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# A numerical model study on the spatial and temporal variabilities of dissolved oxygen in Qinzhou Bay of the northern Beibu Gulf

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**Abstract**

Oxygen facilitates the breakdown of the organic material to provide energy for life. The concentration of dissolved oxygen (DO) in the water must exceed a certain threshold to support the normal metabolism of marine organisms. Located in the northern Beibu Gulf, Qinzhou Bay receives abundant freshwater and nutrients from several rivers which significantly influence the level of the dissolved oxygen. However, the spatial-temporal variations of DO as well as the associated driving mechanisms have been rarely studied through field observations. In this study, a three-dimensional coupled physical-biogeochemical model is used to investigate the spatial and seasonal variations of the DO and the associated driving mechanisms in Qinzhou Bay. The validation against observations indicates that the model can capture the seasonal and inter-annual variability of the DO concentration with the range of 5–10 mg/L. Sensitivity experiments show that the river discharges, winds and tides play crucial roles in the seasonal variability of the DO by changing the vertical mixing and stratification of the water column and the circulation pattern. In winter, the tide and wind forces have strong effects on the DO distribution by enhancing the vertical mixing, especially near the bay mouth. In summer, the river discharges play a dominant role in the DO distribution by inhibiting the vertical water exchange and delivering more nutrients to the Bay, which increases the DO depletion and results in lower DO on the bottom of the estuary salt wedge. These findings can contribute to the preservation and management of the coastal environment in the northern Beibu Gulf.

**Key words:** river plume, dissolved oxygen, stratification, physical-biological model

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## 1 Introduction

With the fast development of urban areas, the population growth rapidly, resulting in large emissions of various pollutants in estuaries (Bennett et al., 2001; Boyer and Howarth, 2008). The nutrient inputs such as nitrogen and phosphorus caused estuarine eutrophication, bottom water hypoxia (dissolved oxygen concentration (DO) $< 2$ mg/L), degradation of water quality, and harmful algal blooms (Diaz and Rosenberg, 2008; Visser et al., 2005). The habitat degradation and unbalance of ecosystems resulting from human activities have posed a threat to sustainable development in coastal areas. In particular, the DO has been declining in the world's estuarine and coastal waters for the past few decades, due to the increase in global temperatures and nutrients discharged (Breitburg et al., 2018; Diaz and Rosenberg, 2008). It is thus important to understand the temporal and spatial variability of DO in estuaries as well as the associated dynamical mechanisms (Yu et al., 2015b).

The distribution of DO is modulated by both variable physical processes and biological responses over different time scales, such as on the Baltic Sea, the Zhujiang (Pearl) River Estuary and the Changjiang River Estuary (Carstensen et al., 2014; Li et al., 2021; Zhang et al., 2018). Li et al. (2020) investigated that tide-induced mixing plays a critical role in the DO budget due to the biophysical responses to the spring-neap tide cycle. The seasonal variability of DO is usually related to the development of hypoxia in the coastal ocean, where water ventilation is not able to resupply the amount of oxygen consumed by organic matter (Capet et al., 2013). Previous studies have shown that the hypoxic extent increased because of rising anthropogenic nutrient inputs from the watershed (Obenour et al., 2013). The statistical regression models showed that the nitrogen load could explain 24% of the variability in the observed hypoxic areas over the Texas-

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Louisiana continental shelf (Forrest et al., 2011). Bianchi et al. (2010) suggested that the hypoxic area had a similar correlation with either nutrient loading or river flow because of the high correlation between nutrient loading and river discharge. Therefore, it is very important to evaluate the role of river discharge on the variability of dissolved oxygen.

Located in the northwestern Beibu Gulf, Qinzhou Bay is an important estuary with extraordinary ecological and economic values by providing a habitat for the Chinese white dolphin, shellfish, and mangroves (Jiang et al., 2020; Lu et al., 2020; Pan et al., 2021a). Like many other estuaries in the world, the ecosystem of Qinzhou Bay has also been influenced by natural and human activities (Wang et al., 2021a; Zhang et al., 2019a). Field investigations on nutrients, chlorophyll, and DO show that eutrophication is a growing problem in Qinzhou Bay in recent decades (Lao et al., 2020; Lu et al., 2020; Yang et al., 2015, 2019; Zhang et al., 2019a). The water is in a phosphorus-limited state in Qinzhou Bay because of a higher nitrogen-to-phosphorus ratio than the Redfield value in most years (Yang et al., 2015). In addition, previous studies suggested that meteorological factors play an important role in the seasonal variability of nutrients in Qinzhou Bay (Zhang et al., 2019a). The annual runoff and aquaculture result in the decreasing distribution of nutrient concentration from the inner bay to the outer bay (Lan, 2011; Yang et al., 2015). Numerical models have been used to study variations of pollutants and nutrients in Qinzhou Bay (Chen et al., 2017; Wang et al., 2014, 2021a). More recently, Pan et al. (2021b) analyzed the spatial and temporal distributions of ecological variables and the nutrient budget in the Beibu Gulf using a coupled hydrodynamic-biological model. However, the spatial-temporal variability of DO and how it is determined by the interaction of winds, runoff and tidal mixing has never been explored in Qinzhou Bay.

Utilizing a coupled hydrodynamic and ecosystem model Regional Ocean Modeling System (ROMS), this study aims to investigate spatial and temporal variability of chlorophyll, nutrients and DO in Qinzhou Bay from 2010 to 2019. The rest of this paper is organized as follows. The observational data and model setup are described in Section 2. Validation of the model and analysis are presented in Section 3, followed by a discussion in Section 4. Conclusions are given in Section 5.

## 2 Materials and methods

### 2.1 *Field observations and satellite data*

*In situ* hydrodynamics, nutrients, and satellite surface chlorophyll data are utilized to validate the model. Tidal elevation data (Fig. 1b) are from a tide gauge located at Qinzhougang Port. The spring-neap tidal currents at the C1 station (Fig. 1b) are from two stationary vessels (Yang et al., 2019). Monthly nutrient data are from field cruises between May 2017 and April 2018 in the inner bay (Zhang et al., 2019a). The monthly mean surface chlorophyll concentrations from 2010–2019 are extracted from MODIS (https://oceancolor.gsfc.nasa.gov/l3/order/). The climatological monthly chlorophyll is used to describe chlorophyll variation in the study area. In addition, the temperature-salinity and DO were collected from 2011–2018 at twenty-four stations (Zhang, 2020), and the mean values in the inner and the outer bay are used to assess the model's performance in capturing the physical and biological processes (Fig. 1b).

### 2.2 *Numerical model*

A coupled physical-biological model is used to study the relative contribution of river discharge and oceanic dynamics to the seasonal variability of dissolved oxygen in Qinzhou Bay and the adjacent sea areas. The physical model is based on the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005), which has been set up for the sediments simulation of the Beibu Gulf by Cheng et al. (2017). Our model domain covers the northern Beibu Gulf and the entire Qinzhou Bay (Fig.1a). An orthogonal curvilinear coordinate system is designed to follow the coastline. The model domain is set up with 583 × 532 horizontal grid cells with a resolution of 0.1–2 km in the horizon and 10 vertical terrain-following s-levels, with high resolution near the surface and bottom to accurately resolve the surface and bottom boundary layers. The tidal water level and depth-averaged tidal velocity for the model are obtained from the Oregon State Tidal Prediction Software TPXO8, including 8 tidal constituents of $P_1$, $Q_1$, $O_1$, $K_1$, $M_2$, $S_2$, $N_2$, and $K_2$. The open boundary conditions for the temperature, salinity and baroclinic current are radiation conditions. The temperature and salinity are derived from the monthly Hybrid Coordinate Ocean Model (HYCOM) model outputs (http://hycom.org/hycom). Atmospheric pressure and wind forcing are derived from monthly data provided by the ERA5 (Fifth Generation ECMWF Atmospheric Reanalysis). The climatological monthly freshwater discharges from the Maoling, Qinjiang, Dafeng and Nanliu rivers are used the same as those of Gao et al. (2013). We initially assume that the statistical distribution of the river force is adequate for our domain because the seasonal cycle of DO is more sensitive to the

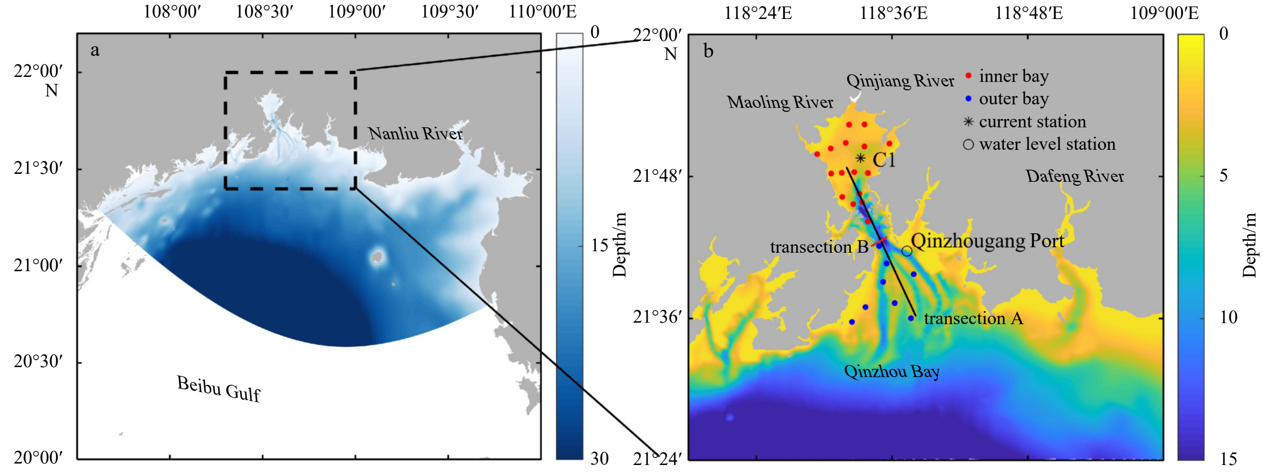

**Fig. 1.** The model domain (a) and the locations of observation stations (b).

variations in river discharge at longer time scales (Scully, 2013). Then, the climatological monthly discharges during 2012–2017 are multiplied by some factors (Table 1), which are the annual runoff ratios between time series and climatological data (Chen and Lin, 2020).

The pelagic nitrogen cycle model of Fennel et al. (2006) is coupled with the physical model and has been extended to include phosphate (Laurent et al., 2012). The model contains 13 state variables, including nitrate ($NO_3^-$), ammonium ($NH_4^+$), phosphate ($PO_4^{3-}$), chlorophyll (Chl), phytoplankton (Phy), zooplankton (Zoo), two forms of small detritus (Sdetritus C and Sdetritus N), two forms of large detritus (Ldetritus C and Ldetritus N), oxygen (Oxyg), total inorganic carbon (TIC), and total alkalinity (TALK). The detailed model feature was described in the Supplement to Laurent et al. (2017). The Fennel model has been successfully applied to study the spatial and temporal variability of nutrients and hypoxia in the Gulf of Mexico and Changjiang River Estuary (Fennel and Laurent, 2018; Zhang et al., 2019b). Most of the parameters used in our study are based on the values in Laurent et al. (2017), with slight adjustments according to previous experimental results (Xu et al., 2020; Zhang et al., 2020). The initial value and boundary conditions for nutrients and dissolved oxygen are derived from the World Ocean Atlas 2013 climatology (WOA13), while those for chlorophyll are from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data using a vertical extrapolation parameterization by Morel and Berthon (1989). The phytoplankton, zooplankton, and detritus are also from the SeaWiFS data, and the ratio of chlorophyll concentration in Liu et al. (2010) is adopted. The seasonal chlorophyll concentration and monthly nutrient concentrations in rivers are obtained from the published data (Lu et al., 2020; Zhang et al., 2019a). The model runs for 11-year simulation from 1 January 2009 to 31 December 2019, and the daily output data from the last 10 years is used in this research.

**Table 1.** The multiplying factors of monthly discharge for different rivers during 2012–2017

| Year | Maoling River | Qinjiang River | Dafeng River | Nanliu River |
|---|---|---|---|---|
| 2012 | 1.17 | 0.67 | 0.36 | 0.71 |
| 2013 | 2.92 | 1.65 | 1.67 | 1.75 |
| 2014 | 0.86 | 0.72 | 0.86 | 0.97 |
| 2015 | 2.16 | 0.56 | 1.30 | 1.12 |
| 2016 | 0.97 | 1.10 | 1.20 | 1.17 |
| 2017 | 0.94 | 1.02 | 1.52 | 1.72 |

## 3 Variability of surface chlorophyll, salinity, temperature, DO and nutrients

### 3.1 *Model validation against observations*

The simulated water level and velocity are compared with the observations (Fig. 2). The simulated water level is highly consistent with the observations between April and May 2011 in Qinzhougang Port (Fig. 2a). The simulated velocity and direction are also very close to the observations (Figs 2b and c). In addition, we calculate the Root Mean Square Error (rmse) and correlation coefficient (*r*). For water level and velocity, the results of statistics show small rmse and large *r* values. These results demonstrate our model has good performance in capturing the hydrodynamic characteristics. As a result, using our model to diagnose how multiple physical processes impact the DO field is reliable. The comparison between the simulated monthly chlorophyll and the climatological monthly chlorophyll from MODIS shows a good agreement with each other (Fig. 3a), with the correlation coefficient as high as 0.67 (Fig. 3b). Moreover, the model captures well the mean monthly of surface $PO_4^{3-}$, $NO_3^-$, and $NH_4^+$ ($r$ = 0.59, 0.77, 0.85) in the inner bay, with higher concentration in spring (Figs 4a–c). For the surface DO ($r$ = 0.85), both model results and observations show a seasonal variation with higher concentration in winter and lower value in summer (Fig. 4d), but the value is underestimated by the model compared to observed data in winter. Furthermore, the observational data in the outer bay (not published) show bottom DO is close to 6 mg/L in summer and 8 mg/L in winter. Similarly, our model results show the bottom DO is between 6 mg/L and 8 mg/L.

### 3.2 *Seasonal and interannual variability of surface chlorophyll, salinity, temperature and DO*

We compare the modeled monthly mean surface chlorophyll concentrations with MODIS data from 2010 to 2019 (Fig. 5). The model reproduced reasonably the seasonal and inter-annual variations of the chlorophyll, which is persistently high during warm months and low during cold months. These results show a similarity to the temporal variability of chlorophyll concentration at the shallow water zone in the northern South China Sea,

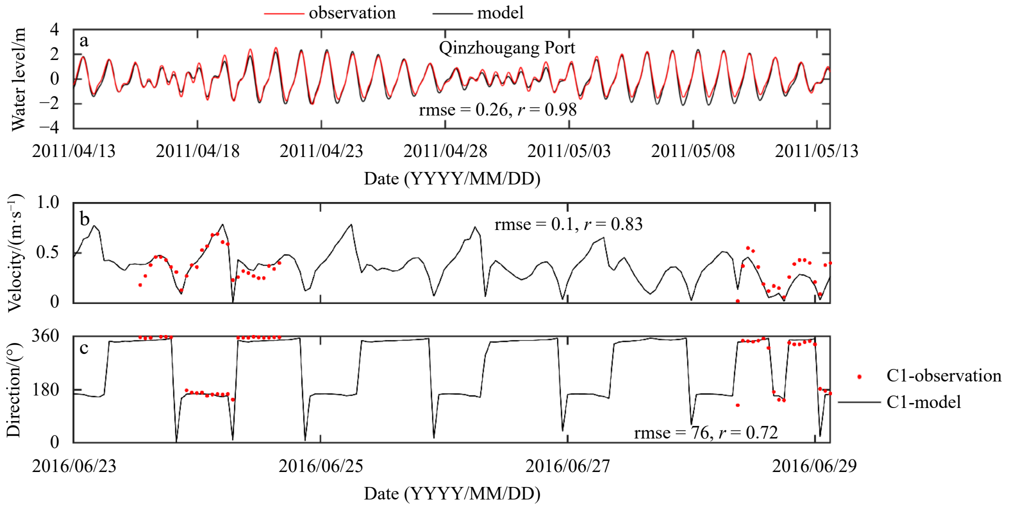

**Fig. 2.** The observed and simulated water level at Qinzhougang Port (a), velocity (b) and direction (c) at Station C1.

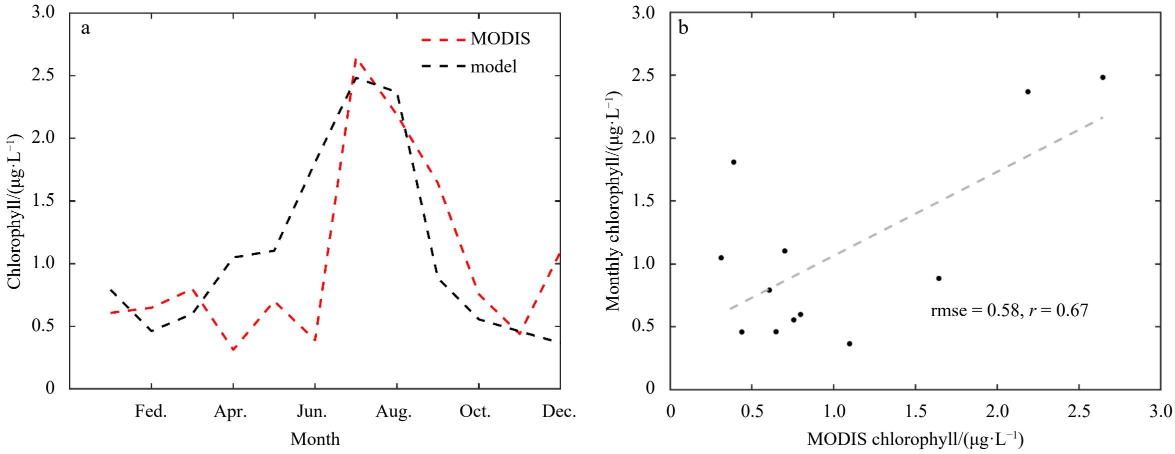

**Fig. 3.** The seasonal variation (a) and scatter plot of the monthly chlorophyll concentration (b) from MODIS and model simulation.

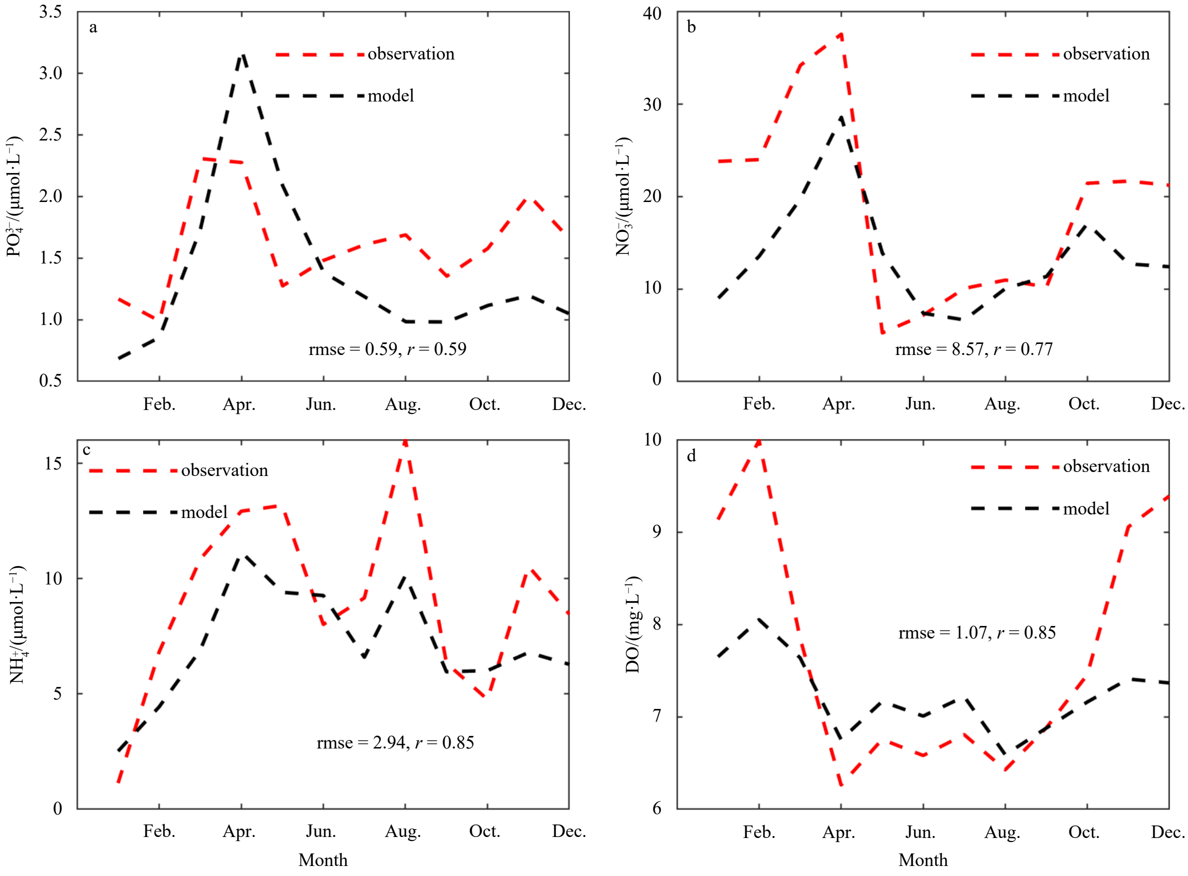

**Fig. 4.** The observed and simulated the mean monthly of surface $PO_4^{3-}$ (a), $NO_3^-$ (b), $NH_4^+$ (c) and DO (d) concentrations in the inner bay (as indicated in Fig. 1b).

which was affected by the seasonal variations of riverine nutrients and air temperature (Ma et al., 2013). The correlation coefficient ($r = 0.37$) is not as good as for the climatological results (Fig. 3). The significant discrepancy between the model results and observations could be attributed to various factors, including oversimplification of river inputs.

Both the observed and modeled monthly mean surface salinity, temperature, and DO in the inner bay show strong seasonal cycles with low (high) values in summer (winter) (Fig. 6). In addition, the modeled DO shows very low values in summer during 2013 and 2015, probably due to the larger river outflow (Fig. 6a, Table 1). Similar results are observed in the outer bay (Fig. 7) with higher salinity values (Fig. 7a). The model simulates well the observed patterns of the surface salinity, temperature, and DO, although underestimates the observed values to some extent. For salinity, the reason for the small correlation coefficients ($r = 0.22$, 0.19) may be the temporal mismatch between monthly mean modeling results and daily sampling data. The model performance for DO in the inner bay ($r = 0.35$) is not as good as in the outer bay ($r = 0.52$). The pollutants from the coast may contribute to this difference because of our model without the impacts of wastewater (Wang et al., 2021a).

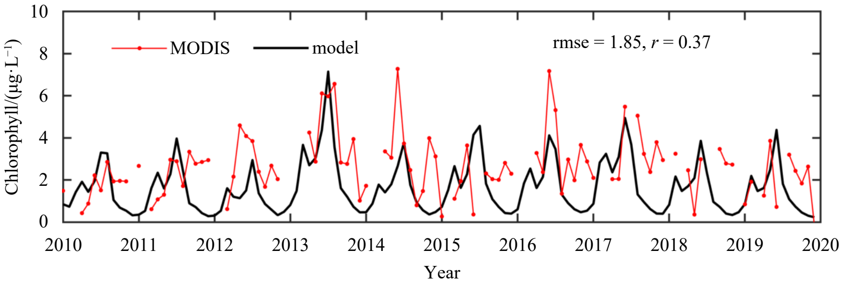

**Fig. 5.** The monthly chlorophyll concentration from MODIS and model simulation from 2010 to 2019.

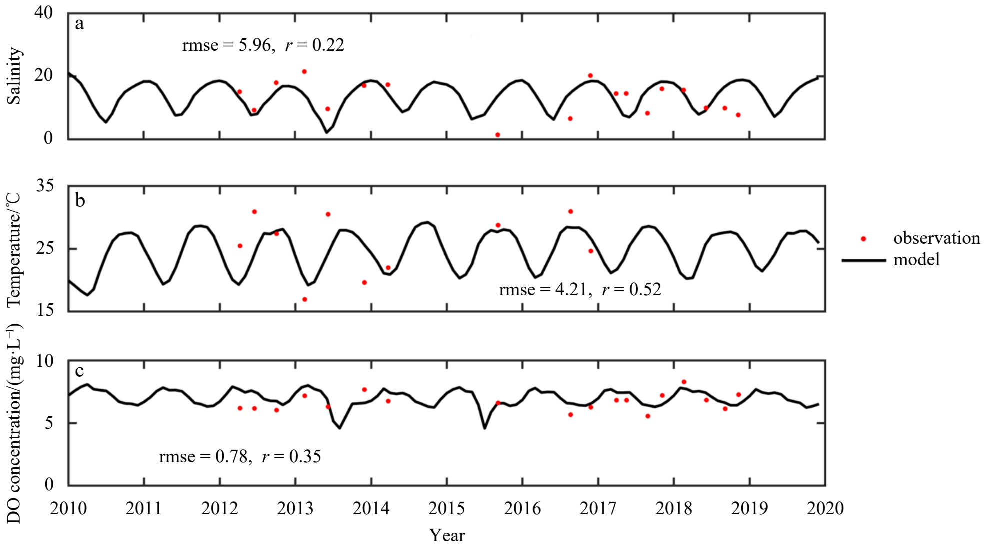

**Fig. 6.** The observed and simulated monthly mean surface salinity (a), surface temperature (b), and DO concentration (c) in the inner bay from 2010 to 2019.

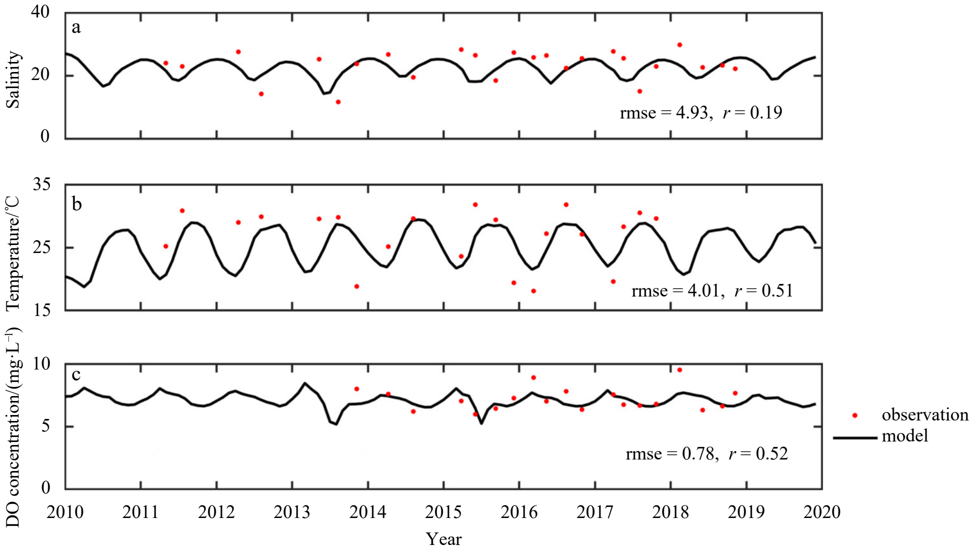

**Fig. 7.** The observed and simulated monthly mean surface salinity (a), surface temperature (b), and DO concentration (c) in the outer bay from 2010 to 2019.

### 3.3 *The seasonal variability of salinity, DO and nutrients on the transections*

Figure 8 shows the monthly mean salinity and DO along transection A, which display the strong seasonal variations. In winter, the river discharge mainly influences salinity and DO within the inner bay (Figs 8a and b). A larger DO horizontal gradient arises in the inner bay while a uniform DO distribution exists in the outer bay (Fig. 8b). In summer, the river plume spreads to the outer bay with lower surface salinity (Fig. 8c). A lower DO value occurs at the bottom of the outer bay (Fig. 8d) because the stratified wa-

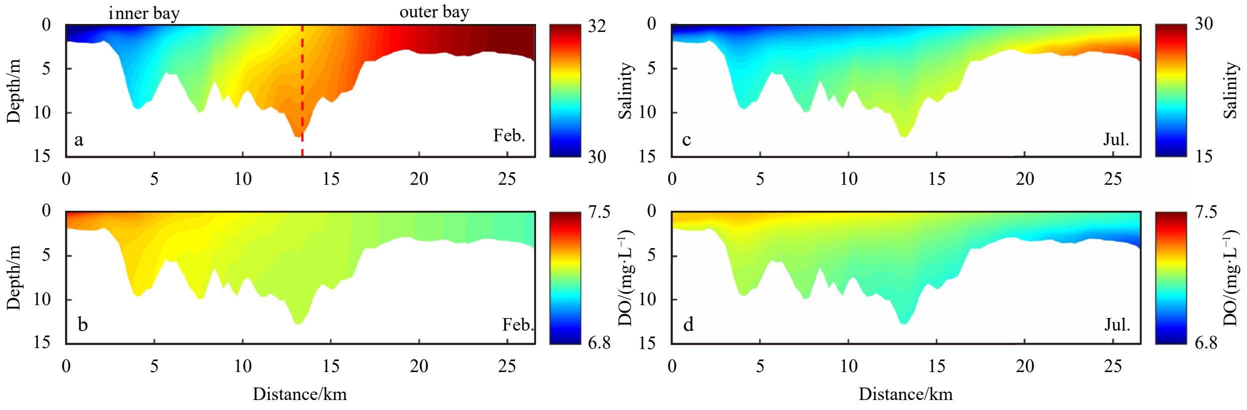

**Fig. 8.** The monthly mean salinity (a, c) and DO concentration (b, d) in winter (February, left panels) and summer (July, right panels) along transection A (as indicated in Fig. 1b). The red dotted line shows the location of transection B shown in Fig. 10.

ter column inhibits the DO vertical exchange between the river plume and seawater. The riverine water transports more nutrients seaward and stimulates the phytoplankton growth, which is converted to oxygen-consuming materials after dying. In general, the simulated distributions of DO show a decrease from the inner bay to the outer bay (Figs 8b and d).

Nutrient concentrations are higher in the inner bay and lower in the outer bay (Fig. 9). Larger monthly mean $NH_4^+$, $NO_3^-$ and $PO_4^{3-}$ arise in the inner bay during winter due to smaller river discharge (Figs 9a, b and c). In the outer bay, these nutrient concentrations are low and vertically uniform due to the enhanced mixing in the water column during winter. In summer, the monthly mean $NH_4^+$, $NO_3^-$ and $PO_4^{3-}$ show an intense vertical gradient in both the inner and outer bay which is affected by river plumes (Figs 9d, e and f). In addition, lower $NH_4^+$, $NO_3^-$ and $PO_4^{3-}$ are found in the bottom of the outer bay during summer.

Figure 10 shows the vertical distribution of salinity and DO along transection B. For both the monthly mean salinity and DO, stronger stratification is seen in summer (Figs 10c and d) than in winter (Figs 10a and b), probably due to the larger river discharge in summer. For the monthly mean $NH_4^+$, $NO_3^-$ and $PO_4^{3-}$ along transection B, similar vertical distributions are found in winter and summer (not shown).

## 4 Discussions

Hypoxia has been widely reported in estuaries and shelf regions due to water eutrophication and changes in physical forcing (Breitburg et al., 2018; Li et al., 2021; Scully, 2013; Zhang et al., 2018). In Qinzhou Bay, the observed data showed that oxygen concentrations larger than 5 mg/L in the inner bay responded to moderate enrichment (Lu et al., 2021; Zhang et al., 2019a). Zhang et al. (2019a) suggested that the nutrients mainly came from rivers, and were affected by precipitation, temperature, and high irradiation. Wang et al. (2021b) suggested that submarine groundwater discharge played an important role in dissolved inorganic nutrient sources. Moreover, Kaiser et al. (2013) found that the tidal currents dispersed land-derived nutrients offshore into Beibu Gulf, leading to low concentrations near the estuary.

The seasonal fluctuations and heterogeneously spatial distributions may complicate the monitoring of DO, leading to contradictory conclusions when interpreting data from different sources (Capet et al., 2013). The numerical models are important complements that help understand the important factors caus-

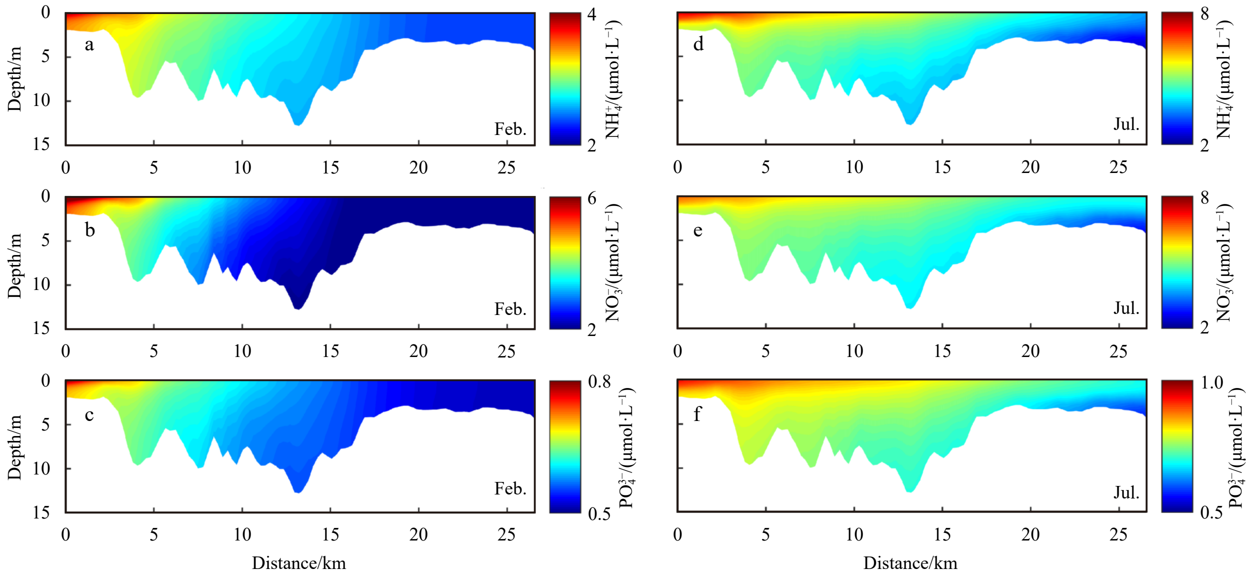

**Fig. 9.** The monthly mean concentrations of $NH_4^+$ (a, d), $NO_3^-$ (b, e), and $PO_4^{3-}$ (c, f) in winter (February, left panels) and summer (July, right panels) along transection A (as indicated in Fig. 1b).

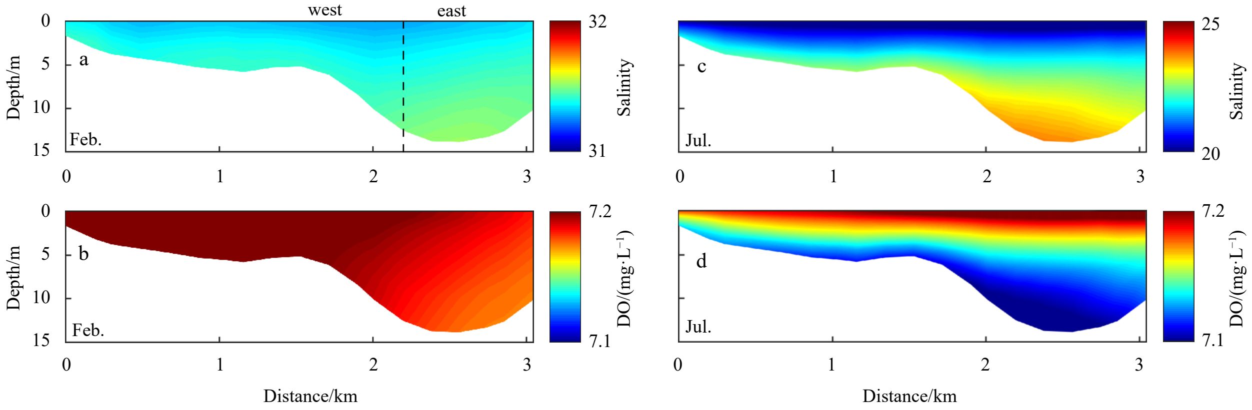

**Fig. 10.** The monthly mean salinity (a, c) and DO concentration (b, d) in winter (February, left panels) and summer (July, right panels) along transection B (as indicated in Fig. 1b). The black dotted line shows the location of transaction A shown in Figs 8 and 9.

ing the variability of DO (Fennel et al., 2013; Fennel and Laurent, 2018; Laurent et al., 2017; Yu et al., 2015b). Although our model underestimates DO in winter (Fig. 4d), the results show that DO is sensitive to temporal changes in river discharge (Figs 6c and 7c). Because of the uncertainty in estimating groundwater discharge and surface runoff along the shoreline, it is usually difficult to obtain an accurate river discharge (Du et al., 2019). To examine the influence of river discharge, wind and tide on DO distribution, we used the monthly nutrient concentrations, climatological monthly freshwater discharge, tide and wind to force the model as a control run (denoted as CTRL). In contrast, another four sensitivity experiments (Table 2) were carried out to demonstrate how each factor contributes to the DO distribution in Qinzhou Bay. Each experiment was conducted for one year, and the monthly averaged outputs were analyzed.

### 4.1 *The impact of river discharges on DO distribution*

The river nutrient concentration and stratification play substantial and comparable roles in the interannual variability of hypoxia (Obenour et al., 2012). The impact of river discharge on the seasonal variability of DO had already been discussed by Scully (2013), who found that the increases in river discharge led to an increase in hypoxic volumes, independent from the associated biological response to higher nutrient delivery. The joint effect of river plume and shelf benthic waters results in a notable pycnocline, which weakens the mixing over the water column. The stratification induced by river discharge can form a physical bound that affects the organic matter inputs and respiratory oxygen consumption and inhibits the DO diffusion from river plumes (Cui et al., 2019; Hetland and DiMarco, 2008). The DO may reduce as a result of stratification and oxygen consumption (Yu et al., 2015a).

**Table 2.** List of experiment parameters

| Experiment | Nutrient | River discharge | Tide | Wind |
|---|---|---|---|---|
| CTRL | 100% | 100% | Yes | Yes |
| 0.6RD | 100% | 60% | Yes | Yes |
| 1.5RD | 100% | 150% | Yes | Yes |
| Notide | 100% | 100% | No | Yes |
| Nowind | 100% | 100% | Yes | No |

To examine the impact of variable river discharges on DO distribution in Qinzhou Bay, we carried out a set of sensitivity experiments with different riverine inputs (Table 2) while preserving the nutrient loading, and compared the difference with the control experiment. During winter, the effects of river discharge mainly appear in the inner bay (Figs 11a and b). As the river discharge varies, the oxygen concentrations reduce with lower discharge (Fig. 11a) and increase with higher discharge (Fig. 11b). During summer, the river discharge mainly causes the variability of bottom dissolved oxygen (Figs 11c and d). The oxygen concentration in the water column below 5 m increases by about 0.15 mg/L with lower discharge (Fig. 11c), whereas it reduces by more than 0.05 mg/L with higher discharge (Fig. 11d).

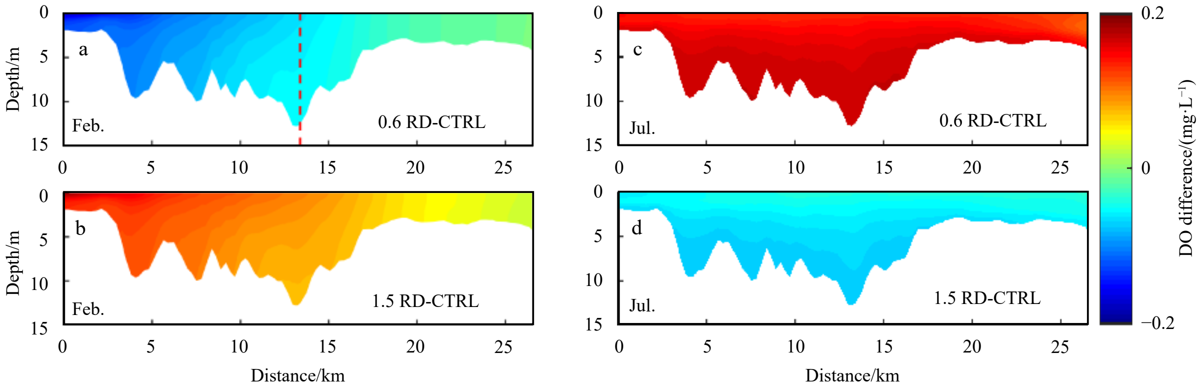

**Fig. 11.** The differences of DO concentration against the control experiment for the sensitivity experiments 0.6 RD-CTRL (a, c) and 1.5 RD-CTRL (b, d) in winter (February, left panels) and summer (July, right panels) along transection A (as indicated in Fig. 1b).

These results suggest that the higher river discharge could be the reason for the lower DO in the summer of 2013 and 2015 (Fig. 6c). Particularly, the variation of DO in the inner bay is more sensitive to the increase in river discharge and nutrient loading. Scully (2013) suggested that increases in river discharge lead to an increase in stratification and nutrient delivery, both of which tend to decrease the DO below the pycnocline. On the opposite, a reduction in river discharge means a decrease in stratification and nutrient delivery, both of which tend to increase the DO below the pycnocline. Our results followed these mechanisms in summer, but not in winter. This is possible due to the advective fluxes associated with the discharge variations. The DO increase is limited at low discharge because of decreased advective fluxes.

### 4.2 *The impacts of tides and winds on DO distribution*

The tidally induced and wind-driven circulation can modulate the mixing and stratification (Li et al., 2020). To evaluate the role of tide and wind in the seasonal variation of DO, two sensitivity experiments including no tide (Notide) and no wind (Nowind) were carried out. During winter, the results from the CTRL-Notide experiment indicate that the tidal forcing reduces (increases) the surface (subsurface) DO in the inner bay, while it reduces DO in the whole water column in the outer bay (Fig. 12a). During summer, the tidal forcing reduces (increases) DO in the upper (bottom) water in both the inner and outer bays (Fig. 12c). Compared with the effect of river discharge (Fig. 11), the tide forcing leads to a unified vertical distribution of DO by enhancing the vertical mixing of seawater, especially in summer when the stratification is stronger (Fig.12c). The seasonal variation of winds strongly influences the seasonal cycle of water exchange, and the varying wind-driven circulation interacts with the plume to jointly regulate the transport of nutrients and detritus, water vertical mixing, and residence time (Li et al., 2021). The results from the CTRL-Nowind experiment indicate that winds enhance DO in the whole water column in winter, especially in the outer bay (Fig. 12b); during summer, DO increases in the upper water in the inner bay while it reduces in the bottom water in the outer bay, which could be caused by the wind-driven currents that restrict the seaward advection of DO (Fig. 12d).

Feng et al. (2014) suggested that winds influence hypoxic by changing the vertical and horizontal distributions of the low salinity and the high chlorophyll water on the shelf. The upwelling-favorable winds reduce stratification in nearshore regions and enhance the mixing of the water column (Yu et al., 2015a). The wind speed and direction in Qinzhou Bay have pronounced seasonal variability, i.e., northerly (southerly) with a higher (lower) speed in winter (summer). To further examine the respective effects of winds, we investigate the seasonal change in currents induced by winds (Fig. 13). During winter, the wind-driven currents are seaward dominant at the surface (Fig. 13a) and east-northward dominant at the bottom (Fig. 13b) in the outer bay, which is favorable to the seaward transport of DO (Fig. 12b). In inner bay, the wind-driven currents is weaker and has a smaller effect on DO (Fig. 12b). During summer, the wind-driven currents are landward dominant at the surface (Fig. 13c) and westward dominate at the bottom (Fig. 13d), which inhibits the seaward transport of DO (Fig. 12b).

## 5 Conclusions

In this study, a numerical model is used to investigate the spatial and seasonal variabilities of dissolved oxygen in Qinzhou Bay, as well as the key dynamic processes. The model captures well the main features and seasonal variation of surface nutrients but underestimates dissolved oxygen during winter due to the complex physical processes. Comparisons with MODIS data demonstrate that high chlorophyll concentrations in Qinzhou Bay persist during the warm season, while the concentrations are low during the cold season. During summer, the river plumes induce strong stratification which inhibits DO vertical exchange and thus leads to lower DO in the bottom of the outer bay. In contrast, the tide forcing enhances the mixing of seawater and thus leads to higher DO in the bottom of both the inner and outer bay during summer. Furthermore, the enhancement of mixing induced by winds, the wind-driven currents are favorable to the offshore transport of DO in winter while they inhibit it in summer, leading to higher (lower) DO in the outer (inner) bay in winter and higher (lower) DO in the inner (outer) bay in summer. In this paper, however, the relative importance of nitrogen and phosphorus on the variability of DO and the effect of nutrient enrichment on the long-term evolution of DO are not examined yet due to the lack of observations. Therefore, further research on these issues, including conducting more field monitoring and numerical modeling for Qinzhou Bay, is necessary. This will be our focus for future work.

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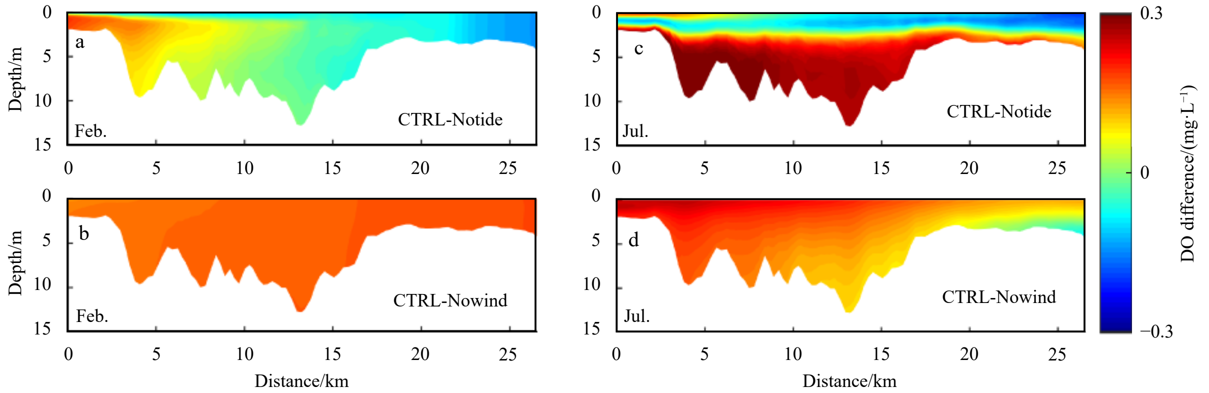

**Fig. 12.** The differences of DO concentration against the control experiment for the sensitivity experiments CTRL-Notide (a, c) and CTRL-Nowind (b, d) in winter (February, left panels) and summer (July, right panels) along transection A (as indicated in Fig. 1b).

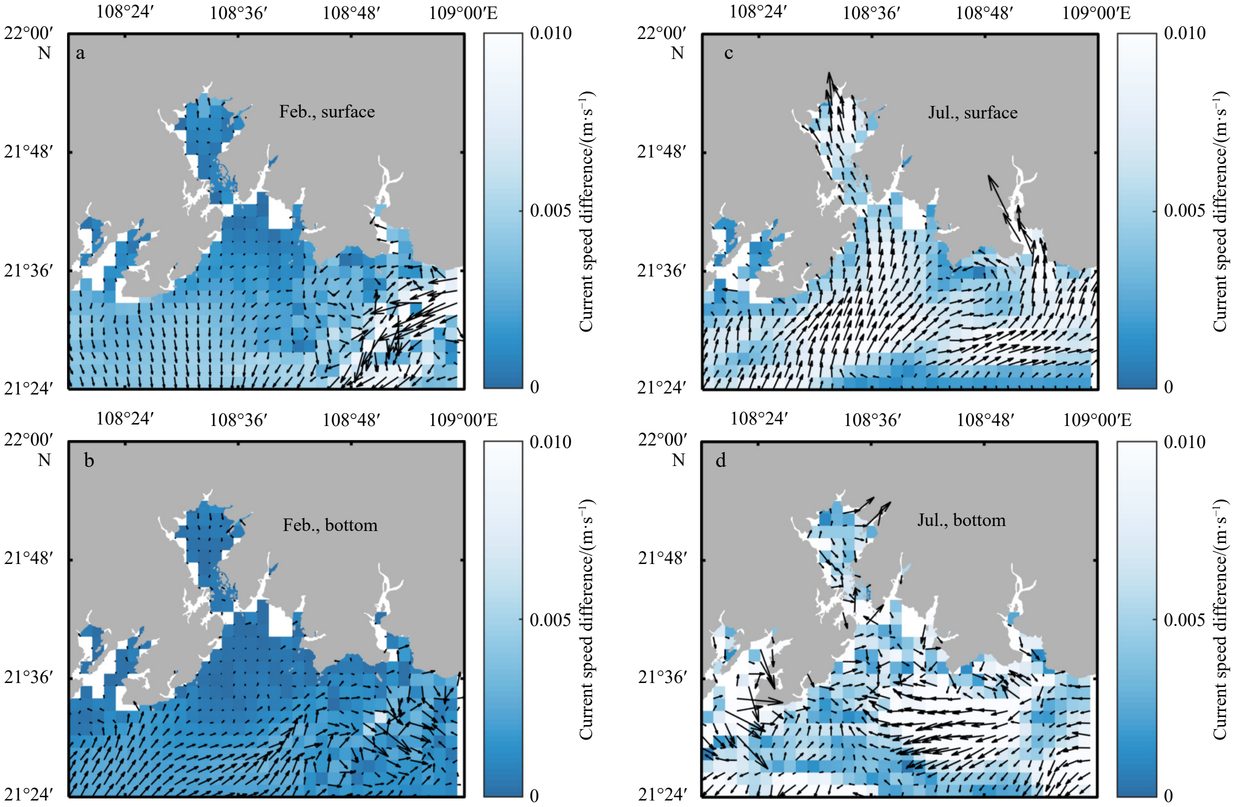

**Fig. 13.** The differences of the monthly mean surface (a, c) and bottom (b, d) currents against the control experiment for the sensitivity experiment in winter (February, left panels) and summer (July, right panels).

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## References

Bennett E M, Carpenter S R, Caraco N F. 2001. Human impact on erodable phosphorus and eutrophication: a global perspective: increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. BioScience, 51(3): 227–234, doi: 10.1641/0006-3568(2001)051[0227:HIOEPA]2.0.CO;2

Bianchi T S, DiMarco S F, Cowan J H, et al. 2010. The science of hypoxia in the Northern Gulf of Mexico: A review. Science of The Total Environment, 408(7): 1471–1484, doi: 10.1016/j.scitotenv.2009.11.047

Boyer E W, Howarth R W. 2008. Nitrogen fluxes from rivers to the coastal oceans. In: Capone D G, Bronk D A, Mulholland M R, et al, eds. Nitrogen in the Marine Environment. 2nd ed. New York: Elsevier, 1565–1587

Breitburg D, Levin L A, Oschlies A, et al. 2018. Declining oxygen in the global ocean and coastal waters. Science, 359(6371): eaam7240, doi: 10.1126/science.aam7240

Capet A, Beckers J M, Grégoire M. 2013. Drivers, mechanisms and long-term variability of seasonal hypoxia on the Black Sea northwestern shelf—is there any recovery after eutrophication?. Biogeosciences, 10(6): 3943–3962

Carstensen J, Andersen J H, Gustafsson B G, et al. 2014. Deoxygenation of the Baltic Sea during the last century. Proceedings of the National Academy of Sciences of the United States of America, 111(15): 5628–5633

Chen Xiaofeng, Lin Lisu. 2020. The variation of rivers pollutant flux and influencing factors in Guangxi Beibu Gulf. Science & Technology Information (in Chinese), 18(14): 62–67

Chen Zhenhua, Xia Changshui, Qiao Fangli. 2017. Numerical simulation of water exchange in the Qinzhou Bay of China. Haiyang Xuebao (in Chinese), 39(3): 14–23

Cheng Gaolei, Gong Wenping, Wang Yaping, et al. 2017. Modeling the circulation and sediment transport in the Beibu Gulf. Acta Oceanologica Sinica, 36(4): 21–30, doi: 10.1007/s13131-017-1012-4

Cui Yongsheng, Wu Jiaxue, Ren Jie, et al. 2019. Physical dynamics structures and oxygen budget of summer hypoxia in the Pearl River Estuary. Limnology and Oceanography, 64(1): 131–148, doi: 10.1002/lno.11025

Diaz R J, Rosenberg R. 2008. Spreading dead zones and consequences for marine ecosystems. Science, 321(5891): 926–929, doi: 10.1126/science.1156401

Du Jiabi, Park K, Dellapenna T M, et al. 2019. Dramatic hydrodynamic and sedimentary responses in Galveston Bay and adjacent inner shelf to Hurricane Harvey. Science of The Total Environment, 653: 554–564, doi: 10.1016/j.scitotenv.2018.10.403

Feng Yang, Fennel K, Jackson G A, et al. 2014. A model study of the response of hypoxia to upwelling-favorable wind on the northern Gulf of Mexico shelf. Journal of Marine Systems, 131: 63–73, doi: 10.1016/j.jmarsys.2013.11.009

Fennel K, Hu Jiatang, Laurent A, et al. 2013. Sensitivity of hypoxia predictions for the northern Gulf of Mexico to sediment oxygen consumption and model nesting. Journal of Geophysical Research: Oceans, 118(2): 990–1002, doi: 10.1002/jgrc.20077

Fennel K, Laurent A. 2018. N and P as ultimate and proximate limiting nutrients in the northern Gulf of Mexico: implications for hypoxia reduction strategies. Biogeosciences, 15(10): 3121–3131, doi: 10.5194/bg-15-3121-2018

Fennel K, Wilkin J, Levin J, et al. 2006. Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget. Global Biogeochemical Cycles, 20(3): GB3007

Forrest D R, Hetland R D, DiMarco S F. 2011. Multivariable statistical regression models of the areal extent of hypoxia over the Texas-Louisiana continental shelf. Environmental Research Letters, 6(4): 045002, doi: 10.1088/1748-9326/6/4/045002

Gao Jingsong, Xue Huijie, Chai Fei, et al. 2013. Modeling the circulation in the Gulf of Tonkin, South China Sea. Ocean Dynamics, 63(8): 979–993, doi: 10.1007/s10236-013-0636-y

Haidvogel D B, Arango H G, Hedstrom K, et al. 2000. Model evaluation experiments in the North Atlantic Basin: simulations in nonlinear terrain-following coordinates. Dynamics of Atmospheres and Oceans, 32(3–4): 239–281, doi: 10.1016/S0377-0265(00)00049-X

Hetland R D, DiMarco S F. 2008. How does the character of oxygen demand control the structure of hypoxia on the Texas-Louisiana continental shelf?. Journal of Marine Systems, 70(1–2): 49–62

Jiang Ronggen, Huang Shuyuan, Wang Weili, et al. 2020. Heavy metal pollution and ecological risk assessment in the Maowei Sea mangrove, China. Marine Pollution Bulletin, 161: 111816, doi: 10.1016/j.marpolbul.2020.111816

Kaiser D, Unger D, Qiu Guanglong, et al. 2013. Natural and human influences on nutrient transport through a small subtropical Chinese estuary. Science of The Total Environment, 450–451: 92–107

Lan Wenlu. 2011. Variation of organic pollution in the last twenty years in the Qinzhou Bay and its potential ecological impacts. Acta Ecologica Sinica (in Chinese), 31(20): 5970–5976

Lao Qibin, Liu Guoqiang, Shen Youli, et al. 2020. Distribution characteristics and fluxes of nutrients in the rivers of the Beibu Gulf. Haiyang Xuebao (in Chinese), 42(12): 93–100

Laurent A, Fennel K, Cai Weijun, et al. 2017. Eutrophication-induced acidification of coastal waters in the northern Gulf of Mexico: Insights into origin and processes from a coupled physical-biogeochemical model. Geophysical Research Letters, 44(2): 946–956, doi: 10.1002/2016GL071881

Laurent A, Fennel K, Hu J, et al. 2012. Simulating the effects of phosphorus limitation in the Mississippi and Atchafalaya River plumes. Biogeosciences, 9(11): 4707–4723, doi: 10.5194/bg-9-4707-2012

Li Dou, Gan Jianping, Hui Rex, et al. 2020. Vortex and biogeochemical dynamics for the hypoxia formation within the coastal transition zone off the Pearl River Estuary. Journal of Geophysical Research: Oceans, 125(8): e2020JC016178, doi: 10.1029/2020JC016178

Li Dou, Gan Jianping, Hui Chiwing, et al. 2021. Spatiotemporal development and dissipation of hypoxia induced by variable wind-driven shelf circulation off the Pearl River Estuary: observational and modeling studies. Journal of Geophysical Research: Oceans, 126(2): e2020JC016700, doi: 10.1029/2020JC016700

Liu Kon-Kee, Chao S Y, Lee Hung-Jen, et al. 2010. Seasonal variation of primary productivity in the East China Sea: A numerical study based on coupled physical-biogeochemical model. Deep-Sea Research Part II: Topical Studies in Oceanography, 57(19–20): 1762–1782, doi: 10.1016/j.dsr2.2010.04.003

Lu Dongliang, Huang Xueren, Yang Bin, et al. 2021. Composition and distributions of nitrogen and phosphorus and assessment of eutrophication status in the Maowei Sea. Journal of Ocean University of China, 20(2): 361–371, doi: 10.1007/s11802-021-4557-y

Lu Dongliang, Kang Zhenjun, Yang Bin, et al. 2020. Compositions and spatio-temporal distributions of different nitrogen species and lability of dissolved organic nitrogen from the Dafengjiang River to the Sanniang Bay, China. Marine Pollution Bulletin, 156: 111205, doi: 10.1016/j.marpolbul.2020.111205

Ma Aohui, Liu Xiangnan, Li Ting, et al. 2013. The satellite remotely-sensed analysis of the temporal and spatial variability of chlorophyll a concentration in the northern South China Sea. Haiyang Xuebao (in Chinese), 35(4): 98–105

Morel A, Berthon J F. 1989. Surface pigments, algal biomass profiles, and potential production of the euphotic layer: Relationships reinvestigated in view of remote-sensing applications. Limnology and Oceanography, 34(8): 1545–1562, doi: 10.4319/lo.1989.34.8.1545

Obenour D R, Michalak A M, Zhou Yuntao, et al. 2012. Quantifying the impacts of stratification and nutrient loading on hypoxia in the northern Gulf of Mexico. Environmental Science & Technology, 46(10): 5489–5496

Obenour D R, Scavia D, Rabalais N N, et al. 2013. Retrospective analysis of midsummer hypoxic area and volume in the northern Gulf of Mexico, 1985–2011. Environmental Science & Technology, 47(17): 9808–9815

Pan Ke, Lan Wenlu, Li Tianshen, et al. 2021a. Control of phytoplankton by oysters and the consequent impact on nitrogen cycling in a subtropical bay. Science of The Total Environment, 796: 149007, doi: 10.1016/j.scitotenv.2021.149007

Pan Huanglei, Liu Dishi, Shi Dalin, et al. 2021b. Analysis of the spatial and temporal distributions of ecological variables and the nutrient budget in the Beibu Gulf. Acta Oceanologica Sinica, 40(8): 14–31, doi: 10.1007/s13131-021-1794-2

Scully M E. 2013. Physical controls on hypoxia in Chesapeake Bay: A numerical modeling study. Journal of Geophysical Research: Oceans, 118(3): 1239–1256, doi: 10.1002/jgrc.20138

Shchepetkin A F, McWilliams J C. 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Modelling, 9(4): 347–404, doi: 10.1016/j.ocemod.2004.08.002

Visser P M, Ibelings B W, Mur L R, et al. 2005. The ecophysiology of the harmful cyanobacterium microcystis. In: Huisman J, Matthijs H C P, Visser P M, eds. Harmful Cyanobacteria. Dordrecht: Springer, 109–142

Wang Cui, Cai Ling, Wu Yaojian, et al. 2021a. Numerical simulation of the impact of an integrated renovation project on the Maowei Sea hydrodynamic environment. Scientific Reports, 11(1): 17059, doi: 10.1038/s41598-021-96441-1

Wang Xilong, Su Kaijun, Chen Xiaogang, et al. 2021b. Submarine groundwater discharge-driven nutrient fluxes in a typical mangrove and aquaculture bay of the Beibu Gulf, China. Marine Pollution Bulletin, 168: 112500, doi: 10.1016/j.marpolbul.2021.112500

Wang Yuhai, Tang Liqun, Wang Chonghao, et al. 2014. Combined effects of channel dredging, land reclamation and long-range jetties upon the long-term evolution of channel-shoal system in Qinzhou Bay, SW China. Ocean Engineering, 91: 340–349, doi: 10.1016/j.oceaneng.2014.09.024

Xu Lingjing, Yang Dezhou, Greenwood J, et al. 2020. Riverine and oceanic nutrients govern different algal bloom domain near the Changjiang Estuary in Summer. Journal of Geophysical Research: Biogeosciences, 125(10): e2020JG005727, doi: 10.1029/2020JG005727

Yang Liuzhu, Yang Liling, Pan Hongzhou, et al. 2019a. Characteristics of recent evolution in Qinzhou Bay influenced by human activities. Journal of Tropical Oceanography (in Chinese), 38(6): 41–50

Yang Jing, Zhang Renduo, Zhao Zhuangming, et al. 2015. Temporal and spatial distribution characteristics of nutrients in the coastal seawater of Guangxi Beibu Gulf during the past 25 years. Ecology and Environmental Sciences (in Chinese), 24(9): 1493–1498

Yang Bin, Zhou Jiabin, Lu Dongliang, et al. 2019b. Phosphorus chemical speciation and seasonal variations in surface sediments of the Maowei Sea, northern Beibu Gulf. Marine Pollution Bulletin, 141: 61–69, doi: 10.1016/j.marpolbul.2019.02.023

Yu Liuqian, Fennel K, Laurent A. 2015a. A modeling study of physical controls on hypoxia generation in the northern Gulf of Mexico. Journal of Geophysical Research: Oceans, 120(7): 5019–5039, doi: 10.1002/2014JC010634

Yu Liuqian, Fennel K, Laurent A, et al. 2015b. Numerical analysis of the primary processes controlling oxygen dynamics on the Louisiana shelf. Biogeosciences, 12(7): 2063–2076, doi: 10.5194/bg-12-2063-2015

Zhang Dong. 2020. The influence factors for spatio-temporal changes of nutrients and the quantitative reduction of terrestrial TDN in Qinzhou Bay (in Chinese)[dissertation]. Nanning: Guangxi University

Zhang Haiyan, Fennel K, Laurent A, et al. 2020. A numerical model study of the main factors contributing to hypoxia and its interannual and short-term variability in the East China Sea. Biogeosciences, 17(22): 5745–5761, doi: 10.5194/bg-17-5745-2020

Zhang Dong, Lu Dongliang, Yang Bin, et al. 2019a. Influence of natural and anthropogenic factors on spatial-temporal hydrochemistry and the susceptibility to nutrient enrichment in a subtropical estuary. Marine Pollution Bulletin, 146: 945–954, doi: 10.1016/j.marpolbul.2019.07.056

Zhang Wenxia, Wu Hui, Hetland R D, et al. 2019b. On Mechanisms controlling the seasonal hypoxia hot spots off the Changjiang River Estuary. Journal of Geophysical Research: Oceans, 124(12): 8683–8700, doi: 10.1029/2019JC015322

Zhang Wenxia, Wu Hui, Zhu Zhuoyi. 2018. Transient hypoxia extent off Changjiang River estuary due to mobile Changjiang River Plume. Journal of Geophysical Research: Oceans, 123(12): 9196–9211, doi: 10.1029/2018JC014596