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Detection of Floating Marine Litter Transport Structure Based on Particle Relative Dispersion in Mulan Bay, Hainan

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Abstract: Based on the FVCOM model and particle tracking model, this study simulates the material transport process in Mulan Bay and the surrounding sea areas of Hainan, and analyzes the dispersion characteristics and transport structure of the floating marine litter using the Relative Dispersion (RD) method. The results show that Mulan Bay, as a semi-enclosed area on the eastern side of the Qiongzhou Strait, plays a significant role in intercepting and accumulating floating marine litter. In spring and autumn, Mulan Bay demonstrates a clear interception effect on the floating marine litter transported from the Qiongzhou Strait. In summer, influenced by the southwest wind, the floating marine litter tends to be transported towards the northeast. In winter, under the strong influence of the northeast monsoon, the interception and accumulation capacity of Mulan Bay is significantly enhanced, making it a key area controlling the transport of floating marine litter in the Guangdong sea area. The research results provide scientific basis for the marine litter management in Hainan.

1 Introduction

Mulan Bay in Hainan is surrounded by the sea on three sides, forming a cone-shaped peninsula that protrudes into the Qiongzhou Strait, naturally creating a relatively independent semi-enclosed area. This area plays a significant role in intercepting floating marine litter from the northern South China Sea and the Qiongzhou Strait, leading to the accumulation of marine plastic litter in Mulan Bay, which poses a threat to marine landscapes and the ecological environment. In recent years, research on marine plastic litter has mainly focused on source-sink analysis, transport patterns and dynamics, monitoring, and management [1]. A deeper understanding of the transport structure of floating marine litter in Mulan Bay is essential for advancing marine litter management in Hainan.

In the study of marine material transport structures, the Lagrangian passive particle statistical method has become an important tool for revealing oceanic dynamic processes and material transport mechanisms [2,3]. This method tracks the particle movement trajectories and analyzes their statistical properties, effectively representing ocean flow characteristics, material mixing, and diffusion processes [4]. Lagrangian particle statistical analysis can be divided into single-particle, double-particle, and multi-particle statistics according to the number of particles in the statistical unit. Among them, the single-particle statistical method, based on Taylor's theory [5], is primarily used to study absolute dispersion (AD), which refers to the diffusion behavior of an individual particle relative to its initial position, and is widely applied in large-scale ocean process studies. On this basis, Batchelor [6] and Bennett [7] introduced the double-particle statistical method, which further developed the concept of relative dispersion (RD). By analyzing the relative separation process of particle pairs under advection and turbulence, RD provides a more intuitive reflection of particle diffusion characteristics. To more comprehensively describe the dispersion characteristics of particles in a fluid, Fredj [8] and others proposed the four-particle RD method, which, by introducing more statistical units, can identify material transport structures such as mixing barriers. This method provides new insights into the understanding of oceanic dispersion processes and their ecological effects. RD methods have unique advantages in representing the impact of turbulence mixing and multi-scale diffusion on material transport, and have been widely applied in fields such as pollutant dispersion, plankton distribution, and marine accident search and rescue [9].

This study, based on the Finite-Volume Community Ocean Model (FVCOM) and the particle tracking model, simulates the material transport process in Mulan Bay and the surrounding sea areas of Hainan, using the RD method to analyze the dispersion characteristics and material transport structure of floating marine litter in Mulan Bay.

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2 Data and Method

2.1 The hydrodynamic model

This study establishes a hydrodynamic model based on the FVCOM to simulate the hydrodynamics in the area including Hainan Island, Beibu Gulf, and the western Guangdong coastal waters. The model domain spans the longitude range of 105.6°E–115.6°E and latitude range of 15.4°N–22.9°N. The model utilizes an unstructured triangular grid in the horizontal direction, controlled by seven governing equations: continuity equation, temperature-salinity equation, momentum equation, and density equation. The unstructured triangular grid consists of 29,420 nodes and 57,140 grid cells (see Figure 1). The minimum grid step size is 250m. To better fit the complex coastline, the vertical direction uses sigma coordinates, dividing the water depth into five layers uniformly.

The bathymetric data are derived from the hydrographic surveys published by the Hydrographic Bureau in 2024. The depth at each grid node is obtained through interpolation (see Figure 2).

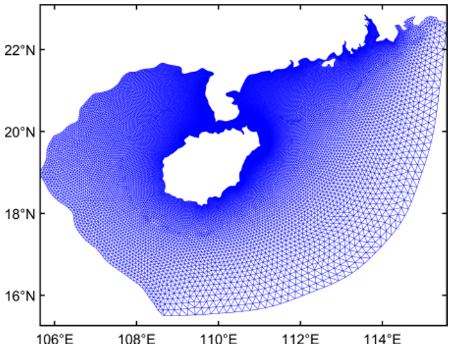


Figure 1. Model Grid Distribution Map

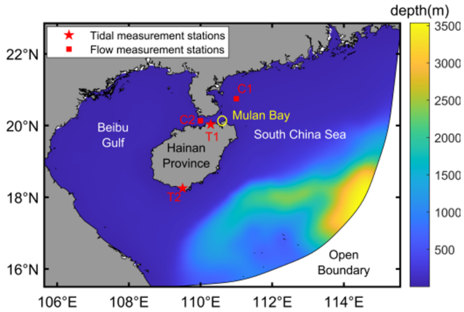


Figure 2. Model Water Depth Distribution Map

At the open boundary, the tidal constituents M2, S2, O1, K1, P1, Q1, N2, and K2 are selected. The tidal data from January 1, 2020, 00:00 to March 31, 2021, 23:00 with a 1-hour interval are forecasted using the TPXO7.2 model. The tidal level forecast is made using the following formula:

$$Z(t) = s_0 + \sum_{j=0}^{n} \left(H_j \cos\left(\sigma_j t - g_j\right)\right) \tag{1}$$

Where $Z(t)$ represents the water level at time t, and σ_j, H_j, g_j represent the angular frequency, amplitude, and phase of the j tidal constituent, respectively. s_0 is the mean sea level.

The main river runoff in the region includes the Zhujiang (Pearl River) and Nandu River. The runoff data are taken from the "2020 Water Resources Bulletin" and "2020 Hainan Province Water Resources Bulletin". The atmospheric forcing is derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) fifth-generation reanalysis dataset ERA5, providing wind field data with a temporal resolution of 1 hour and a spatial resolution of 0.25°. The model adopts a cold start method, initializing the velocity and water level to zero. It is a positive pressure model, with constant values for temperature and salinity, set at 18°C and 30 psu, respectively. To accommodate changes in seabed topography, the bottom friction coefficient is set to 0.0012, and the velocity field output interval is 1 hour.

2.2 Lagrangian Particle Tracking Model

In the long-distance transport of marine substances, convection plays a significantly stronger role than diffusion. Therefore, this study focuses solely on particle convection, using a fourth-order explicit Runge-Kutta method for the solution. To avoid particle loss, particles return to their previous positions after contacting the land boundary. The particle trajectory is expressed in integral form as:

$$X(t_0 + \Delta t) = X(t_0) + \int_{t_0}^{t_0+\Delta t} v(x,\tau)\, d\tau \tag{2}$$

Where $v(x,\tau)$ is the two-dimensional velocity field generated by the model, $X(t_0)$ representing the particle's initial position; Δt is the time step; and $X(t_0 + \Delta t)$ represents the particle's final position.

2.3 Relative Discreteness

The four-particle relative discreteness (RD) method is a multi-particle statistical approach based on a particle tracking model. It characterizes the dispersal behavior of particle groups by using the position information of the particles at both the initial and final times. This method takes the central particle as a reference point and calculates the displacement changes of the four nearby particles to generate the RD field. The regions in the RD field with the largest gradient changes typically exhibit continuous linear structures, known as "ridges." These structures reflect the characteristics of particle diffusion or aggregation. Based on the direction of time integration, the RD field can be divided into forward and backward types: in the forward RD field, the "ridges" represent regions where particle diffusion is more significant, indicating a mixing barrier, with materials on both sides gradually separating over time. In the backward RD field, the "ridges" mark the boundaries of areas where materials are aggregating and have an attracting effect on surrounding particles. The RD calculation formula is as follows:

$$RD^2 = \frac{1}{4} \sum_{j=1}^{4} \left(z_j(t_0 + \tau) - z_k(t_0 + \tau)\right)^2 \tag{3}$$

Where t_0 represents the initial time when the particle was released, τ represents the time interval, $z_k(t_0 + \tau)$

represents the position of particle k at time $(t_0+\tau)$, and $z_j(t_0+\tau)$ represents the positions of four particles z_1,z_2,z_3,z_4 at time $(t_0+\tau)$, respectively. The units are in kilometers (km).

In this study, particles are uniformly released every 1 km within the model domain, with the FVCOM hydrodynamic field driving particle movement. The particle positions are obtained, and the relative discreteness (RD) is calculated to quantify the diffusion extent of the particle group.

3 Research Results

3.1 Model validation

In this study, we validated the water level, flow velocity, and flow direction simulated by the model (see Figure 3). The validation data were obtained from the tidal and current data provided by the National Marine Science Data Center (http://mds.nmdis.org.cn). The simulation results are generally consistent with the observed data, indicating that the model can provide a reliable flow field for subsequent research.

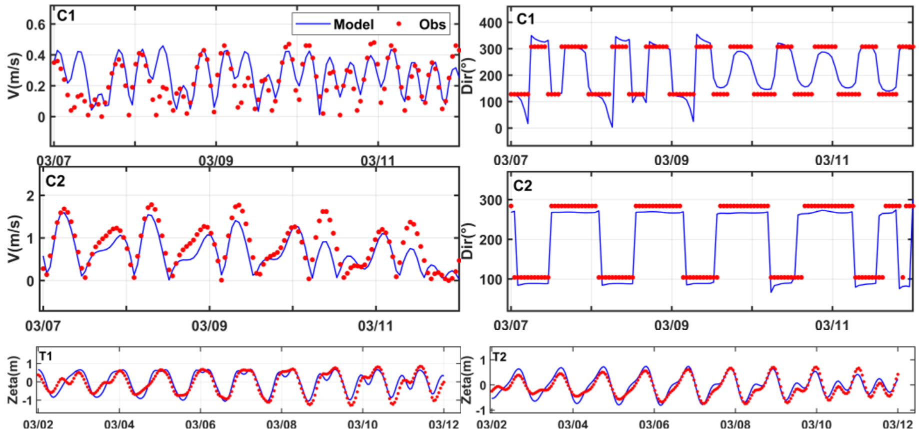


Figure 3. Model validation results for tidal currents and tides

3.2 Discrete Characteristics

This section calculates the forward and backward RD fields for four seasons in the northwestern South China Sea using particle tracking, to study the transport structure and diffusion of marine debris in Mulan Bay. The integration time is 720 hours, with a time step of 3600 seconds. Particles are uniformly released at intervals of 1000 meters in the model domain, with a total of 580,000 particles released. Forward tracking uses forward integration, with release times on March 1, June 1, September 1, and December 1, 2020. Backward tracking uses backward integration, with release times on March 30, June 30, September 30, and December 30, 2020. This study focuses only on the transport structure of marine debris, so the model's surface flow field is used for the particle tracking experiment.

Spring RD Field. The results of the forward RD field (see Figure 4) show significant material diffusion characteristics in the waters around Hainan Island during spring. On the 15th day of integration, a clear RD ridge structure has formed along the coast east of the Qiongzhou Strait. By the 30th day of integration, the nearshore RD "ridge" is stably distributed in the Qiongzhou Strait and the eastern coastal waters of Hainan Island. As the integration time increases, the particles further diffuse toward the northeastern waters, indicating that the Qiongzhou Strait and the eastern coastal waters of Hainan Island have strong material diffusion capabilities, with the diffusion range extending eastward toward the Qiongzhou Strait as the integration time increases.

The results of the backward RD field show that the Qiongzhou Strait has a significant material aggregation effect during spring. The RD structure is mainly concentrated in the Qiongzhou Strait and extends toward the Beibu Gulf as the integration time increases, indicating that this area has a strong material aggregation ability, with the aggregation range expanding toward the Beibu Gulf over time.

In spring, the Qiongzhou Strait and the eastern coastal waters of Hainan Island are both active areas for material diffusion and important areas for material aggregation. Mulan Bay, located on the east side of the Qiongzhou Strait, has a certain intercepting effect on the marine debris transported toward the Qiongzhou Strait.

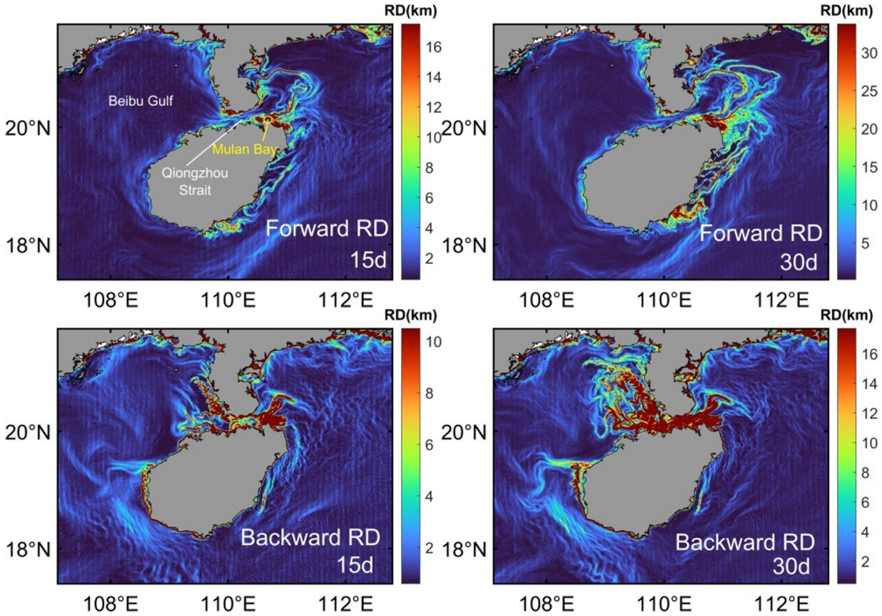


Figure 4. Forward and backward RD fields in spring

Summer RD Field. The forward RD field (see Figure 5) results indicate significant material diffusion characteristics in the waters surrounding Hainan Island during the summer. When integrated up to day 15, the RD value in the nearshore waters of the eastern Hainan Island is relatively high, and a clear coastal RD ridge structure forms between Hailing Island in Guangdong Province and the Pearl River Estuary, as well as in the Qiongzhou Strait, showing a southwestward diffusion pattern. When the integration time increases to 30 days, the RD structure in the Guangdong waters shifts westward and extends toward the northeast corner of Wenchang City in Hainan Province, while the RD ridge structure in the Qiongzhou Strait remains stable, showing no significant changes.

The backward RD field results show that after 15 days of integration, a clear RD structure has formed near the northeast corner of Hainan Island and the Pearl River Estuary. By day 30, the RD structure in the northeast of Hainan Island extends along the coastline toward the nearshore waters of Guangdong, while the RD ridge structure in the Beibu Gulf remains relatively stable, further expanding northward with time. It is important to note that reflective boundary conditions may cause false high-value areas in the nearshore regions (such as the spotted structure in the backward field around 110°E, 17.8°N), and this paper considers only the clear linear RD ridge structures in the figures as the true material transport pathways.

During the summer, the prevailing southwest monsoon forms a clear diffusion channel between the northeastern corner of Hainan and the nearshore waters of Guangdong, with a material convergence area forming on the eastern side of the Leizhou Peninsula. This suggests that marine debris in Mulan Bay tends to be transported northeastward in the summer.

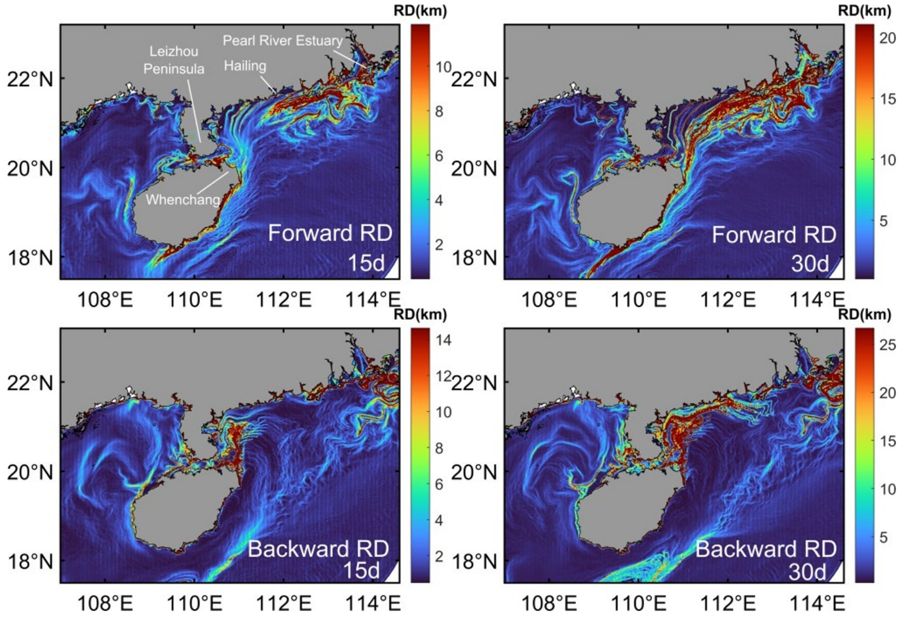


Figure 5. Summer Forward and Backward RD Fields

Autumn RD Field. The RD ridge structures in autumn (see Figure 6) are concentrated in the eastern Qiongzhou Strait and the deep waters to the east of Hainan Island (113°E, 18°N–22°N), with the structure gradually becoming clearer as the integration time increases. The values of the forward RD field are significantly higher than those of the backward RD field, indicating strong diffusion capabilities in this area.

In autumn, the material transport characteristics in Mulan Bay are similar to those in spring, but the RD values are noticeably lower than in spring, indicating a weakening of material diffusion and convergence intensity compared to the spring season. The RD ridge structure in Mulan Bay remains stable and extends in the northeast direction, forming a new small-scale material convergence zone in the adjacent waters of Mulan Bay. This suggests that Mulan Bay and its surrounding waters continue to be key areas for the transport of marine debris in autumn.

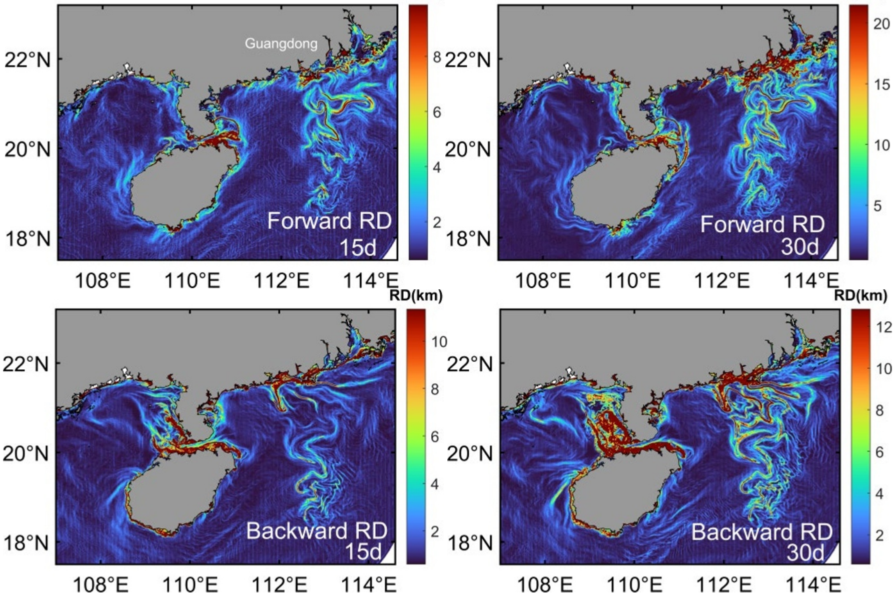
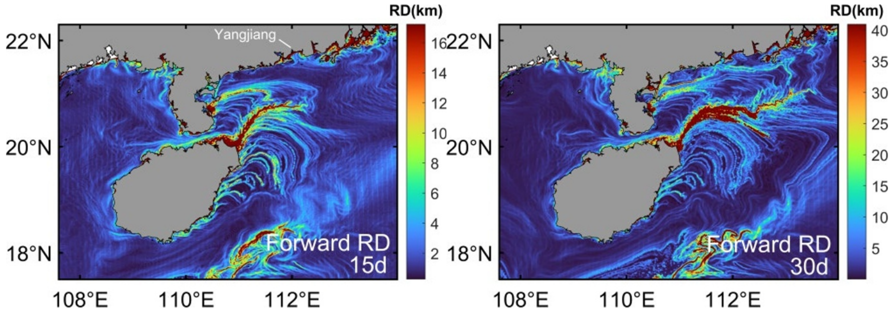


Figure 6. Autumn Forward and Backward RD Fields

Winter RD Field. The forward RD field (see Figure 7) results show that by day 15 of integration, a dense and ordered RD ridge structure has formed from the northeastern part of Hainan Island to the eastern side of Leizhou Peninsula, showing obvious diffusion characteristics. When the integration time is extended to 30 days, the RD ridge structure stretches eastward, expanding into the waters of Yangjiang in Guangdong. The structures in the Beibu Gulf and Qiongzhou Strait are stable, with no clear RD ridge structures observed.

The backward RD field structure remains stable, with RD ridge structures present across the model region, most notably in the nearshore waters. As the integration time increases, the RD ridge structure slightly strengthens.

Influenced by the strong northeast monsoon, the winter RD field in Mulan Bay shows a significant aggregation capability, with a notably enhanced interception and convergence effect on marine debris. This makes Mulan Bay a crucial area for controlling the transport of marine debris in the Guangdong waters.



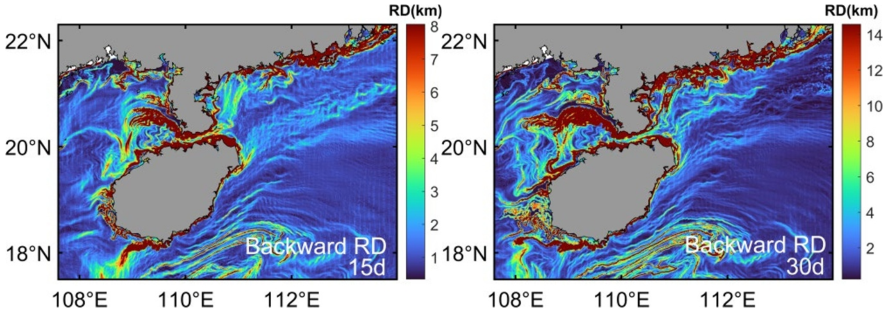


Figure 7. Winter Forward and Backward RD Fields

4 Conclusion

This paper constructs the hydrodynamic field in the northwest part of the South China Sea based on the FVCOM model, simulates the material transport process using the particle tracking method, and investigates the material transport structure using the RD method. The results show that, during spring and autumn, Mulan Bay has a certain interceptive effect on the transport of marine litter towards the Qiongzhou Strait. In summer, marine litter in Mulan Bay tends to be transported towards the northeast. However, in winter, the interceptive and aggregation effects of Mulan Bay on marine litter are significantly enhanced, making it a key area for controlling the transport of marine litter in the Guangdong waters.

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