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Key Points:

- A high-resolution, nested coupled modeling system was developed to investigate POC dynamics in the Pearl River Estuary during Typhoons
- Model results indicate a transition from a mixed terrestrial and marine POC before typhoon to a dominance of terrestrial during typhoon
- Typhoons Hato and Pakhar (2017) shifted the PRE from a potential carbon source into a potential carbon sink

Supporting Information:

Supporting Information may be found in the online version of this article.

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Impact of Typhoons Hato and Pakhar (2017) on Particulate Organic Carbon Transport in the Pearl River Estuary, China: A Numerical Study

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Abstract Estuaries play a crucial role in the transport and cycling of particulate organic carbon (POC) from terrestrial ecosystems to the ocean. However, an understanding of the processes controlling POC dynamics under extreme weather conditions is still lacking. In this study, we established a high-resolution, coupled atmosphere–ocean–biogeochemistry modeling system for the Pearl River Estuary to investigate the mechanisms controlling POC dynamics during a strong successive typhoon event (Hato and Pakhar, 2017). Our simulation results show that before the typhoons, the POC distribution was characterized by two distinct maxima, sustained by terrestrial inputs and marine production, respectively. However, during the typhoons, strong hydrodynamic conditions and reduced light availability suppressed local primary production, leading to an increase in the dominance of terrestrial POC. In Lingding Bay (LB) and the Western Four Outlets (WFO), POC was mainly supported by regenerated production, whereas in the shallow coastal region (SCR) outside the estuarine, new and regenerated production played an equal role. Regarding POC sinks, zooplankton excretion served as the dominant sink in the outer LB and SCR regions, while sediment denitrification played an equally significant role in the inner LB and WFO. Budget analysis revealed that although the estuary acted as a weak carbon source on an annual basis, successive typhoons can transform it into a weak carbon sink. Our simulation provides novel insights into the impact of extreme weather on POC within estuaries, benefiting the maintenance of ecological health and the development of effective water quality management strategies under global warming.

Plain Language Summary Particulate organic carbon (POC) transport and cycling in estuaries and coastal oceans are strongly influenced by typhoons; however, the relative importance of the various physical and biogeochemical processes involved remains unclear. In this study, we used a modeling approach to investigate the underlying mechanisms, taking the Pearl River Estuary—a subtropical estuary in southern China—as an example. The model results indicate that prior to a typhoon, both terrestrial and marine POCs were present in the study region. However, during the typhoons, strong hydrodynamic disturbances and low light availability suppressed local marine POC production. Combined with a sudden increase in discharge, the terrestrial POC became predominant. The dominant biogeochemical sources and sinks varied across subregions of the estuary. Regenerated production dominated POC generation in Lingding Bay and the Western Four Outlets, while new production became important in the shallow coastal region. Zooplankton excretion was the main process reducing POC in the outer Lingding Bay and shallow coastal region, whereas sediment denitrification played a key role in the inner Lingding Bay and Western Four Outlets. Given the increasing annual frequency of typhoons affecting estuarine and coastal waters, and the important role of POC in water quality, this research holds significant value for management efforts.

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1. Introduction

Particulate organic carbon (POC) is defined as all combustible non-carbonate carbon that can be collected on filters with pore sizes ranging from 0.7 to 1.0 μm (Kharbush et al., 2020). POC in the ocean can be formed through phytoplankton converting dissolved inorganic carbon (DIC) into organic carbon via photosynthesis in the euphotic layer or derived from terrestrial sources through rivers (Burdige, 2005). Estuaries play an important role in the transport and cycling of POC from terrestrial ecosystems to the ocean (Bauer et al., 2013; Cai, 2011; Dai et al., 2022; Friedlingstein et al., 2023; Regnier et al., 2022). The distribution, transport and transformation of POC within estuaries are critical for water quality issues. For example, intensified remineralization of POC increases oxygen consumption and promotes hypoxia, while the degradation of POC raises the pCO_2 levels, which alters the acid-base chemistry of seawater. This results in decreased pH and calcium carbonate saturation states, a phenomenon known as ocean acidification (Cai et al., 2017; Feng et al., 2019; Signorini et al., 2019; Zheng et al., 2024).

Located on the southern coast of China, the Pearl River Estuary (PRE) is a large estuary surrounded by multiple megacities in the Pearl River Delta region. The Pearl River, fed by three major tributaries (the West, North, and East Rivers) and numerous local rivers, ranks as China's second-largest river by freshwater discharge. Its annual discharge averages approximately $330 \times 10^9 \text{ m}^3 \text{ year}^{-1}$ (Zhang et al., 1999). Freshwater, nutrients and terrestrial organic carbon are delivered through eight primary outlets into three sub-estuaries, Lingding Bay, Modaomen, and Huangmaohai Bay, significantly influencing POC dynamics in the PRE. Over the past decade, in situ and remote sensing data, and numerical models, have been used to study the spatiotemporal distribution, sources, sinks, transformation, and fluxes of POC in the PRE system. For example, by analyzing the carbon isotopic composition ($\delta^{13}\text{C}_{\text{POC}}$, $\delta^{13}\text{C}_{\text{DIC}}$), Guo et al. (2015) reported that POC exhibits a significant power-law distribution, decreasing rapidly in low-salinity zones and more gradually in the high-salinity region. They found that POC was marine-sourced for most of the year, but terrestrial organic carbon became predominant during the high-discharge wet season in May. Using a three-dimensional coupled physical-biogeochemical model, Liang et al. (2020) investigated the annual POC cycle in the PRE. They estimated that the annual riverine POC input was about $0.67 \text{ Tg-C yr}^{-1}$, of which approximately 60% was deposited and remineralized within the estuary, with only 40% exported to the Northern South China Sea (NSCS). Export was higher in summer than in other seasons due to seasonal river discharge and wind patterns. More recently, Wang et al. (2025) combined high-resolution remote sensing data with a numerical model to estimate monthly POC fluxes into the PRE and export to the NSCS from 2001 to 2020. Their results indicated a decline in the annual mean POC flux entering the PRE, largely attributed to dam construction. Concurrently, increased river runoff and more frequent northerly winds have reduced POC deposition within the PRE, thereby enhancing the POC flux into the NSCS.

Although the seasonal, interannual, and long-term spatiotemporal variability of POC in the PRE has been well investigated in the studies cited above, the impact of short-time scale extreme weather events, such as typhoons, has not yet been explored. Field studies employing stable isotope analysis and satellite observations, combined with numerical hydrodynamic models, have demonstrated that the strong hydrodynamic conditions induced by typhoons can significantly impact the transport of POC in multiple estuaries worldwide (Hounshell et al., 2019; Osburn et al., 2019; Paerl et al., 2020; Van Dam et al., 2018; Wang et al., 2023). Specifically, typhoon induced heavy rainfall can pulse substantial terrestrial organic carbon into estuarine and coastal waters, dramatically increasing POC concentrations over short timescales (Pradhan et al., 2016). Furthermore, typhoons can elevate marine-sourced POC by enhancing terrestrial nutrient inputs and promoting deep-water nutrient upwelling (Derrien et al., 2020; Lao, Chen, et al., 2023). Additionally, typhoons can generate ocean fronts and intensify vertical mixing within estuaries, leading to a sudden increase in suspended POC concentration and its subsequent decomposition (Chen et al., 2024, 2025; Wang et al., 2023). However, due to the complex hydrodynamic and biogeochemical processes being highly coupled, a quantitative assessment of their relative importance in affecting POC dynamics is still challenging based on in situ and satellite observations. For example, they cannot clarify whether the observed marine POC results from wind-induced nutrient injections or from the horizontal advection of high-POC water.

Numerical models enable us to estimate the relative role of physical and biogeochemical processes in regulating organic carbon dynamics in estuarine and coastal oceans. It has been widely used under normal weather conditions (Clark et al., 2020; Druon et al., 2010; Yao et al., 2024); however, applications of these models to extreme weather conditions are rare, as physical models forced with re-analysis data are challenging to capture the

significant changes in hydrodynamic conditions induced by rapid atmospheric disturbances. Recently, the application of coupled ocean-atmospheric-biogeochemical models has significantly advanced our understanding of the phytoplankton responses to storm passages in estuaries and coastal oceans (Feng et al., 2022; Zang et al., 2020). However, responses of POC have not been discussed, as these studies did not incorporate a carbon cycle module.

In this study, we developed a nested, three-dimensional, high-resolution coupled “atmosphere-ocean-sediment-biogeochemistry” modeling system that explicitly represents carbon cycle processes to investigate the transformation and transport of POC in the PRE, a subtropical estuary frequently affected by typhoons. Taking the consecutive strong typhoon events of Hato and Pakhar in 2017 as a case study, we conducted a process-based analysis of POC distribution, cycling, and export, and potential impact on sea-air CO₂ level. The study is organized as follows: Section 2 details the configuration of the nested model, which is based on a previous coarse-resolution “ocean-atmosphere-biogeochemical” modeling system. Section 3 first validates the model against in situ and satellite-derived measurements, then examines the spatiotemporal variability of Particulate Organic Carbon (POC) and its transformation through physical and biogeochemical processes, as well as the lateral POC flux between the Pearl River Estuary (PRE) and adjacent northern South China Sea (NSCS) coastal waters during the passage of Typhoons Hato and Pakhar. Finally, Section 4 evaluates the impact of the typhoons on the POC budgets and the role of the PRE in modulating sea-air CO₂ fluxes, discusses the advantages and limitations of the current modeling approach, and suggests directions for future research. Section 5 presents the conclusions of the current study.

2. Methods

2.1. About the Successive Typhoons Hato and Pakhar

Typhoons Hato and Pakhar formed over the northwest Pacific Ocean in late August 2017. Hato formed on 20 August 2017 as a tropical depression over the northwest Pacific Ocean. It then moved westward, passing through the Luzon Strait on August 22nd at 08:00 Beijing Time and making landfall near Zhuhai (113.2°E, 22.1°N), Guangdong Province, on August 23rd at 12:50 Beijing Time (<https://typhoon.slt.zj.gov.cn/>). On August 23rd at 13:00 Beijing Time, its maximum wind speed was estimated at 52 m/s near its center. Pakhar formed over the northwest Pacific Ocean and intensified into a tropical storm on August 24th. Its track was close to that of Hato, and it entered the PRE on August 26th at 21:00 Beijing Time, with the maximum sustained near-surface wind speed of 30 m/s. Pakhar made landfall near Jiangmen (113.5°E, 22.4°N) in Guangdong Province on August 27th at 09:00 Beijing Time (<https://typhoon.slt.zj.gov.cn/>), and dissipated later that day on August 27th at 20:00 Beijing Time (Figures 1a and 1c).

2.2. The Model Setup

2.2.1. Physical Model Configuration

Our modeling system was built on the Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) modeling system (Warner et al., 2008, 2010). COAWST is an open-source model platform that consists of the Weather Research Forecasting (WRF), Regional Ocean Modeling System (ROMS) and the Simulating Wave Nearshore (SWAN) model. Both the Community Sediment Transport Modeling System (CSTMS, Warner et al., 2008, 2010) and the Biogeochemistry Model (Fennel et al., 2006, 2011) are included in ROMS to simulate sediment transport and carbon cycle, respectively. The model coupling toolkit (Jacob et al., 2005) enables the interaction among different model compartments.

In our previous studies (Feng et al., 2022; Luo et al., 2023; Meng et al., 2024; Pang et al., 2025), we established a coupled ocean-atmosphere-biogeochemistry model in the northern South China Sea shelf region. The model consists of a 12-km WRF and a 4-km ROMS (hereafter referred to as NSCSROMS). For details on the model configuration, please refer to Feng et al. (2022). As the primary focus of this work is the PRE, we set up a new high-resolution ocean model, PreROMS, and nested it in the coarser-resolution NSCSROMS shelf model (Figure 1a). The model domain spans from 112.6°E to 115.4°E and from 21.1°N to 23.4°N, covering the entire Lingding Bay and several sub estuaries (Huangmaohai, Jitimen, Modaomen, Mirs and Daya Bay) as well as part of the northern South China Sea (Figure 1c).

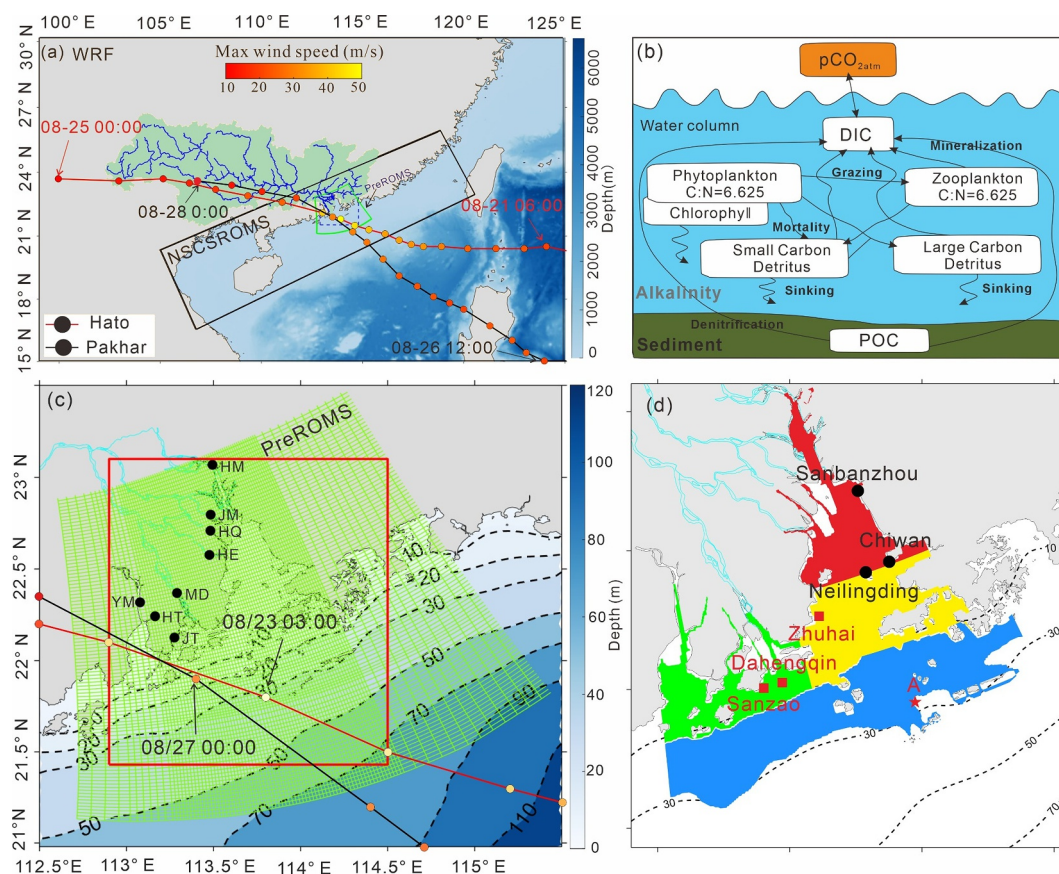


Figure 1. Model configuration and subregions for analysis. (a) Domains of the coupled modeling system: the WRF model (entire panel), the coarse resolution ROMS for the Northern South China Sea (NSCSROMS, black box), and the nested high-resolution ROMS for the Pearl River Estuary (PreROMS, green box). The center of Typhoon Hato and Pakhar at every 6-hr are shown (red and black solid line, respectively). (b) Schematic of the Fennel biogeochemistry module in ROMS for the carbon cycle. (c) Enlarged view of the high resolution PreROMS domain. River inputs from eight outlets (from right to left: Humen (HM), Jiaomen (JM), Honqilimen (HQ), Hengmen (HE), Modaomen (MD), Jitimen (JT), Hutiaomen (HT), and Yamen (YM)) are marked with black dots. The tracks of Typhoon Hato and Pakhar every 6-hr by passing the PreROMS domain are overlaid. The red box indicates the analysis region for panel (d); (d) Subregions for analysis in Figures 12 and 13: Inner Lingding Bay (ILB, red); Outer Lingding Bay (OLB, yellow), Western Four Outlets (WFO, green), and Shallow Coastal Region (SCR, blue). Monitoring stations are also shown, including normal water level (Black squares: Shanbanzhou, Chiwan, Neilingding), storm surge (Red squares: Zhuhai, Dahengqin, Sanzao), and buoy for continuous temperature and salinity measurements (Red star: A).

The horizontal grid spacing varies across the domain, with the highest resolution (300 m) in Lingding Bay, and the lowest resolution (~ 2 km) in the southwest corner. The average grid spacing is 600 m. The model employs 20 stretched, terrain-following vertical layers, with surface and bottom stretching parameters of 6.0 and 4.0, respectively. The model is configured to use the recursive MPDATA 3-D advective scheme for tracers and a third-order upwind advection scheme for 3-D horizontal momentum. For the turbulence closure mixing scheme, the Mellor and Yamada (1982) with the stability functions from Kantha and Clayson (1994) is implemented. The background diffusivities for momentum and tracers are set to 5×10^{-5} and 5×10^{-6} m^2/s , respectively.

The high resolution PreROMS has three open boundaries (eastern, western and southern), which implement the Tidal and Subtidal Concurrent Open Boundary Condition (TST-OBC) proposed by Liu and Gan (2016). The TST-OBC integrates a Flather-type scheme for tidal forcing and an Orlanski-type radiation scheme for subtidal forcing, enabling the model to effectively simulate concurrent tidal and subtidal flows. This approach minimizes dynamic inconsistencies and artificial energy reflection at the open boundaries, thereby improving the realism of the simulated circulation in the estuarine-coastal system. Hydrodynamic variables, including temperature, salinity, and SSH were all provided by the NSCSROMS. The western and southern open boundaries of the

Table 1
Definitions of Biogeochemical Parameters Used in State Variable Equations

Symbol	Description	Value	Units	Source
K_{chl}	Light attenuation coefficients for chlorophyll	0.02486	$(\text{mgChl m}^{-2})^{-1}$	Wang et al. (2019)
K_{NH_4}	Half-saturation constant for ammonium uptake	2	mmole Nm^{-3}	Lima and Doney (2004)
K_{NO_3}	Half-saturation constant for nitrate uptake	2	mmole Nm^{-3}	Lima and Doney (2004)
K_P	Half-saturation concentration of phytoplankton ingestion	2	$(\text{mmole Nm}^{-3})^{-2}$	Lima and Doney (2004)
K_W	Light attenuation coefficients for water	0.04	m^{-1}	Wang et al. (2019)
K_{sed}	Light attenuation for sediment	5.2	$(\text{kg m}^{-2})^{-1}$	Wang et al. (2019)
α	Initial slope of the P-I curve	0.025	$(\text{W m}^{-2})^{-1} \text{ day}^{-1}$	Geider et al. (1997)
m_p	Phytoplankton mortality rate	0.15	day^{-1}	Taylor et al. (1991)
par	Fraction of light that is available for photosynthesis	0.43	Dimensionless	Zielinski et al. (2002)
g_{max}	Zooplankton maximum growth rate at 0°C	0.6	day^{-1}	Fasham (1995)
μ_0	Phytoplankton growth rate	0.59	day^{-1}	Andersen et al. (1987)
ω_p	Vertical sinking velocity for phytoplankton	0.1	day^{-1}	Lima and Doney (2004)
ω_{LD}	Vertical sinking velocity for large detritus	5	day^{-1}	Lima and Doney (2004)
ω_{SD}	Vertical sinking velocity for small detritus	0.1	day^{-1}	Lima and Doney (2004)
ω_{RS-N}	Small detritus remineralization rate	0.3	day^{-1}	Leonard et al. (1999)
ω_{RL-N}	Large detritus remineralization rate	0.01	day^{-1}	Leonard et al. (1999)
τ	Aggregation parameter	0.02	day^{-1}	Lima and Doney (2004)

NSCSROMS were forced by open ocean tides, including eight major tidal constituents (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , and Q_1). The parameters for these tidal constituents—such as their periods, phase lags, amplitudes, and elliptical velocity parameters—were derived from the TPXO global tidal data available at <https://www.tpxo.net/home>.

2.2.2. The Carbon Cycle Model

The Fennel biogeochemistry model had a nitrogen cycle with explicit consideration of carbonate chemistry (Fennel et al., 2008; Laurent et al., 2017). The version of the model we used incorporates 11 state variables, including phytoplankton, chlorophyll, zooplankton, nitrate, ammonium, DIC, total alkalinity (TA), and two detritus pools (small and large detritus, each split into nitrogen and carbon, as shown in Figure 1b). TA was treated as a conservative tracer in this study. POC is calculated as the total carbon in phytoplankton, zooplankton, small and large detritus, which is converted from the total nitrogen through the Redfield ratio. Critical biogeochemistry model parameters are listed in Table 1.

2.2.3. River Inputs and Initialization

River inputs were prescribed at model grid cells near the mouths of the eight major river channels in the PRE: Humen (HM), Jiaomen (JM), Hongqilimen (HQ), Hengmen (HE), Modaomen (MD), Jitimen (JT), Hutiaomen (HT), and Yamen (YM; Figure 1c). Daily river discharge data were obtained from the Pearl River Water Resources Commission of the Ministry of Water Resources (<http://www.pearlwater.gov.cn/>). Riverine nitrogen nutrient concentrations (NO_3 , NH_4 , and organic nitrogen) were based on monthly measurements from March 2005 to February 2006 (Lu et al., 2009). Riverine DIC and TA concentrations were measured seasonally at Zhong Da Wharf, Xijiang, Beijiang and Dongjiang stations in 2018 and 2019. The measurements at these four stations were averaged and used as the representative concentrations for the eight river outlets. Monthly riverine POC concentrations from 2011 to 2017 were derived from remote sensing retrieval by Wang et al. (2025) and were partitioned into zooplankton, phytoplankton, and large and small detritus carbon at a ratio of 1:10:60:180 based on field measurements (Guo et al., 2015; Li et al., 2006, 2018).

To initialize the model, a parallel simulation was conducted using the coarse resolution NSCSROMS-Fennel from 01 January 2008 to 31 December 2017. The physical and biogeochemical fields from 01 January 2010 were

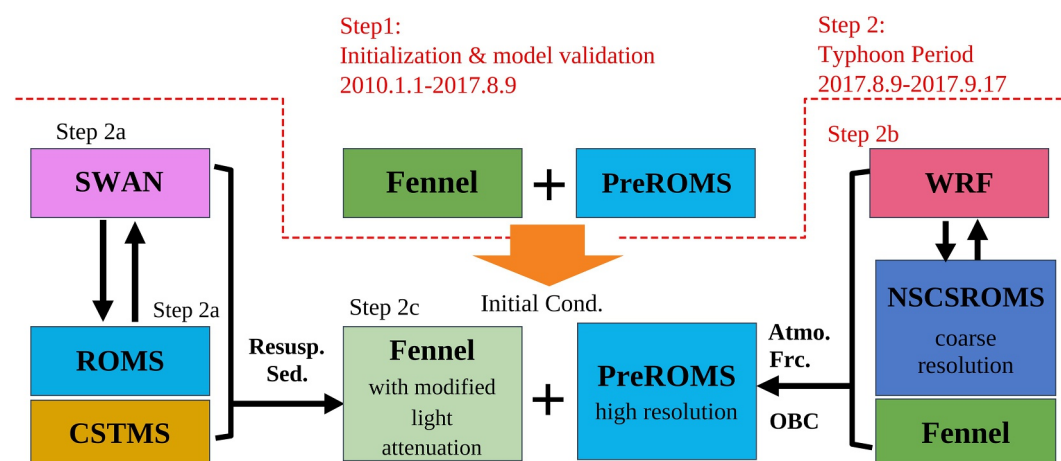


Figure 2. Flow chart of the model simulation, including a 10-year initial simulation and a 40-day typhoon period for Hato and Pakhar using the nested coupled modeling system. Step 1: A coupled high-resolution physical-biogeochemical model (PreROMS-Fennel) was run to provide initial conditions for the typhoon period and for model validation. Step 2: The coupled ocean-sediment-wave model (ROMS-CSTMS-SWAN) was run to simulate resuspended sediment. Subsequently, the coupled atmosphere-ocean-biogeochemistry model (WRF-ROMS-Fennel) was run to provide atmospheric forcing and open boundary conditions for the high-resolution PreROMS-Fennel typhoon period simulation.

interpolated onto the high-resolution PreROMS grid to serve as initial conditions. The initialization allowed the model to complete its spin-up within approximately 3 months; therefore, simulation results starting from 2011 were used for model validation and analysis.

2.2.4. The Running Procedure of the Nesting Modeling System

To investigate the POC response to Typhoons Hato and Pakhar, the coupled one-way nesting modeling system was run in two steps. Step 1 consisted of an initial spin-up period from 01 January 2010 to 09 August 2017, using the coupled PreROMS-Fennel model with the carbon cycle module. During this stage, the model was forced with the ERA 5 atmospheric reanalysis data set, which provided hourly data for air-temperature, relative humidity, pressure, precipitation, longwave and shortwave radiation. Daily physical and biogeochemical variables from the long-term NSCSROMS-Fennel data set mentioned above were used as open-boundary conditions. The last day of the spin-up (09 August 2017) was used as the initial condition for the subsequent typhoon simulation. Step 2 is the typhoon-period simulation, which comprises three sub-steps (Figure 2). (a) The coupled SWAN and ROMS model with the CSTMS sediment module (Warner et al., 2008, 2010) was run to obtain the 3D field of resuspended sediment induced by the typhoons (Chen et al., 2019). The model included riverine sediment based on measurements from Ou (2019); therefore, the output represents the total. (b) The coupled NSCSROMS, WRF and Fennel model was run to generate high-frequency wind fields and open boundary conditions. (c) The coupled PreROMS-Fennel was run for 40 days (August 09–17 September 2017), forced with the hourly atmospheric wind fields and open boundaries from step (b). The 3D field of resuspended sediment from step (a) was incorporated into the carbon biogeochemistry module to calculate the light attenuation term.

2.3. The In Situ and Satellite Observations for Model Validation

The model was validated against in situ and satellite observations for both physical and carbon-related biogeochemical variables, including sea surface temperature (SST), sea surface salinity (SSS), sea surface height (SSH), DIC, TA and POC (Table S1 in Supporting Information S1). Due to the difficulty of conducting research cruises during typhoons and the associated intense cloud cover, almost all data we collected was under normal weather conditions. As a result, the comparison mostly used the simulation results during the initialization period, except for SSH from Zhuhai, Dahengqin, and Sanzao stations, which recorded the sea level variability during the passage of Typhoons Hato and Pakhar.

The model skill metrics are compactly visualized on Taylor diagrams (Taylor, 2001), which are plotted on a polar coordinate system and summarized skill metrics including correlation coefficient (r), standard deviation (SD),

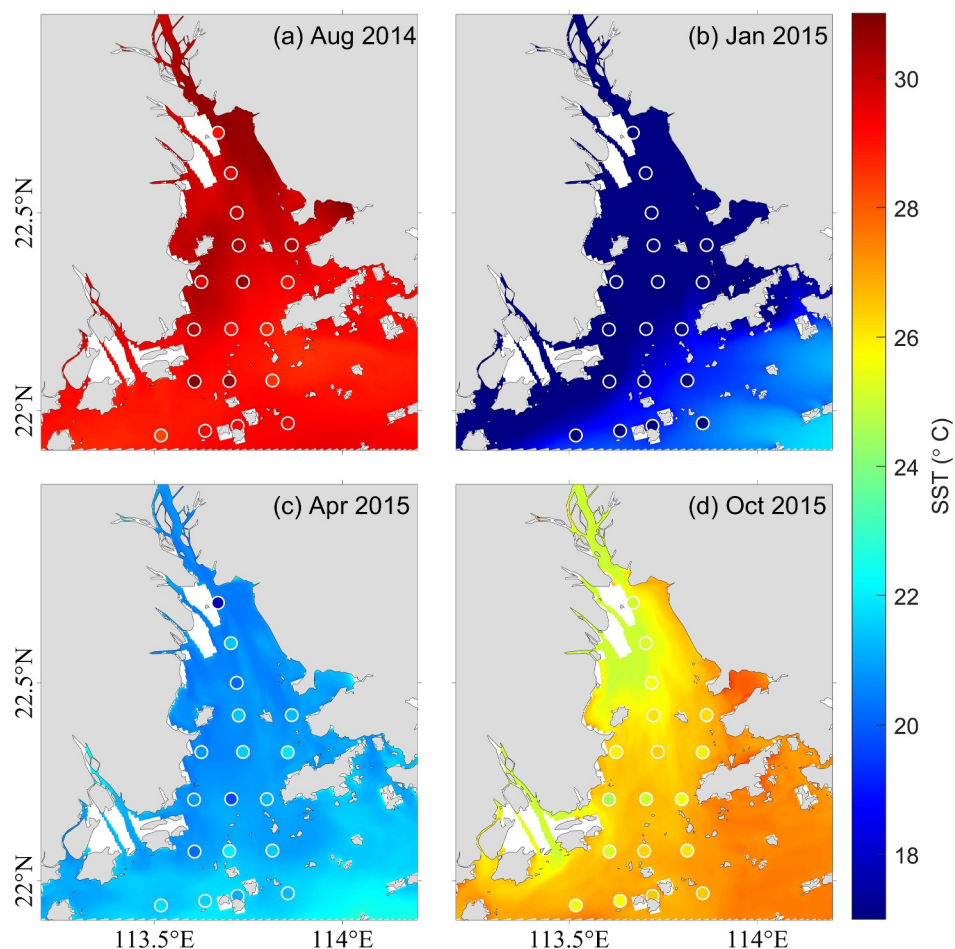


Figure 3. Comparison of observed and simulated sea surface temperature (SST) in Lingding Bay for (a) August 2014; (b) January 2015; (c) April 2015; and (d) October 2015. The background color represents the simulated SST, and the dots show the field observations.

and unbiased root mean square difference (RMSD); skill metrics are calculated by first retrieving the model data at the observational/satellite pixels, and then normalized by the standard deviation of observational/satellite to allow for the plotting of multiple different data sets on the same diagram. On the normalized Taylor diagram, the reference point sitting at (1,0) represents a perfect skill score.

3. Result

3.1. Model Validation

We first compared the simulated hydrodynamic and carbon-related biogeochemical variables with in situ and satellite observations (Table S1 in Supporting Information S1). The assessed variables included SST, SSS, SSH, DIC, and TA. The results demonstrate consistent spatial-temporal patterns between the model outputs and the observations for these variables (Figures 3–8). For SST, the model successfully replicated the observed spatial-temporal variability during the four cruises from 2014 to 2015. The SST was largely spatially uniform but exhibited strong seasonal variability (Figure 3). For instance, in summer (August 2014, Figure 3a), the average temperature was as high as $29.6 \pm 0.5^{\circ}\text{C}$ (the model data were extracted at the observational location for this calculation), close to the observed $29.7 \pm 0.7^{\circ}\text{C}$. In winter (January 2015, Figure 3b), the values were as low as $17.1 \pm 1.3^{\circ}\text{C}$ and $16.4 \pm 0.5^{\circ}\text{C}$ in the model and observation, respectively. Similarly, the model successfully captured the spatial-temporal variability of SSS, which gradually increased from the upper to the lower Lingding Bay. A large area of low-salinity water (<15 PSU) extended beyond the bay mouth during summer (August 2014) but was confined to the upper Lingding Bay during winter (January 2015, Figures 4a–4d). This seasonal pattern is

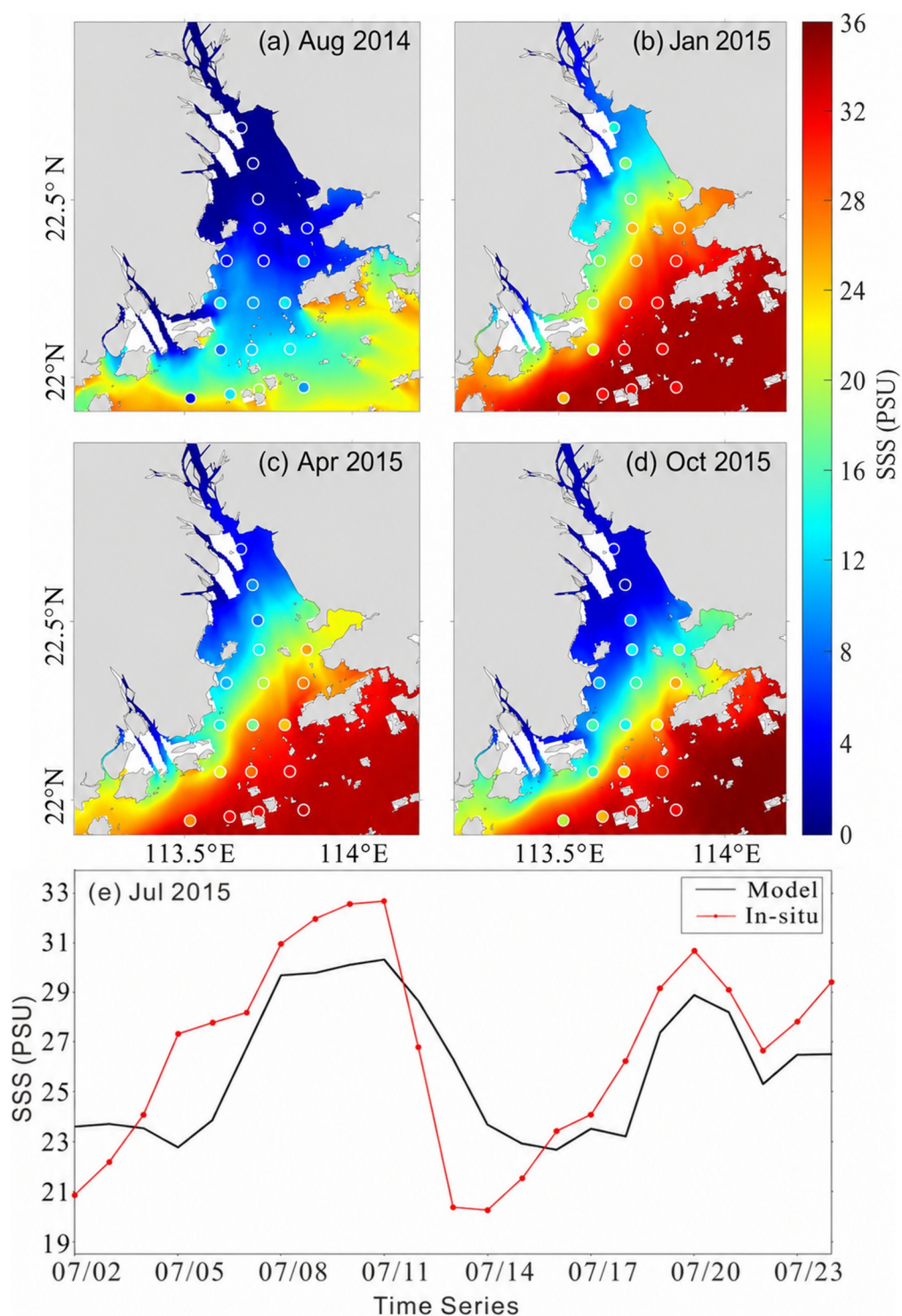


Figure 4. Comparison of field observed and simulated sea surface salinity (SSS) in Lingding Bay for (a) August 2014; (b) January 2015; (c) April 2015; (d) October 2015; and (e) time-series comparison with continuous in situ data from Buoy A. The background color represents the simulated SSS and dots show the observation.

consistent with the fluctuation of Pearl River runoff between the wet (April–September) and dry (October–March) seasons. Additionally, we compared the model output to a continuous SSS record from a buoy located outside Lingding Bay but within the 30m isobath during the summer of 2–24 July 2015 (Figure 4e). The model

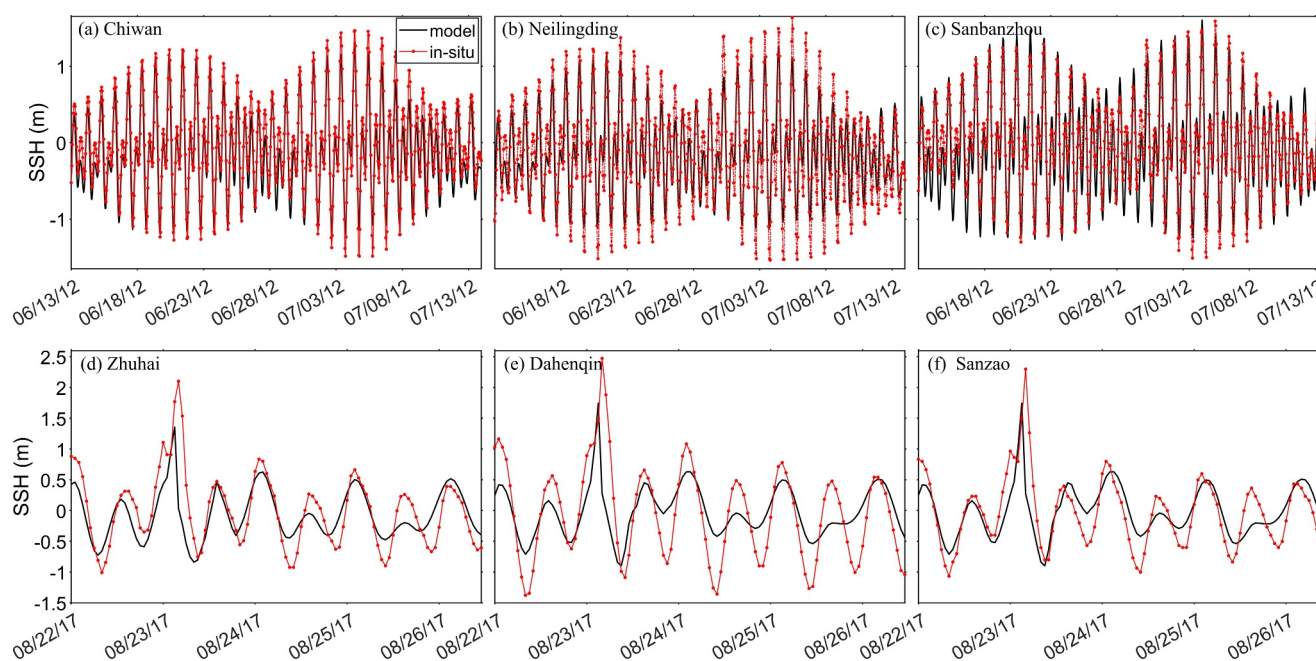


Figure 5. Comparison of observed and simulated sea surface height (SSH) under normal conditions (a–c) and during the passage of typhoons Hato and Pakhar (d–f). Station locations are shown in Figure 1d.

successfully captured the observed salinity peaks on July 11 and 20, as well as the trough on 14 July, which were influenced by tidal fluctuations. The simulated SSS averaged at 26.0 ± 2.7 PSU, closely matching the observational mean 26.7 ± 3.9 PSU.

The model was first evaluated for SSH using data from the upper and middle bay stations at Chiwan, Neilingding and Shanbanzhou (Figure 1d; Table S1 in Supporting Information S1), which recorded measurements from 13 June to 13 July 2012 (Figures 5a–5c). The model accurately reproduced tidal fluctuations at the three stations. It successfully captured the irregular semidiurnal tidal pattern, characterized by two high and two low water levels within a lunar day, as well as the spring–neap cycle that occurs approximately every half-month. For instance, the maximum SSH during the spring tide occurred on 4 July in both the observations and simulations. The simulated maximum SSH values were 1.3, 1.3, and 1.6 m at Chiwan, Neilingding, and Shanbanzhou, respectively, close to the observational values of 1.5, 1.6, and 1.6 m. Furthermore, simulated SSH was evaluated at the lower-bay station Zhuhai as well as the Modaomen Bay station Dahengqin and Jitimen Bay station Sanzao. These stations recorded data from 22 to 26 August 2017, a period when Hato and Pakhar passed by (Figures 5d–5f). The results show a pronounced SSH increase due to storm surge during the typhoons' passage. On 23 August, the simulated SSH peaks were approximately 1.4, 1.8, and 1.8 m at Zhuhai, Dahengqin, and Sanzao, respectively, whereas the observed peaks were higher at 2.1, 2.5, and 2.3 m. The simulated surge was slightly weaker than the observations, possibly because waves were not coupled to the PREROMS-Fennel model in the second stage run (see Figure 2).

Next, we compared the simulated DIC and TA with cruises having laboratory measurements of DIC and TA in Jul 2017 (Figure 6). Both model and observational results show that DIC and TA gradually increase from the estuary toward the nearshore waters. By extracting the model data at the observational time and location, the simulated DIC and TA in July 2017 were 1488 ± 221 mmol-C/kg and 1682 ± 330 meq/m³, slightly smaller than the observed values (1680 ± 167 mmol-C/kg for DIC and 1891 ± 246 meq/m³ for TA).

Lastly, the simulated POC was comparable with satellite retrievals from 2011 to 2017 (Figure 7). Seasonally averaged results show that POC concentrations gradually decreased from the upper to the lower bay, with greater accumulation on the western side. On the left side of Lingding Bay, the model underestimated the satellite POC concentrations, possibly because the riverine nutrient data used were from 2005 to 2006, which are lower than the actual levels observed during 2011–2017. This resulted in lower primary production and consequently reduced

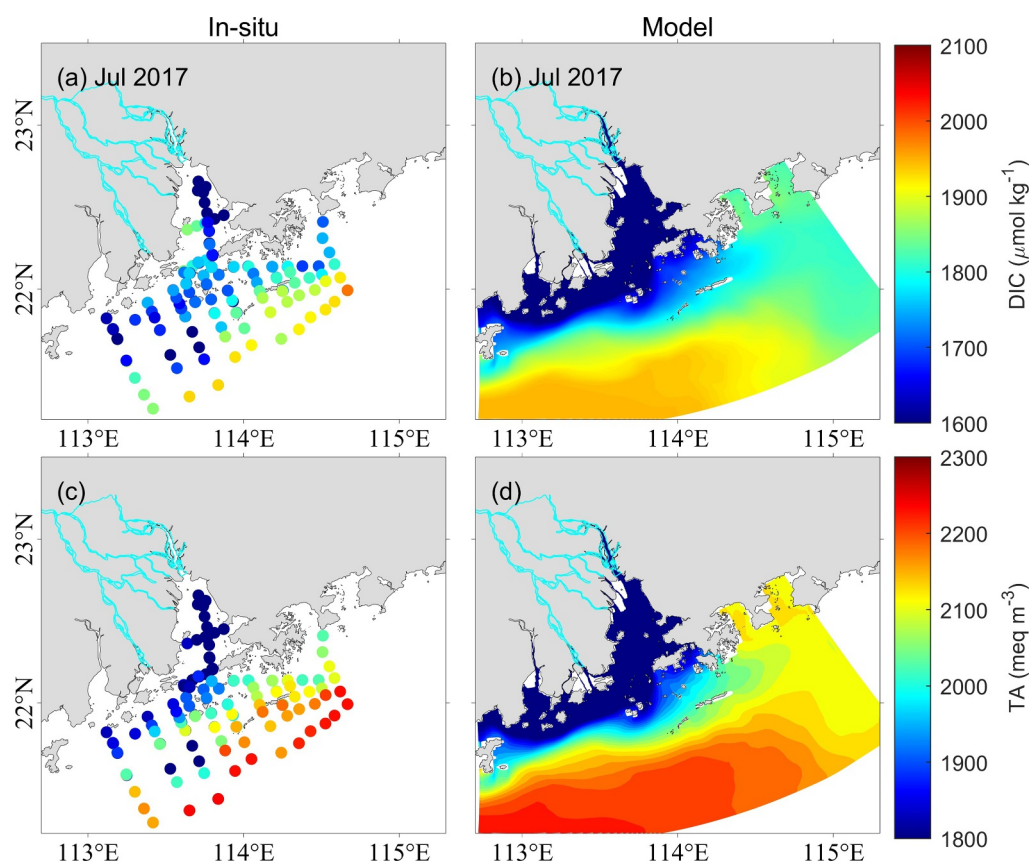


Figure 6. Comparison of observed (a, c) and simulated (b, d) dissolved inorganic carbon (DIC) and total alkalinity (TA) for July 2017.

marine POC generation. The concentrations reached a maximum in summer in both the model (0.55 ± 0.1 mg C/L) and observations (0.51 ± 0.18 mg C/L), and a minimum in winter (model: 0.33 ± 0.07 mg C/L; observation: 0.40 ± 0.11 mg C/L).

To better visualize the model-observational quantitative comparison results, the model's skill is presented on a Taylor diagram (Figure 8). The comparisons for SSS and SST indicate that the model performed well in replicating the seasonal spatial-temporal variability of SST, with a correlation coefficient of 0.98, a root-mean-square deviation (RMSD) of 0.19, and a standard deviation of 0.96. The skill for seasonal SSS is slightly lower, with a correlation coefficient of 0.94, an RMSD of 0.38, and a standard deviation of 1.1. The model's skill in replicating summer daily SSS from the buoy was lower than that for seasonal SSS, exhibiting a correlation coefficient of 0.78, an RMSD of 0.9, and a standard deviation of 1.43 (Figure 8a).

The comparison for SSH shows that the model performed better under normal weather conditions than during typhoon periods (Figure 8b). For the Neilingding, Chiwan and Shanbanzhou stations, the correlation coefficients were between 0.9 and 0.95, and the RMSDs were 0.3–0.6. For the Zhuhai, Sanzao and Dahengqin Stations, the correlation coefficients were ~ 0.7 , and the RMSDs ranged from 1.0 to 1.5.

For DIC and TA, the model exhibited high correlation coefficients (DIC: 0.6; TA: 0.87) and low RMSDs (DIC: 0.99; TA: 0.56). Furthermore, the model demonstrated strong skill in reproducing the spatial-temporal variability of POC, with a correlation coefficient of 0.84, an RMSD of 1.29, and a standard deviation of 2.01.

Overall, our model demonstrated sufficient skill in replicating the spatiotemporal variability of both hydrodynamic and critical carbon-related biogeochemical variables. We are therefore confident in using it to investigate the impact of typhoons on POC within the PRE and adjacent regions.

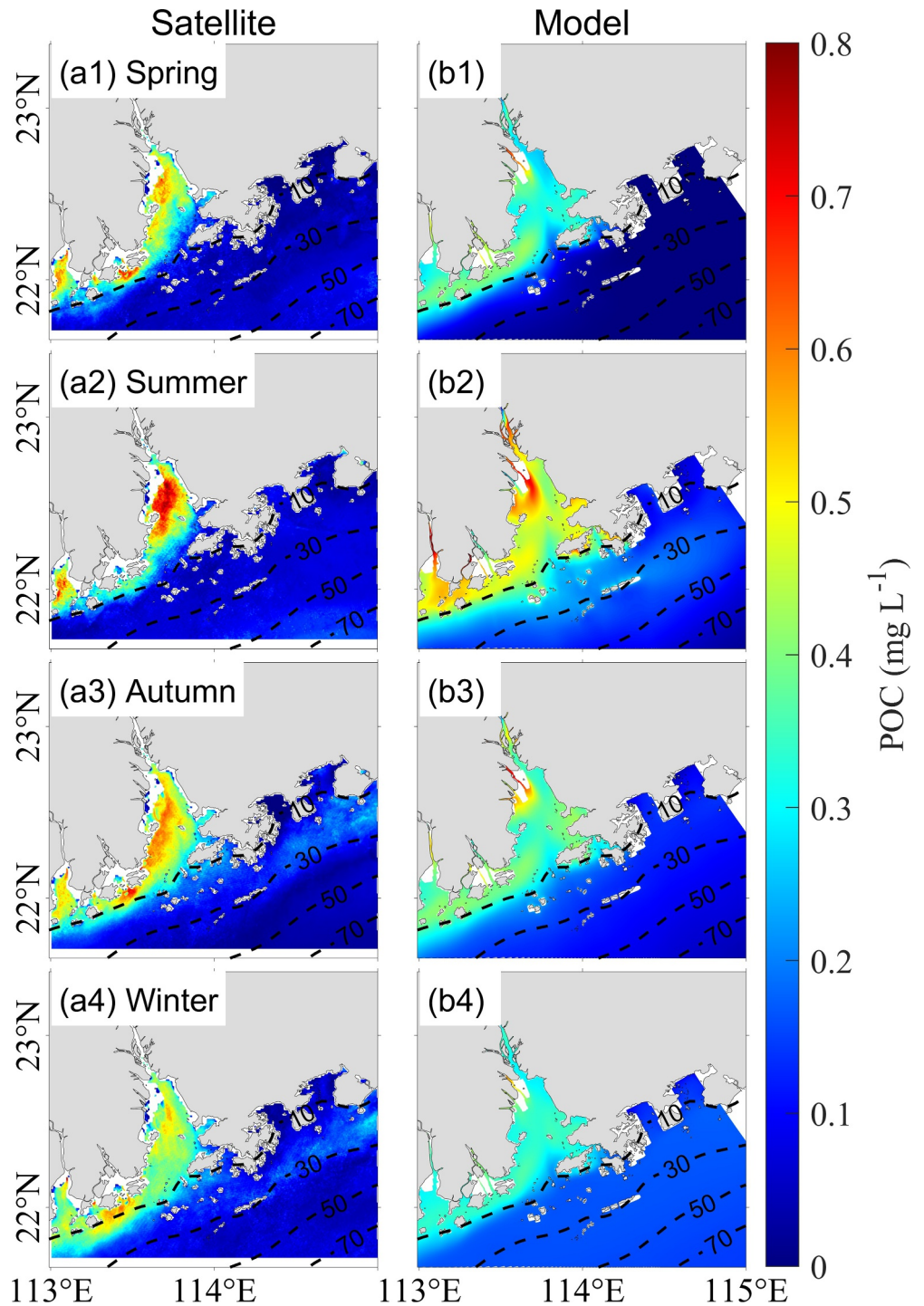


Figure 7. Comparison of particulate organic carbon (POC) from (a1–a4) satellite retrieval and (b1–b4) model simulation. Data are averaged seasonally over the period 2011–2017. From top to bottom, the panels represent Spring (March–May), Summer (June–August), Autumn (September–November), and Winter (December–February). Satellite POC data are from Wang et al. (2025).

3.2. Spatial-Temporal Variability of POC Distribution Under the Impact of Hato and Pakhar

To evaluate the impact of the two typhoons on the distribution characteristics of POC, we calculated the daily average simulation results from 09 Aug–17 Sep 2017. The spatial distributions of POC at critical snapshots --

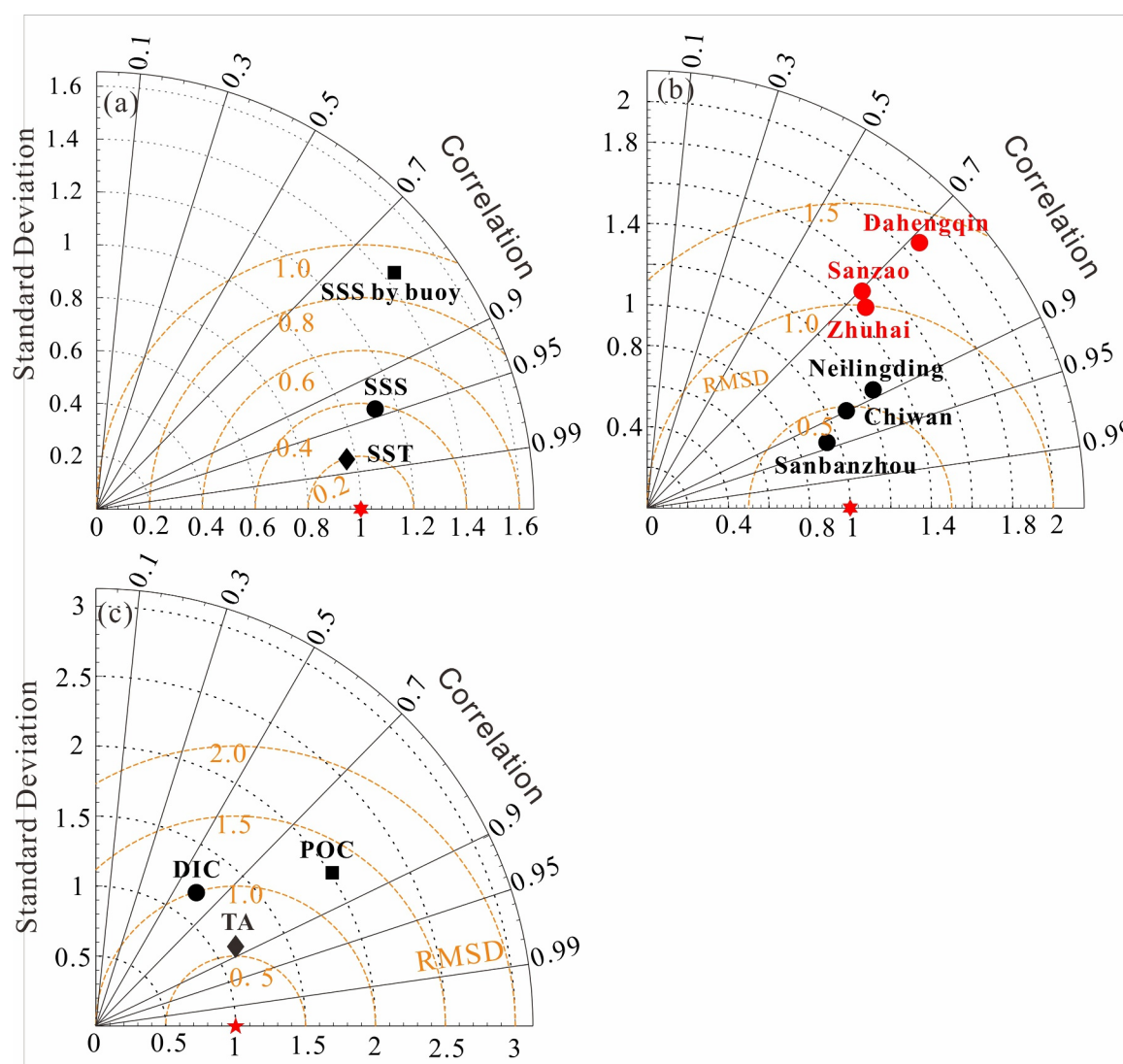


Figure 8. Summary Taylor diagrams quantifying model performance for physical and biogeochemical variables: (a) SST and SSS, (b) SSH, and (c) DIC, TA and POC. The skill assessment used multiple validation data sets: in situ cruise measurements (collocated pairs), continuous buoy records (time series from Figures 4e and 5) and satellite derived POC (monthly climatology from 2011 to 2017, as shown in Figure 7).

before (17 Aug), during (23 and 27 Aug), and after the typhoons (02, 08, and 14 Sep) are shown in Figures 9 and 10. The daily vertical averaged POC concentrations in four sub-regions, including the western four outlets (WFO), inner Lingding Bay (ILB), outer Lingding Bay (OLB), and the shallow coastal region (SCR), are presented in Figure 11. To examine the mechanisms driving the above spatial-temporal variability, we plotted the daily wind field, river runoff, strength of stratification, vertical mixing, SST and SSC as well (Figure S1 in Supporting Information S1).

Horizontally, the concentrations of POC in both surface and bottom waters exhibit a declining trend from the river outlets toward the shallow coastal region (Figure 9), consistent with the observations reported by Guo et al. (2015). The area with elevated POC concentrations (>0.5 mg C/L) is more extensive (>30 m isobath) at the surface (Figure 9a) than at the bottom (<10 m isobath) (Figure 9b) because the Pearl River plume is a surface-advected plume (Liao et al., 2020; Yankovsky & Chapman, 1997).

Prior to the typhoons, elevated concentrations of POC (>0.8 mg C/L) were observed in two primary zones: near the outlets of the river channels and in the shallow coastal waters outside Lingding Bay (within the 31 PSU isohaline) (Figure 9a1 and 9b1). Similar bimodal spatial distribution has been documented in previous studies

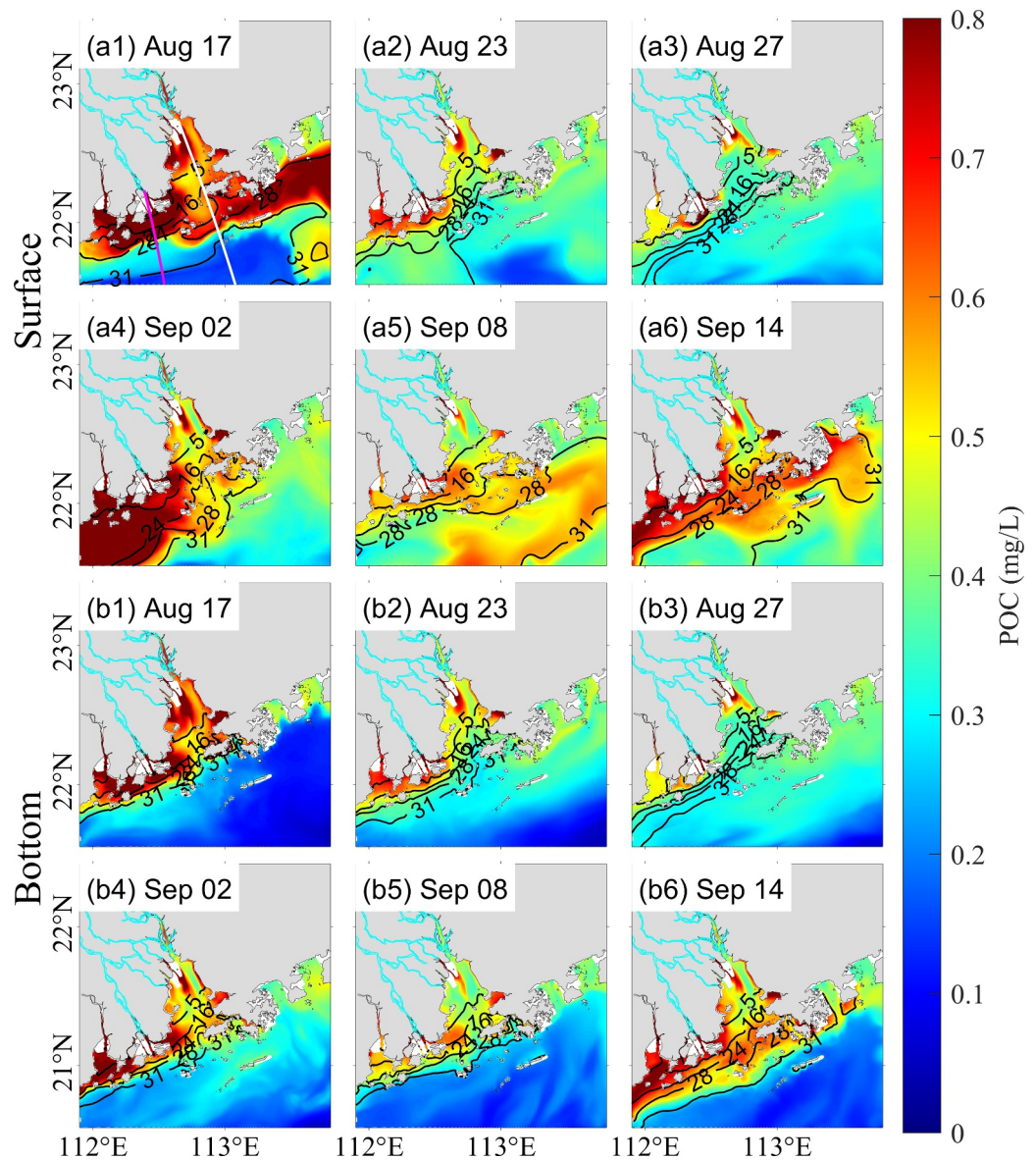


Figure 9. Horizontal distributions of simulated POC (color, Units: mg-C/L) and salinity (black contours) in the surface (a1–a6) and bottom (b1–b6) layers. The snapshots show conditions before (August 17), during (August 23rd, 27th), and 1–3 weeks after (September 2nd, 8th, and 14th) the passage of Typhoons Hato and Pakhar. The white and magenta lines in panel a1 show the cross-section location in Figure 10; Figure S2 of Supporting Information S1.

based on in situ observations (He et al., 2010; Li et al., 2018; Zhao et al., 2025). This pattern is associated with high river discharge and the prevailing southwesterly summer monsoon (Figure S1a in Supporting Information S1). On one hand, the river delivers a substantial amount of terrestrial POC, which is deposited near the river mouth. On the other hand, the southwesterly winds facilitate the offshore transport of riverine nutrients, promoting the formation of marine POCs.

During the typhoons (Figures 9a2, 9a3 and 9b2, 9b3), the wind shifted from offshore to onshore (Figure S1a in Supporting Information S1). High POC waters were confined to the river mouth and did not spread beyond the PRE. Following the passage of the two typhoons, wind speeds decreased, although the direction continued to vary synoptically (Figure S1a in Supporting Information S1). Consequently, POC in coastal waters exhibited a distinct spatial pattern. In the 1st week after the typhoon passage, POC primarily accumulated along the western bank of

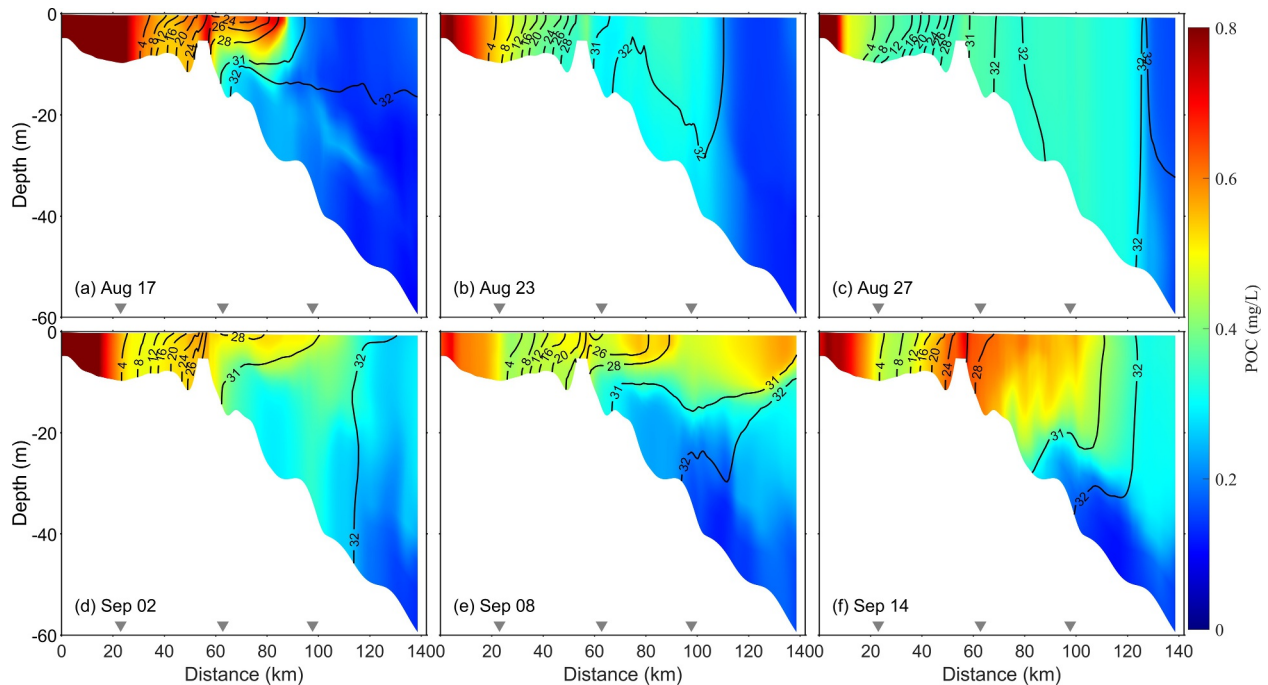


Figure 10. Cross-sectional distributions of simulated POC (color, Units: mg-C/L) and salinity (black contours) before (August 17), during (August 23rd, 27th), and 1–3 weeks after (September 02, 08, and 14) the passage of Typhoons Hato and Pakhar. The location of cross-section A is shown in Figure 9a1. Gray triangles mark the boundaries between the ILB, OLB and SCR as defined in Figure 1d.

the PRE adjacent to WFO. The high-POC water mass extended offshore in a southeasterly direction during the 2nd week but retreated toward the nearshore region in the 3rd week. Notably, both before and after the typhoons, a low POC zone was observed within Lingding Bay, where the maximum turbidity inhibits photosynthesis (Li et al., 2025).

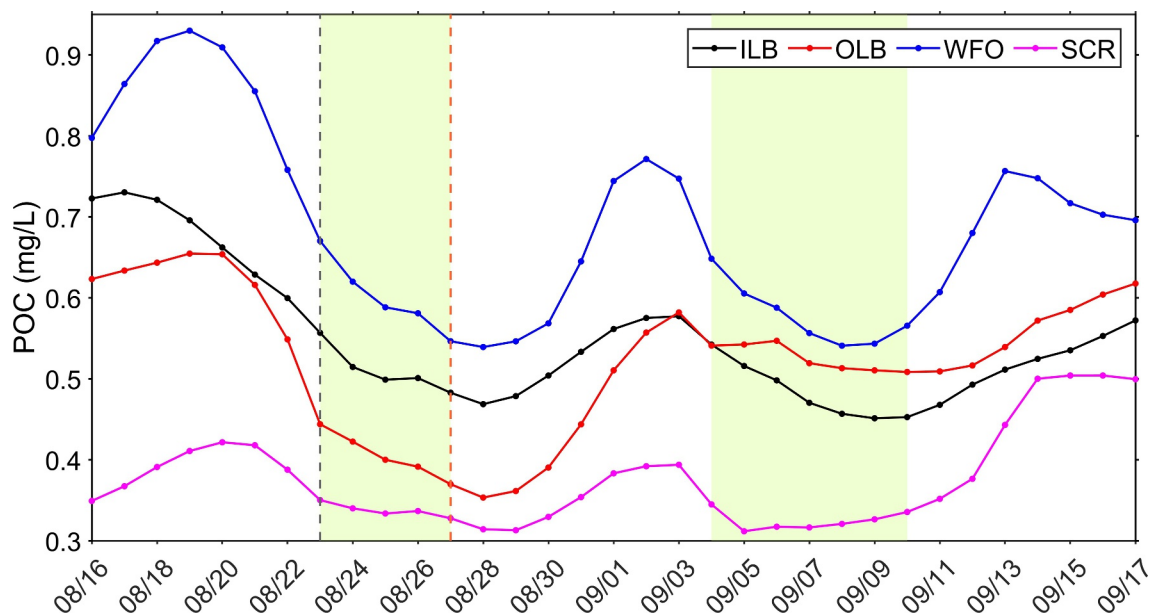


Figure 11. Time series of simulated spatially averaged POC concentrations within the four subregions for the CTRL run. The background shading highlights the periods before, during, and 1–3 weeks after typhoons Hato and Pakhar. The vertical dotted line indicates the date on which Typhoons Hato (gray) and Pakhar (orange) passed through the study area.

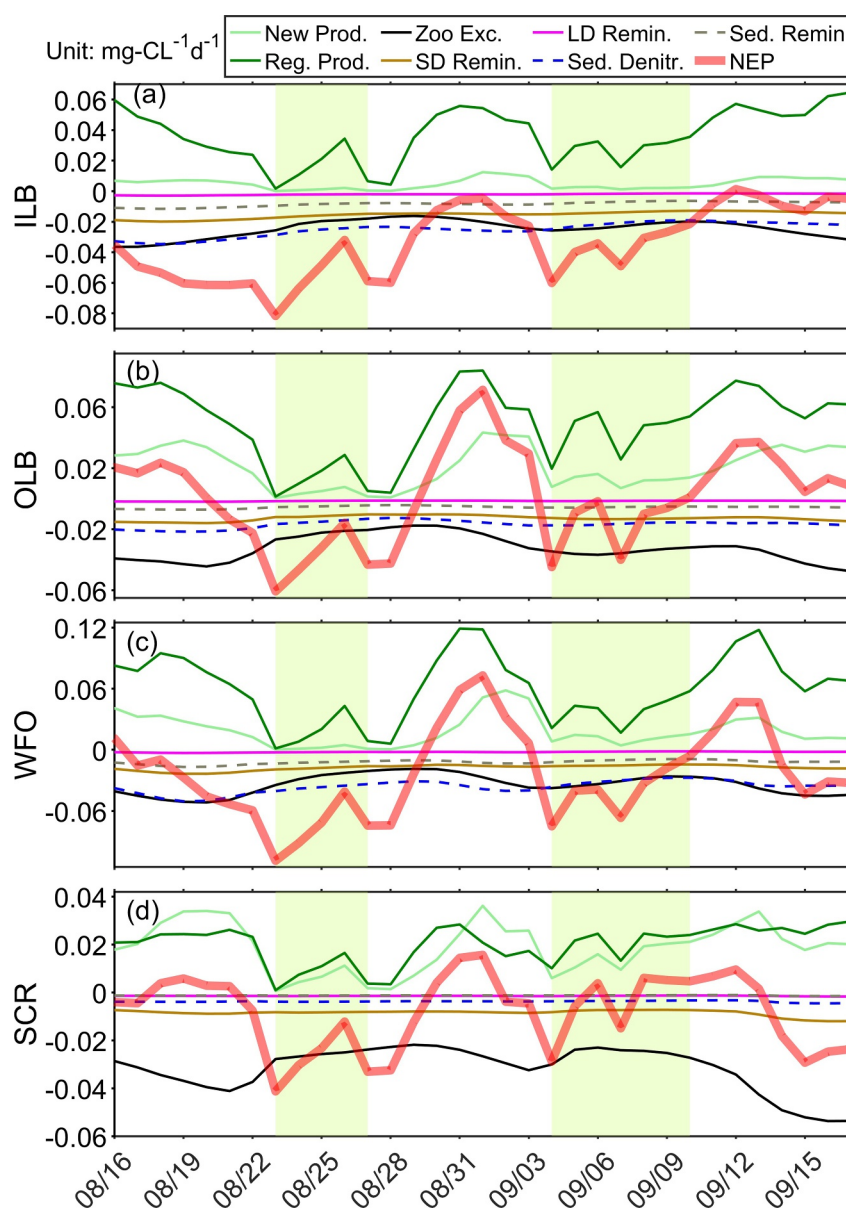


Figure 12. Daily averaged rates of biogeochemical processes including new and regenerated primary production (New & Reg. Prod.), zooplankton excretion (Zoo Exc.), small and large detritus remineralization (SD & LD Remin.), sediment denitrification (Sed. Denitr.) and remineralization (Sed. Remin.), affecting POC concentrations within the inner Lingding Bay (a), Outer Lingding Bay (b), Western Four Outlets (c), and the Shallow Coastal Region (d) (see Figure 1d). NEP was calculated as $\text{New Prod.} + \text{Reg. Prod.} - \text{Zoo Exc.} - \text{SD Remin.} - \text{LD Remin.} - \text{Sed. Denitr.} - \text{Sed. Remin.}$.

The spatial distribution of POC concentration along the pre-defined Transect A (Figure 9) provides further details on its variation from the ILB to SCR (Figure 10). Before the typhoon, distinct salinity stratification developed in the SCR (Figure 10a). During the passage of the typhoon, enhanced vertical mixing resulted in a nearly homogeneous vertical distribution of both POC and salinity, with POC and salinity contours aligning with each other, indicating conservative mixing behavior (Figures 10b and 10c). 1-week after the typhoon, salinity stratification re-established conditions similar to those observed before the typhoon (Figure 10d). 2-weeks after the typhoon, high POC concentrations and stratified waters extended further offshore (Figure 10e) from the OLB to the SCR, where the distributions of POC and salinity became decoupled as salinity increased (4~31PSU). This decoupling was also observed in the 3rd week after the typhoon, suggesting the dominance of biogeochemical processes in this region.

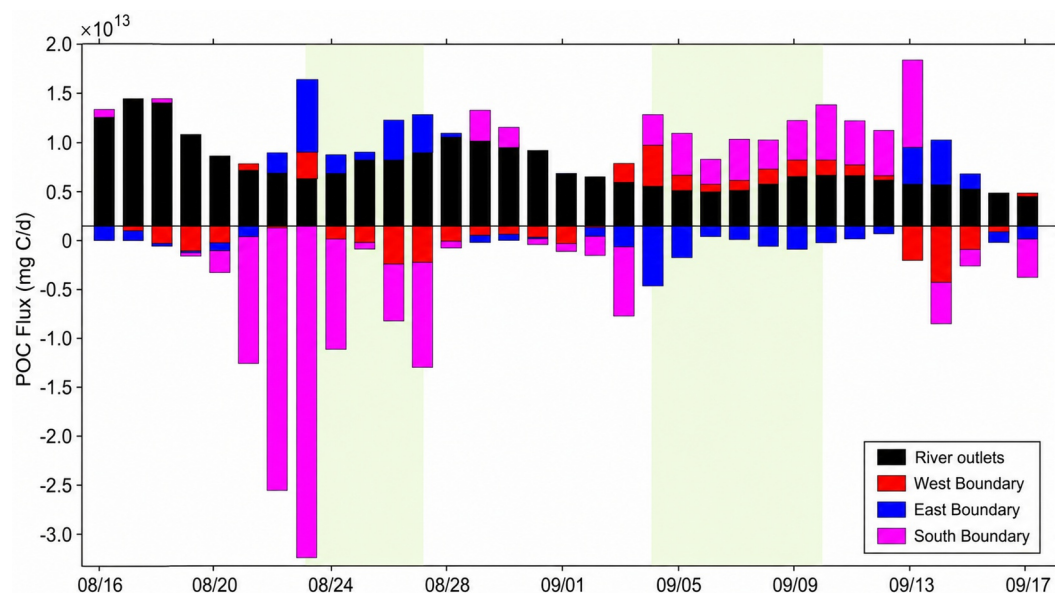


Figure 13. Daily exchange fluxes of POC across four boundaries of PRE and adjacent regions (see Figure 1d for their locations) in the PRE.

Figure 11 shows the vertically averaged time series of POC in four sub-regions. Prior to the typhoon, the vertically averaged concentration of POC gradually decreased from the ILB & WFO toward the OLB and SCR regions (Figure 11). The relatively lower POC in the ILB region compared to the WFO region can be attributed to the higher SSC in the turbidity maximum zone. During the typhoon events (23–27 August), POC concentrations decreased across all four regions, despite an increase in river discharge during this period (Figure S1b in Supporting Information S1). After the passage of the typhoon, the temporal variability of POC exhibited distinct patterns in relation to river discharge, peaking in the 1st and 3rd weeks while reaching a trough in the 2nd week. Notably, there were distinct characteristics observed from Lingding Bay to SCR: (a) In the OLB region, POC concentrations were lower than those in the ILB region during the 1st week after the typhoon, but increased rapidly and exceeded those in the ILB region from the 2nd week; (b) In the SCR region, a rapid increase in POC began in the 3rd week, reaching a maximum concentration significantly higher than that recorded in the 1st week after the typhoon.

3.3. Biogeochemical Sources and Sinks Controlling POC Variability

The above spatial-temporal variability of POC is intimately linked with various biogeochemical processes. To explore the mechanisms, daily vertical average rates of multiple biogeochemical sources and sinks, as well as the overall impact, the net ecosystem production (NEP) are shown in Figure 12. POC production originates from primary production, which consists of new (supported by nitrate), and regenerated production (supported by ammonium). POC consumption in the water column includes zooplankton excretion and remineralization of both small and large detritus, calculated by summing the equations for phytoplankton, zooplankton, and small and large detritus as described by Fennel et al. (2006). Sediment loss includes both remineralization and denitrification. According to Fennel et al. (2006), after POC reaches the sediment, 1/4 is remineralized and 3/4 are denitrified.

The source terms, including the new and regenerated primary production, demonstrate pronounced fluctuations in the entire simulation period, while the sink terms, such as the zooplankton excretion, small and large detritus remineralization, and sediment denitrification, exhibit relatively smooth variations.

Prior to Typhoon Hato (16th–22nd Aug), both regenerated and new production gradually decreased in the ILB, OLB, and WFO regions due to a significant reduction in river runoff following a flooding event (Figure S1b in Supporting Information S1). Consequently, the two predominant sink terms, zooplankton excretion and sediment denitrification, also decreased.

During the passage of the two typhoons (23rd–27th Aug), the river discharge increased markedly; however, both new and regenerated PP maintained relatively low levels. This was because on one hand, the sudden increase in SSC (Figure S1e in Supporting Information S1) inhibited phytoplankton photosynthesis. On the other hand, the increased discharge reduced the residence time of phytoplankton, preventing nutrient uptake and the formation of marine POC (Feng et al., 2022). Besides, as river discharge increased suddenly, large amounts of terrestrial POC were delivered into the PRE; this may shift the POC composition in PRE from a mix of terrestrial and marine POC prior to the typhoons to a dominance of terrestrial POC during their passage. Additionally, both new and regenerated production experienced a sudden drop one day prior to the passage of typhoons (22nd–23rd Aug; 26th–27th Aug), primarily due to cyclonic winds inducing offshore transport (Figure S2b in Supporting Information S1). As primary production weakened, POC loss through zooplankton excretion also gradually decreased, leading to sediment denitrification becoming a predominant sink in the ILB and WFO regions.

Following the passage of the typhoons, as the strength of hydrodynamic conditions and SSC reduced, phytoplankton resumed nutrient uptake, resulting in an increase in both new and regenerated PP across all four regions. As PP increased, both zooplankton excretion and sedimentary denitrification losses also increased. In the ILB region, it is noteworthy that during the 1st week after the typhoon, sediment loss was greater than zooplankton excretion. Consequently, NEP remained negative at $-15.1 \times 10^{-3} \text{ mg C L}^{-1} \text{ d}^{-1}$. In contrast, in the OLB region, both new and regenerated production increased significantly, with new production exceeding that of the ILB region by more than 3.7 times, shifting the NEP from negative to positive ($24.4 \times 10^{-3} \text{ mg C L}^{-1} \text{ d}^{-1}$). As a result, the POC concentration in this region surpassed that of the ILB region from the 2nd week onward (Figure 11).

In the SCR region, although nutrient availability supports relatively high phytoplankton growth, a significant part of the phytoplankton is grazed by zooplankton. Consequently, zooplankton excretion in the 3rd week was considerably higher than in the previous 2 weeks. As a result, both the biomass of zooplankton and the amount of small detritus increased significantly, resulting in higher POC concentrations in the 3rd week compared to the 1st week.

In summary, the predominant biological sources and sinks of POC are highly variable during the passage of successive typhoons. In the ILB, OLB and WFO regions, regenerated production exceeds new production, indicating that a substantial fraction of POC is rapidly recycled in these three subregions. In contrast, in the SCR region, the new and regenerated production were comparable. Before and 1-week after the typhoon, new production exceeded regenerated production, reflecting a more efficient utilization of riverine nutrients. However, 3 week after the typhoon, regenerated production predominates as an increase in biomass of zooplankton and small detritus, as the regenerated nutrients. Regarding sinks, zooplankton excretion serves as the dominant sink in the OLB and SCR regions. Conversely, sediment denitrification plays an equally significant role in the ILB and WFO regions, as riverine terrestrial POC is deposited near the river mouth. This results in negative NEP during the entire simulation period, indicating that the region acts as a potential carbon source, consistent with the in situ study by Guo et al. (2009). The sediment denitrification sink is more pronounced in these two regions during and 1-week after the typhoon, as heavy rainfall associated with the typhoons pulsed a large amount of terrestrial POC and resulted in corresponding deposition.

3.4. POC Flux Between PRE and Adjacent Systems

We aimed to investigate the lateral export of POC from estuaries to the coastal ocean during typhoon events. We calculated the POC export from four boundaries. The calculations at the eastern, western and southern boundaries involved multiplying the velocity perpendicular to the interface by the POC concentrations and the vertical area of each grid cell, followed by integrating all vertical cells across the boundary. River inputs were calculated directly by multiplying river discharge by POC concentration. As shown in Figure 13, the PRE continuously exchanges POC with adjacent coastal waters under the combined effects of river discharge and wind fields. Prior to August 20, river runoff was high, while winds were weak, oscillating between southwest and southeast (Figures S1a and S1b in Supporting Information S1). This resulted in substantial riverine POC to the PRE, with limited export to adjacent coastal waters. As cyclonic winds approached and passed from 21st to 27th Aug, river discharge increased again, continuously delivering more terrestrial POC into the PRE. However, these cyclonic winds simultaneously generated strong on-offshore currents (Figures S2b and S2c in Supporting Information S1), leading to a significant POC export from the western and southern boundaries to adjacent systems. Following the passage of the typhoon and prior to September 04, winds weakened and became highly variable, while river

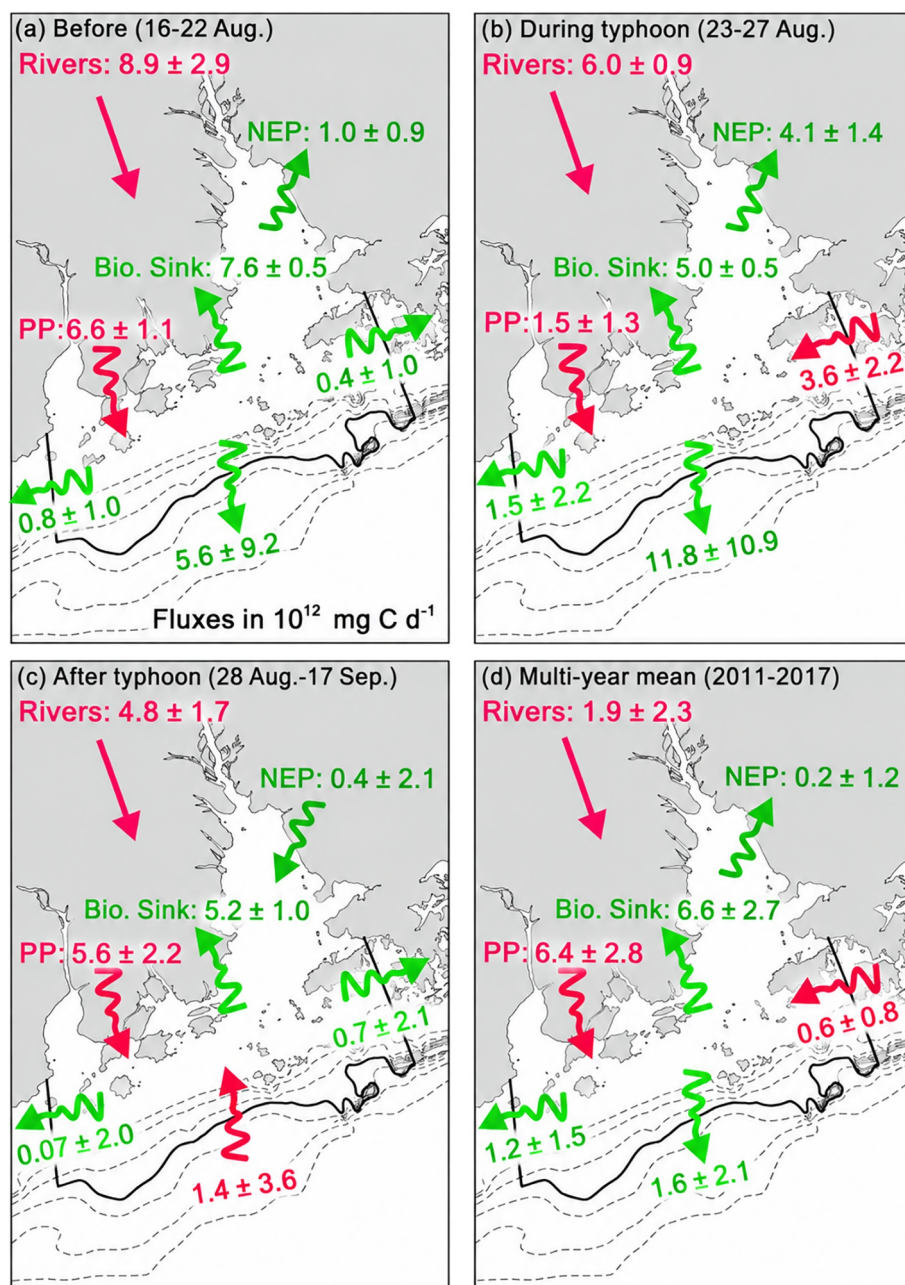


Figure 14. The averaged POC budget for the Pearl River Estuary and adjacent coastal ocean before (a), during (b) and after (c) the typhoons, as well as the 2011–2017 mean (d). Unit: $1 \times 10^{12} \text{ mg C d}^{-1}$. The exchange of POC between the inner analytical region and exterior NSCS was estimated using velocity and POC concentrations at each time step along the east, west and south boundaries (see Figure 1). Here, PP (primary production) includes both new and regenerated production, and the biological sink (BioSink) encompasses zooplankton excretion, remineralization of small and large detritus, sediment denitrification and remineralization. Red are positive values and green are negative. Net Ecosystem Production (NEP) was calculated as $\text{NEP} = \text{PP} - \text{Bio. Sink}$.

discharge decreased. Consequently, POC exchange at all three boundaries was greatly reduced. In the 2nd week after the typhoon (until September 11), river discharge increased once more. Under prevailing southwesterly winds, POC was exported from the southern boundary at the surface but imported in the lower layer, resulting in a net input of POC. Subsequently, after September 13, decreased river discharge and oscillating winds led to variable POC exchange between the PRE and adjacent systems.

Overall, during the simulation period, approximately $6.9 \pm 0.2 \times 10^{12}$ mg-C d⁻¹ of POC was exported from the PRE. The passage of a typhoon significantly enhances the export efficiency. From 23 to 27 Aug, the strong cyclonic winds resulted in a substantial export of POC at $-9.7 \pm 7.1 \times 10^{12}$ mg-C d⁻¹, representing a 46% increase compared to the pre-typhoon period and approximately 16.2 times the export during the post-typhoon period.

4. Discussions

In this study, we employed a coupled physical-biogeochemical model to investigate the transport and transformation of POC in the Pearl River Estuary. Recent model simulations have indicated that the PRE serves as a net source of atmospheric CO₂ on an annual basis (Liang et al., 2020). However, the role of typhoons in modulating the POC budget and their potential contributions to atmospheric CO₂ levels remain unexplored. In this section, we first evaluate the impact of typhoons on POC budgets (Figure 14) and their potential influence on sea-air CO₂ fluxes. We then discuss the advantages and limitations of the current modeling approach.

4.1. The Role of Typhoon in Modulating the POC Budget of the Pearl River Estuary

We first conducted a POC annual budget analysis for the entire simulation period from 2011 to 2017 (Figure 14d). The multi-year results indicate that the Pearl River delivers approximately $1.9 \pm 2.3 \times 10^{12}$ mg C d⁻¹ of POC to the PRE, whereas the amount fixed by photosynthesis is three times greater than the river input ($6.4 \pm 2.8 \times 10^{12}$ mg C d⁻¹). This finding is consistent with Guo et al. (2015), which suggests that POC in PRE is predominantly marine sourced. Approximately 80% of the POC input was lost through biological activities ($6.6 \pm 2.7 \times 10^{12}$ mg C d⁻¹), resulting in a small negative NEP of $-0.2 \pm 1.2 \times 10^{12}$ mg C d⁻¹. This result aligns with Liang et al. (2020), who estimated that the PRE acts as a potential weak source of atmospheric CO₂.

We next calculated the POC budget before, during and after the typhoon (Figures 14a–14c). Prior to Typhoon Hato, the PRE experienced a flooding event that resulted in a total input of $8.9 \pm 2.9 \times 10^{12}$ mg C d⁻¹ of POC from the river. Approximately 85% of this input was lost to both water column and sediment consumption ($-7.6 \pm 0.5 \times 10^{12}$ mg C d⁻¹). However, primary production could only partially compensate for the POC loss ($6.6 \pm 1.1 \times 10^{12}$ mg C d⁻¹), resulting in a significantly negative NEP that was approximately 5 times larger than the multi-year average ($-1.0 \pm 0.9 \times 10^{12}$ mg C d⁻¹).

During the passage of successive typhoons, heavy rainfall resulted in a significant pulse of POC ($6.0 \pm 0.9 \times 10^{12}$ mg C d⁻¹) into the PRE. However, intense hydrodynamic conditions and reduced light availability hindered nutrient utilization, leading to primary production of only 1/4 of the river input ($1.5 \pm 1.3 \times 10^{12}$ mg C d⁻¹). The total loss to the water column and sediment consumption accounted for 75% of both the river input and biological production ($-5.6 \pm 0.5 \times 10^{12}$ mg C d⁻¹), resulting in a stronger negative NEP three times greater than that of the pre-typhoon period ($-4.1 \pm 1.4 \times 10^{12}$ mg C d⁻¹). Additionally, strong cyclonic winds induced substantial export of POC, estimated at $-9.7 \pm 7.1 \times 10^{12}$ mg C d⁻¹, which was over 1.5 times greater than the river input. Overall, these processes resulted in a pronounced negative residual of $\sim -7.8 \times 10^{12}$ mg C d⁻¹, indicating that the system was experiencing a loss of POC.

Following the passage of the typhoon, as SSC and the hydrodynamic conditions in the PRE gradually stabilized, the influx of excess nutrients from the river stimulated rapid phytoplankton growth, resulting in primary production as high as $5.6 \pm 2.2 \times 10^{12}$ mg C d⁻¹, more than the amount of river input again ($4.8 \pm 1.7 \times 10^{12}$ mg C d⁻¹). In contrast, POC consumption, associated with water consumption and sediment loss, was about 93% of the biological production ($5.2 \pm 1.0 \times 10^{12}$ mg C d⁻¹). Consequently, the NEP shifted from negative to positive, reaching a value of $0.4 \pm 2.1 \times 10^{12}$ mg C d⁻¹. This suggests that the system has the potential to absorb CO₂ and transitioned from being a carbon source into carbon sink. Meanwhile, about 2.2×10^{12} mg C d⁻¹ POC was exported from the open boundaries, leading to a total residual of 5.8×10^{12} mg C d⁻¹. This indicates that the system is in the process of replenishing POC.

It is known that the PRE and the adjacent NSCS are located in a subtropical region frequently affected by tropical cyclones (TCs). The activity of typhoons has increased due to global warming, leading to numerous studies on their impact on water quality issues in this region, such as phytoplankton blooms, the dissolved carbon system, sediment dynamics, water age and hypoxia (Fang et al., 2022, 2025; Feng et al., 2022; Guo et al., 2026; Kuss et al., 2021; Li et al., 2025; Meng et al., 2024; Yu et al., 2022; Zhang et al., 2021; Zhao et al., 2021). These

investigations have revealed that: (a) typhoon induced flooding shortens the residence time in the PRE and flushes phytoplankton over short-time scales, whereas riverine and subsurface nutrient inputs subsequently fuel phytoplankton blooms in the nearby coastal waters (Feng et al., 2022); (b) typhoon can trigger a sequence of surface- $p\text{CO}_2$ responses, including an initial decrease from cooling, a subsequent increase due to vertical mixing, and a later decline driven by biological carbon uptake (Meng et al., 2024; Yu et al., 2020); (c) Successive typhoons, such as Hato and Pakhar, can enhance sediment resuspension and modify seaward sediment transport, even though hydrodynamic conditions return to normal quickly (Li et al., 2025); (d) typhoons may weaken strong up-estuary surge waves, thereby reducing exchange between estuarine and coastal waters and increasing depth-averaged water age (Zhang et al., 2021); and (e) typhoons can completely destroy hypoxia in the PRE when passing by the estuary, but would restore it within a week, as increased river discharge suppresses wind-driven turbulent mixing and stabilizes the water column (Zhao et al., 2021). Although organic type of carbon is highly associated with phytoplankton primary production and resuspended sediment, and exerts a substantial influence on surface $p\text{CO}_2$ levels and hypoxic conditions, the impact on organic carbon and the consequence are seldom investigated and assessed in this region comparing to other estuary and coastal oceans around the world (Asmala et al., 2021; Chen et al., 2024; Drupp et al., 2011; Hung et al., 2010; Lao et al., 2023a, 2023b; Lu et al., 2022; Osburn et al., 2019; Paerl et al., 2018; Zhou et al., 2021). To date, only Lao, Chen, et al. (2023) have investigated the mechanisms of organic matter decomposition and its composition following Typhoon Merbok (2017) in the northern South China Sea, utilizing multiple isotopic and geochemical tracers. They concluded that the decomposition of organic matter is primarily driven by POM, and that it occurs regardless of phytoplankton blooms, which is unfavorable for the preservation of organic matter in sediments. Our results indicate that the system underwent a POC discharge process during the passage of successive typhoons, consistent with their findings. Besides, we provide a quantitative measure of the relative contribution of individual physical and biological processes, which is difficult to know from stable-isotope analysis.

4.2 Model Caveats and Potential Improvements.

Although numerical methods have been widely applied to diagnose the impact of organic carbon dynamics within estuaries and coastal oceans, most of these studies have focused on normal weather conditions (Clark et al., 2020; Druon et al., 2010; Yao et al., 2024). Only Brown et al. (2014) investigated organic carbon transport in the Neuse River Estuary during and after Hurricane Irene. However, their study treated organic carbon as a conservative tracer, neglecting its transformation through biogeochemical processes, which likely overestimated the amount of organic carbon from the estuaries and underestimated the amount of CO_2 fluxes.

Although our nested modeling system effectively represents crucial physical and biogeochemical processes, several limitations remain in the current studies. For instance: (a) We found that the composition of POC within the PRE was a mixture of terrestrial and marine sources before the typhoons, but it shifted to terrestrial dominance during their passage. This was mainly because the model simulated the spatial distribution of POC and the inhibition of primary production. Further examination should be done by explicitly distinguishing terrestrial and marine POC using source-specific tracers in the model (Yu et al., 2020) or stable isotopes in observations (Lao, Chen, et al., 2023). Besides, our discussion here is limited to only one successive typhoon event, which was notably strong and made landfall to the left of PRE. Stable isotope studies have shown that the dynamics of POC and contribution to atmospheric CO_2 also depend on the strength and trajectory of typhoons (Chen et al., 2024, 2025). It would be worthwhile to investigate other typhoon cases with different characteristics in the future. (b) The model assumes that all organic matter settling to the bottom is fully denitrified and remineralized. However, this assumption overlooks the contribution of POC buried in bottom sediments, which has increased over the past 100 years (Dai et al., 2022). Therefore, it is essential to enhance the representation of sediment processes in future model development; (c) The model riverine material inputs, including inorganic nutrients (NO_3 and NH_4), organic nitrogen, and carbon are overly simplistic. For example, the concentrations of dissolved inorganic nutrients and organic nitrogen were prescribed using monthly observations from 2005 to 2006, while the simulations target typhoon events in 2017. Given the documented long-term trends in nutrient conditions in the PRE (Tao et al., 2021), these historical data are likely to underestimate actual riverine materials during 2017. Furthermore, all riverine material concentrations are represented as fixed monthly values, which overlook the well-known high variability facts at event scales. For example, a sudden increase in river runoff can substantially elevate riverine POC concentrations by mobilizing substantial amounts of soil- and wetland-derived organic carbon within a short-time (Asmala et al., 2021; Coynel et al., 2005; Dhillon & Inamdar, 2013). Therefore, these simplifications concerning riverine materials may introduce uncertainties in NEP, terrestrial POC inputs, and the simulated POC

concentrations. Lastly, Riverine DIC and TA were derived by averaging seasonal observations from four stations and applying the resulting values to all eight outlets. This approach neglects inter-tributary differences in carbonate endmembers and may bias local estimates of DIC, TA, and $p\text{CO}_2$, particularly in low-salinity regions such as the Western Four Outlets and Inner Lingding Bay during high-discharge periods. To address these deficiencies, establishing a contemporaneous high-frequency observational network to monitor riverine nutrients, organic matter, and carbon system observations would be beneficial, but it may be costly. A more feasible alternative would be to couple a process-based land ecosystem model, such as Dynamic Land Ecosystem Model (DLEM) (Tian et al., 2012), as has been done in the Chesapeake Bay and the Gulf of Mexico (Feng et al., 2015; Xue et al., 2016; Yao et al., 2021); (c) The existing physical model does not fully couple the wave model with the hydrodynamic-biogeochemistry model. Waves can affect the coastal carbon cycle through processes, such as Stokes drift, vertical mixing, breaking, and bubble formation. A recent study combining high spatiotemporal resolution satellite data and numerical models have demonstrated that bottom sediment resuspension caused by wave-induced bottom shear stress greatly elevates the lateral flux of POC from the estuary to the coastal ocean. Coupling the wave model and investigating its influence would be valuable in future research (Gu et al., 2021; Onink et al., 2019; Song et al., 2019; Zhang et al., 2026). However, improving the process-based model requires observational data to refine the model parameterization schemes and validate its outputs. We believe that a future observational system to autonomously monitor water-quality responses to land-derived materials and physical forcings associated with typhoon events in the PRE would be worthwhile.

5. Conclusions

In this study, we established a high-resolution, three-dimensional nested coupled atmosphere–ocean–biogeochemistry modeling system in the PRE and adjacent coastal oceans to investigate the spatiotemporal distribution, transport, and transformation of POC during the passage of the successive typhoons Hato and Pakhar in 2017. We also assessed how the passage of these typhoons potentially impacts the role of the PRE in modulating sea–air CO_2 fluxes. Our findings revealed that on an annual basis, PRE performed as a carbon source. However, the passage of strong typhoons Hato and Pakhar results in a POC discharge-recharge process, which may turn the PRE into a weak carbon sink.

Over the past decade, typhoon activity has intensified due to global warming (Balaguru et al., 2012, 2016; Li et al., 2024; Wang et al., 2022). The annual number of typhoons making landfall in and near the estuarine-coastal regions has also increased (IPCC, 2023; Seneviratne et al., 2012a, 2012b). We believe that our model provides a novel perspective on the dynamics of POC in the PRE. Adapting our modeling approach to other estuarine and coastal areas, such as the Chesapeake Bay, the Gulf of Mexico, and the Changjiang Estuary, would enhance our ability to estimate and understand land-to-ocean carbon cycling and transport under extreme weather conditions. Given the importance of POC to water quality issues, such as hypoxia and ocean acidification, we believe that our study would be beneficial for maintaining the ecological health of the estuaries and facilitating the development of more effective water quality management strategies.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The observational data used in this research are archived in Zenodo (Huang, 2026). The open-source COAWST modeling system used in this study is available from the U.S. Geological Survey (n.d.).

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