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Key Points:

- The hypoxia west off Pearl River estuary is extrinsically controlled by biophysical fluxes and intrinsically by local hydrodynamics
- Remineralization of organic matter in the water column and sediment and local unique hydrodynamics formed and maintained the bottom hypoxia
- Water column stability was provided by wind and freshwater discharge while local rotating current provided favorable residence time

Supporting Information:

- Supporting Information S1
- Data Set S1

Correspondence to:

J. Gan,

magan@ust.hk

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Joint Effects of Extrinsic Biophysical Fluxes and Intrinsic Hydrodynamics on the Formation of Hypoxia West off the Pearl River Estuary

Zhongming Lu^{1,2} (D), Jianping Gan^{3,4,5} (D), Minhan Dai⁶ (D), Hongbin Liu^{3,5,7}, and Xiaozheng Zhao¹

JGR

¹Division of Environment and Sustainability, Hong Kong University of Science and Technology, Hong Kong, ²Institute for Advanced Study, Hong Kong University of Science and Technology, Hong Kong, ³Department of Ocean Science, Hong Kong University of Science and Technology, Hong Kong, ⁴Department of Mathematics, Hong Kong University of Science and Technology, Hong Kong, ⁵State Key Laboratory in Marine Pollution, Hong Kong, ⁶State Key Laboratory of Marine Environment, Xiamen University, Xiamen, China, ⁷Division of Life Science, Hong Kong University of Science and Technology, Hong Kong

Abstract Using field measurements and a process-oriented three-dimensional coupled physical-biogeochemical numerical model, we investigated the physical and biogeochemical processes governing the bottom hypoxic zone west off the Pearl River estuary. The intensity and area of the hypoxia grew with increasing total nutrient input from the Pearl River that has increased continuously in recent decades. The hypoxic zone was formed and maintained largely associated with the stable water column where the stability was provided simultaneously by wind stress and freshwater discharge, favorable local hydrodynamics for flow convergence, and westward organic matter transport. Wind stress altered the stratification, while freshwater discharge changed the stratification and baroclinic velocity shear simultaneously. Two-layered flow with a cyclonically rotating current around a coastal salient edge of the western shelf off the estuary hydrodynamically enhanced the local convergence, allowing sufficient residence time in the bottom for the remineralization of organic matter produced in the hypoxic zone and organic matter transported into the region. Our results suggest that a combination of unique local hydrodynamic feature and decomposition of organic matter in water column (and possibly in the sediment) are the cause of the formation and maintenance of the bottom hypoxia on the western shelf of the estuary but mypoxid and organic matter in water.

Plain Language Summary Hypoxia results in *dead zones* in the ocean. It often occurs in the bottom waters below surface eutrophication due to decomposition of organic matter in the water column and also possibly in sediment. Both physical and biogeochemical processes in the ocean control the formation of the eutrophication and hypoxia. This study investigates these processes for an observed strong hypoxia zone off Pearl River estuary using a numerical model and field measurement data. Through comprehensive analyses, we found that the intensity and area of the hypoxia grew with increasing total nutrient input from Pearl River. The hydrodynamic conditions of ocean flow field such as stability of the water column associated with wind forcing and freshwater buoyancy discharge, local flow convergence, and external organic matter input provide favorable conditions for the formation of hypoxia.

1. Introduction

Hypoxia occurs when oxygen consumption in the water column cannot be replenished by supply. When the level of dissolved oxygen (DO) falls below 2–3 mg/L, hypoxia appears (Chu et al., 2005; Dai et al., 2006; Rabalais et al., 2002). Both natural processes and anthropogenic activities can lead to hypoxia in a marine environment. Hypoxia occurs naturally in upwelling zones with high productivity or in restricted basins and fjords where water exchanges are limited (Helly & Levin, 2004; Rabalais et al., 2010; F. Zhang, 2001). Hypoxia due to anthropogenic activities is a consequence of eutrophication driven by the increasing human input of nutrients and organic matter (Cai et al., 2011). Hypoxia has been spreading rapidly in frequency and extent in coastal and estuarine areas, which has important environmental consequence (Breitburg et al., 2018).

Many studies indicate that the remineralization of organic matter in the hypoxic zone is associated with autochthonous organic carbon production fueled by excessive terrestrial nutrient input (Rabalais et al., 2014; Turner & Rabalais, 1994; H. J. Wang et al., 2016; J. Zhang et al., 2010). Hypoxia generally has a positive

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Figure 1. Map with topography and isobaths (in meters) of the model domain (enclosed by the blue solid lines) and the zoomed-in area (enclosed by the red dashed lines) of the PRE and adjacent shelf. The zoomed-in area is shown as a colored map, where the sampling stations are represented by black stars. The red circle in the inset map denotes the Gaoyao hydrological station. The blue circle in the inset map denotes station A7. The box created by the white dashed line in the colored map is the area west off the PRE and is the calculation region that produced Figures 14 and 15e. The white solid line in the colored map represents Section A. Yellow solid lines divide the upper, middle, and lower part of the PRE. The wind speed and direction during the sampling period are shown by the wind rose in the lower left corner. PRE = Pearl River estuary; WGL = Waglan Island.

correlation with nutrient loading (Hagy et al., 2004). Other studies suggest that oxygen is consumed in the water column through the aerobic respiration of allochthonous organic matter coming from wastewater discharge and nitrification (Dagg et al., 2007; He et al., 2014; Swarzenski et al., 2008). In addition to the biogeochemical controls in generating hypoxic zones, hydrodynamics plays a critically important role. For example, stratification can inhibit ventilation and reduce oxygen replenishment in the bottom layer. Stratification can be regulated by freshwater discharge from large rivers (Bianchi et al., 2010; Wiseman et al., 1997) due to the buoyancy flux. Local wind forcing also affects vertical circulation and mixing (L. X. Wang & Justic, 2009).

The Pearl River estuary (PRE) is a subtropical estuary located in the northern part of the South China Sea. The PRE can be divided into upper, middle, and lower estuary (Figure 1; Lu & Gan, 2015). Freshwater discharge from the Pearl River has an annual average flow rate of about 10,000 m³/s (Zhai et al., 2005). The Pearl River is the world's seventeenth largest river in terms of freshwater discharge (Dai et al., 2014). Over the last 30 years, rapid industrial and agricultural development and urbanization have produced large amounts of anthropogenic nutrients input into the PRE and onto the adjacent shelf (Callahan et al., 2004; Harrison et al., 2008; Huang et al., 2003). Year-round hypoxia has been observed in the upper reaches of the estuary with microbial respiration predominantly supported by the aerobic respiration of allochthonous organic matter, and nitrification being the significant contributors to oxygen consumption. (Dai et al., 2006, 2008; He et al., 2010, 2014).

Low oxygen in an estuary is often linked with estuarine circulation, vertical mixing, and benthic oxygen consumption. Previous studies suggested that large-scale hypoxia was unlikely to occur in the lower estuary and its adjacent waters because of relatively stronger wind mixing and the shallow water depth (Harrison et al., 2008; Rabouille et al., 2008; Yin et al., 2004). However, based on long-term time series observations, Qian et al. (2018) found that bottom oxygen decreased by ~2 µmol·kg⁻¹·year⁻¹ in the PRE during the last 25 years, and they observed that hypoxia has worsened in the lower PRE and adjacent shelf in recent years. Su et al. (2017) identified strong hypoxia in the lower PRE in July 2014. In addition, modeling studies have also identified temporal and spatial variations in bottom hypoxia that were mainly induced by salinity front and stratification (Luo et al., 2009). H. Zhang and Li (2010) investigated the sources and sinks of oxygen in the PRE and found that sediment oxygen demand played the dominant role in hypoxia generation because of the shallow topography and high deposition rate of particulate organic matters. Wei et al. (2016) explored the effects of wind and river discharge on hypoxia on the eastern side of the lower PRE during summer. They indicated that the hypoxic zone responded differently to changes of river discharge at different inlets and that the wind speed had a stronger effect on hypoxia than the wind direction. B. Wang et al. (2017) investigated the oxygen dynamics in the PRE and found that re-aeration and sediment oxygen demands were the two major processes controlling the bottom hypoxia in this region.

Despite the many observational and modeling efforts, there remain numerous uncertainties on the formation process of hypoxia or the role of spatiotemporally varying coupled physical-biogeochemical processes on hypoxia generation in the PRE. Furthermore, hypoxia studies in the PRE have mainly focused on axial transect of PRE and the eastern side of the lower PRE when Pearl River plume was advected eastward by the southwesterly wind-driven coastal current during summer (Gan, Li, et al., 2009). Few studies have investigated hypoxia occurring west off the PRE. We know little about hypoxia on the western side of the PRE and adjacent coastal waters so far. Furthermore, nutrient loading in the PRE increased more than sevenfold during the last three decades (Ma et al., 2009), and a much stronger hypoxia as compared to those observed in the previous studies can be expected nowadays.

In this study, we investigated the time-dependent, three-dimensional evolution of hypoxia on the western shelf off the PRE under various control factors by elucidating the biogeochemical processes. We used process-oriented numerical experiments to reveal the fundamental processes that controlled the intensity and location of bottom hypoxia in the region.

2. Materials and Methods

2.1. Observational Data

We used field measurements from 5 to 17 July 2015. The measurements helped identify the characteristics of hypoxia on the western shelf off the PRE and informed the modeling study. The field survey occurred during a typical summer southwesterly monsoon (Figure 1).

We measured salinity and temperature using a Seabird 911 plus conductivity-temperature-depth profiler (Sea Bird Electronics, Inc.) with a precision of ± 0.0005 S/m and ± 0.005 °C. The conductivity-temperature-depth was raised and lowered at ~0.2 m/s. We collected the discrete samples of nitrate (NO₃) and phosphate (PO₄) using a Rosette sampler with GO-FLO bottles (General Oceanics Co.). We determined NO₃ and PO₄ colorimetrically using a flow injection analyzer (QuAAtro nutrient analyzer, Seal Analytical, Inc.) with the detection limits of 0.04 and 0.08 μ M, respectively. We determined chlorophyll-a using the standard fluorometric method (Parsons et al., 1984) and a Trilogy laboratory fluorometer (Turner Designs, Inc.) with a detection limit of 0.025 μ g/L. We measured DO using the Winkler titration method (Bryan et al., 1976) with a precision of ± 0.06 mg/L. We obtained long-term wind speed at Waglan Island (WGL) and river discharge data at Gaoyao station from the Hong Kong Observatory (http://www.weather.gov.hk/wxinfo/ts/display_element_ff_e.htm) and the Information Center of Water Resources, Bureau of Hydrology, the Ministry of Water Resources of P. R. China (http://xxfb.hydroinfo.gov.cn/ssIndex.html), respectively. The wind speed and discharge served as references for setting up the sensitivity cases in our numerical study.

2.2. Ocean Model and Implementation

We developed a coupled physical-biological model for the PRE based on a validated physical model by Zu and Gan (2015). The physical model adopts the hydrostatic primitive Regional Ocean Modeling System (ROMS; Shchepetkin & McWilliams, 2005). Our computational domain extends from 20.9°N, 112.7°E in the southwest corner to 23.3°N, 115.0°E in the northeast corner (Figure 1). The curvilinear grid with a (400, 200)-dimensional array for the horizontal coordinates (x, y) has a horizontal resolution of ~0.8 km. Vertically, we adopted a 30-level stretched generalized terrain-following coordinate system with higher resolution in the surface and bottom layers. Other relevant details about the numerical techniques and implementations can be found in Zu and Gan (2015).





Figure 2. Schematic of the biogeochemical model. The boxes represent the biogeochemical variables. The boxes above and below the gray dashed line represent variables in the water column and sediment, respectively. The black arrows indicate the biogeochemical processes of the aquatic ecosystem. The green arrows represent the processes in the sediment. The dashed arrows represent the air-sea oxygen exchange.

The biological model was coupled with the physical model at identical temporal and spatial resolutions. It is a nitrogen, phosphorus, phytoplankton, zooplankton, and detritus (NPPZD) model (Figure 2) that Gan et al. (2014) developed. The model is based on the ROMS biological module to reflect the P limitation status that widely exists in estuarine and coastal waters (Gan et al., 2014). The biological parameters (Table 1) adopted in the NPPZD model were set based on previous studies in this region and on studies of other oceans around the world (Fennel et al., 2006; Gan et al., 2014; Spitz et al., 2005). We adopted the oxygen model of Fennel et al. (2006), in which oxygen was consumed by remmineralization of organic matter, biological matabolism, and nitritification of ammonium to nitrate in both water column and sediment (Figure 2 and equation (A4) in Appendix A).

We conducted a process-oriented modeling study by forcing the model with a typical southwesterly wind stress equal to 0.025 Pa (Gan, Cheung, et al., 2009) over the entire computational domain. The underlying processes and mechanisms of hypoxia development involve multiforcing in the complex coupled physical and biogeochemical system. We adopt process-oriented modeling based on the simplified but representative forcing in order to better isolate the processes, which otherwise may not be able to resolve solidly (Zu & Gan, 2015).

We initialized the model with horizontally uniform salinity, temperature, NO_3 , PO_4 , DO, and chlorophyll profiles obtained from the field measurements at Station A7 (Figure 1). We calculated the initial values of phytoplankton, zooplankton, and detritus from chlorophyll data by assuming the ratios of 1.59, 0.3, and 0.7 for chlorophyll/phytoplankton, zooplankton/phytoplankton, and detritus/phytoplankton, respectively (Gan et al., 2014).

To investigate the impact of external forcing, we applied an active open boundary condition (OBC; Gan & Allen, 2005) to the open boundaries of our computational domain (Figure 1). The active OBC is able to integrate the effect of external forcing along the open boundaries into the simulation. In our case, the summer (June to August) mean variables obtained from a model that covered the entire northern South China Sea shelf (Gan, Li, et al., 2009; Gan et al., 2014) provided the external physical and biogeochemical fluxes. In our sensitivity experiments, in order to investigate the impacts of local forcing (e.g., river discharge and wind) on hypoxia, we excluded the effects from external biogeochemical forcing by applying a passive OBC for all biogeochemical variables.



 Table 1

 Biogeochemical Model Parameters

Biogeoenennear moder i drameters			
Description	Symbol	Value	Unit
Phytoplankton growth rate at 0 °C	μ_0	0.59	day_1^{-1}
Light attenuation due to seawater	<i>k</i> water	0.04	m^{-1}
Light attenuation by chlorophyll	k _{Chla}	0.025	(m ² mg Chla) ⁻¹
Initial slope of the P-I curve	α	0.05	mg C (mg Chla W m ^{-2} day) ^{-1}
Maximum cellular chlorophyll: C ratio	θ_{m}	0.054	mg Chla (mg C) $^{-1}$
Cellular P:N ratio	r _{PN}	0.0625	-
Half saturation for phytoplankton NO ₃ uptake	k _N	0.8	mmol/m ³
Half saturation for phytoplankton NH ₄ uptake	k _A	0.8	mmol/m ³
Half saturation for phytoplankton PO ₄ uptake	k _P	0.06	mmol/m ³
Phytoplankton mortality rate	m _{Phyto}	0.15	day^{-1}
Zooplankton maximum grazing rate	g _{max}	0.5	day^{-1}
Zooplankton assimilation efficiency for nitrogen	β	0.75	-
Zooplankton half-saturation constant for ingestion	k _{Phyto}	1	mmol N/m ³
Zooplankton basal metabolism	/ _{BM}	0.1	day^{-1}
Zooplankton specific excretion rate	LE	0.1	day ⁻¹
Zooplankton mortality rate	m _{Zoo}	0.025	$day^{-1} (mmol_N/m^3)^{-1}$
Small detritus remineralization rate for nitrogen	r _{SDN}	0.03	day ⁻¹
Large detritus remineralization rate for nitrogen	r _{LDN}	0.01	day ⁻¹
Small detritus remineralization rate for phosphorus	r _{SDP}	0.075	day
Large detritus remineralization rate for phosphorus	<i>r</i> _{LDP}	0.025	day ⁻¹
Coagulation rate	τ	0.1	day^{-1}
Sinking velocity for small detritus	W _{SD}	2	m/day
Sinking velocity for large detritus	WLD	20	m/day
Sinking velocity for phytoplankton	WPhyto	1	m/day
Maximum nitrification rate	n _{max}	0.1	day
Threshold PAR for nitrification inhibition	Io	0.0095	W/m ²
Half-saturation PAR for nitrification inhibition	k _l	0.036	W/m ²

Note. PAR = photosynthetic active radiation.

We set the river discharge to 18,400 m³/s and the daily average solar radiation to 195 W/m² with a diurnal cycle distribution. We made the salinity, temperature, NO₃, and PO₄ of the river water equal to 3 practical salinity units, 28.6 °C, 60 μ M, and 1 μ M (Cai et al., 2004), respectively. We neglected contribution of riverine input of organic matter to the hypoxia, because most of the phytoplankton from the river discharge are inactive (Dai et al., 2008; Lu & Gan, 2015), and most of the oxygen-consuming organic matter were derived from marine sources (Qian et al., 2018; Su et al., 2017). The model was run for 50 days.

3. Observational Features and Model Results

The field observations and model simulations illustrate the biogeochemical features of the PRE and the adjacent shelf for typical summer conditions. Figure 3 shows the time series of model-simulated domainaveraged salinity, temperature, NO₃, and chlorophyll. The model was run for 50 days, and it reached the physical and biogeochemical quasi steady state in about 30 days. We analyzed the quasi-steady model outputs on day 40.

3.1. River Plume and Ecosystem Responses

Figure 4 shows the observed and simulated horizontal distributions of surface salinity, NO₃, and chlorophyll (Chl-*a*). The observed and the modeled distributions exhibit qualitatively similar biophysical features. Phytoplankton biomass began to appear in the middle of the estuary several days after the freshwater input, then moved downstream as freshwater gradually filled the whole estuary. It reached equilibrium at about day 20. In the upper and middle estuaries, phytoplankton levels remained very low although the nutrient concentration was high, likely due to the strong flushing of river discharge and high water turbidity (Lu & Gan, 2015). The freshwater veered westward inside the PRE but advected eastward over the shelf because of the upwelling shelf current (Gan, Li, et al., 2009). When the freshwater input from the Pearl River exited the mouth of the PRE, a southeastward-expanding freshwater bulge formed outside the entrance of the estuary (Figures 4a



Figure 3. Time series of domain-averaged (a) salinity, (b) temperature, (c) NO₃, and (d) chlorophyll.

and 4d). Between the PRE and the shelf, where the shelf current was weak, the main body of the bulge remained steady while the freshwater at its edge flowed further downstream.

The bulge contained a high concentration of nutrients (Figures 4b and 4e) from agriculture, industrial, and sewage discharges into the drainage area of the Pearl River (Gan et al., 2010). The high nutrient concentration, favorable residence time, photosynthetic active radiation, and stable water column stimulated a phytoplankton bloom in this region (Figures 4c and 4f; Lu & Gan, 2015). Figure 5 shows the phytoplankton response along Section A based on a phytoplankton budget in the NPPZD system computed with equation (A1). We found that the high source (indicating high production) and sink terms were located in the bulge area (between latitudes 22.4°N and 21.9°N), which agree well with the high chlorophyll zone found in our model simulations and field observations.

3.2. Eutrophication and Bottom Hypoxia

High phytoplankton production generally results in a high DO concentration due to photosynthesis. Therefore, surface DO can increase from less than 7 mg/L in the upper estuary to over 8 mg/L in the lower estuary next to the shelf waters as shown by the field observations and model results (Figures 6a and 6c).









Figure 5. Water column-integrated terms in the phytoplankton equation (equation (A1)) along Section A (refer to Figure 1). Pprod = phosphorusbased production (under P limitation), Nprod = nitrogen-based production (under N limitation), Hadv = horizontal advection, ZooG = zooplankton grazing, mort = mortality, Coag = coagulation, sink = sinking, rate = variation rate. Some small terms (such as vertical advection, horizontal diffusion, and vertical diffusion) have been omitted to keep the figure clean. The data are averaged from days 36 to 45.

The highest DO concentration was generally outside the estuary's mouth where favorable biophysical conditions can form the strongest phytoplankton bloom in the surface layer (Lu & Gan, 2015). The organic particles produced by metabolism increased dramatically with the intensive biological production in the surface layer. Hypoxia was generated when these particles (mainly detritus of different sizes) sank through the pycnocline and settled in the bottom layer and the oxygen consumed during their remineralization exceeded the oxygen replenished by diffusion, turbulent mixing, or advection of oxygenated water (Rabouille et al., 2008). There were no data available on the in situ particulate organic carbon, but our simulation results (not shown) indicate that the level of both large and small detritus in the bottom water can be much higher than those in the surface water, similar to the hypoxic zone of the East China Sea (H. J. Wang et al., 2016).

Strong hypoxia was observed and simulated in the bottom layer (Figures 6b and 6d) with the strongest hypoxia occurring on the western shelf off the PRE. However, both chlorophyll and DO in the surface layer at this location were relatively low (Figures 5 and 6), contrary to our common understanding. A relatively weak hypoxic center appeared in the eastern PRE (in Hong Kong waters) in the model results but was not fully covered by survey measurements. In fact, our recent repeated measure-

ments showed that hypoxia in the western waters was generally stronger than the one in the east. The simulated bottom DO was also higher than the DO observed in our study. This was likely associated with the lower river discharge during the survey period. The effect of the river discharge on hypoxia is discussed in section 4.



Figure 6. Horizontal distributions of (a, c) surface and (b, d) bottom dissolved oxygen (mg/L). The top row shows the observations, and the bottom row shows the model simulations on day 40. The black dots in the top row of figures indicate the sampling stations.



Figure 7. Horizontal distributions of (a) surface and (b) bottom velocity vectors and magnitudes (color contours) on day 40. The vectors are of the same size so they represent the direction only. (c) Bottom dissolved oxygen (mg/L) without river nutrient input. The red and blue contour lines represent the 30- and 50-m isobaths, respectively.

Overall, the model captured the observed physical circulation, ecosystem response, and the bottom hypoxia well. The model reproduced the observed large hypoxic zone on the western shelf off the estuary. This motivated us to conduct process-oriented investigations of the characteristics and formation mechanism of hypoxia in response to external and local biophysical conditions.

4. Analysis and Discussion

The regional hypoxia was a synergistic product of a suite of physical and biogeochemical factors. It could have been externally imported or locally generated. Eutrophication and water column stability are believed to be the two most important causes. Understanding the unique controlling factors for the hypoxia on the western shelf off the PRE is key to understanding the formation and maintenance mechanism.

4.1. External Contributors

4.1.1. Input From the Upper Estuary

As we indicated in section 3.2, there was low DO in the upper reaches of the PRE in the observed and simulated results. The formation mechanisms of hypoxia in the upper reaches of the PRE are known to be quite different from eutrophication-induced hypoxia in the coastal area. The degradation (aerobic respiration) of huge amounts of anthropogenic organic matter results in strong DO consumption (Zhai et al., 2005). At the same time, nitrification also contributes significantly to hypoxia (up to ~30%; Dai et al., 2008).

In the midestuary, however, the DO was higher at the surface and bottom most likely because the organic matter was consumed and diluted when the river water was discharged into the estuary, as supported by the sharply decreasing trend of NH_4 concentration from upper to lower estuaries (Dai et al., 2008). Therefore, the hypoxia input from the upper estuary unlikely contributed to the hypoxia occurring on the western shelf off the PRE. Based on three endmember mixing models and isotopic composition of dissolved inorganic carbon, Su et al. (2017) estimated that ~ 65% of the oxygen-consuming organic matter was derived from marine sources. Through the analysis of the stoichiometric relationship between oxygen consumption and C/N ratio, Qian et al. (2018) also suggested that locally produced organic matter was the main source of bottom hypoxia off the PRE.

4.1.2. Lateral Transport

Driven by the southwesterly summer monsoon, the northeastward coastal current transported the organic matter and low DO water upstream from west boundary. The surface coastal currents (Figure 7a) flowed mostly parallel to the coastline before reaching the PRE. The currents veered offshore with the river plume (Figure 4d). At the same time, the bottom currents (Figure 7b) generally flowed shoreward and the strongest shoreward flow occurred in the lee of the coastal cape (Gan & Allen, 2002; Liu & Gan, 2014) near the western shelf off the PRE.

To further illustrate the effect of lateral transport on bottom hypoxia, we disabled the nutrient input from river discharge in the model. Figure 7c shows that no bottom hypoxia occurred on the western shelf off the PRE when the terrestrially sourced eutrophication was removed. The overall DO concentration was



Figure 8. Simulated horizontal distributions of the bottom dissolved oxygen (mg/L) under (a) 0%, (b) 50%, (c) 100%, and (d) 200% of the standard nutrient concentration in the river discharge.

greater than 4 mg/L. To isolate the key mechanisms and processes better, we then excluded the western external biogeochemical inputs.

4.2. Local Source—Eutrophication

Nutrients are the predominant source contributing to hypoxia development in estuarine and coastal areas (Diaz & Rosenberg, 2008). Excessive nutrient input often leads to an overgrowth of algae that results in hypoxia (Zhu et al., 2016). The intensity and duration of hypoxia are closely related to the nutrient input. However, there is little evidence to suggest that a simple linear response exists between nutrients and hypoxia intensity (Kemp et al., 2009). To assess hypoxia's response to nutrient loading in the PRE, we varied the nutrient concentrations in the river in a series of sensitivity experiments.

The most important process for oxygen consumption in the water column and sediment is aerobic respiration (equation (A2); Zhai et al., 2005). Nitrification, which typically contains ammonia oxidation and nitrite oxidation, is another important process that contributes to oxygen consumption (equation (A3); Dai et al., 2006). The rate of change of DO in the model due to biogeochemical sources and sinks is given by equation (A4) (Fennel et al., 2006). Oxygen consumption due to zooplankton metabolism is relatively small because the zooplankton biomass is generally much smaller than the biomass of phytoplankton and detritus (Gan et al., 2010).

Based on the fact that the nutrient loading in the PRE increased more than sevenfold during the last three decades (Ma et al., 2009), we designed an experiment to examine the hypoxia response to riverine nutrient input. Figure 8 shows the bottom DO under four different river nutrient concentrations ranging from 0% to 200% of the current value. The bottom DO was strongly correlated with the river nutrient discharge. When there was no nutrient input, the bottom DO was almost saturated within the 30 m isobath except for in the upper part of the estuary (Figure 8a), indicating the dominant role of nutrients in the hypoxia occurring in this region. To reveal the response process and to quantify the nutrient effect, we used a hypoxia index (*HI*):



Figure 9. (a) Time series of the variation in *HI* under 0%, 50%, 100%, and 200% of the standard nutrient concentration in the river discharge; (b) variations in *HI*, DO, and the water volume of the hypoxic zone ($V_{hypoxia}$) with the nutrient discharge. The data represent model results averaged from days 36 to 45. *HI* = hypoxia index; DO = dissolved oxygen.

$$HI = V_{\rm hypoxia} \times [AOU]_{\rm hypoxia} \tag{1}$$

where $V_{hypoxia}$ is the volume of hypoxic water given by $V(DO^*) = \iint_{DO < DO^*} dxdydz$. DO^* is the upper limit of the *DO* concentration for hypoxia (=2 mg/L in this study). [*AOU*]_{hypoxia} is the mean apparent oxygen utilization of the hypoxic water. *AOU* is defined by $AOU = [O_2]_{eq} - [O_2]$, where $[O_2]_{eq}$ is the saturated *DO* concentration related to in situ temperature and salinity. [O₂] is the in situ DO concentration (Zhai et al., 2005).

In the model, we computed $[AOU]_{hypoxia}$ using $[AOU]_{hypoxia} = \frac{1}{V_{hypoxia}} \int [AOU] dV_{hypoxia}$.

Figure 9a shows the simulated time series of the *HI* for the cases with different river nutrient concentrations. Hypoxia began on about day 20 and continued to develop over a long period. The lengthy development period was the time needed for the river discharge to flow from upstream, the surface algae to bloom, the bottom organic matter to accumulate, and for remineralization. The *HI* increased rapidly after day 20 and peaked on about day 40. The *HI* was at quasi-equilibrium after day 40. There were many fluctuations throughout the whole period, which was probably due to the formation-expansion-burst lifecycle of the freshwater bulge outside the mouth of the PRE (Gan, Li, et al., 2009) and the stability of the water column throughout the spring-neap tidal cycle. These cases also show that the *HI* grew substantially when nutrients increased exponentially from 0% to 100% (*HI* increased over 7 times when nutrient concentration increased from 50% to 100%). *HI* increased only about 3 times when nutrients increased from 100% to 200% (Figure 9b).

Our results show that DO decreased for another 10 days after the biomass reached equilibrium on day 30 (Figure 3). Figure 9b also shows decreasing DO (which means increasing *AOU*) and increasing total volume of hypoxic water ($V_{hypoxia}$) when the nutrient concentration in the river discharge grew, suggesting that the intensity and volume of hypoxia could be enhanced simultaneously.

There are very few analyses on the correlation between hypoxia and eutrophication (Kemp et al., 2009). Numerical models often predict a simple linear response of hypoxia to nutrient loading (Arhonditsis & Brett, 2004). Our model results suggest that the biogeochemical responses to nutrients or eutrophication are more complex. The growth of hypoxia in response to nutrient loading is not always linear; in fact, it may become highly nonlinear when nutrient loading increases from low level because biomass growth is largely nonlinear (Gan et al., 2010). The DO concentration remains relatively stable after nutrient level exceeded 100%, because the extremely low DO concentration (~1.1 mg/L) in the hypoxic zone formed a large concentration gradient with the ambient waters, which enhanced the exchange flux of DO and increased the volume of hypoxic zone (Figure 9b).

4.3. Maintenance Mechanism—Water Column Stability

Hypoxia is generated and maintained only when DO consumption exceeds DO replenishment. Particulate and dissolved organic matters that result from eutrophication are the major consumers, whereas water column ventilation regulated by stratification is key to replenishment (Obenour et al., 2012).

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Figure 10. Horizontal distributions of (a, e) observed *BF*, (b, f) simulated *BF*, (c, g) simulated *VS*, and (d, h) simulated *Ri* in the surface (top row) and bottom (bottom row) layers. BF = buoyancy frequency; VS = velocity shear.

Water column stability is determined by stratification and vertical shear. Stability and shear are indicated by the Richardson number $Ri = \frac{-g_{dz}^2}{\rho\left(\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2\right)}$, buoyancy frequency $BF = \sqrt{-\frac{g}{\rho}\frac{\partial \rho}{\rho}}$, and velocity shear $VS = \left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z}\right)^2$, where ρ is potential density; g is the gravitational acceleration; z is the vertical coordinate directed upward; u is the east-west velocity component; and v is the north-south velocity component. A large Ri (>0.25) or BF and a small VS indicate a stable water column (Miles, 1961).

In the bottom layer of the PRE, the observations reveal that relatively high *BF* occurred on the west coast, which agrees qualitatively with our model results (Figures 10e and 10f). The region where *BF* was high in the bottom layer coincided with the location of hypoxia. High *BF* in the surface layer was mostly spread over the shelf outside the estuary mouth (Figures 10a and 10b) and within the freshwater bulge. An algal bloom has been observed frequently in this area during past summers when the phytoplankton growth rate was higher than the water turnover rate (Lu & Gan, 2015).

Our model results show that there was a higher VS along the west coast of the PRE in both surface and bottom layers (Figures 10c and 10g). The higher shear was mainly due to the changing direction of velocity in the water column (Figure 7). The distribution of *Ri* generally followed the distribution of *BF* in both layers, suggesting that the effect of VS was relatively small, particularly in the bottom layer. As shown in Figure 10h, the region with the largest *Ri* coincided with the area of hypoxia on the western shelf off the PRE.

4.3.1. Wind Stress

Wind-driven mixing has a significant effect on water column stability in the PRE and on the adjacent shelf due to the shallow water depth and the relatively weak pycnocline. To understand the effect of wind on hypoxia, we investigated the responses of hypoxia to different wind stress forcings ranging from 0% to 200% of the standard summer wind stress of 0.025 Pa (Figure 11). The wind variation can be seen in the observed winds (Figure 12a). In general, the intensity of hypoxia was inversely related to wind stress.

When there was no wind (0% of the standard run), the low DO freshwater was transported from the upper reaches to the estuary mouth and contributed to the bottom hypoxia (Figure 11a). Under this no-wind condition, the DO that was replenished from the atmosphere was greatly reduced. The reduction in replenishment occurred because the air-sea oxygen flux F_{0_2} is determined by

$$F_{O_2} = k_{O_2} \cdot \left(O_2^{\text{air}} - O_2^{\text{sea}}\right), \tag{2}$$

where k_{O_2} is the transfer velocity in the air-sea interface and is exponentially correlated with wind speed (Wanninkhof et al., 2009). O_2^{air} is the oxygen concentration in the air, and O_2^{sea} is the oxygen concentration in the surface seawater. In contrast, the bottom hypoxia largely disappeared when the wind stress was 200% of the standard run (Figure 11d).



Figure 11. Horizontal distributions of the bottom DO (mg/L) under (a) 0%, (b) 50%, (c) 100%, and (d) 200% of the standard wind stress. DO = dissolved oxygen.



Figure 12. (a) Climatological daily wind speed at WGL (refer to Figure 1) based on observations from 1990 to 2015 (Hong Kong Observatory). The gray dots are the daily mean wind speeds. The blue solid line is the smoothed seasonal trend. The shaded pink region depicts summer. (b) The simulated time series variation in *HI* under 0%, 50%, 100%, and 200% of the standard wind stress. (c) Variation in *HI*, DO, and $V_{hypoxia}$ with the wind stress. The data represent model results averaged from days 36 to 45. *HI* = hypoxia index; DO = dissolved oxygen.





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Figure 13. Time series variation in *HI* under 20%, 50%, 100%, and 150% of the standard river discharge in (a) Scenario 1 and (b) Scenario 2. (c) variation in *HI* in the two scenarios as a function of the river discharge. The results are averaged from days 36 to 45. (d) Variation in total nutrient (NO₃ and PO₄) input with river discharge in Scenario 1. *HI* = hypoxia index; DO = dissolved oxygen.

The time series of *HI* showed the same situation, but we found that the bottom hypoxic zone was formed earlier (before day 20) under the forcing of a weaker wind stress (Figure 12b). We also noticed that the fluctuation of *HI* was more pronounced under weaker wind stress reflecting the fluctuating freshwater bulge caused by the spring-neap tidal cycle. The DO concentration, *HI*, and volume of the hypoxic zone changed dramatically at 50% of the standard wind stress forcing and quickly reached a nonhypoxic state when wind forcing approached 200% of the wind stress (Figure 12c).

4.3.2. Freshwater Discharge

The buoyancy input from a river enhanced the stratification of the water column while carrying the terrestrial nutrient input (Lu & Gan, 2015). We conducted experiments with different river discharge rates to identify the effect of freshwater discharge on hypoxia.

The first experiment (Scenario 1) involved a constant nutrient concentration with different river flow rates. Scenario 1 was close to reality because the nutrient concentration did not change significantly with the river flow rate (He et al., 2014; J. Zhang et al., 1999). The second experiment (Scenario 2) involved a constant total nutrient input from the river (as in the standard case), while the nutrient concentration varied with the river discharge rate. The results of Scenarios 1 and 2 are shown in Figure 13.

We first applied an extremely low river flow rate that was 20% of the standard run, or 3,680 m³/s, which represented the typical flow rate during the dry season. With this extremely low rate, no hypoxia was generated in either scenario regardless of the nutrient concentration. The nonhypoxic result indicates the critical role of freshwater discharge in the formation and maintenance of a stable water column (near-zero *Ri* in Figure 14b) and in hypoxia. *HI* increased with the river flow rate until the latter reached 100% of the standard run for both scenarios. *HI* was higher in Scenario 2 than in Scenario 1 (Figures 13a–13c) in the lower percentage rate initially, because the total amount of nutrient input in Scenario 1 was relatively small when the discharge rate was less than 100%. *HI* increased linearly in Scenario 1 as the flow rate increased further to 150% of the standard run, which represented the peak value in the wet season. However, *HI* decreased with increased river discharge in Scenario 2, although the total nutrient loading was the same as that in the standard case (Figure 13c). In addition, the water column stratification strengthened largely with increased discharge (Figure 14b). The different trends of *HI* between Scenarios 1 and 2 indicated that the buoyancy input from the river was a key factor in the



Figure 14. *BF*, *VS*, and *Ri* averaged over the western bottom hypoxic region (Figure 1) for the s experiments with different levels of (a) wind stress and (b) river discharge. BF = buoyancy frequency; VS = velocity shear.

formation of hypoxia when the discharge rate was less than 100% of the standard case, but the nutrient effect would exceed the effect of river discharge when the discharge rate increased further.

The responses of hypoxia to wind stress and freshwater discharge demonstrate that water column stability was strengthened under weaker wind and higher flow rates (Figure 14) that all occurred in summer. We observed that a favorable wind stress and freshwater discharge must occur simultaneously to generate the bottom hypoxia on the western shelf off the PRE. By decomposing *Ri* into *BF* and *VS*, we found that wind stress affected the water column stability by changing *BF*. A medium wind stress would minimize *VS*. However, river discharge regulated the water column stability through both *BF* and *VS*, which shows that buoyancy affects the stratification and the circulation in the PRE.

4.4. Location of Occurrence—Convergence

The bottom hypoxia on the western shelf off the PRE was identified in the observations and model results (Figure 6). We also observed a higher water column stability in the observations and model results at the same location (Figure 10). High nutrient loading and strong water column stability stimulated high biological production outside the estuary in the surface layer (Figures 4c and 4f). However, these favorable conditions for forming and maintaining hypoxia are still not sufficient to explain why the organic matter (large and small detritus) accumulated and was remineralized in the observed hypoxic zone.

Detritus is produced during biological metabolism as indicated by equations (A5) and (A6). Small detritus sinks at one tenth of the velocity of large detritus (Fennel et al., 2006; Table 1), so its spatiotemporal distribution is more easily modulated by estuarine and shelf circulation. Figures 15a and 15b show the horizontal distribution of large and small detritus in the bottom layer of the PRE, respectively. The area with high quantities of large detritus correspond to the surface bloom center (Figure 4f), but the distribution of small detritus shares a very similar pattern with DO (Figure 6d). There must have been external sources of small detritus in the bottom layer of the hypoxic zone. This inference can be supported by the velocity and transport of detritus across Section A in the PRE (Figures 15c and 15d). While currents flowed northeastward due to the forcing of a prevailing southwesterly monsoon, a strong southwestward transport flowed through the entire water column around 22.2 N under the influence of estuarine topography and the Coriolis force (Wong, Chen, Xue, Dong, Guan, & Su, 2003a; Wong, Chen, Xue, Dong, Su, & Heinke, 2003b). We observed the westward and southwestward transports of total nitrogen (dissolved inorganic nitrogen and particulate organic nitrogen) through the eastern and northeastern boundaries of the hypoxic region, indicating the importance of the nitrogen supply through the boundary (Figure 15e). Most of the fluxes entering the region with hypoxia (the box in Figure 1) exited through the southern boundary (Figure 15f).



Figure 15. Simulated horizontal distribution of (a) large and (b) small detritus in the bottom layer. (c) Velocity (m/s) and (d) transport of large and small detritus (mmol $N \cdot m^{-2} \cdot s^{-1}$) normal to Section A (refer to Figure 1 for location). Positive values indicate an eastward direction. (e) Time series of depth-integrated total nitrogen transport through different boundaries of the hypoxic region (see Figure 1 for location). Positive values refer to inward flux. (f) Time series of averaged large and small detritus and *AOU* in the bottom layer within the hypoxic region. *AOU* = apparent oxygen utilization.

The bottom velocity field rotated cyclonically over the salient edge of the coastal cape, and created a convergence in the hypoxic region (Figure 7b and Figure 16a). Figure 16b illustrates the bottom convergence in the study area according to equation (3):

$$Convergence = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}, \tag{3}$$

where u is the east-west velocity component; v is the north-south velocity component; and x and y are the horizontal grid sizes in the u and v directions, respectively. Negative value denotes a convergence of flow field.

Figure 16b shows that the strongest convergence mainly occurred on the western shelf off the estuary, coincident with the hypoxic zone, similar to that found in the estuary of the Pregolya River (Lin et al., 2016). Figures 16c and 16d indicate that the rotating flow in the western lower estuary and the same rotating and weakening flow over the western shelf off the PRE jointly contributed to the convergence. The curvature, shear vorticity due to the highly variable coastline, and bottom topography likely regulated the unique convergence/divergence distribution in this area. Organic matter accumulated in the convergence zone in the bottom layer. When the organic matter coupled with a very low current velocity, strong water column



Figure 16. Simulated horizontal distributions of (a) bottom velocity vectors and magnitude (color contours); (b) convergence, (c) $\frac{\partial u}{\partial x}$ and (d) $\frac{\partial v}{\partial y}$ averaged over the bottom 2 m. The regions enclosed by black solid lines represent hypoxic zones (DO < 2 mg/L). The vectors are of the same size, which means they represent the direction only. The magnitude of velocity is shown by color contour in the same figure. DO = dissolved oxygen.

stratification, and a long residence time due to flow convergence, favorable conditions emerged for hypoxia to form in the region.

5. Concluding Remarks

We examined the formation process and mechanism of a hypoxic zone west off the PRE using field measurements and a three-dimensional coupled physical-biogeochemical model. Unlike the frequently reported hypoxic waters east off PRE, hypoxia west off PRE was generally stronger but received less attention. Yet the processes for the formation and maintenance of the western hypoxic zone exhibited distinct characteristics.

Both measurements and model studies showed the distinct hypoxic zone in the bottom layer west off the PRE were linked with the signatures of eutrophication and biogeochemical characteristics in the surface layer. We identified the multibiophysical processes governing hypoxia in the region and found that the hypoxia development involved river inputs of buoyancy and nutrients, water column stability induced by wind and buoyancy forcing, and flow convergence for favorable biological residence time and accumulation of organic matter. We investigated their interactive controls on hypoxia.

As the river discharged high concentrations of nutrients into the PRE, the freshwater moved southeastward at the surface in the coastal waters immediately outside the PRE. Phytoplankton biomass accumulated in the lower estuary and the adjacent shelf where the flushing effect and the turbidity of the water became weaker. Observations and model simulations showed a higher *BF* in the surface and the bottom layers on the western shelf off the PRE. The high *BF* region coincided with the hypoxic region, suggesting the important role of water column stability in the formation and maintenance of hypoxia. Water column stratification was largely controlled by the intense wind stress and buoyancy input from the river. Hypoxia was inhibited when the wind stress was twice as large as the climatological mean wind stress. In contrast, under weaker (lower than the mean) wind stresses, the hypoxia developed quickly due to greater water column stability.

Freshwater discharge brings large amounts of nutrients for eutrophication in the surface layer and for hypoxia in the bottom layer. In addition, the discharge provides strong buoyancy input which creates a stable water column for hypoxia to develop and persist. Hypoxia cannot be generated when the river flow rate is too low even if there is enough nutrient input. We found that the intensity and area of hypoxia grew with increasing river discharge when nutrient concentration was kept constant. However, when we increased river discharge (buoyancy) while keeping the total nutrient input unchanged, hypoxia grew with increasing river discharge and then weakened after reaching climatological mean value. Stability increased with increased river discharge mainly through strengthening stratification (*BF*) despite an enhanced vertical *VS*. The wind stress regulated the water column's stability mainly by changing *BF*, while freshwater discharge achieved that by additionally changing *VS*.

The two-layered cyclonically rotating current near the salient edge of the western shelf off the PRE hydrodynamically enhanced the local convergence. The convergence allowed the organic matters produced locally and remotely sufficient residence time to develop into hypoxia within the region.

In addition to the steady nutrient input from the river, hypoxia was formed and maintained on the western shelf off the PRE as a result of (1) the stable water column made possible by wind stress and freshwater discharge simultaneously and (2) local hydrodynamics favorable for flow convergence and net westward transport of organic matter into the region. The first controlling condition was the extrinsic forcing, while the second was the intrinsic consequence.

Appendix A: Formulations of Biogeochemical Variables

$$\frac{\partial [Phyto]}{\partial t} = \mu [Phyto] - m_{p} [Phyto] - \tau ([SDet] + [Phyto]) [Phyto] - g_{max} \frac{[Phyto]^{2}}{k_{Phyto} + [Phyto]^{2}} [Zoo] - w_{Phyto} w \frac{\partial [Phyto]}{\partial t},$$
(A1)

where *Phyto*, *SDet* and *Zoo* represent phytoplankton, small detritus, and zooplankton, respectively. μ , $m_{\rm p}$, τ , $g_{\rm max}$, $k_{\rm Phyto}$, and $w_{\rm Phyto}$ are the corresponding coefficients for phytoplankton growth rate, phytoplankton mortality rate, coagulation rate, zooplankton maximum grazing rate, zooplankton half-saturation constant for ingestion, and the sinking velocity of phytoplankton, respectively.

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138O_2 + 18HCO_3^{-} \xrightarrow{bacteria} 124CO_2 + 16NO_3^{-} + HPO_4^{2-} + 140H_2O$$
(A2)

$$NH_{4}^{+} + 1.89O_{2} + 1.98HCO_{3}^{-} \xrightarrow{bacteria} 0.984NO_{3}^{-} + 0.016C_{5}H_{7}O_{2}N + 1.90CO_{2} + 2.93H_{2}O$$
(A3)

in which, C₅H₇O₂N is the cell stoichiometry for bacteria when phosphorus is excluded.

$$\frac{\partial [DO]}{\partial t} = k_{\text{prod}} [Phyto] - k_{\text{nitri}} [A] - (k_{\text{meta}} + k_{\text{excret}}) [Zoo] - k_{\text{remin}} [Det] + Flux$$
(A4)

in which A is ammonia, *Det* is detritus, and *Flux* is oxygen air-sea flux or other external source/sink (e.g., advection). k_{prod} , k_{nitri} , k_{meta} , k_{excret} , and k_{remin} are the corresponding coefficients for phytoplankton production, nitrification, zooplankton metabolism, zooplankton excretion, and detritus remineralization, respectively.

$$\frac{\partial [LDN]}{\partial t} = \tau ([SDN] + [Phyto])^2 - r_{LDN} [LDN] - w_{LD} \frac{\partial [LDN]}{\partial z}$$
(A5)

$$\frac{\partial [SDN]}{\partial t} = g_{\max} \frac{[Phyto]^2}{k_{Phyto} + [Phyto]^2} (1 - \beta) [Zoo] + m_{Zoo} [Zoo]^2 + m_{Phyto} [Phyto] - \tau ([SDN] + [Phyto]) [SDN] - r_{SDN} [SDN] - w_{SD} \frac{\partial [SDN]}{\partial z},$$
(A6)



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where LDN and SDN represent N fraction of large and small detritus, respectively; r_{LDN} and r_{SDN} are the remineralization rate for N fraction of large and small detritus, respectively; w_{Ld} and w_{SD} are the sinking velocity of large and small detritus, respectively; β is the zooplankton assimilation efficiency; and m_{ZOO} is the zooplank-

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