (strain-dominated) and negative (vorticity-dominated) domains, but for numbers very close to zero the parameter is dominated by noise. The rule of thumb in the ocean community is to normalize the parameter to its standard deviation, then only consider a data point meaningful if it is at least 0.2 standard deviations from 0.

The Okubo-Weiss parameter is plotted at the ocean surface in Figure 1. This plot is an example of the standard visualizations currently employed in the oceanography community. Using our three-dimensional data, we extract only voxels with negative Okubo-Weiss values at least 0.2 standard deviations from 0, and paint those voxels as solid cubes. By further placing these extracted eddies on a bathymetric map also extracted from the simulation data, we arrive at our new visualization, shown for the North Atlantic’s Gulf Stream in Figure 2. In other sections of the world, Figure 3 shows eddies associated with the Kuroshio Current off the coast of Japan, and Figure 4 shows eddies off the coast of Australia associated with the Antarctic Circumpolar Current.

These pictures all indicate that, while Okubo-Weiss identifies eddies both at and below the surface of the ocean, it also identifies high-vorticity features that should not be considered eddies, particularly meanders in the Gulf Stream and the Kuroshio Current, as well as several small-scale features that we consider noise. To mitigate this, we add an additional filtering criterion. We compute the angle that each point’s velocity vector makes with a vector pointing east. These angles are then discretized into four domains: 0 to 90 degrees, 90 to 180 degrees, 180 to 270 degrees, and 270 to 360 degrees. Figure 5 shows the same vorticity-dominated domain as Figure 2, but recolored to show the angle domain each point falls within.

Since an eddy is a circular flow, we expect that an eddy should contain velocity vectors in all four angle domains, and that its center point should be at the intersection of these four domains. Indeed, the vorticity-dominated regions of the Gulf Stream that are most likely eddies do show a cross-shaped pattern in their angle domains, indicating that the current is circling the center of the eddy. However, several of the larger meanders also contain all four angle domains, either due to making a sufficiently sharp hairpin turn, or by making S-shaped turns. Instead, for using these angle domains to discriminate between eddies and meanders, we require that each angle domain make up at least a certain share of the total eddy. Based on experimentation, we arrived at a requirement of 8%, which we use for our analyses in the next section.

4 GLOBAL CHARACTERIZATION

In addition to demonstrating a capability of visualizing ocean eddies directly, we have also developed a computational capability to analyze the distribution, size, thickness, and depth of eddies around the world. The previous section laid the groundwork for extracting eddies: after using the Okubo-Weiss parameter to find vorticity-dominated regions (defined as connected components of points with Okubo-Weiss negative values at least 0.2 standard deviations from 0), we only keep those connected components with all angle domains representing at least 8% of the total component, and containing at least 20 points in one horizontal plane to further ensure that eddies are not just simulation noise.

The metrics alluded to above—volume, radius, minimum and maximum depth, thickness (difference between minimum and maximum depth), vorticity sign (whether the eddy spins clockwise or counter-clockwise)—can easily be computed from these connected components. Visualizations like those in the above section, however, are only useful for looking at isolated regions of the ocean, due primarily to the density of information being displayed. Additionally, we would like to know about the general behavior of the ocean rather than its behavior at individual time steps. To this end, we pursue temporal averaging of eddy characteristics.

A traditional approach is to produce one-dimensional line plots with respect to latitude, as in Figures 7 and 8. These graphs already provide some general information about eddies around the globe. Particularly, Figure 7 shows the huge number of eddies around the Antarctic Circumpolar Current, as well as spikes in the mid-latitudes caused by the Gulf Stream and Kuroshio Current. Figure 8, showing whether eddies are deep columns or shallow pancakes also confirms some expectations: eddies near the equator, where the Coriolis forces are weak, tend to be very thin, while the strong and numerous eddies around the major currents form large columns. Both plots also reveal the relative sparsity and weakness of eddies in the Arctic, and the regions just north and south of the equator.

However, the computational power available nowadays allows us to generate temporal averages from an amount of data sufficient to produce statistics as a function of both latitude and longitude, shown in Figures 9, 10, and 11. The first thing to notice about these two-dimensional plots is the significance of the three
Figure 5: High-vorticity features are again extracted from the Gulf Stream. This time, the voxels composing the features are colored based on the angle each voxel's velocity vector makes with an east-pointing vector, so a voxel with east-moving water will have an angle of 0°, a voxel with north-moving water will have an angle of 90°, and so forth. The angles are discretized into four domains: voxels with angle between 0° and 90° are colored purple, voxels with angle between 90° and 180° are colored green, voxels with angle between 180° and 270° are colored yellow, and voxels with angle between 270° and 360° are colored red. Features that are definitely eddies contain a nearly equal mixture of all four angle domains, while meanders, which move primarily in one or two directions, are correspondingly dominated by one or two angle domains. To use this as a discriminator, we require that features have at least 8% of their voxels be from each angle domain.
currents: the Gulf Stream just left of center, the Kuroshio Current near the right edge, and the Antarctic Circumpolar Current along the bottom. Concentrations of deep eddies are seen in two regions, one being that of the Gulf Stream, the other being that of the ACC, with its most northerly excursion into the area known as the Brazil-Malvinas confluence, just off Argentina, being particularly notable in this respect. It is known that eddies are a principal means through which momentum is transferred from near the surface to depth, energizing the deep circulation of the ocean [11]. These are regions in which that vertical transfer of momentum can be expected to be particularly strong.

5 Conclusion
We have developed and demonstrated a simple yet effective method of eddy identification, implemented in parallel on a local thirty-two core supercomputer. In the context of the large datasets that we intend to study, and even in the more limited context of this initial demonstration, the parallel processing capability facilitates the multiple iterations required to perform the analysis.

Ongoing work to apply this new capability to the characterization of the model's eddy field represents a contribution not only to physical oceanography but also to climate science, as the ocean model serves as a component of one of the world's foremost climate models. Within the context of this prominent model, the method is being used in order to produce a characterization of eddies by region. This characterization will include a unique evaluation of the vertical extent of the eddies, an analysis that is expected to fill in gaps in the understanding of what establishes large-scale ocean basin circulations, advancing the study of ocean dynamics while also identifying leading-order limitations in the model that may yet be addressed and corrected. Particular attention will be focused on the Arctic, where little is known about the eddy field and the degree to which eddy-mean flow feedback may work to establish the large-scale circulation of that basin. Finally, in later work we intend to track eddies with time to investigate their propagation speeds, lifetime, and growth rates, and how these quantities vary by latitude and region.

References
Eddy Count

Figure 9: Our new visualization of eddy statistics, showing the total number of eddies averaged across 9 time steps as a function of both latitude and longitude. This reveals quite a bit more information than the simple one-dimensional plots: the Gulf Stream, Kuroshio Current, and Antarctic Circumpolar Current are all easily identifiable. Furthermore, the behaviors of eddies caused by these currents are also brought out by this visualization, such as eddies spinning off the southern coast of Africa and the southwest coast of Australia, and the various courses eddies take after the Gulf Stream leaves the eastern American coast.

Radius

Figure 10: A visualization of average eddy radius across 9 time steps as a function of latitude and longitude. The bulk of the eddies in the Antarctic Circumpolar Current are fairly narrow, while eddies get wider as one approaches the equator. In the Gulf Stream, the eddies appear to get narrower as one looks northward.
Figure 11: Average eddy thickness (defined as the distance from the top to the bottom of the eddy), weighted by the eddy’s volume, averaged across 8 time steps, as a function of latitude and longitude. Especially thick eddies only seem to appear around the main jet of the Gulf Stream, and all along the Antarctic Circumpolar Current. As expected, eddies near the equator are extremely thin.