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Visualization Method for Mesoscale Eddies Characteristics in Ocean Flow Fields Based on Variable Particle Systems

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Abstract: Visualization of ocean flow fields is a major area of interest in marine science. Existing visualization methods based on randomly generated particles tend to exhibit a uniform distribution. While this approach effectively represents ocean flow fields, it inadequately conveys the characteristic structures within the flow in an intuitive manner. Ocean eddies, as crucial components of ocean dynamics (Patrizio & Thompson, 2021), are key features in visualizing ocean flow fields. Mesoscale eddies, which contain 90% of the ocean's kinetic energy, play a vital role in transporting this energy. These eddies significantly influence local marine environments and are instrumental in understanding the kinetic energy of ocean flow fields, providing valuable insights for fields such as oceanography, meteorology, and climate research. The aim of this study is to establish a method based on variable particle systems. Initially, a feature set for mesoscale eddies and a parameter set for variable particles are defined. By mapping the feature set to the parameter set, we express the characteristic structure of mesoscale eddies dynamically. Using ocean flow field data, we demonstrate the method's ability to effectively highlight the characteristic structures of mesoscale eddies within the flow field through qualitative and quantitative evaluation metrics. By analyzing and visualizing ocean flow fields, we can gain a deeper understanding of their spatiotemporal evolution, thereby uncovering the patterns and regularities of their movement. This research approach not only facilitates the effective development, utilization, and sustainable management of marine resources but also aligns with the demands of digital ocean technology for visualizing marine spatial information.

Keyword: Ocean flow field; Mesoscale eddies; Variable particles; Mapping; Feature visualization.

1.0 Introduction

As an important component of ocean dynamics (Patrizio & Thompson, 2021), mesoscale eddies contain 90% of the ocean's kinetic energy and play a crucial role in oceanic energy transportation. Previous research has devised methodologies for detecting, tracking, dissipating, and forecasting mesoscale eddies in the ocean (Adams et al., 2017; Banesh et al., 2021; Dong et al., 2014). For example, Okubo and Weiss introduced the OW (Okubo-Weiss) method in 1970 for identifying mesoscale eddies, and in 2004, Morrow applied this method to study eddies in the eastern boundary flow. Another approach, the Winding Angle (WA) method, was proposed by Porteal et al. (1998), focusing on the geometric contours of the flow field. This method identifies vortices by detecting the vortex center and tracking a series of instantaneous streamlines arranged in a spiral around it. Subsequently, Dong et al. (2011) extended geometric contour-based techniques to ocean vortex detection by using sea surface temperature (SST) datasets to monitor eddies in ocean basins. Morrow (2004) used a 7.5 cm Sea Surface Height (SSH) closed contour method, Wang (2003) employed a 10 cm Sea Level Anomaly (SLA) closed contour method, and Chaigneau and Pizarro applied a 6 cm SLA closed contour method to study and analyze mesoscale eddies and boundaries in the Indian Ocean, Southern Ocean, South China Sea, and eastern South Pacific during 2003, 2004, and 2005, respectively.

Vortex tracking methods are generally divided into two categories (Wang, 2018). The first is the nearest neighbor method, which searches for the nearest vortex center with the same polarity across consecutive time intervals. This method is relatively simple, computationally efficient, and suitable for tracking well-separated eddies in the ocean. The second approach is the similarity method, an extension of the nearest neighbor method. It describes the dimensionless characteristic parameters of vortices to determine their similarity for matching across continuous time periods. Flow field visualization (Song & Liu, 2020) is a technique that transforms flow field data into two-dimensional or three-dimensional graphics, images, or animations. This technique aids in analyzing flow field patterns and interrelations, thereby facilitating the study of complex phenomena such as marine ecosystems and climate change. With the increasing amount of ocean data, conventional visualization methods struggle to adequately depict intricate flow field structures. Consequently, the quest for presenting oceanic flow field data more intuitively and comprehending the ocean's underlying laws has emerged as a focal point in research. Among various approaches, feature-based visualization has emerged as a nascent method. Features (Sun et al., 2001) refer to meaningful shapes, structures, changes, and phenomena within the flow field, such as vortices and shock waves. By extracting features to underscore the key structures inherent in the raw data, researchers can intuitively discern detailed characteristics. Silver and Zabusky introduced a method for feature extraction from scalar and vector fields using image processing techniques, categorizing feature states into generation, continuation, extinction, decomposition, and merging to facilitate feature tracking and display (Silver et al., 1991; Silver & Zabusky, 1993).

Particle systems represent a simulation expression method employing computer graphics and image processing techniques, primarily suited for simulating irregular and abstract natural phenomena such as smoke, clouds, and ocean currents. Since Reeves (1998) first proposed the concept of particle systems in 1983, this method has found widespread application in simulating effects like explosions and flames. Sims (1990) introduced a flexible method for particle rendering (SIMS901), while Hin and Post (1993) enhanced the particle method by leveraging particle motion trajectories for displaying three-dimensional flow fields. Since the 1990s, research on particle systems has gradually burgeoned in China, with applications extending into ocean environment simulation and oceanic data visualization, undergoing continuous refinement. For instance, Li (2014) focused on process-based streamline visualization technology of oceanic current fields using particle systems, providing a crucial tool for expressing oceanic phenomena and delving into oceanic dynamic processes. These methodologies play a pivotal role in observing the intricate motion processes of oceanic eddies. To better represent natural phenomena like irregular fluids, He et al. (2015) employed probabilistic methods for controlling particle density, whereas Fu & Ai (2019) managed particle density by establishing particle thresholds within the grid. However, all aforementioned approaches uniformly depict the flow field. For complex oceanic flow fields, uniform distribution fails to fully capture their characteristic structural phenomena. Addressing the characteristic distribution of particle density, Li et al. (2013) utilized varying particle densities to delineate distinct spaces, accomplishing the construction of cloud particle models. Experimental results validated the effectiveness of employing different cloud particle densities in rendering more realistic 3D cloud scenes.

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Based on these premises, this study addresses the challenge of intuitively analyzing the characteristic structures within ocean flow field visualizations by focusing on ocean flow field feature visualization. Initially, the study identifies, extracts, and tracks the feature structure of mesoscale eddies based on the closed contour method for sea surface height anomalies, capturing their spatial distribution and spatiotemporal evolution. Subsequently, this paper introduces a variable particle system method, grounded in particle system theory, to explore the feasibility of representing fuzzy, abstract, and irregularly shaped natural phenomena. Compared to traditional approaches, the proposed variable particle system method effectively highlights characteristic structures within the ocean flow field, thereby enhancing the feature visualization of these fields.

2.0 Research Foundation and Approach

2.1 Mesoscale Eddies and Their Extraction Methods

Mesoscale eddies are significant phenomena within oceanic flow fields, constituting a vital component of the marine physical environment. Their temporal scale ranges from several days to several months, while their spatial scale spans tens to hundreds of kilometers (Y. Li & Wang, 2012). Based on their rotational direction, mesoscale eddies can be categorized into cyclonic eddies (CE) and anticyclonic eddies (AC). Regarding the extraction of mesoscale eddies, Dong et al. (2014) classified extraction methods into two categories based on data types: Lagrangian methods and Euler methods. The Lagrangian method entails identifying vortices based on the trajectory data of water masses or matter particles, whereas the Euler method relies on instantaneous snapshot data or spatial field data for identification. As this study utilizes spatial field data, the Euler method is employed for mesoscale eddy extraction. The Euler method is further subdivided into physical parameter-based methods, flow field geometric contour-based methods, hybrid methods combining physical parameters and flow field geometric contours, and closed contour methods based on sea surface height anomalies.

2.2 Particle System Visualization Method

The particle system method is an effective visualization tool used to depict the dynamic characteristics of a flow field by simulating the trajectories of numerous particles within it. Each particle in this method undergoes a specific lifecycle, encompassing stages of birth, motion, and extinction. By computing the positions of particles at various time points and connecting the resulting trajectories, a dynamic visualization effect of the flow field data can be achieved.

Firstly, regarding particle generation, when dynamically visualizing vortices, a predetermined number of particles must be generated within the selected area. This process primarily involves determining the position, quantity, size, and color of the particles. The dynamic motion trajectory of the vortex is then represented by the movement of these particles.

Secondly, concerning particle motion, the initial velocity of each particle is determined by the velocity at its starting point, which is divided into horizontal and vertical components. The subsequent position of a particle is determined by its current location, initial velocity, and the time interval. Through integral calculation, these particles dynamically reflect changes in the vortex trajectory.

Finally, for particle extinction, a lifecycle and extinction boundary are established. Upon reaching the end of their lifecycle, the attributes of the particles are deleted, and new particles are generated to maintain a constant total particle count. Figure 1 illustrates a schematic diagram of particle trajectory calculation..

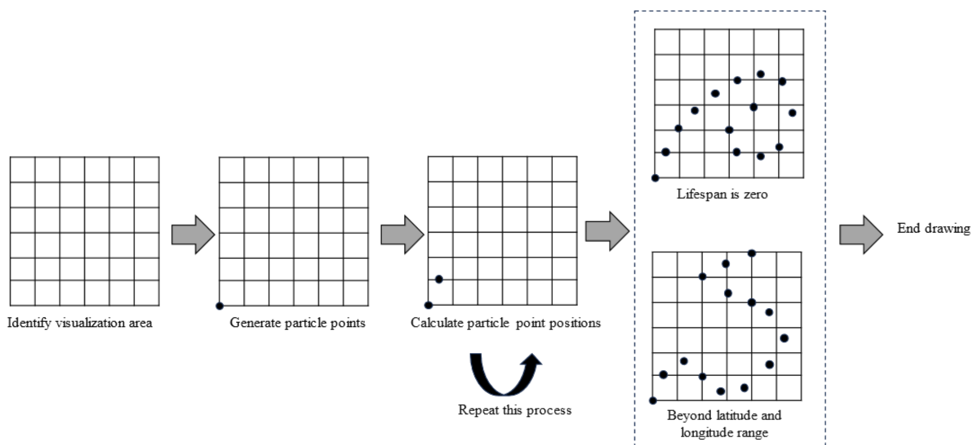

Figure 1: Schematic diagram of particle trajectory calculation.

2.3 Visualization of Mesoscale Eddy Features Based on Variable Particles

In traditional methods, particles are primarily generated randomly within a predetermined range of longitude and latitude. This is accomplished using various algorithms, such as direct generation algorithms, domain-based generation algorithms, and the Sobol algorithm (Fang et al., 2018) for generating random particles. Although simulating the motion trajectories of numerous particles within a flow field can effectively capture the dynamic characteristics of the flow field, complex flow fields present challenges such as visual clutter and indistinct features during the visualization process. Randomly generated particles may not fully capture the characteristic structural phenomena of such flow fields. Hence, this article proposes a variable particle visualization method tailored to mesoscale eddy feature sets. Figure 2 illustrates the schematic diagram of the method's structure.

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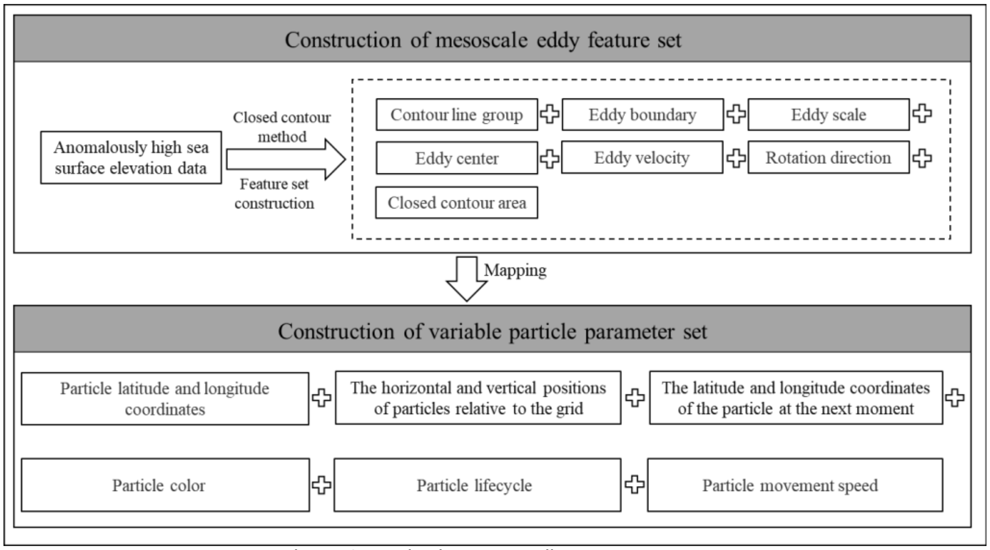

Figure 2: Method structure diagram

3.0 Visualization Method of Mesoscale Eddy Features Based on Variable Particles

3.1 Construction of the Mesoscale Eddy Feature Set for Visualization

The ocean flow field exhibits various complex characteristic structures, including vortices, shock waves, and turbulence. Visualizing all the data from the flow field can lead to visual confusion and obscure key features. To address this issue, a feature set of mesoscale eddies is constructed to enable the visualization of these structures. In this study, the closed contour method based on sea surface height anomalies is employed to identify mesoscale eddies. Compared to other vortex identification methods, numerous research findings (Chaigneau & Pizarro, 2005; Morrow et al., 2004; Wang et al., 2003) have demonstrated that the closed contour method not only eliminates the need for calculating geostrophic flow, thereby reducing computational complexity, but also yields satisfactory identification results. Throughout the identification process, standards set by Chelton et al. (2011) and other scholars (Cui et al., 2017; Lin et al., 2007; Wang et al., 2019) are referenced. The definition of mesoscale eddy characteristic parameters is outlined in the table below.

Table 1: Mesoscale eddy feature set

Mesoscale eddy feature set	Parameter composition
$S_i, i=1,2,\ldots n$	$s_{i1}, s_{i2}, \ldots s_{ij}, i, j=1,2,\ldots n$
$E_i, i=1,2,\ldots n$	$Area_i, Boundary_i, Scale_i, Center_i, Speed_i, Rotate_i$

Where, S_i is the contour line group, $Area_i$ is the area of the outermost closed contour line, $Boundary_i$ is the vortex boundary, $Scale_i$ is the scale size of the vortex, $Center_i$ is the position coordinate of the vortex center, $Speed_i$ is the flow velocity of the vortex, and $Rotate_i$ is the rotation direction of the vortex.

For the boundaries of eddies, considering that a key characteristic of mesoscale eddies is a series of closed sea surface anomaly contour lines, the streamlines of eddies in the eddy current field caused by Earth's rotation typically run parallel to or overlap with these closed sea surface height anomaly contour lines. Thus, the outer edge of the eddies can be determined by identifying the outermost closed contour lines. The scale of a vortex is represented by the radius of a circle with the same area.

$$Scale_i = \sqrt{Area_i / \pi} \quad (1)$$

3.2 Construction of a Variable Particle Parameter Set for Expressing Mesoscale Eddy Features

When dynamically visualizing vortices, it is necessary to generate a certain number of particles within the feature area and use the motion of these particles to represent the dynamic motion trajectory of the vortex. In traditional methods, particles are primarily generated randomly within a defined range of longitude and latitude. Commonly employed algorithms for particle generation include direct generation algorithms, domain-based generation algorithms, and Sobol algorithms (Fang et al., 2018). To control particle density, latitude and longitude grids are often utilized to regulate the number of particles within each grid. However, in complex ocean flow fields, characterized by intricate structures, mesoscale eddies exhibit fluidity in their characteristic structures. Their shapes and sizes vary within the corresponding latitude and longitude grids, resulting in irregular vector fields at the boundaries. Uniform distribution methods are insufficient to fully capture their characteristic structural phenomena. To address these challenges, this paper proposes a variable particle method. This method adaptively generates particles and defines particle velocity based on the vortex center, boundary, and vortex flow velocity. Its aim is to emphasize specific flow field characteristics and enhance visualization effects. The construction of the variable particle parameter sets is outlined in the table below:

Table 2: Variable particle parameter set

Particle parameter set	Parameter composition
$CanvasParticle$	$(lng, lat), (x, y), (tlng, tlat), color, age, speed$

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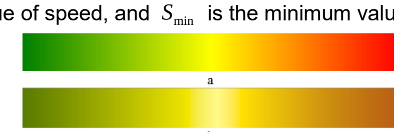
Where, (lng, lat) represents the latitude and longitude coordinates of the particle's initial position. Setting the initial position ensures that particles are generated within the vortex range; (x, y) represents the horizontal and vertical positions of particles relative to the grid. This conversion is crucial for visualizing particle movements on the screen during the visualization process; $(tlng, tlat)$ represents the latitude and longitude coordinates of the particle at the next time step, displaying its spatial trajectory and facilitating the intuitive observation of fluid movement patterns; $color$ represents the color of particles, which is mapped to the magnitude of flow velocity. This mapping intuitively reflects the flow velocity magnitude in the flow field; age represents the lifecycle of a particle, enabling simulation of decay and dissipation processes, thus reflecting actual dynamic characteristics within the flow field; $speed$ represents the movement speed of particles, directly simulating fluid velocity. Faster-moving particles correspond to regions with higher flow velocity, while slower-moving particles correspond to regions with lower flow velocity.

3.3 *Variable Particle Visualization Method for the Mesoscale Eddy Feature Set*

Mapping plays a crucial role in the visualization process of flow fields. It involves transforming processed normalized data into geometric data. At this stage, abstract data concepts need to be mapped to specific geometric objects. This primarily involves mapping the constructed mesoscale eddy feature set to the particle parameter set, as illustrated in Table 3. Based on the constructed mesoscale eddy feature set, it is determined that if the particle points are within the vortex boundary range, the initial position of the particles should be adjusted to increase the density of particles within the mesoscale eddy range, thereby better displaying the vortex structure in the flow field. The trajectory of particles can intuitively represent the dynamic changes in the flow field. In areas with high vortex flow velocity, particles move faster, while in areas with low vortex flow velocity, they move slower. By employing color mapping methods combined with visual perception, the velocity of vortices can be visually represented by distinguishing between different colors or shades based on their speed. Due to the similarity between blue and ocean background colors, the visualization effect is not as prominent. Therefore, the RGB color mapping used in this article is shown in Figure a of Table 3, where the maximum speed value is represented in red and the minimum speed value is represented in green. Additionally, for individuals with color vision disorders, such as red visual impairments, an alternative design is shown in Figure b.

Regarding the velocity vector of a vortex, it is mapped to the initial velocity of the particles, with components divided into horizontal and vertical directions. The latitude and longitude coordinates of the particles in the subsequent moments are calculated through linear interpolation and fourth-order Runge-Kutta algorithm (RK4) integration, based on their current position and flow velocity. This process dynamically reflects trajectory changes in the vortex. In the northern hemisphere, anticyclonic vortices rotate counterclockwise (and cyclonic vortices rotate clockwise), with the particle motion trajectory representing the vortex's rotation direction. Finally, for particle extinction, the boundary is adaptively defined based on the vortex boundary. The attributes of extinct particles are deleted, and new particles are generated to maintain a constant total particle count. Through this mapping process, a foundation is laid for subsequent drawing and display.

Table 3: Mapping Method from Feature Set to Parameter Set

Feature set	Parameter set	Mapping method
$Boundary_i, Center_i$	$(lng, lat), (x, y)$	coordinate transformation $cartesian(x, y, z) = fromDegress(lng, lat, 0)$ $screen(x', y') = wgs84ToWindowCoordinates(scene, cartesian(x, y, z))$ lng is longitude, lat is latitude, (x, y, z) are components of the Cartesian coordinate system, $scene$ is the scene object
$Speed_i$ vector	$(tlng, tlat), speed$	Bilinear interpolation and RK4 algorithm(Wilde et al, 2018)
$Speed_i$ size	$color$	RGB color mapping $r = round\left(255 \times \frac{i}{n}\right)$ $g = round\left(255 \times \left(1 - \frac{i}{n}\right)\right)$ $s = S_{min}\left(\frac{S_{max} - S_{min}}{n} \times i\right), 0 \le i \le n$ $round$ is used for rounding, n is the number of color segments used to determine the number of intervals between the generated color range and the speed value range, and i represents the index of the loop iteration, calculating the color ratio corresponding to each speed interval and speed value. S_{max} is the maximum value of speed, and S_{min} is the minimum value of speed.  a b

*a: Normal Visual Color Mapping b:Red Visual Impairment Color Mapping

3.4 *Implementation of Visualization Method for Mesoscale Eddy Features Based on Variable Particles*

In the direct visualization method for large and complex vector fields, multiple arrows can easily cause visual clutter (Kosara et al., 2004). The geometric visualization method cannot fully and accurately present the overall detailed information of ocean current vector fields

(Verma et al., 2000). The texture visualization method requires high computational power and complex algorithms (Van Wijk, 2002). In contrast, the feature visualization method can extract relevant features according to the researcher's needs, effectively filtering out irrelevant data, thereby reducing the information volume and improving data processing efficiency. By quantitatively describing these features, it can also help users gain a deeper understanding of the data's meaning and underlying patterns (Sun et al., 2001).

Therefore, this paper proposes a visualization method for mesoscale eddy features based on variable particles. The feature visualization method based on this approach is illustrated in Figure 3. Firstly, a feature set of mesoscale eddies and a variable particle parameter set are constructed, and mesoscale eddies are identified and extracted from spatiotemporal field data. Secondly, the constructed feature set is mapped to the particle parameter set, where: (1) The initial generation density of particles is adaptively adjusted based on the position of the vortex boundary; (2) The flow velocity is represented by color; (3) Particle motion trajectories are calculated based on streamline integration; and (4) Particle extinction is determined based on several conditions: a particle has a zero life cycle during its motion; the life cycle is not zero but exceeds the latitude and longitude range; and for particles at the mesoscale eddy boundary, if they exceed the vortex boundary, they are also marked as extinct. Finally, the mesoscale eddies are visualized.

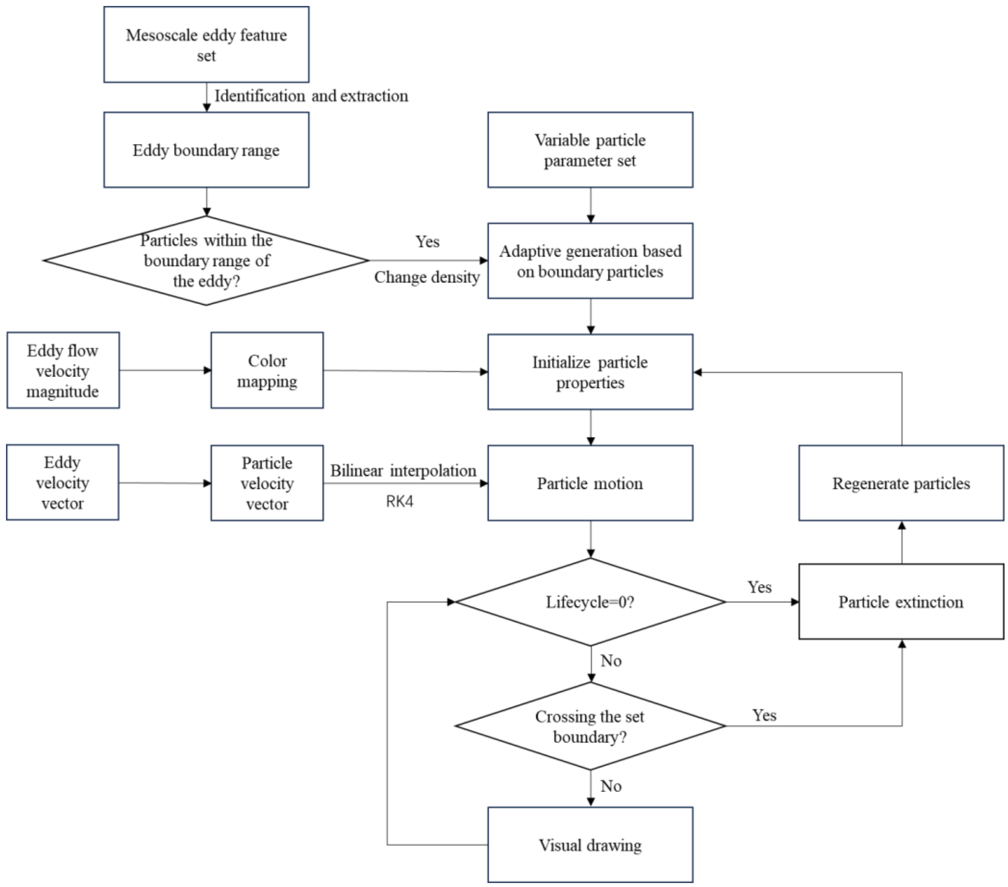


Figure 3: Visualization Method of Mesoscale Eddy Fatures Based on Variable Particles.

4.0 Experiment and Verification

4.1 Raw Data and Preprocessing

The satellite data used in this study includes Sea Level Anomaly (SLA) data and ocean surface current data. The SLA data originates from the gridded products provided by the Copernicus Marine Environment Monitoring Service (CMEMS) (https://doi.org/10.48670/moi-00148). The SLA values are estimated using optimal interpolation, combining Level 3 (L3) along-track measurements from different altimeter missions. The provided data spans from January 1993 to June 2023, with a temporal resolution of one day and a geographic coverage ranging from 89.87°S to 89.88°N and 179.87°W to 179.88°E, with a spatial resolution of 0.25° x 0.25°.

The Ocean Surface Current Analyses Real-time (OSCAR) is a global surface current database funded by NASA. The OSCAR surface mixed layer velocity is derived from satellite observations of sea surface height, ocean vector winds, and sea surface temperature gradients, calculated using simplified physical models that incorporate geostrophy, Ekman dynamics, and thermal wind dynamics. The ocean surface current data is published at "https://podaac.jpl.nasa.gov/dataset/OSCAR_L4_OC_INTERIM_V2.0," under the name Ocean Surface Current Analyses Real-time (OSCAR) Surface Currents - Interim 0.25 Degree (Version 2.0). The data files are in NetCDF format and include variables such as zonal and meridional velocities (U and V) as well as the zonal and meridional geostrophic velocity components (Ugosa and Vgosa). The provided data spans from January 1993 to December 2020, with a temporal resolution of daily intervals, covering the geographic range of 89.75°S to 89.75°N and 180°W to 180°E, and with a spatial resolution of 0.25° x 0.25°.

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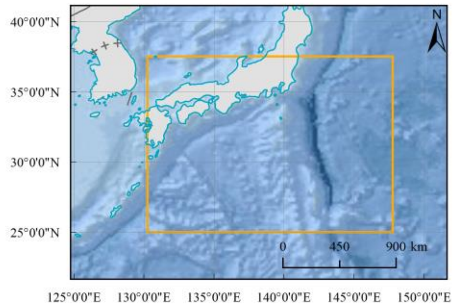


Figure 4: Case Display Area

Firstly, utilizing the NetCDF4 library in the Python programming language, the selected NetCDF format source data is processed to convert it into a readable format. This process involves extracting latitude and longitude coordinates, Sea Level Anomaly (SLA) values, as well as the U and V components of ocean surface currents. To ensure consistency in longitude and latitude coordinates, the SLA data undergoes preprocessing, which includes handling missing and outlier values to maintain data integrity and consistency. Subsequently, the preprocessed SLA data is integrated with the U and V components of ocean surface currents. The data integration process involves merging these variables into a unified data structure to ensure their correspondence at the same latitude and longitude positions.

4.2 Identification and Extraction Results of Mesoscale Eddies

This article utilizes Sea Level Anomaly (SLA) data to identify and extract mesoscale eddies in the study area from 2000 to 2009, employing the closed contour method and specific criteria for vortex identification. Results from May 1st of each year are selected for presentation. The graphs indicate that the majority of identified single-day mesoscale eddies occur in the waters surrounding Japan, with a corresponding latitude range of [insert latitude range]. This observation aligns with the complex seabed terrain around the Sea of Japan, which influences water flow direction and velocity, thereby facilitating eddy formation. Furthermore, the identified results are comparable to those of Cui et al. (2017), which also identified some mesoscale eddies within the latitude range of [insert latitude range]. However, these eddies have smaller diameters, consistent with the article's criteria for identifying mesoscale eddies with a diameter greater than 60 km.

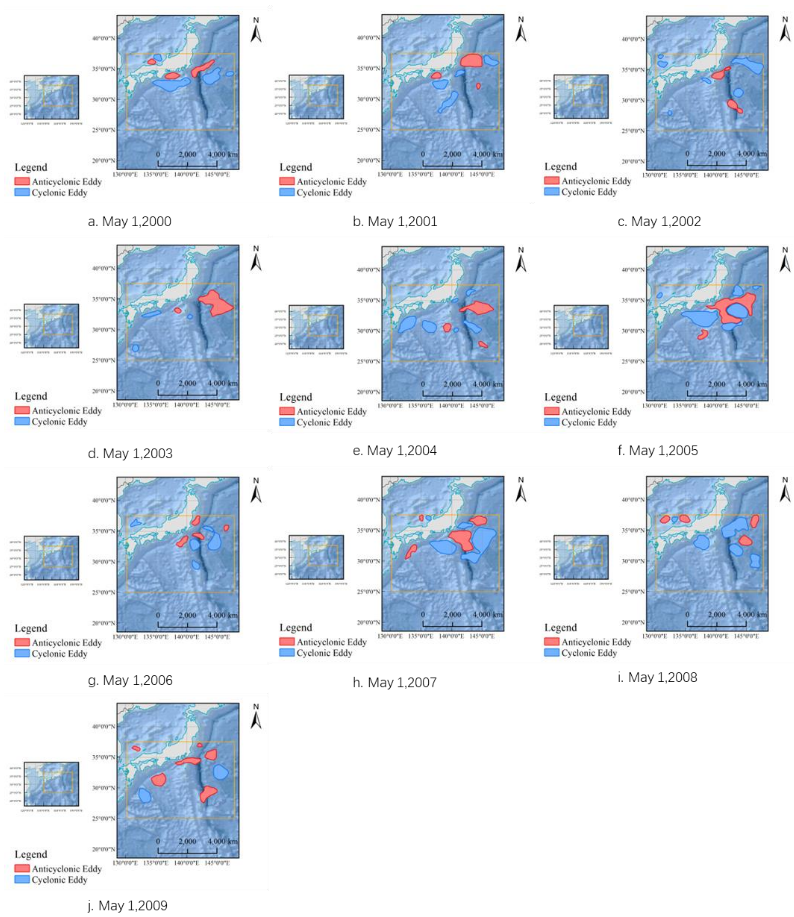


Figure 5: Vortex Identification Results from May 1, 2000 to 2009.

4.3 Visualization Results and Analysis Based on Variable Particle Systems

Based on the identification and extraction of mesoscale eddies, a vortex feature set is constructed, facilitating the visualization of these eddies by mapping the feature set to a variable particle parameter set. Figure 7 presents a visual comparison between the randomly generated particle method and the variable particle method, with color mapping achieved using standard visual color mapping techniques. The evaluation of the visualization results is conducted from both qualitative and quantitative perspectives. Qualitatively, the preservation of the flow field's topological structure is assessed (Wang, 2021), while quantitatively, the image coverage of generated streamlines under the same number of particles is compared (Pan, 2008).

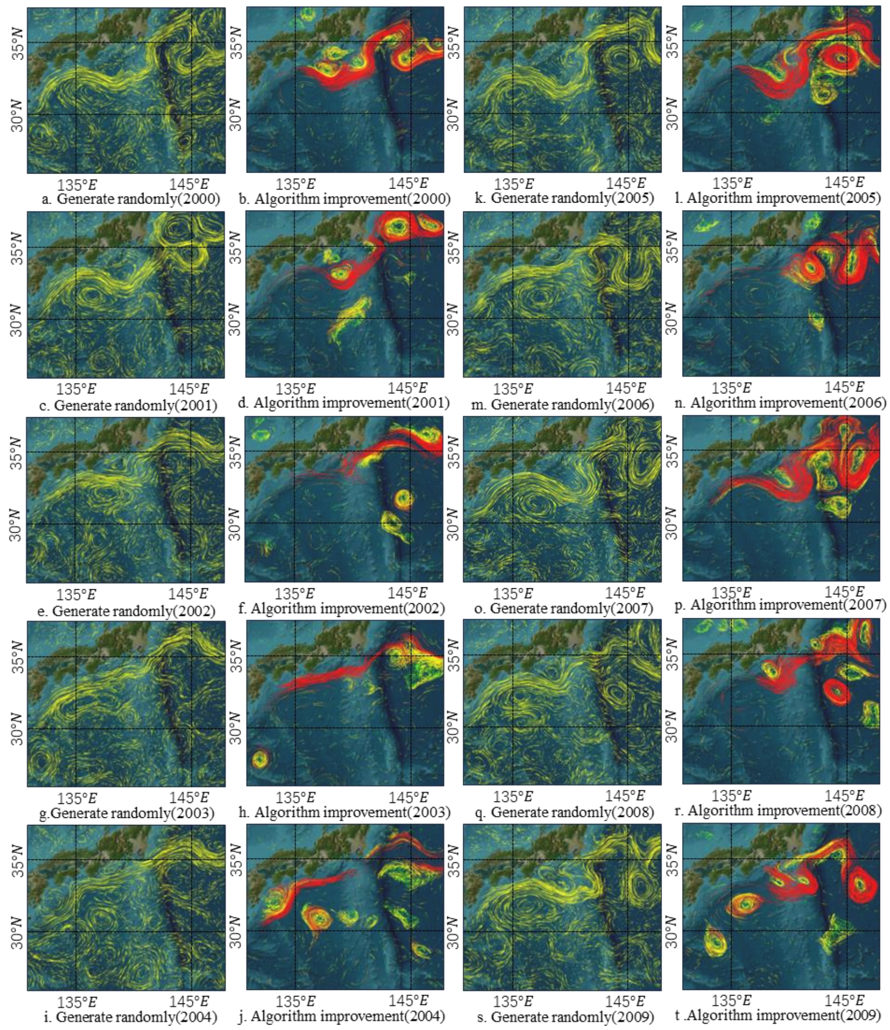
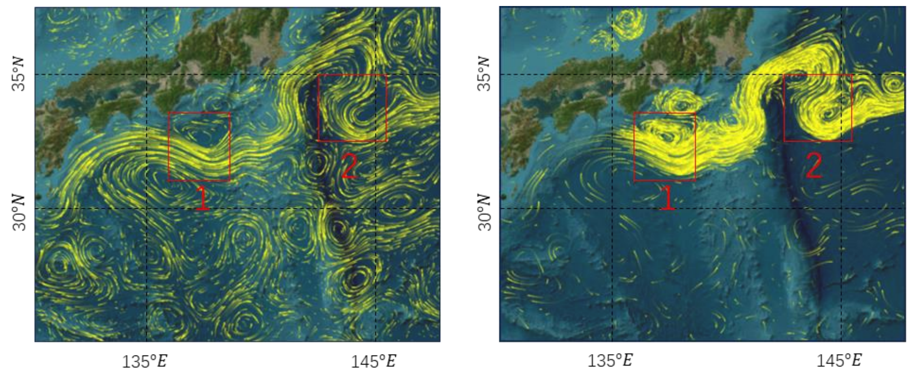


Figure 6: Comparison Chart Drawn from May 1, 2000 to 2009.

Based on the quantitative metric of image coverage generated by streamlines with the same number of particles, this paper employs the HSV color space proposed by Smith to calculate the image coverage of streamlines generated at the same scale in the same time and space. The color parameters include hue (H), saturation (S), and value (V). The HSV color space has two notable properties: first, the value (V component) is separated from the color information, which does not affect the color representation of the image; second, the hue (H component) and saturation (S component) are closely related to human color perception. These properties make the HSV color space more intuitive and suitable for developing image processing and analysis algorithms that align with the color perception characteristics of the human visual system.

Through the application of the HSV model, and using the two mesoscale vortices identified on May 1, 2000, as examples, their distribution is shown in Figure 7. Based on the identified locations of the mesoscale vortices, the corresponding regions selected are 31°-33.5°N, 136°-139°E and 32.5°-35°N, 142.5°-145.5°E. Using the HSV color space calculation method, the streamline coverage of the ocean flow field generated by different methods was compared, as shown in Table 4. Under the same number of particles, the image coverage of streamline trajectories generated by the proposed variable particle method is significantly improved. This indicates that more streamlines are produced within the boundary range of the mesoscale vortices, allowing for a more detailed depiction of the vortex structure. Additionally, as the number of particles increases, the streamline coverage also increases. Compared to the ocean flow field visualization method using randomly generated particles, the streamline trajectories generated by the variable particle algorithm yield more streamlines in the mesoscale vortex regions, effectively describing the trajectory movement of the vortices. The RGB to HSV color space conversion formula is shown in:

$$\begin{cases} H_1 = \arccos\left\{ \dfrac{\left[(R-G)+(R+G)\right]/2}{\sqrt{\left((R-G)^2+(R-B)(R-G)\right)}} \right\} \\ H = \begin{cases} H_1, B \le G \\ 360 - H_1, \ \text{else} \end{cases} \\ S = \dfrac{\max(R,G,B) - \min(R,G,B)}{\max(R,G,B)} \\ V = \dfrac{\max(R,G,B)}{255} \end{cases}$$



a. Random generation b. Algorithm improvement

Figure 7: May 1, 2000 Comparison Region

Table 4: Comparison of Streamline Image Coverage with Fixed Particle Numbers

Region One		
Number of particles	Randomly generated coverage	The coverage of algorithm improvement
2000	0.29%	1.77%
3000	1.47%	3.87%
4000	1.67%	6.80%
Region Two		
Number of particles	Randomly generated coverage	The coverage of algorithm improvement
2000	0.21%	0.94%
3000	0.90%	2.65%
4000	2.72%	6.97%

To compare the detailed visualization effects of the two selected mesoscale eddies concerning the qualitative indicator of the flow field's topological structure, we employed the variable particle system method, adjusting the particle density within the mesoscale eddy's center and boundary range. As depicted in Figures 8b and 9b, the streamline trajectories drawn using the enhanced algorithm exhibit notable characteristics. They emphasize the distribution of streamline trajectories within the boundary range of the mesoscale eddy, particularly highlighting clearer and more distinct visualization effects at the vortex center. The structure and shape of the vortex become more defined and prominent, while the contrast between the flow field inside and outside the vortex becomes more evident. This enhanced visualization method effectively portrays the formation, evolution, and dissipation processes of vortices, aiding in the discernment of their interaction with the surrounding environment.

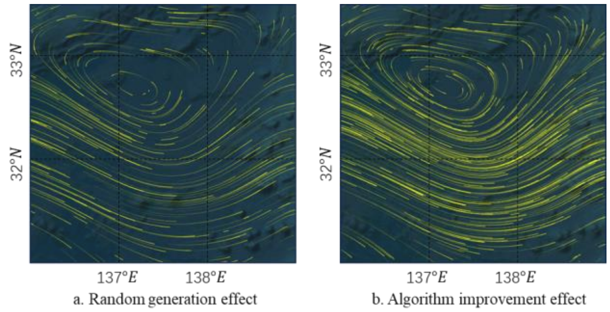


Figure 8: Comparison of Visualization Effects of Mesoscale Eddy in Region One

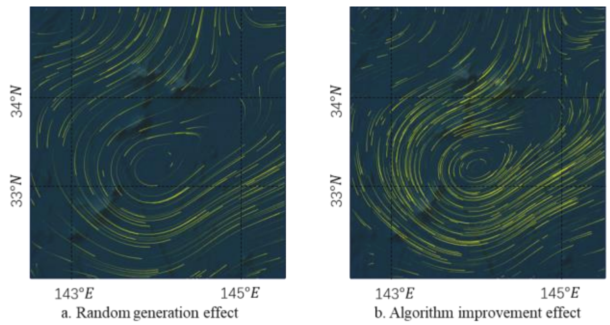


Figure 8: Comparison of Visualization Effects of Mesoscale Eddy in Region Two

In summary, compared to traditional methods of randomly generating particles, the streamlines produced by the variable particle system method proposed in this paper effectively identify the characteristic structures of mesoscale eddies in the ocean flow field. Additionally, color mapping provides clearer information regarding the magnitude of flow velocity, thereby enhancing the dynamic visualization effect of the ocean flow field.

5.0 Conclusion and Discussion

Visualization of ocean flow fields using particle systems is a crucial research direction in marine science. This paper introduces a methodology that constructs a feature set of mesoscale eddies and a parameter set of variable particles. By mapping the feature set to the parameter set of variable particles, mesoscale eddy features are effectively visualized.

Compared to traditional particle generation methods—such as those by Fang (2018), who optimized particle management; Chai (2023), who distributed particles uniformly and randomly based on grid size; and Fu & Ai (2019), who controlled particle density by setting particle thresholds within the grid—these approaches aim to visualize the flow field uniformly. However, in complex ocean flow fields where structural characteristics dynamically change, uniform distribution fails to fully capture the characteristic structural phenomena.

The variable particle system method proposed in this study, which incorporates a mesoscale eddy feature set and a variable particle parameter set, offers a more accurate representation of flow field characteristics and provides a more realistic simulation of mesoscale eddy motion. Utilizing this variable particle parameter method, future research will aim to visualize the features of various ocean flow fields and analyze their coupling effects.

Nevertheless, for a comprehensive understanding of ocean flow environments, it is crucial to integrate and visualize not only mesoscale eddies but also other vector field data, such as turbulence and boundary flow, as well as scalar field data like temperature and salinity. Addressing how to effectively integrate and visualize these diverse data types remains a challenge for future research.

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