Numerical Analysis of Monsoon Impact on Sediment Transport in the Eastern Qiongzhou Strait

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Abstract. This study employs a coupled SCHISM-WWM model to investigate monsoon controls on sediment dynamics in the eastern Qiongzhou Strait, a vital marine sand reservoir. Modeling results demonstrate distinct sediment transport by monsoons. Winter northeast monsoons drive westward currents with northern sector velocities averaging 17.83 cm/s (peak 44.86 cm/s), sustaining high-energy flow conditions that optimize sediment mobility in central-eastern areas and enable efficient offshore-directed sediment transfer. Conversely, summer southwest monsoons establish eastward circulation marked by velocity heterogeneity (maximum 41.49 cm/s), where flow deceleration and directional variability in sheltered zones promote preferential sediment accumulation. Winter's northeast monsoon generates westward bedload fluxes (0–15,000 kg/m) driven by currents exceeding 20 cm/s, whereas summer southwest monsoons induce eastward transport (up to 25,000 kg/m) through localized vortex deposition. Spatial analysis indicates tidal dominance over western sediment flux (80% contribution), contrasting with monsoonal current control in eastern regions (65% flux contribution). These insights contribute to a deeper understanding of the mechanisms governing monsoon-influenced sediment transport.

1 Introduction

Marine sand, a key marine mineral resource, ranks second in economic value only to offshore oil, making it the second-largest marine mining sector [1]. The Qiongzhou Strait north of Hainan Island contains sandy-gravel sediments formed by bidirectional tidal currents. Its eastern mouth develops finger-like sand ridges through flow deceleration, forming a key sand deposit area in China. Sediment sources here combine three components: tidal erosion debris, coastal current deposits, and open-sea materials [2-3]. Studies estimate China's shallow shelf holds ~670 billion m^3 of marine sand, with ~800 million m^3 concentrated in the eastern entrances of Qiongzhou Strait [4].

The Qiongzhou Strait, a narrow channel connecting the Beibu Gulf and western Guangdong seas, exhibits an east-west orientation with tidal patterns transitioning from irregular semidiurnal to diurnal tides westward. Dominant rectilinear tidal currents flow along the east-west axis [5-6]. Previous studies have characterized hydrodynamic fields, sediment transport patterns, and grain size distributions, particularly addressing tidal and wave influences on sediment dynamics [7-8]. Wind-driven currents also significantly modulate coastal sediment transport, as evidenced by flow reversal patterns in seasonal sediment transport observed at England's Blyth Estuary [9].

The South China Sea (SCS), a prominent monsoon-dominated region, exhibits marked seasonal variability in hydrodynamic regimes (circulation, wave fields) under monsoonal forcing. These dynamics likely govern sediment transport patterns in the Qiongzhou Strait's eastern tidal sand ridge zone, though previous studies have yet to systematically investigate this linkage. This study employs the SCHISM model to simulate tidal and current conditions, analyzing seasonal hydrodynamic variations on sediment transport.

2 Materials and Methods

2.1 SCHISM numerical mode settings

This study utilizes the Wind Wave Module (WWM) coupled within the SCHISM framework to investigate

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wave-current-sediment interactions in the Qiongzhou Strait and adjacent waters. The WWM extends the hydrodynamic capabilities of SCHISM by integrating spectral wave dynamics through a semi-implicit finite element/finite volume solver, explicitly resolving wave action balance equations with JONSWAP spectral boundary conditions and Thornton-Guza whitecapping parameterization. Unlike standalone hydrodynamic models, the WWM outputs key wave-specific variables including significant wave height (Hs), peak wave period (Tp), and directional wave spectra, alongside coupled momentum exchange terms such as radiation stress tensors (Sxx, Sxy, Syy) and wave-induced bottom shear stress (τb_wave). These parameters fundamentally alter sediment transport predictions.

The model configuration encompasses the northwestern South China Sea (105–113°E, 16–22°N), utilizing an unstructured triangular mesh comprising 49,221 nodes and 91,827 elements. Bathymetric data were integrated from SRTM15+ (15 arc-second resolution) and official Chinese nautical charts. Spatial resolution ranges from 200 m within the strait to 15 km at open boundaries. Vertical discretization employs 40 layers: 20 sigma layers for shallow waters (≤40 m) and terrain-following z-levels (5–200 m thickness) for deeper regions (40–2,200 m). Tidal forcing was imposed through TPXO8 altimetry-assimilated boundary conditions, with tidal elevation validation conducted using coastal gauge observations.

2.2 Calculation of bedload sediment transport

Previous work has shown that the sediments at the eastern entrance of the Qiongzhou Strait are mainly bed load [10]. Bedload sediment transport rate uses Hardisity formula [11]:

$$q_b = k_1\left(U_{100}{}^2 - U_{100cr}{}^2\right)U_{100} \tag{1}$$

where k_1 is the coefficient, which is a function of sediment grain size, kg·s^2/m^4,is the bedload transport rate, kg/(m·s); U_{100} is the velocity vector at 1 m from the bottom, m/s; U_{100cr} is the critical incipient velocity at 1 m from the bottom, m/s. U_{100} can be obtained from interpolation of the u and v. U_{100cr} is a function of sedimentary granularity, and its expression is as follows [12]:

$$U_{100cr} = 122.6d_{50}{}^{0.29},\ d < 0.2\ \text{cm} \tag{2}$$

where d_{50} is the sediment median particle size, cm.

k_1 is a function related to sediment grain size, and its expression is as follows [13]:

$$k_1 = 0.10\exp\left(\frac{0.17}{d_{50}}\right),\quad d_{50} > 0.2\text{mm} \tag{3}$$

$$k_1 = \frac{1}{8.9d_{50}{}^{0.42}},\quad d_{50} < 0.2\text{mm} \tag{4}$$

3 Results

3.1 Monsoon Circulation in the Waters

Residual currents, defined as non-tidal flow components, represent net material transport vectors critical for sediment dynamics. Simulations under tidal-only and combined tidal-monsoonal forcing (Figures 1-2) reveal distinct seasonal patterns. Winter northeast monsoons drive surface current intensification (maximum 44.86 cm/s) in the strait's northern sector, with mean velocity reaching 17.83 cm/s. High-velocity zones (>20 cm/s) facilitate sediment suspension and long-distance transport, while low-velocity areas (<10 cm/s) promote localized deposition.

Summer southwest monsoons reduce mean velocity to 7.1 cm/s despite comparable peak speeds (41.49 cm/s). Prevalent vortex structures in eastern sectors induce sediment retention and depositional thickening, contrasting with winter's unidirectional transport regime.

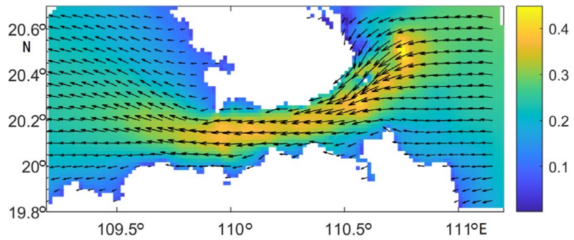


Figure 1. Characteristics of surface current velocity distribution in the Qiongzhou Strait under the influence of winter monsoons (m/s).

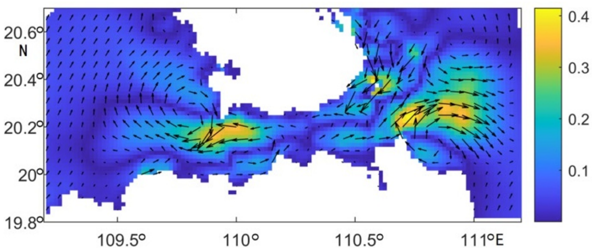


Figure 2. Characteristics of surface current velocity distribution in the Qiongzhou Strait under the influence of summer monsoons (m/s).

3.2 Time-series of bed load transport rate

To quantitatively evaluate monsoon-tide forcing impacts on sediment flux, hydrodynamic-sediment coupling processes were analyzed at opposing strait entrances (Site A: western; Site B: eastern; Figure 3). Integrated numerical simulations of monsoon-forced circulation and tidal currents were performed, with monsoonal contributions isolated through hydrodynamic decomposition via tidal signal subtraction from composite time-series. Spectral analysis of bedload transport time-series revealed periodic fluctuations governed by nonlinear monsoon-tide phase interactions, demonstrating significant spatial divergence in hydrodynamic forcing mechanisms between eastern and western sectors.

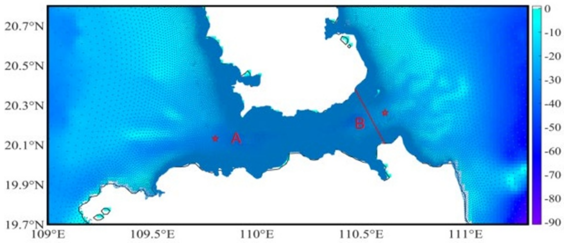
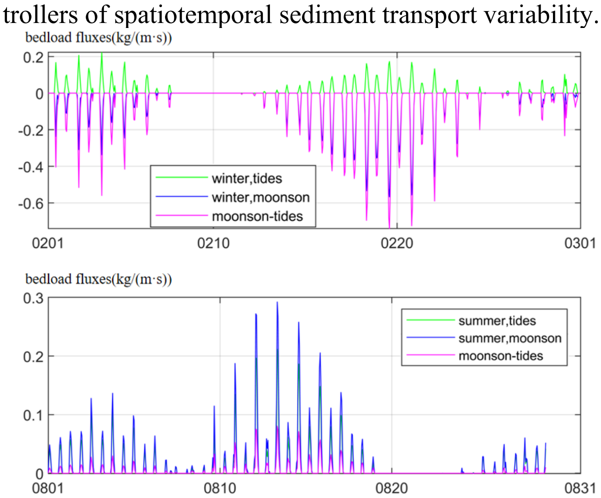


Figure 3. Characteristics of surface current velocity distribution in the Qiongzhou Strait under the influence of summer monsoons (m/s).

Seasonal variations in sediment transport rates at the eastern and western entrances of the strait are illustrated in Figure 4. During winter spring tides in the Qiongzhou Strait's eastern mouth, tidal forcing drives eastward bedload transport at 0.01-0.05 kg/(m·s), exhibiting distinct periodic fluctuations. Monsoon-induced bedload transport operates at one-tenth magnitude with opposing direction, showing maximum tidal-monsoon divergence (~0.01 kg/(m·s)) during spring tides that diminishes with tidal attenuation. Tidal transport here equals 20% of the western mouth's flux, while monsoonal contributions remain significantly lower.

Summer conditions reduce tidal transport by 60-70%, with weak monsoonal transport aligning directionally. Seasonal-spatial patterns emerge: winter monsoons dominate western mouth dynamics, while summer monsoons exert minimal influence across the study area. These findings highlight tide-monsoon interactions as key controllers of spatiotemporal sediment transport variability.



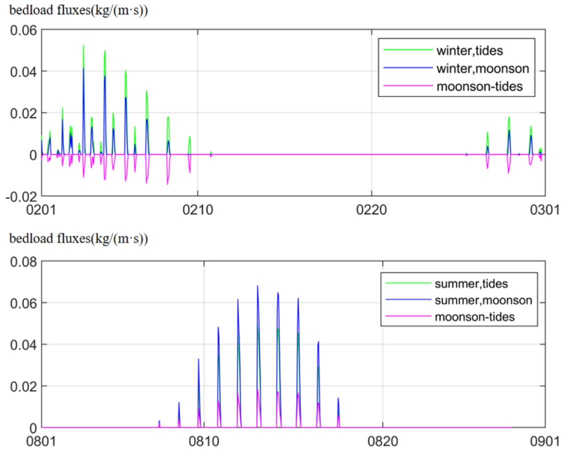


Figure 4. Sediment transport rate at (a) the western entrance and (b) at the East Entrance. Green indicates conditions influenced solely by tides, blue signifies conditions affected both tide and monsoons, and pink represents the difference between green and blue lines. The upper panel represents winter monsoon, while the lower panel corresponds to summer monsoon.

3.3 Bed load transport across sections

Figure 5 illustrates the monthly variations in unit-width bedload transport at Section B of the eastern entrance. Seasonal sediment dynamics in the eastern inlet exhibit distinct flow reversals. Southwest monsoon winds establish a dominant eastward flow pattern during summer, with sediment transport fluxes reaching 0–25,000 kg/m. In winter, northeast monsoon winds induce a 180°shift in hydrodynamic vectors, reducing westward transport intensity to 0–15,000 kg/m. This flow-sediment reversal confirms the pivotal role of monsoon circulation in estuarine sediment dynamics.

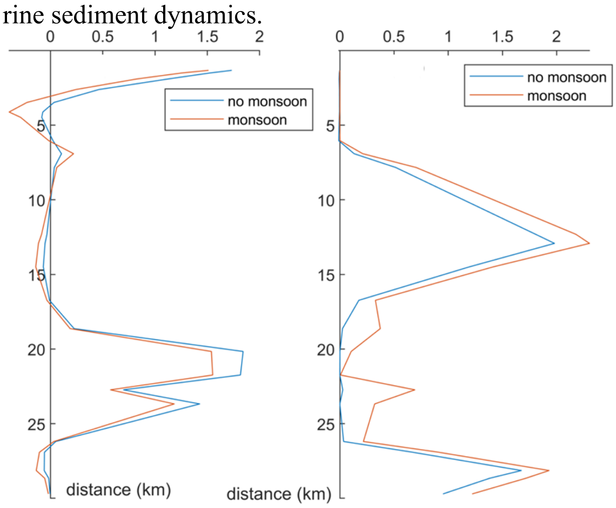


Figure 5. The bed load monthly unit width transport of section B (location shown in Figure 3) in the Qiongzhou Strait, (a) for winter and (b) for summer; positive values indicate eastward direction; negative values indicate westward direction.

4 Conclusions

High-velocity zones (>20 cm/s) under winter monsoons facilitate suspended sediment export, contrasting with summer vortex structures that promote localized deposition. The eastern tidal sand ridge system thus functions as a seasonal sediment capacitor. Tidal forcing dominates sediment transport in the western strait, accounting for 80% of flux magnitude, whereas monsoonal currents prevail in the eastern sector. Winter monsoons amplify tidal transport divergence by 20–50% during spring tides, while summer conditions suppress tidal contributions by 60–70%, demonstrating nonlinear coupling between periodic tidal forces and sustained monsoonal forcing.

Monsoon circulation governs a bidirectional sediment transport regime. Northeast winter monsoons establish westward residual currents with bedload fluxes of 0–15,000 kg/m, while southwest summer monsoons reverse hydrodynamic vectors eastward, amplifying transport magnitudes to 0–25,000 kg/m. This 180° flow-sediment reversal directly links monsoon seasonality to estuarine sedimentary architecture.

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