

Study on the characteristics and influencing factors of suspended sediment front in the eastern Qiongzhou Strait

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Abstract: The eastern shoal of the Qiongzhou Strait is considered a crucial potential sand resource, and its sediment dynamics are of great interest for both environmental and economic reasons. To better understand these dynamics, this study employed the ROMS (Regional Ocean Modeling System) ocean model to simulate suspended sediment transport during the winter and summer of 2019. The model incorporated a variety of environmental factors, including wave conditions, tidal forces, currents, temperature, and salinity, to capture the complex interactions affecting sediment movement. The simulation results revealed significant seasonal variations in sediment transport patterns and the shape of sediment fronts. During the winter months, sediment primarily moves eastward, with increased sediment concentration observed near the eastern shoal. This results in the pushing of the sediment front further offshore. Conversely, in the summer, the sediment transport pattern reverses, with sediment moving in the opposite direction. Wind waves, especially near the eastern Leizhou Peninsula and the Qiongzhou Strait, play a crucial role in influencing sediment movement, particularly near the shoal. These findings highlight the complex interplay of seasonal factors in shaping sediment dynamics in this region.

1 Introduction

The Qiongzhou Strait is located between the Leizhou Peninsula and Hainan Island. It is adjacent to the South China Sea in the east and the Beibu Gulf in the west. It is an important water and material exchange channel [1]. The Qiongzhou Strait's hydrodynamic features include earlier tides and larger tidal ranges on the west side compared to the east, leading to flood tide currents flowing eastward and ebb tide currents flowing westward [2-5]. However, the residual current of the Qiongzhou Strait is westward flow all year round, and the net water and sediment transport directions of the strait are consistent [5].

The eastern shoal of the Qiongzhou Strait is an important potential sand resource in China. However, research gaps persist regarding dynamics of suspended sediments within the strait and their governing mechanisms. Previous studies by Cheng et al. [1] revealed distinct seasonal sediment transport patterns: westward movement in winter and eastward migration in summer. Satellite remote sensing observations have identified a persistent suspended front between the eastern shoal of the Qiongzhou Strait and the South China Sea, characterized by sharp gradients in suspended sediment concentration. Investigating this frontal system and its controlling mechanisms is crucial for revealing sediment source-to-sink processes, understanding land-sea interactions, informing global material cycling models, and supporting marine ecosystem conservation.

This study employs the Regional Ocean Modeling System (ROMS) to examine suspended sediment transport patterns in the Qiongzhou Strait, with particular focus on analyzing wind-wave interactions and their impacts on the stability and dynamics of the suspended sediment front.

2 Materials and methods

2.1 Study area

The Qiongzhou Strait exhibits a characteristic bathymetric division: a central tidal deep trough exceeding 200 m depth due to intense tidal scouring, flanked by tidal deltas at both termini. Shallow shoals develop eastward from the 50 m isobath. Satellite observations reveal the eastern shoal contains the South China Sea's highest suspended sediment concentrations, demonstrating a marked lateral gradient - northern bank levels surpass southern counterparts, with both significantly exceeding central channel deposits [5].

2.2 Numerical model

The Regional Ocean Modeling System (ROMS) employs a numerical framework based on Reynolds-averaged Navier-Stokes equations incorporating Boussinesq and hydrostatic approximations [6]. Vertical turbulence closure adopts the MY2.5 scheme, while horizontal

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viscosity is parameterized through the Smagorinsky formulation [7,8]. This three-dimensional model utilizes orthogonal curvilinear grids horizontally and sigma-coordinate stretching vertically. Specifically, our implementation combines Type 2 and Type 4 vertical coordinate transformations detailed in standard ROMS configurations [9].

The model domain spans 19.0°-23.5°N, 108.7°-114.7°E, resolved with 370×300 grids at 1.8 km horizontal resolution. Ten sigma-layer vertical stratification incorporates bathymetric data from nautical charts and GEBCO composites (minimum depth: 2 m; Figure 1). Initial conditions derive from HYCOM monthly T/S profiles, with surface forcing from ERA5 wind/heat flux datasets. Open boundary implementation combines eight principal tidal constituents (K1, O1, P1, Q1, M2, S2, N2, K2) for semi-diurnal and diurnal harmonic forcing.

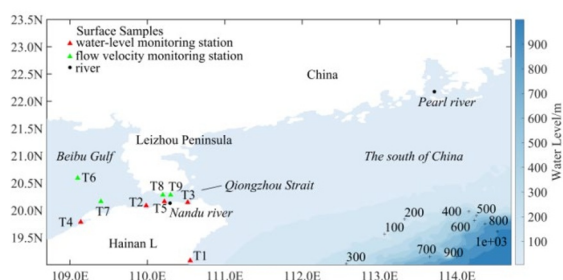


Figure 1. Distribution of tidal current and tidal level monitoring stations

The coupled modeling framework integrates the third-generation spectral wave model SWAN with ROMS through Model Coupling Toolkit (MCT). SWAN feeds ROMS critical wave parameters (significant height, wavelength, period, direction, dissipation energy) through radiation stress gradients in the momentum equations [10]. Bidirectional data exchange includes ROMS providing SWAN real-time bathymetry updates, sea surface elevation, and current velocities.

The sediment transport model in ROMS adopts the Coastal Sediment Transport Module (CSTM) [11]. This study uses sediment particle sizes of 0.004 mm (clay), 0.032 mm (silt), and 0.128 mm (sand), with a critical shear stress of 0.12 N/m² and a sediment settling velocity of 1×10⁻⁴ m/s.

2.3 Model validation

Water level verification used tidal data from the National Marine Science Data Center (April 2019), the verification results are shown in Figure 2. While current data came from Weizhou Island and Xinying Bay (National Ocean Data Center) for April 1, 2019, and August 24-25, 2020, the verification results are shown in Figure 3. These results demonstrate high simulation accuracy, providing a reliable hydrodynamic field for suspended matter transport modeling.

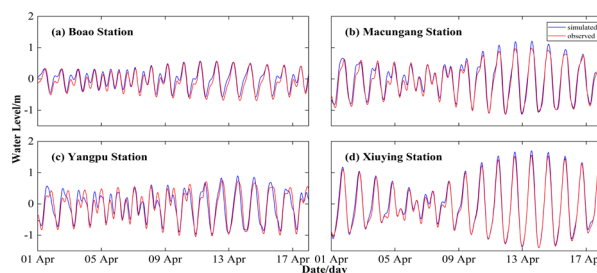


Figure 2. Water level verification. The blue lines show simulated, and the red lines show observed.

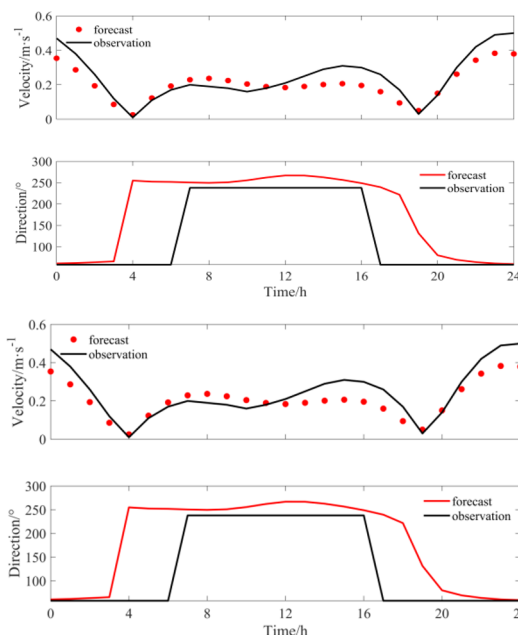


Figure 3. Verification of flow velocity and direction in Weizhou Island (2019.4.1) and Xinying Bay (2020.8.24-25)

3 Results and discussion

3.1 The circulation characteristics of the study area

The ocean current dynamics are affected by many factors, such as tidal forcing, sea surface wind field and baroclinicity. In this paper, the effects of various factors on the ocean circulation are tested. The distribution of circulation (tidal residual current) field driven by tides is shown in Figure 4. In June, the tide-induced residual current in the strait mainly flows from the Beibu Gulf from west to east, but in the northern part of the strait, it meets the Guangdong coastal current from east to west, resulting in a smaller velocity in the northern part. The central and southern residual currents is less affected by the coastal current in western Guangdong, and the flow velocity is larger. In winter, the residual current in the middle of Qiongzhou Strait flows from east to west, and the coastal current in western Guangdong is divided into two streams, which flow to the northwest and southwest respectively.

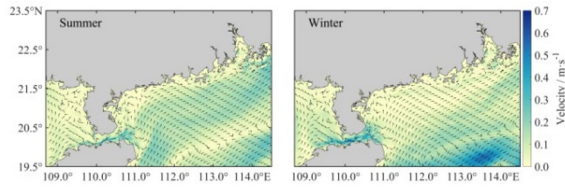


Figure 4. Vertical average monthly average tidal residual current diagram

The combined circulation distribution (Figure 5) shows that monsoon winds generate a fixed eastward coastal current along western Guangdong, with wind waves being the main driver, especially in winter. In summer, water flow from the southeast of Hainan Island turns westward at the east mouth of Qiongzhou Strait, forming a vortex and a westward flow. The westward flow in Qiongzhou Strait is stronger in winter due to the influence of the coastal current in western Guangdong.

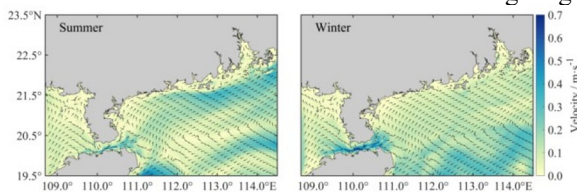


Figure 5. Circulation distribution under the influence of multiple factors

3.2 Suspended sediment transport characteristics

3.2.1 Tidal and tidal current effects

Figure 6 shows the transport of suspended solids driven by tides and tidal currents. The concentration is generally low, ranging from 5-15 mg/L in summer and 5-20 mg/L in winter. Winter concentrations are higher, but the highest point in both seasons is consistently located on the southeast side of Douluosha.

The simulation shows that the northern suspended sediment front is weak and short, indicating limited influence of tides and tidal currents on suspended sediment transport along the western coast of Guangdong. In the eastern Qiongzhou Strait, other factors also contribute to sediment transport. The suspended sediment front differs in shape and position between summer and winter, particularly around Naozhou and Xinliao Islands. In summer, the concentration is low, the front is small and weak, and more curved towards the shore, while in winter, the opposite occurs.

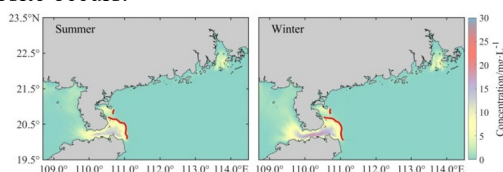


Figure 6. Vertical time average suspended solids concentration distribution, a is the simulation results in June, b is the simulation results in December.

3.2.2 Effects of wind and waves

Figure 7 shows the distribution of suspended solids under the combined influence of wind and wave. The simulation indicates a general increase of about 5 mg/L in the coastal areas of Guangxi, Pearl River Estuary, Naozhou Island, eastern Xinliao Island, and central Qiongzhou Strait. Near Douluosha, the concentration rises by nearly 10 mg/L. The suspended sediment front becomes stronger, and the suspended matter in the eastern Leizhou Peninsula and Qiongzhou Strait shifts from isolated to connected.

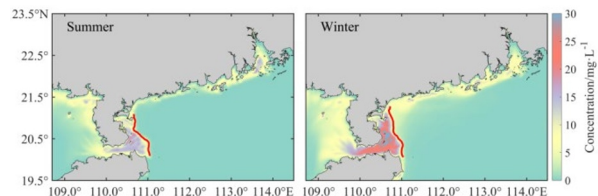


Figure 7. Vertical time average suspended solids concentration distribution, a is the simulation results in June, b is the simulation results in December.

3.2.3 Energy flux verification

Energetic flux, or energy flux density, refers to the energy passing through a unit width section from the seabed to the sea surface per unit time. In the marine environment, it typically involves the transfer of energy through waves, currents, or wind, affecting water movement and suspended matter transport. The energy flux is decomposed into two orthogonal components ($W \cdot m^{-1}$):

$$\begin{cases} \Psi(U) = \rho U D \left(\frac{U^2 + V^2}{2} + g\eta \right) \\ \Psi(V) = \rho V D \left(\frac{U^2 + V^2}{2} + g\eta \right) \end{cases} \quad (1)$$

Therefore, in a period of time T, the energy passing rate can be expressed as:

$$(E_{fu}, E_{fv}) = \frac{1}{T} \int_0^T \int_{-H}^{\eta} [\Psi(U), \Psi(V)] dz dt \quad (2)$$

Among them: E_{fu} and E_{fv} represent the energy flux in the U and V directions; h denotes water depth; z represents the vertical coordinate; they represents the tidal energy flux in the east-west and north-south directions respectively.

Figure 8 shows the energy flux, with the south bank of the central Qiongzhou Strait having the highest flux, about twice as much in winter as in summer. This is due to both high flow velocity on the south bank and a flow from the north bank, which boosts the tidal current flux. The eastern Qiongzhou Strait also displays a fan-shaped distribution, aligning with sediment concentration, indicating a close relationship between tidal currents and the formation of the suspended sediment front.

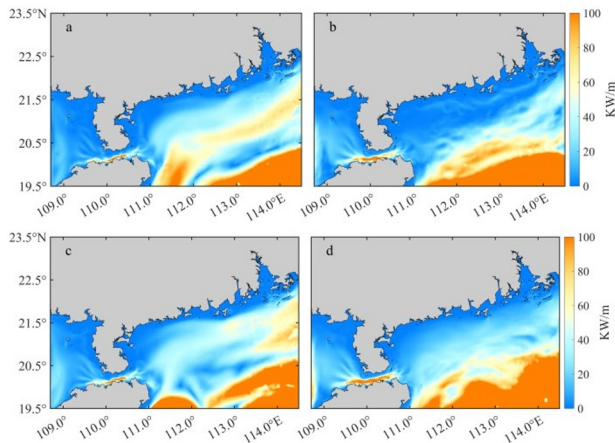


Figure 8. The vertical monthly average energy flux distribution: a and b are the summer and east season results under tidal current, while b and d are the summer and winter results under wind and wave action.

4 Conclusion

This paper uses the ROMS to simulate suspended matter transport at the eastern mouth of the Qiongzhou Strait for one year, controlling four variables: tide, tidal current, wind current, and wave. The simulation results reveal the characteristics of suspended sediment transport and the impact of wind and wave in the study area. The main conclusions are as follows:

(1) Suspended matter concentration in the eastern Qiongzhou Strait shows clear seasonal variation. Sediment transport is eastward in summer and westward in winter, with higher suspended solid concentrations in winter than in summer.

(2) The suspended sediment front in the eastern Qiongzhou Strait shows clear seasonal variation. In summer, it is close to shore and weak near Naozhou Island and Xinliao Island, while in winter, it moves farther from shore and becomes more intense.

(3) Wind waves significantly affect suspended sediment concentration and the intensity of the sediment front, especially in the eastern Leizhou Peninsula and eastern Qiongzhou Strait.

References

1. Gaolei C, Wenping G, Yaping W, et al. Modeling the circulation and sediment transport in the Beibu Gulf [J]. *Acta Oceanologica Sinica*, 2017, 36(04): 21-30.
2. Tong Changliang, Wu Xiangbai, Chen Fei, et al. Analysis of dynamic geomorphology at the east entrance of Qiongzhou Strait based on tidal current numerical simulation [J]. *Marine Geology Frontiers*, 2024, 40(9): 38-48..
3. Wei Cong, Chen Bo. Numerical Simulation of 3-D Tide and Tidal Current in the Beibu Gulf[J]. *Periodical of Ocean University of China*, 2023, 53(S1): 1-10. .
4. Tong Changliang, Song Jiawei, Deng Kaizhang, et al. Progress of marine sand resource exploration

around Hainan Island and suggestions for selection of exploration areas [J]. *Journal of Marine Sciences*, 2022, 40(3): 33-48.

5. Lin Junchuan, Kong Deming, Chen Fajin, et al. Climatic and environmental changes over the last 1 000 years as recorded by the sediments in Beibu Gulf [J]. *Journal of Marine Sciences*, 2022, 40(3): 49-61.
6. Chu Yanhao, Wu Wenjuan, Li Peng, et al. Temporal and spatial dynamics of suspended sediment and its driving mechanism in the Yellow River Estuary[J]. *Haiyang Xuebao*, 2022, 44(6): 150-163..
7. Azevedo Correia de Souza J M, Suanda S H, Couto P P, et al. Moana Ocean Hindcast—a> 25-year simulation for New Zealand waters using the Regional Ocean Modeling system (ROMS) v3. 9 model [J]. *Geoscientific Model Development*, 2023, 16(1): 211-231.
8. Smagorinsky J. General circulation experiments with the primitive equations: I. The basic experiment[J]. *Monthly weather review*, 1963, 91(3): 99-164.
9. Shchepetkin A F, McWilliams J C. The regional oceanic modeling system (ROMS): a split-explicit, topography-following-coordinate oceanic model [J]. *Ocean modelling*, 2005, 9(4): 347-404.
10. Li Yan, Bo Zhaohai. The ability of SWAN model to simulate wave height in the Yellow Sea and Bohai Sea [J]. *Ocean Prediction*, 2005, 3: 75-82.
11. Warner J C, Sherwood C R, Signell R P, et al. Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model [J]. *Computers & geosciences*, 2008, 34(10): 1284-1306.