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(Review Article)

Simulate the current dynamics process and predict the trajectory of plastic waste flowing out to sea from estuaries in the Gulf of Tonkin

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Abstract

This paper presents the results of a numerical simulation of flow dynamics in the northern Vietnam Sea. Based on these results, the trajectories of plastic waste from river mouths in the northern Vietnam Sea are predicted. The numerical simulation is based on the ROMS model for the northern Vietnam Sea and surrounding areas, in combination with data collected from a Vietnam-France international cooperation project (Study, evaluation, and prediction of the transport and dispersion of small plastic waste in the Van Uc River mouth area). The dynamic regime of the study area is considered to simulate the main wind seasons. The results show that the flow field in the Northern Vietnam Sea follows the tidal phases. In the rising tide phase, the general trend is for the flow to move from the south to the north. Conversely, in the falling tide phase, the general trend is for the flow to move from the north to the south. The flow speed in the tidal phases is largest at about 65-70 cm/s and smallest at about 5-10 cm/s. The much larger surrounding area outside the Northern Vietnam Sea has a very complex flow field, with many different flow areas and vortices. There is a belt of vortices that extends for hundreds of kilometers, with an average flow speed that is higher than the flow in the Northern Vietnam sea. Based on the flow field and the frequency of occurrence in the area near the Vietnamese coast where rivers flow out, the frequency of flow flowers are used to predict the trajectories of plastic waste from river mouths into the sea. The results of the calculations and predictions, when compared with the actual data, show good agreement.

Keyword: Flow dynamics; Northern Vietnam sea; Trajectories; Waste

1. Introduction

The study of ocean currents in the northern Vietnam Sea and the surrounding area using the ROMS (Regional Ocean Modeling System) model has produced promising results. ROMS is an open-source model that has been used and developed by many authors around the world. It can be used to simulate a wide range of spatial and temporal scales, from coastal waters to the world's oceans, for periods of a few days, months, or even decades. ROMS solves the hydrodynamic equations for a free-surface ocean with complex topography. The horizontal grid is created using a curvilinear orthogonal grid (Vreugdenhil grid) and the vertical grid is created using a sigma coordinate system (as described by Arakawa, A. and Lamb, 1977; Mellor et al., 1985). The advantage of ROMS is its ability to simulate the effects of topography on currents more accurately than conventional finite difference models, but it also has some drawbacks, such as numerical errors in the calculation of pressure gradients at locations with large slopes in the study area. The study of the dynamics of currents in the Northern Vietnam Sea and the surrounding area has been carried out by several authors, including: *Duong (2021),* who studied synoptic eddies and found that the Northern Vietnam Sea has many different forms of eddies. *Duong (2015),* who found the presence and existence of eddies in different regions of the western Pacific, which are often formed by strong western boundary currents. Metzger and Hurlburt (1996), who predicted the appearance of eddies in the South China Sea during monsoon periods. Liu et al., who found a system of small eddies that dominate the northern and southern regions of the South China Sea during the northeast monsoon

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season. Huijie Xue et al. (2022), who extended the study area to longitude 150°E and constructed a map of the current field, predicting the presence of eddies in the South China Sea. Jianyu Hu et al. (2000), who drew a qualitative picture of the current field in the South China Sea with the presence of some eddies.In the northern Vietnam Sea, Cuong et al. (2016) found that the circulation system in the winter is divided into two distinct regions. In the nearshore area, the current tends to flow along the coast. Vinh et al. (2013) found that the areas with high current speeds are located outside the Nam Trieu, Van Uc, Ba Lat, and Day River mouths at the transition point between the rising or falling tide phases. The areas with low current speeds (less than 0.2 m/s) are the nearshore waters and far from the river mouths.At low tide, the current still exists but is only concentrated near the inner river mouth area with a common speed of 0.3-0.5 m/s in the dry season and 0.4-0.7 m/s in the rainy season. Chung et al. (2014) found that there is a cyclonic eddy, the activity of this eddy also changes according to the seasonal winds. Huong (2013) found that some of the main features of the circulation in the Northern Vietnam Sea are the existence of a western boundary current throughout the year and the presence of an anticyclonic eddy in the northern part of the gulf during the summer.

Based on the ocean dynamics regime to study the process of transporting plastic debris in the marine environment. By linking global data on solid waste, population density, and economic status, it is estimated that about 300 million tons of plastic waste have been generated in coastal countries and tens of millions of tons have entered the ocean.Most plastics decompose slowly and are stored for hundreds of years in the natural environment, causing negative impacts on marine and ocean ecosystems. van Sebille, E. et al. (2015) used plankton nets to collect data on the distribution of plastic debris at the sea surface and combined this with three ocean surface circulation models to interpolate the trajectories of plastic debris in space. Mansui J. et al. (2022) modeled the transport and accumulation of floating marine debris in the Mediterranean basin to explore the possibility of long-term accumulation structures existing in the northern Vietnam sea.

The use of ROMS to study the dynamics of currents and preliminary analysis of the frequency of occurrence to predict the trajectory of plastic waste from river mouths in the northern Vietnam Sea into the sea yielded acceptable results.

2. Research basis and methods

2.1. Governing equations

The basis for the study of ocean currents in the Northern Vietnam sea and the surrounding area is the implementation and development of the ROMS model. The governing equations of ROMS are established on three coordinate systems: Cartesian - Sigma - Orthogonal curvilinear. The Cartesian coordinate system with x increasing in the east, y increasing in the north, and z increasing in the vertical direction from bottom to top. The motion equation in the Cartesian coordinate system is as follows:

$$\frac{\partial u}{\partial t} + \vec{v}.\Delta u + w\frac{\partial u}{\partial z} - fv = -\frac{\partial \phi}{\partial x} + F_u + D_u \quad \text{..............(1)}$$

$$\frac{\partial v}{\partial t} + \vec{v}.\Delta v + w\frac{\partial v}{\partial z} - fu = -\frac{\partial \phi}{\partial y} + F_v + D_v \quad \text{..................(2)}$$

The free surface of the sea is determined at the position $z = \zeta$ *(x,y,t)* and the bottom is at the position *z = - H(x,y).* where, $\vec{v}$ is the horizontal velocity vector with components *(u, v)*, w is the vertical component, is the temperature-salinity component and ▯ is the horizontal gradient operator. . In this context, ROMS formulates seven equations:

- The continuity equation for incompressible fluids,
- Two momentum equations in the horizontal direction,
- One momentum equation in the vertical direction,
- The equation of state,
- The thermal diffusivity equation
- The salinity diffusivity equation

By transforming from the Cartesian coordinates (*x, y, z*) to the non-orthogonal coordinate system (Sigma) in the vertical direction (*x′, y′,* σ), then utilizing operators such as $x' = x$, $y' = y$, $\sigma = \dfrac{z - \zeta}{H + \zeta}$ (z = ζ " σ = 0", z =-H " σ =-1"),

We perform coordinate transformations from the Cartesian coordinate system to the Sigma coordinate system, from the sea surface at *z* = ζ to the sea bottom a*z = -H* with non-integer coordinates σ = 0 and σ = -1. In this coordinate system, we obtain the seven governing equations of ROMS. In the orthogonal curvilinear coordinate system, by using the orthogonal operators ξ, η and with boundaries of the domain coinciding with the ξ, η isolines, when the mapping function is defined, the metric coefficients, m and n, are also determined. The metric coefficients m and n of the orthogonal curvilinear coordinate system link the partial derivatives in the ξ and η directions with the real curves, replacing and transforming the ROMS equations in the Cartesian coordinate system into the corresponding seven equations in the orthogonal curvilinear coordinate system.

The study domain covers the range from 13°N to 23°N and 102°E to 123°E, divided into a grid of 90 x 170 nodes with grid spacing dy ranging from 0.111^0 and *dx* about 0.117^0. The seabed topography is interpolated from the global ETOPO-2 bathymetric data with a resolution of 1' arc-minute and divided into 5 layers according to the Sigma coordinate system. Stability and convergence conditions must follow the Courant–Friedrichs–Lewy (CFL) criterion, which Duran has thoroughly presented.

2.2. Data source

At the marine boundary, tidal data is computed using the TPXO7 model, utilizing data from the global version 7.1 of TOPEX/Poseidon (TPXO7.1). In this model, wave components are calculated and interpolated for the grid points within the research area.

The thermal-salinity data in the North of the Northern Vietnam sea and the extended neighboring marine regions are obtained from analyses provided by NOMADS (NOAA Operational Model Archive and Distribution System) and Numerical Weather Prediction (NWP) models. Wind data is extracted from the COAMPS (The Comprehensive Ocean – Atmospheric Data Set) atmospheric model and scatterometer data from satellite observations such as QuikSCAT.

Surface wind data time series are derived from the merged Atmospheric-Ocean Data Set of the Climate Diagnostics Center (CDC), CIRES (Cooperative Institute for Research in Environmental Sciences), and the National Climatic Data Center (NCDC).

Freshwater flux, temperature, evaporation, precipitation, and sea surface tension coefficient throughout the year are acquired from COADS. River boundary conditions use a dataset of water levels measured at the mouth of the Red River.

3. Research Results

3.1. Some Main Characteristics of the Primary Current Field

Based on the tidal rise and fall trends in the northern Vietnam Sea, we observe the following main characteristics of the current field during these tidal phases:

During the initial phase of the rising tide (approximately from 18°N and 11°E, as shown in Figure 1), the general trend of the current field in the northern Vietnam Sea is from the south to the north. The nearshore region of Vietnam exhibits a rather complex flow pattern, with areas of currents directed toward the coast, areas moving northward, and areas with southward flow. The current velocities during this period are relatively low, around 10 cm/s.

In the central part of the gulf, the current field tends to flow uniformly from the south to the north, curving along the Vietnamese coast and Hainan Island (China). The current velocity in this central region remains relatively low, at about 15 cm/s.

In the vicinity of Hainan Island and the Chinese mainland, the current field follows the contour of the island and the coastline, with a general south-to-north direction. The current velocity in this region is higher than the other two areas of the Northern Vietnam sea and can reach speeds of up to 30 cm/s.

In the large neighboring area outside the Northern Vietnam sea , the current field is highly complex, characterized by various distinct current zones and the presence of eddies. There are concentric eddy belts extending for hundreds of kilometers, with current speeds in some parts of this eddy belt reaching 50-70 cm/s.

These observations provide an overview of the primary characteristics of the current flow in the Northern Vietnam sea during different tidal phases.

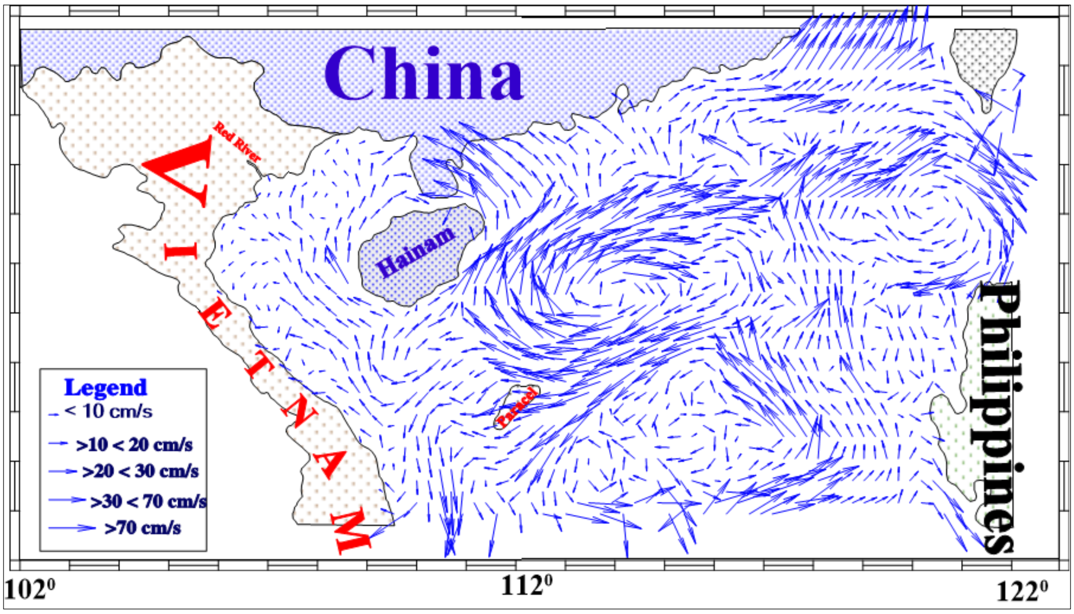


Figure 1 Current Field in the Research Area during the Initial Phase of the Rising Tide

3.2. Strong Rising Tide Phase

During the strong rising tide phase, the general current flow trend across most of the northern Vietnam Sea is from the south to the north. However, the direction of this northward current flow strongly depends on the coastline of Vietnam and Hainan Island (as shown in Figure 2). In the sea areas close to the Vietnamese coast, the current flows more intensively towards the north and is heavily influenced by the Vietnamese coastline, with current velocities averaging around 20-25 cm/s. In the central region of the gulf, the current field predominantly flows from the south to the north, curving along the Vietnamese coastline and Hainan Island (China), with current velocities at this time being notably higher, around 60-70 cm/s. In the sea areas adjacent to Hainan Island and the mainland of China, the current follows the contours of the island and the coastline, moving from the south to the north, with substantial current speeds reaching approximately 60-70 cm/s. In the neighboring large sea areas outside the Northern Vietnam sea , the current field remains highly complex, with little variation compared to the early rising tide phase, and current speeds are nearly identical to those observed during the initial phase.

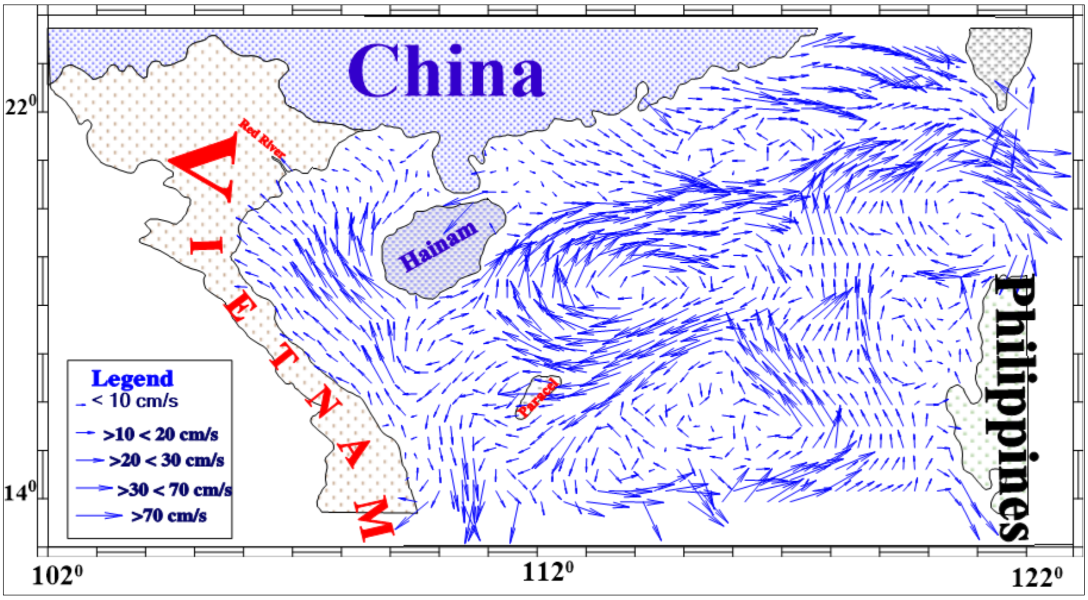


Figure 2 Current Field in the Research Area during the Strong Rising Tide Phase

3.3. Strong Falling Tide Phase

During this phase, the general direction of the current field tends to flow from the north to the south (as shown in Figure 3). The direction of the current near the Vietnamese coast is relatively less complex compared to the early rising tide phase, primarily flowing from the north to the south, following the coastline, with current speeds of approximately 10 cm/s. In the central part of the gulf, the current field tends to flow from the north to the south and depends on the Vietnamese coastline and Hainan Island (China), with current velocities at this time averaging about 12-18 cm/s. In the sea area near Hainan Island and the Chinese mainland, the current field follows the contours of the island and the coastline, moving from the north to the south, with an average current velocity of about 25-30 cm/s. In the large neighboring sea area outside the Northern Vietnam sea , the current field remains similar to that observed during the early rising tide phase and the strong rising tide phase.

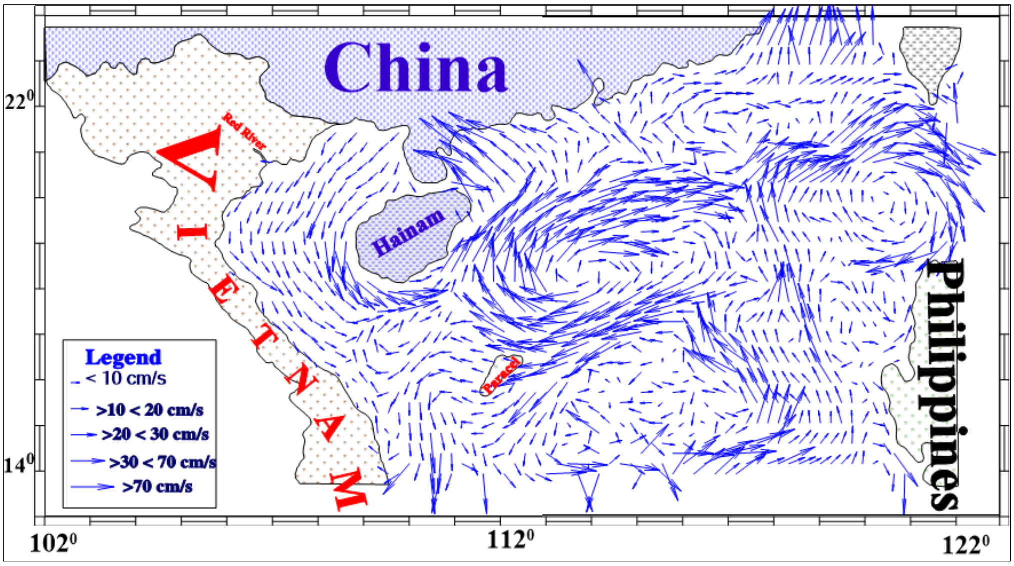


Figure 3 Current Field in the Research Area during the Initial Phase of the Falling Tide

3.4. Strong Falling Tide Phase

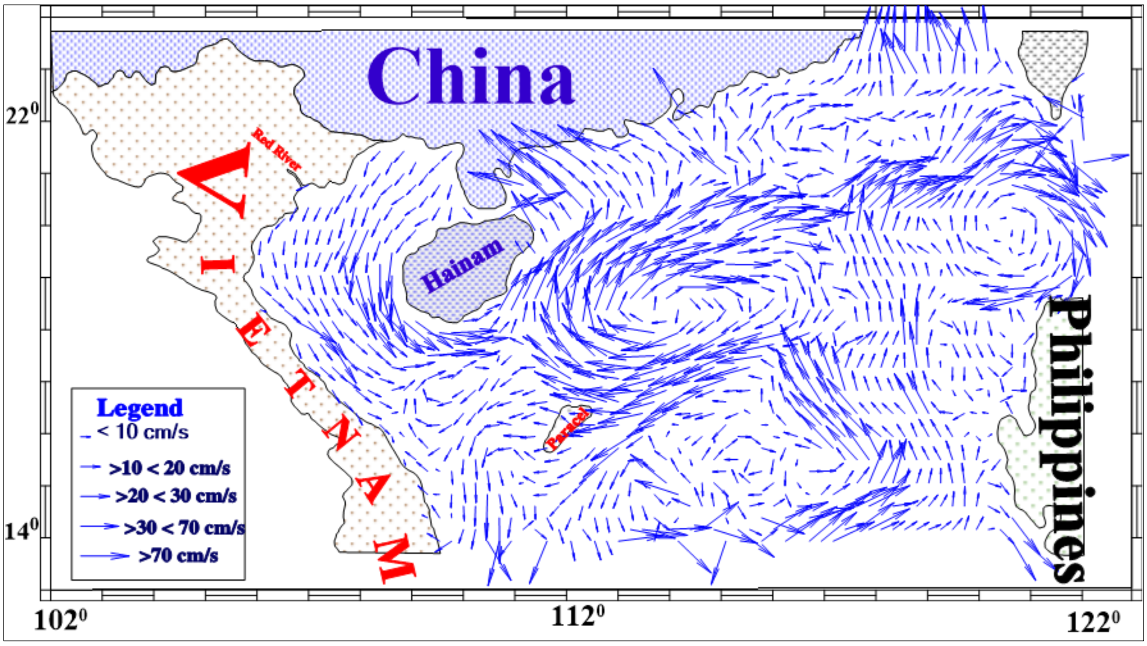


Figure 4 Current Field in the Research Area during the Initial Phase of the Falling Tide

The depiction of the current field in the Northern Vietnam Sea is similar to that during the strong rising tide phase, but the flow direction is reversed. In both cases, the general trend of the current field is from the north to the south (as shown in Figure 4). In the sea areas close to the Vietnamese coast, the current flows predominantly from the north to the south and is heavily influenced by the Vietnamese coastline, with current velocities averaging around 20-25 cm/s. In the central region of the gulf, following the general orientation of the gulf, the current flows from the north to the south and depends on the Vietnamese coastline and Hainan Island (China), with current velocities at this time being notably higher, around 65-70 cm/s. In the sea areas near Hainan Island and the Chinese mainland, the current flow is consistently stronger than in the other two regions of the gulf, with large-scale current velocities reaching about 70 cm/s. In the large neighboring sea area outside the Northern Vietnam Sea, the current field remains highly complex, with little variation compared to the various tide phases within the gulf.

Because plastic waste at any given time and under certain circumstances can be carried out into areas with complex current patterns, it can persist there for an extended period. In the northern Vietnam Sea, the current field nearly maintains the tide phase, while in the vast neighboring areas outside the northern Vietnam Sea, the current field fluctuates with the seasons. Comparing the current field in the research area during the same tide phase but in different seasons, we can observe this phenomenon (as shown in Figures 5 and 6).

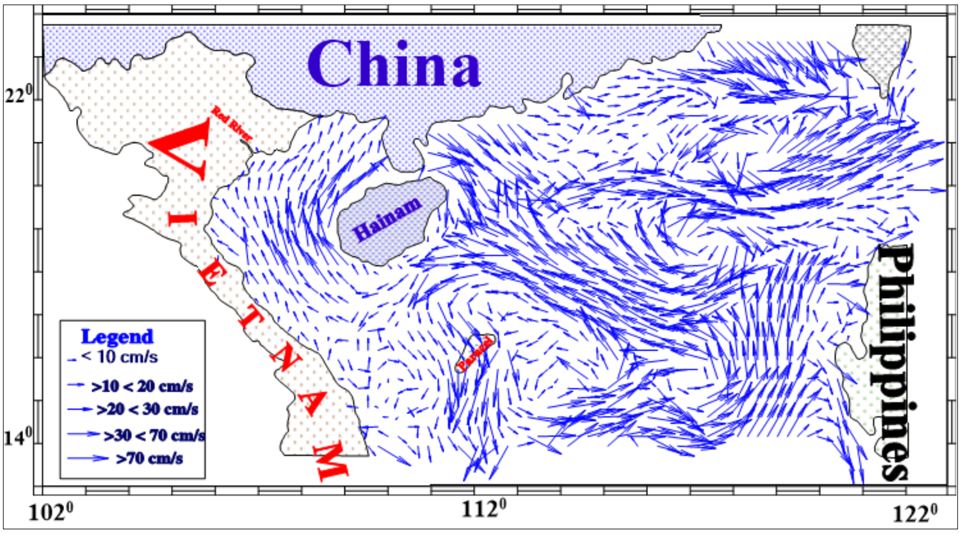


Figure 5 Current circulation in the vicinity of the Gulf of Tonkin in March

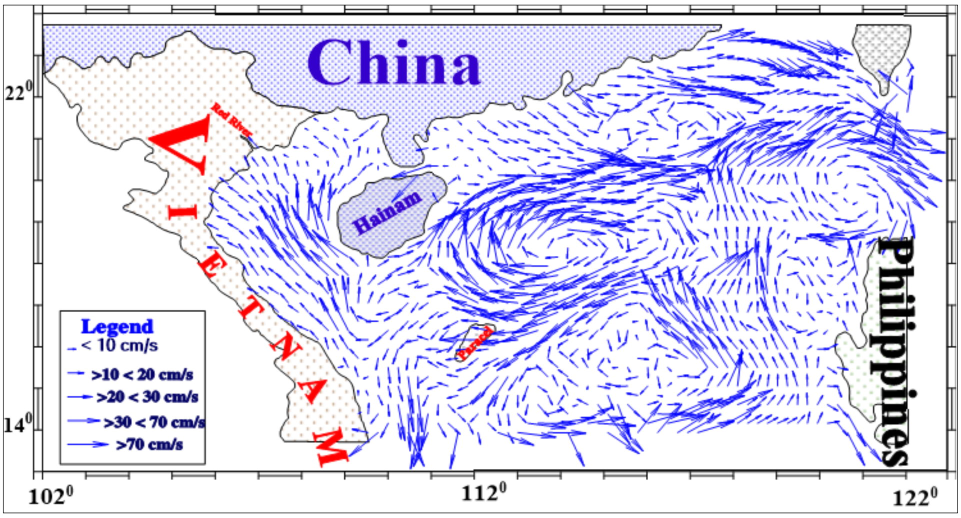


Figure 6 Current circulation in the vicinity of the Gulf of Tonkin in July

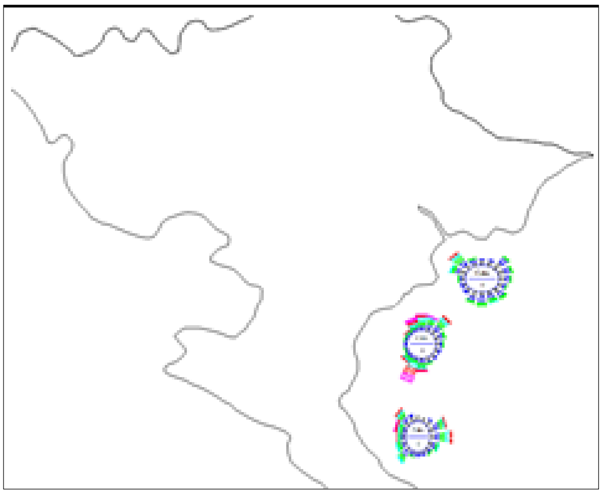
3.5. Predicting the Drift Path of Plastic Waste Based on Current Vector and Flow Frequency

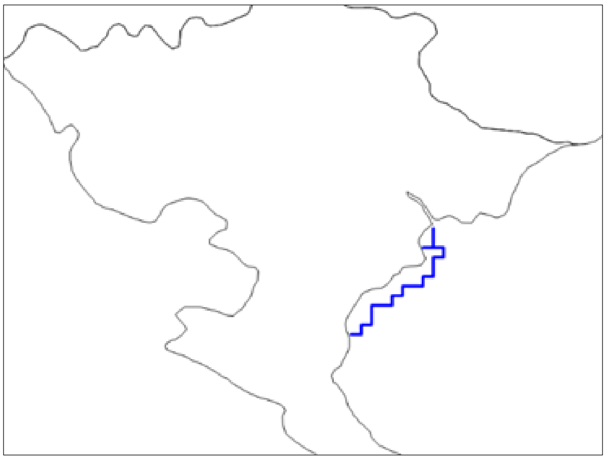
Based on the average current velocity, flow frequency in different directions, average seawater density, grid layout (dx, dy), resistance force, and the plastic waste fragment's lag time, we can calculate and predict the drift path of plastic waste. According to the initial results, assuming that plastic waste is pushed far enough from the river mouths and cannot immediately drift to the shore, the plastic waste will primarily move within the circulation of the northern Vietnam Sea. Using the flow frequency of nodes on the grid near the Vietnamese coastline, we can calculate the predicted transport of plastic waste, which will mainly move according to specific grid points as outlined in Table 1 and the accompanying figure.

Table 1 Prediction table of coordinates of grid points (xi, yi) corresponding to real coordinates

TT	Yi	Xi	Longitude	latitude	
1	35	63	106.7778	20.5753	
2	35	62	106.7778	20.4712	
3	35	61	106.7778	20.367	

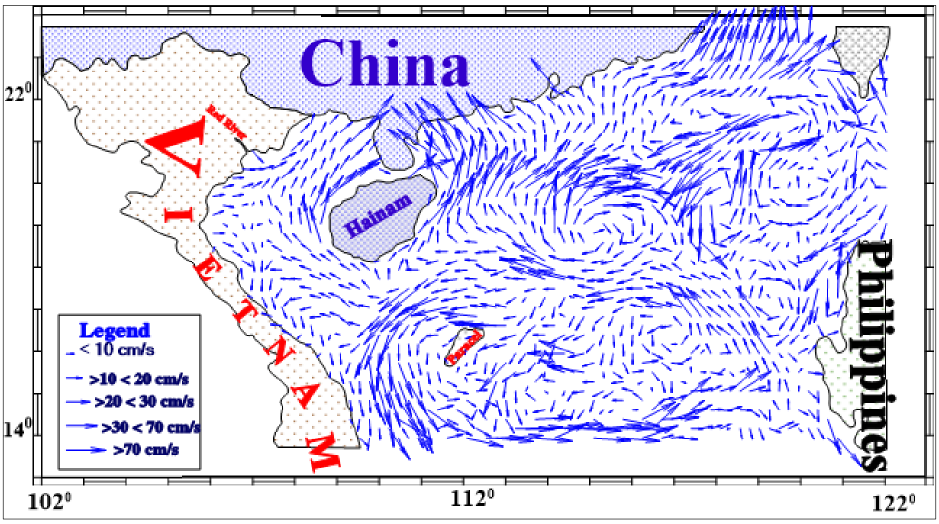
4	34	61	106.6667	20.367
5	36	61	106.8889	20.367
6	36	60	106.8889	20.2628
7	35	60	106.7778	20.2628
8	35	59	106.7778	20.1585
9	35	58	106.7778	20.0541
10	34	58	106.6667	20.0541
11	34	57	106.6667	19.9496
12	33	57	106.5556	19.9496
13	32	57	106.4444	19.9496
14	32	56	106.4444	19.8451
15	31	56	106.3333	19.8451
16	31	55	106.3333	19.7406
17	30	55	106.2222	19.7406
18	29	55	106.1111	19.7406
19	29	54	106.1111	19.6359
20	29	53	106.1111	19.5312
21	28	53	106	19.5312
22	28	52	106	19.4264
23	27	52	105.8889	19.4264





3.6. Verification

Comparison of drift trajectories of floating objects in the East Sea of the Vietnamese Navy and main currents in calculation, there is a good agreement (Figure 7).



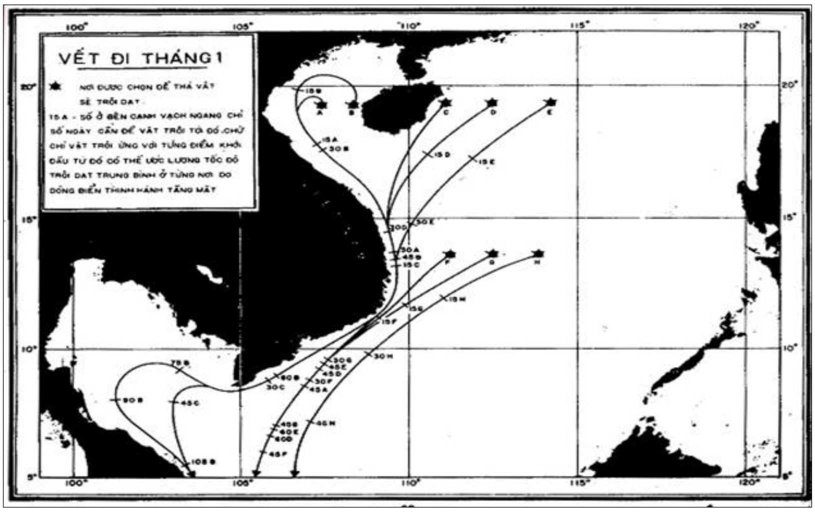


Figure 7 Comparison of calculations (above) , the drift trajectory of a floating object in Sea (below) of the Vietnamese Navy

We verified ROMS using actual measurement data in the region. The data used for validation was collected, including water level fluctuations in the northern Vietnam Sea at the Hon Dau station (Haiphong-Vietnam). We compared the tide data, specifically water level fluctuations, with the actual water level measurements as shown in *Figure 8*.

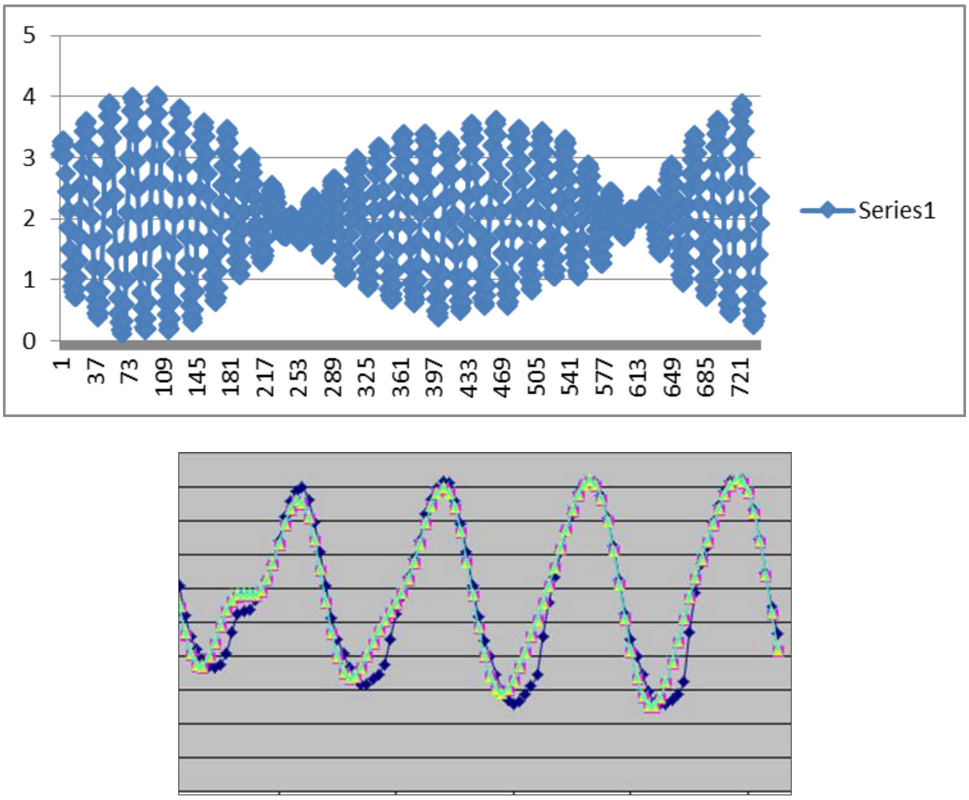


Figure 8 Water level fluctuations at Hon Dau station (above) and compare calculated and actual measured water levels (below)

We used the Root Mean Square Error (RMSE) as a quantitative measure to assess the computational error in comparison to the actual measurements. The criterion for evaluating the error is to minimize the square of the difference between the computed results and the actual water level measurements. This approach allows us to determine the extent to which the model's predictions align with real-world observations, ensuring the accuracy of the model's

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(\eta_i - \eta_i'\right)^2}{N}}$$

In the equation, where η_i is the measured water level, is the computed water level, η_i ' and N is the number of synchronized time points for the water level data.

The RSME result to determine the quantitative error between computed and measured water level fluctuations for May 2021 is 11.3 cm. This error for the long-term water level data reflects the high reliability and accuracy of the model's results, indicating that the model is providing reliable predictions that closely match the actual measurements.

4. Conclusion

Up to this point, there have been numerous research works on the dynamics and drift of marine debris into the sea. However, a study that calculates the forecast for plastic waste from rivers to the sea based on the frequency of occurrence, in other words, relying on the long-term time-varying flow dynamics (including rising and falling tides) is a preliminary step in the research that also provides an overview of the debris drifting into the sea. As an estimate, under certain conditions, plastic waste can travel approximately 112 km (from 20.57530 to 19.42640).

The current flow patterns in the Northern Vietnam Sea follows the tidal phases. During the rising tide, the general trend is a flow from the South to the North. Conversely, during the falling tide, the general trend is a flow from the North to the South. The flow velocity during the largest tidal phases varies from approximately 5-10 cm/s at its lowest to around 65-70 cm/s at its highest.

Several whirlpools exist in the vast areas of the sea surrounding the Northern Vietnam Sea, where the average flow velocity is higher compared to the flow within the gulf. Expanding the research area beyond the Northern Vietnam Sea offers a more comprehensive overview of the dynamics taking place here. This could explain why some marine debris may become trapped in this region for an extended period due to the presence of these whirlpool zones.

The computed results have been verified through real-time measurement data within the research area, demonstrating a significant consistency with the actual measurements.

Compliance with ethical standards

Acknowledgments

This article contributes to the study, assessment and prediction of the process of transporting and dispersing small-sized plastic waste at the Van Uc estuary for the Vietnam - France international project.

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