We thank the editor and reviewer for the constructive comments and suggestions that are very helpful to the revision of our manuscript.

Detailed response to all comments are given below (responses are shown in blue). A revised manuscript with changes marked blue is submitted along with the response.

Editor

Specific Comments

1. R2. "As shown in Figure r2, the year 2006 is a wet year with the total river discharge over 10,000 m3 s-1 and the monthly river discharges during July-August over 20,000 m3 s^{-1}. More justifications on why choosing July and August 2006 please see our response to the comment" In addition of what you expressed in your answer, your approximation will have to consider a comparison all data from July with those of August between 1999 and 2010.

Response:

As suggested, we have included the climatological annual cycle of total river discharges during the years 1999 to 2010 in the Figure 4 of our revised manuscript. The figure together with Figure s1 in the supplement demonstrate that the year 2006 is a wet year and that July and August are among the typical wet season.

Anonymous Referee #1

General Comments

Congratulations for the research work, there is a large amount of work summarised in a clear and well structured document.

Specific Comments

1. Page 4, Line 23: The description of the 1-D model does not refer to any other study, Does this mean that the model was developed for this research? Is there any reference for validating this 1-D model?

Response:

The 1-D model was configured and coupled with the 3-D model as detailed in Hu and Li (2009). The 1D-3D coupled model has been validated and applied to study the water-nutrients-sediment budgets (Hu and Li, 2009; Hu et al., 2011), the oxygen budget (Wang et al., 2017), and the nutrient fluxes between the sediment and overlying waters in the Pearl River Estuary (Liu et al., 2016) . In the revised manuscript, we included more details of the 1D-3D coupled model to make it clearer. References for the validation are given at the end of this file.

2. The configuration description of the 1-D model is quite small in contrast with the ones for the 3-D model and the water quality model.

Response:

As suggested, we included more descriptions of the 1-D model in the 'Physical model' section in our revised manuscript.

3. Page 7, Lines 13 and 14: mention any quantitative description for the temperature and salinity validation as it is done for the tide.

Response:

As suggested, we included some quantitative description for the temperature and salinity validation in our revised manuscript as below:

"The comparisons show small normalized RMSDs (both <0.60 of standard deviations of observations) and high correlations (>0.90 for salinity and >0.80 for temperature) between the model and observations, indicating that the coupled physical model is robust to reproduce the broad-scale features and intra-seasonal patterns of the main hydrodynamic features in the PRE."

More detailed validations can be referred to the Section 3 in our previous study (Wang et al., 2017).

4. Model Validation section: No validation mentioned of the 1-D model

Response:

In this study, we use the 1D-3D coupled model with a purpose to account for the interactions of hydrodynamics between the river network and the estuary. The 1D and the 3D model were run in parallel and they exchange model quantities across the coupling interface. The eight outlets (shown in Figure 1 in original manuscript) are the exchange interface of the 1D and 3D models, which serve as the lower boundaries of the 1D model and at the same time the upper boundaries of the 3D model. At each time step, the 3D model utilizes the simulated discharges obtained from the 1D model as the river boundary forcing, and sends the simulated water levels to the 1D model as the downstream boundary forcing as a feedback. Therefore the eight outlets are very important for the assessment of the coupled model performance. We have validated the simulated water levels and/or river discharges against observations at eight outlets in years 1999 (Hu and Li, 2009) and 2006 (Wang et al., 2017 and P7 lines 8-11 in the manuscript). Note that the validations at eight outlets are for both 1D and 3D models. In our revised manuscript, we now provide more details of the 1D-3D coupled model's configuration (in 'Physical model' section) and validations (section 2.1.2) to make it clearer.

5. Section 2.2: Are there any other hypoxia events reproduced by the model throughout the period Nov. 2005 to Dec. 2006, apart of the summer 2006? Are these events observed or not observed? Is the hypoxia event of summer 2006 the only event simulated by the model?

Response:

As shown in Figures 4 and 5 in the revised manuscript, our model simulates hypoxia from April to October in 2006. In the simulation, the hypoxia starts to develop in April, peaks in August, and disappears in October. However, oxygen observations are only available in July and August 2006 when hypoxia are observed, while for other months no observations are available for validating the model simulated hypoxia. This is one of the main reasons why in the manuscript we only focused on July and August in 2006 to study the impacts of riverine inputs on hypoxia and oxygen dynamics in the Pearl River Estuary. Additionally, the previously reported hypoxia also mainly occurred in July and August (Cai et al., 2013). Another motivation of focusing on July and August is that these two months are among the typical wet seasons in the PRE (Figure 4b), which is in line with our study on the effects of riverine inputs. Results of hypoxia for the whole year were added in the section 3.1 in our revised manuscript. Plus, we also provided more justifications on why we focused on July-August only (section 3.1 in the revised manuscript) and added discussions on how representative or comparable was the hypoxia in this time of the year to that of other months or years (section 4.1 in the revised manuscript).

We agree that it would be an interesting topic to study the annual cycle and multi-years variations of hypoxia in the Pearl River Estuary. However, it will be quite hard to study the annual cycle and multi-years variations of hypoxia in this region due to the insufficiency of observational data. And to our knowledge, there are currently few studies on these two topics. Nevertheless, we believe that our study can provide some scientific basis and guidance for further modelling or observational studies on the hypoxia in the Pearl River Estuary.

6. A map showing the location of the study area in a global context will be a great help for the reader which is not familiar with the study area.

Response:

We tried as suggested but found it hard to find the Pearl River Estuary in a global map. Alternatively, the location of the Pearl River Estuary in a map of South China Sea is now shown in the revised manuscript.

Technical Corrections

- Page 2, Line 17: Why the reference is made on Italic font (Diaz and Rosenberg)

• Not sure which the format for the references within brackets:
Page 2 Lines 19 and 20
Page 5 Line 19
Page 6 Line 8

Response:

We have double checked and corrected the format of references throughout the manuscript.

• Page 10, Line 8: where is the definition for **Cont**? I see there are the names for each simulations. Could be possible to mention this before start describing each of them? (The 7 simulations are named as . . . and summarized in table 1)

Response:

As suggested, we defined the name for each simulation before describing them in the revised manuscript as below:

"Each group has two simulations, where the concentration of one type of the riverine inputs at eight river outlets is decreased and increased by 50%, respectively. These simulations are named as Base, RivDO-50%, RivDO+50%, RivNtr-50%, RivNtr+50%, RivPOC-50% and RivPOC+50%, with the basic information of each simulation presented in Table 1."

• Figure 1a [page 24]: It could be just the pdf copy, but the y-axis (latitude) top and bottom labels are missing a 2 (23.5 and 21.5)

Response:

We have revised the figure. Please see the Figure 1 in our revised manuscript.

Suggestions

• Page 2, Line 13: Enhance instead of exaggerate

Response:

We modified this sentence as:

“The classic paradigm for explaining the relations is that excessive nutrient inputs to the coastal oceans stimulate the high primary productivity there, and the subsequent decomposition of the organic matter in the bottom water consumes significant amount of DO that leads to hypoxia.”

• Page 5, Line 8: There is a reference for the Mellor-Yamada model but not for the Smagorinsky-type formula. It should be a reference for each of them as they are in the same sentence (line).

Response:

Reference has been added in our revised manuscript. The sentence now in the revised manuscript is:

“The horizontal mixing is parameterized by a Smagorinsky-type formula (Smagorinsky, 1963) and the vertical mixing is calculated by the Mellor-Yamada level 2.5 turbulent closure model (Mellor and Yamada, 1982).”

• Page 7 Line 7: Could be possible to specify if the summer is on the north or south hemisphere? It is in the north hemisphere but the suggestion points to be specific as the moths to consider are not the same ones.

Response:

We modified the sentence in the revised manuscript as ‘The physical-biogeochemical model has been validated against available observations during the July of 1999 in Hu and Li (2009) and July-August 2006 in Wang et al. (2017)’.

• Page 18, Line 4: anthropogenic perturbations instead of just perturbations

Response:

Revised as suggested.

Reference

Hu, J. and Li, S.: Modeling the mass fluxes and transformations of nutrients in the Pearl River Delta, China, J. Mar. Syst., 78(1), 146–167, doi:10.1016/j.jmarsys.2009.05.001, 2009.

Hu, J., Li, S. and Geng, B.: Modeling the mass flux budgets of water and suspended sediments for the river network and estuary in the Pearl River Delta, China, J. Mar. Syst., 88(2), 252–266, doi:10.1016/j.jmarsys.2011.05.002, 2011.

Liu, D., Hu, J., Li, S. and Huang, J.: Validation and application of a three-dimensional coupled water quality and sediment model of the Pearl River Estuary, Huanjing Kexue Xuebao/Acta Sci. Circumstantiae, 36(11), 4025–4036, doi:10.13671/j.hjkxxb.2016.0145, 2016 (in Chinese with English abstract).

Wang, B., Hu, J., Li, S. and Liu, D.: A numerical analysis of biogeochemical controls with physical modulation on hypoxia during summer in the Pearl River estuary, Biogeosciences, 14(12), 2979–2999, doi:10.5194/bg-14-2979-2017, 2017.

Anonymous Referee #2

Summary:

In this manuscript the authors use a physical-biogeochemical model to examine a hypoxic event in the Pearl River Estuary (PRE) in July and August 2006. They conduct several numerical experiments in order to determine the relative impact of riverine inputs of oxygen, nutrients and organic matter on hypoxia in the PRE. They specifically examine three processes that affect oxygen dynamics: re-aeration due to air-sea oxygen flux, sediment oxygen demand, and all remaining processes which together is referred to as WCP (water column production). This is a well-written manuscript with some very interesting results, but some clarifications, some more discussion, and a few additional experiments should be performed before publication. The comments below are lengthy, but if addressed fully the resulting paper would be a very valuable contribution to Biogeosciences.

Major comments:

1. As I understand it, all results shown in the manuscript are for July and August 2006. This should be made clearer in the abstract, which is written more like this is the "general" case for the PRE. I understand that the model has only been evaluated for July and August 2006, so we don't really know whether the oxygen concentrations at other times of the year are correct or not; however, as a reader I was very interested to see results for the whole summer (May to September), or even for the whole year, rather than just for two months of one year. How does the temporal variability of hypoxia change in the numerical experiments? This analysis does not seem complete without this addition.

Response:

We have made it clearer in the revised manuscript that the results were based on July and August 2006 only. As suggested, results of hypoxia for the whole year were shown in the section 3.1 in our revised manuscript. Plus, we also provided more justifications on why we focused on July-August only (section 3.1 in the revised manuscript) and added discussions on how representative or comparable was the hypoxia in this time of the year to that of other months or years (section 4.1 in the revised manuscript).

In terms of validations, in this manuscript we have only presented the model-data comparison results in July and August 2006. However, the physical-biogeochemical model has been thoroughly validated against not only physical variables (i.e. water levels, salinity, and temperature), DO concentrations, but also the historical observations of some important biological variables (e.g. chlorophyll and particulate organic carbon) and processes (i.e. re-aeration, sediment oxygen demand, and primary productivity) (see Wang et al., 2017). Our model is able to reproduce the observed hypoxia near the Modaomen sub-estuary and the main processes associated with DO. Previous studies have also reported the hypoxia near the Modaomen sub-estuary with the similar spatial extents and characteristics as the model simulated (Cai et al., 2013; Lin et al., 2001; Zhang and Li, 2010).

2. As a reader, I was also wondering whether July and August 2006 was a typical year. Was 2006 a particularly dry July/August? Or wet time period? Are the results of the sensitivity experiments conducted here likely to hold in other years?

Response:

The year 2006 is a wet year with the total river discharge over 10,000 $m^3 s^{-1}$ (Figure s1 in the supplement of our revised manuscript) and the monthly river discharges during July-August over 20,000 $m^3 s^{-1}$ (Figure 4 in revised manuscript). More justifications on why choosing July and August 2006 are now added to section 3.1 in our revised manuscript. We also added discussions on how representative or comparable was the hypoxia in this time of the year to that of other months or years (section 4.1 in the revised manuscript).

We agree that it would be an interesting topic to study the annual cycle and multi-years variations of hypoxia in the Pearl River Estuary. However, it will be quite difficult to study the annual cycle and multi-years variations of hypoxia due to the insufficiency of observational data. And to our knowledge, there are currently few studies on these two topics. Nevertheless, we believe that our study can provide some scientific basis and guidance for further modelling or observational studies on the hypoxia in the Pearl River Estuary. Guided by this model simulation, we actually have conducted two observation cruises in the Modaomen sub-estuary in January and August this year.

3. One of the main results of this manuscript was that hypoxia in the PRE is not sensitive to nutrient concentrations of the river water entering the region (unlike the Chesapeake Bay and the Gulf of Mexico, for example). This result, however, has to be at least slightly dependent on what value is used for the nutrient concentrations in the eight rivers. What concentrations

are used and are they realistic? Where do these concentrations come from? A terrestrial-biogeochemical or watershed model? More detail is needed here. Also, it sounds as if only the nutrient concentrations were changed in the largest river, not all eight rivers. The authors need to show results of changing the concentrations in all eight rivers, not just the largest, since the smaller ones closest to the hypoxic zone might impact the hypoxia zone more than the large river, which is farther from the region of hypoxia. (The same is true for the oxygen and POC experiments.)

Response:

As suggested, we have included more details of the riverine inputs at the end of the section 2.1.1 in the revised manuscript:

"River boundary conditions of biogeochemical variables were derived from the monthly observations in 2006 collected by the State Oceanic Administration (including nutrients and DO) and from a previous study (including different classes of dissolved organic carbon, particulate organic carbon, dissolved organic nitrogen, particulate organic nitrogen, dissolved organic phosphorus, and particulate organic phosphorus) (Liu et al., 2016)."

We have also improved the explanations of the numerical experiments setting in the section 2.3 in the revised manuscript.

4. This analysis compares the impact of sediment oxygen demand, re-aeration and WCP on hypoxia. However, this is misleading since WCP is the sum of multiple positive and negative terms. Thus this term is likely smaller than its components. For a more complete analysis, the authors need to separate out the various components of WCP, including respiration, nitrification, water column remineralization etc. . . This is particularly important because in the discussion they state that in the PRE water column respiration/remineralization is not as important as it is in places such as the Chesapeake Bay. But we cannot see this (truly interesting!) result unless the authors isolate these terms.

Response:

We understand the reviewer's concerns about the application of water column production (WCP). In our previous study (Wang et al. 2017), we conducted the DO budget analysis and found that the magnitude of nitrification and oxidation are much smaller than the respiration. For the convenience of discussions, we used the water column respiration (WCR, the sum of respiration, nitrification, and remineralization/oxidation) to represent the gross rate of DO consumptions in the water column, a term that has been widely used in the field (Murrell and Lehrter, 2011) and modeling studies (Li et al., 2015; Yu et al., 2015a). According to our budget analysis in Wang et al. (2017), the sediment oxygen demand dominated the DO depletion both for the Pearl River Estuary and the high frequency zone (please see Figure 11a and 12a in Wang et al. 2017), which has been reported by previous studies (Yin et al., 2004; Zhang and Li, 2010) in other years. In the contrast, the hypoxia in the Chesapeake Bay is dominated by the water column respiration (Li et al., 2015). Differences in the relative importance of water column respiration versus sediment oxygen demand in the two systems (the Pearl River Estuary and the Chesapeake Bay) have been widely accepted by other studies (Rabouille et al., 2008; Hong and Shen, 2013).

In this study, we used the water column production (WCP, the sum of water column respiration and photosynthesis), the re-aeration, and the sediment oxygen demand to represent the net effects of water column, the air-sea interface, and the water-sediment interface, respectively. According to our DO budget analysis in Wang et al. (2017), the photosynthesis and respiration were two major oxygen source or sink term in the water column. Considering that photosynthesis and respiration are both closely and directly correlated to phytoplankton growth, they have the similar distributions and responses to changes in riverine inputs. For example, increasing the nutrient loading will facilitate the growth of phytoplankton and hence both photosynthesis and respiration. Based on these reasons, we did not consider each component separately in our current manuscript.

As suggested, we included more detailed explanations of using the WCP in page 6 of the revised manuscript. Equations for each component of the WCP are now included in the Appendix A of the revised manuscript.

5. It is not completely clear why the "physical modulation" method is needed. If this is a fully coupled physical-biogeochemical model (as is stated), then why can't the authors simply save each of the oxygen flux terms in the oxygen budget? Presenting results in units of DO per unit time (as is done in Figure 7) would be much more helpful for the reader. The idea of different "species" of oxygen seems a bit convoluted. Clearly REA, WCP and SOD have

units of oxygen per unit time (see equation 1). Showing figures of these quantities, rather than DO_REA, DO_WCP and DO_SOD would make the manuscript more clearly understandable to readers.

Response:

The physical modulation method (now has been renamed as DO species tracing method in our revised manuscript for clarity) was firstly introduced and implemented in our pervious study (Wang et al. 2017) to understand the underlying processes and mechanisms of hypoxia in the Pearl River Estuary. We also conducted DO budget analysis in our previous study and found the advantages of using DO species tracing method in explaining the occurrence, the spatial extent, and the duration of hypoxia in the Pearl River Estuary. Comparing with the budget analysis, the DO species tracing method can demonstrate the spatial connection of each oxygen source or sink process occurring at different locations (e.g. the influence of sediment oxygen demand on adjacent waters and the vertical penetration of re-aeration supplied oxygen).

In the current study, by using the DO species tracing method, we found the buffering effects of re-aeration. That is, the re-aeration can respond to the anthropogenic perturbations of riverine inputs rapidly and hence moderate the DO changes caused by these perturbations. In addition, we further depicted the interactions between each oxygen source and sink processes quantitatively. For example, in the Cont simulation (now is renamed as Base simulation), the sediment oxygen demand removed surface oxygen by 2.22 mg L^{-1}, which switched the re-aeration from the sink (-1.45 mg L^{-1} day^{-1}) to the source (0.55 mg L^{-1} day^{-1}) of DO in surface waters.

In our revised manuscript, we have provided more details of the DO species tracing method and made the definition of its associated variables clearer (section 2.2 in our revised manuscript).

6. I really like the idea that re-aerated surface waters can penetrate to the bottom water and offset the changes in DO caused, for example, by increased nutrient, DO, or OM riverine inputs. The authors discuss that this is not the case on the Gulf of Mexico shelf, where hypoxia occurs as a very thin layer near the bottom. The comparison and emphasis on the Gulf of Mexico seems a bit out of place, since the PRE seems to be more similar to the Chesapeake Bay in many ways. The discussion could be strengthened by making a three way

comparison between the Chesapeake, Gulf of Mexico and the PRE. Isn't the re-aeration process described here similarly important in the Chesapeake Bay, where hypoxia occurs as a thick layer, which is not far from the surface in a typical July/August?

Response:

Firstly, we appreciate reviewer's encouraging comment on our discussion on the re-aeration. However, there seems some misunderstanding in the discussion about the case of the northern Gulf of Mexico (NGOM). In our manuscript, we conducted the comparison between the PRE and the NGOM with a purpose to explain and understand the strong re-aeration in the PRE. As we discussed in our original manuscript (P17 line 11-17), the strong re-aeration is a result of the high sediment oxygen demand and the shallow waters in the PRE. In the contrast, the re-aeration in the NGOM is overall an oxygen sink to surface waters in summer (Yu et al., 2015b) because of the weaker sediment oxygen demand and deeper waters (P17 line 17-23 in original manuscript). However, we did not state that the oxygen supplied by surface re-aeration cannot penetrate to the bottom waters of the NGOM as there is no published studies investigating this mechanism in NGOM. Actually, we think that without applying the species tracing method, it is hard to estimate the effects of surface re-aeration on the bottom waters because it depends highly on the magnitude of re-aeration, the water depth, and the hydrodynamic conditions.

Secondly, we agree that it will be very interesting to discuss the role of re-aeration on hypoxia in other hypoxic systems (e.g. the NGOM and the Chesapeake Bay) and make the comparisons with the PRE. However, extended discussion is not feasible due to a lack of data and relevant studies in other hypoxic systems. Take the Chesapeake Bay as an example, we don't have re-aeration data to figure out the importance of re-aeration in the Chesapeake Bay. As suggested, we included some explanations for why we did not include the Chesapeake Bay into discussions and our speculations of re-aeration in the Chesapeake Bay in the section 4.3 of our revised manuscript:

"In the other hypoxic system, the Chesapeake Bay as described earlier, extended discussion on the importance of re-aeration is limited by a lack of observations and relevant studies of re-aeration. Nevertheless, according to our results, we can speculate that the re-aeration might be quite important in the Chesapeake Bay because the strong water column respiration can draw down the surface DO concentrations and enhance the re-aeration. However, the penetration of the oxygen supplied by re-aeration to the bottom layer is hard to be estimated without applying the DO species tracing method like our study or method similar in the Chesapeake Bay. In general, more relevant studies are required to examine the role of the re-aeration on hypoxia in the Chesapeake Bay."

7. There is some considerable overlap with the authors' previous publication (Wang et al.,2017, BG). For instance, it appears to me that one of the main points in the abstract of the current manuscript: "Model results showed that hypoxia in the Pearl River Estuary was confined to the shelf off the Modaomen sub-estuary with a hypoxic area of 200km2 mainly due to the combined effect of re-aeration and sediment oxygen demand" was actually a primary result of this previous publication. This should be made clearer in the abstract and introduction. Clearly this study builds off the previous study. Although the previous study is mentioned in the abstract, the differences between the current study and the previous study should be made clearer to the readers.

Response:

As suggested, we have clarified the differences between the current and previous studies in the revised manuscript.

Minor Comments:

8. Abstract last sentence – suggest changing this to: "This study highlights the importance of re-aeration in determining the hypoxic extent and in reducing hypoxia variability in shallow estuaries."

Response:

Revised as suggested. We changed the sentence as below:

"This study highlights the importance of re-aeration in reducing hypoxia variability in shallow estuaries."

We removed "the hypoxic extent" because it is the conclusion from our previous study (Wang et al. 2017).

9. Abstract – Define here (and in introduction) that by re-aeration you mean a flux of oxygen across the air-sea interface. (Currently this doesn't occur until page 6).

Response:

Revised as suggested. The re-aeration is defined in the abstract and introduction in the revised manuscript as below:

(In *Abstract*) "Changes in the riverine inputs of DO and nutrients had little impacts on the simulated hypoxia because of the buffering effects of re-aeration (DO fluxes across the air-sea interface)"

(In *Introduction*) "A more recent study by Wang et al. (2017) further points out that the balance of oxygen in the PRE is mainly controlled by the source and sink processes occurring in local and adjacent waters, among which the re-aeration (DO fluxes across the air-sea interface) and SOD determine the spatial distributions and durations of hypoxia in the PRE."

10. Introduction – Authors could mention climate change as another anthropogenic impact, since recent studies are showing that increasing temperatures have a large impact on increasing hypoxia.

Response:

Revised as suggested. We mentioned climate change in Introduction of the revised manuscript as follow:

"Recent years have also seen an increasing number of studies showing that climate variation contributes to the spreading hypoxia in coastal oceans. The climate variation can change the ocean circulation or the vertical stratification to alter the balance between the oxygen source and sink processes (Rabalais et al., 2010). A modeling study conducted in the Chesapeake Bay has shown the good correlations between the climate variation, stratification, and the observed DO (Du and Shen, 2015). In addition, the global warming, as a symptom of climate variation, is another factor that can enhance the hypoxia. For example, Laurent et al. (2018) predicted a prolonged and more severe hypoxia in the northern Gulf of Mexico under a projected future (2100) climate state where the global warming leads to reduction in oxygen solubility and increased stratification."

11. P2, line 7: Why is there a ten-year lag? Does this occur in an estuary like the PRE? Or maybe it's not relevant here.

Response:

The ten-year lag between eutrophication and hypoxia is estimated on the global scale (Rabalais et al., 2010). There hasn't been study on the time lags between the eutrophication and hypoxia in the Pearl River Estuary. We have deleted this sentence in our revised manuscript.

12. Page 4, line 11: This paragraph is talking about how nutrient inputs to the Pearl River Estuary can impact hypoxia, but this line is about particulate organic carbon, which could be moved to the following paragraph talking about organic matter. Page 4, line 16: What is the organic matter? Is it only POC mentioned in line 11? Or does it include PON (nitrogen) and dissolved organic matter? Which type of organic matter primarily contributes to hypoxia?

Response:

As suggested, we moved this sentence to the next paragraph describing particulate organic carbon in our revised manuscript. In P4 line 16 of the original manuscript, organic matter represents the particulate organic carbon only. We have clarified it in our revised manuscript. Now the sentence in the revised manuscript is:

"In addition to the nutrient loading, the particulate organic carbon (POC) are another important form of anthropogenic inputs that influence the hypoxia in the estuary (~2.5×10^6 t yr^{-1} from the Pearl River network (Zhang et al., 2013))."

13. P4, line 20: How are these models dynamically coupled? If these were dynamically coupled, the estuarine model would provide feedbacks to the riverine model. Is that the case? Also, the model set up seems to assume that there are no freshwater or nutrient sources (from

the land) into Mirs Bay, Daya Bay or Honghai Bay. Is there evidence to support this assumption?

Response:

The 1D river network model and the 3D estuary model are dynamically coupled through the eight river outlets. These two models are run in parallel and their model quantities are exchanged across the coupling interface (eight outlets) during runtime. At each time step, the 3D model utilizes the simulated discharge obtained from the 1D model as the river boundary forcing, while the 3D model sends the simulated water levels to the 1D model as the downstream boundary forcing for the next time step. More detailed descriptions of the coupling can be seen in Hu and Li (2009) and we have included more details in the "Physical model" section of our revised manuscript.

The riverine input of freshwater and nutrient fluxes entering the Mirs Bay, Daya Bay, and Honghai Bay are much lower than those from the Pearl River Network. In addition, the Mirs Bay, Daya Bay, and Honghai Bay are quite far away from the hypoxic zone. In the wet season, the Pearl River Estuary is dominated by the southwesterly monsoon and the Pearl River plume mainly propagate eastward. Therefore, we neglected freshwater or nutrient sources entering the Mirs Bay, Daya Bay, and Honghai Bay, and also neglected contributions of these regions to the oxygen dynamics in hypoxic zone.

14. P5, "Water quality model" section: In this section the authors need to describe more clearly where their riverine biogeochemical concentrations are derived from, since these are at the very heart of their numerical experiments. Do concentrations of the 26 state variables all come from the riverine model described above? If so, more information regarding the details of the biogeochemistry of the riverine model is needed. Where do the outer boundary conditions come from, for the estuarine model? How about atmospheric deposition of nutrients, like nitrate and phosphate? Are all these assumed to be negligible? How realistic is this assumption?

Response:

We added the following in the "water quality model" section (renamed as "biogeochemical model section" in our revised manuscript):

"River boundary conditions of biogeochemical variables were derived from the monthly observations in 2006 collected by the State Oceanic Administration (including nutrients and DO) and from a previous study (including different classes of dissolved organic carbon, particulate organic carbon, dissolved organic nitrogen, particulate organic nitrogen, dissolved organic phosphorus, and particulate organic phosphorus) (Liu et al., 2016). The open boundary conditions of biogeochemical variables were specified following Zhang and Li (2010)."

In this manuscript, we did not include the atmospheric deposition of nutrients because the riverine nutrient input is the dominant nutrient source in the Pearl River Estuary.

15. P6, line 1: Since one of the conclusions of the manuscript is the relative importance of SOD compared to WCP (see abstract), here the terms making up "WCP" need to be written out explicitly.

Response:

There might be some confusion over whether the conclusions are from our previous study (Wang et al. 2017) or this study, which we have better clarified in the revised manuscript. The relative importance of SOD (sediment oxygen demand) and WCP (water column production) is one of the conclusions from our previous study (Wang et al. 2017), but not in current study. This study builds on Wang et al. (2017) to focus on the response of each oxygen source and sink process to the different riverine inputs and their impacts on the hypoxia. We did emphasize the importance of SOD and the re-aeration to hypoxia in this manuscript but only aim to remind readers some key features of hypoxia formation in the Pearl River Estuary before more extensive investigations through sensitivity experiments.

Following the suggestion, equations of each component of WCP and some relevant descriptions have been added in the Appendix A of our revised manuscript.

16. P6, line 7: Please provide the equations for photosynthesis, respiration, nitrification and oxidation (potentially in an appendix), and provide values of all parameters used. (The reference used here for the model is a white paper from 14 years ago. The model has been

adjusted since then. Are the authors really using those original parameters and equations? Please include information on the version of the model that is being implemented.)

Response:

As mentioned in our response to comment #4, we provided the equations for each component of WCP and the descriptions of relevant parameters in the Appendix A of our revised manuscript. The reference here (HydroQual, 2004) is the manual of the RCA. Equations we used in this manuscript are the same as in this document. Parameters are set according to this document and previous studies (Liu et al., 2016; Zhang and Li, 2010) that used the same physical-biogeochemical model for the Pearl River Estuary. Values of the primary parameters have been summarized in Table A2 in our revised manuscript.

17. P6, line 12: Define what is meant by "dissolved matter". Is this dissolved organic matter, i.e. DON and DOC? Or dissolved nutrients, i.e. ammonium? Or both?

Response:

We think here the reviewer meant P6, line 27. Here the 'dissolved matter' is referred to all nutrients and DO considered in our model. We have clarified it in our revised manuscript as below:

"In the RCA, a sediment flux module is incorporated to simulate the depositional flux of particulate organic matter (i.e. particulate organic carbon, particulate organic nitrogen, and particulate organic phosphate), the diagenesis processes in the sediment, and the transport of nutrients and DO from the sediment to the overlying water (Figure 2). Detailed descriptions about the sediment flux module can be seen in the Appendix B."

18. P6, line 18: As above, please provide values of these parameters within this paper (possibly in an appendix.)

Response:

Values of primary parameters have been provided in Table A2 of our revised manuscript.

19. P6, line 27: As above, please provide equations and parameter values for DO_sed (possibly in an appendix)

Response:

As suggested, we have provided equations of DO_sed and descriptions about our sediment flux module in the Appendix B of our revised manuscript.

20. P7, line 2: Earlier the authors stated that this is a dynamically coupled model, but here it sounds as if the water quality model is being run offline from the physical model, which would indicate that there is no dynamic coupling, and the biological simulation cannot impact the physics. Please make it clearer in the text as to whether the models are truly dynamically coupled, or simply run offline.

Response:

True, the physical model and the water quality model are only one-way coupling, where the physical model can affect the water quality model but the water quality model cannot impact the physical model. As suggested, we have revised the model description in our manuscript.

20. P 7 line 4: What data is being referred to here and how was it used? Data assimilation? Forcing? Validation?

Response:

Here we refer to the data used as the model input (e.g. riverine input and open boundary conditions) and for the model validation. We removed this sentence in the revised manuscript and instead we gave more detailed descriptions as below:

"Initial conditions were obtained from a two-month spin-up simulation which was repeated for three times to reach a steady state. River boundary conditions of biogeochemical variables were derived from the monthly observations in 2006 collected by the State Oceanic Administration (including nutrients and DO) and from a previous study (including different classes of dissolved organic carbon, particulate organic carbon, dissolved organic nitrogen, particulate organic nitrogen, dissolved organic phosphorus, and particulate organic phosphorus) (Liu et al., 2016). The open boundary conditions of biogeochemical variables were specified following Zhang and Li (2010)."

21. P7, line 7: There are actually very few observations of DO presented in Wang et al. (2017). Are these really the only observations available of DO in the PRE region? Is nothing more available since 2006? It also looks like the oxygen data shown in Wang et al. rarely, if ever, actually go hypoxic?

Response:

During 2006, we only have observations in July and August. However we do have collected and analyzed the observation data from 1993 to 2009 (Figure r3), finding that there are very limited observations near the Modaomen sub-estuary (where the high frequency zone is located). Nevertheless, the model simulated hypoxia near the Modaomen sub-estuary in this study has also been reported in previous observational (Cai et al., 2013; Lin et al., 2001) and modelling studies (Zhang and Li, 2010), and the simulated spatial extent and characteristics here are consistent with those from previous studies. Additionally, noticing that the available oxygen data for validating simulated hypoxia is insufficient, in Wang et al. (2017) we have thoroughly validated the model against not only physical variables (i.e. water levels, salinity, and temperature), DO concentrations, but also the historical observations of some important biological variables (e.g. chlorophyll and particulate organic carbon) and processes (i.e. re-aeration, sediment oxygen demand, and primary productivity).

For the observational data in Wang et al. (2017), the minimum observed DO concentrations are below the hypoxic level (defined as 3 mg L^{-1} here) and the observed hypoxic area is about 150 km^2 (please see Figure r1). It should be noted that the hypoxic area shown in Figure r1 was estimated based on the observation available at limited time and space and might not fully represent the true state of hypoxia in the entire Pearl River Estuary.

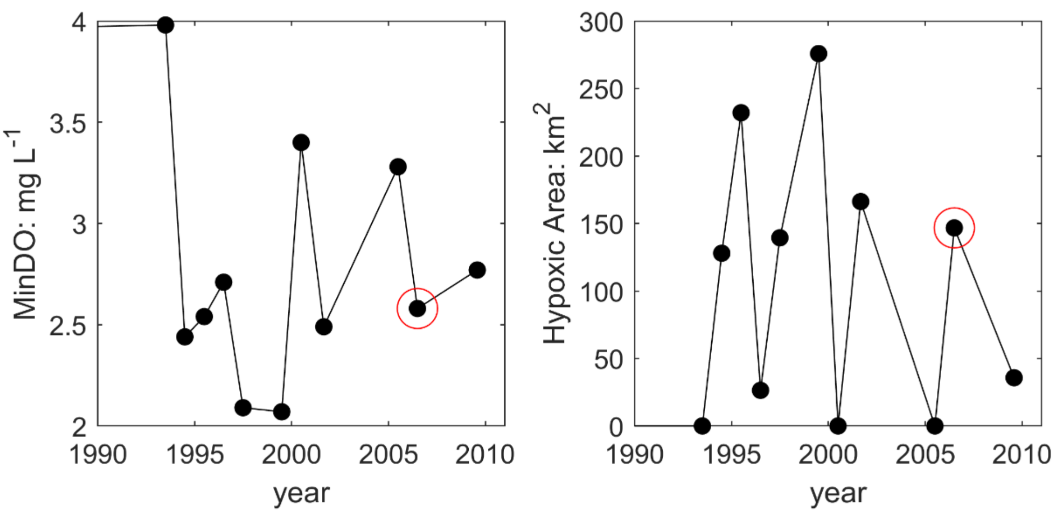

Figure r1. Multi-years variations in the observed minimum DO concentration (left panel) and hypoxic area. Red cycles indicate the July-August 2006.

22. P8, line 3: Because the authors have only evaluated model results for oxygen in July and August 2006, does this mean these results only are valid for that year? Is that a particularly wet year or a dry year? Or an average year? Can you put this year in perspective? (Perhaps in the discussion?)

Response:

Please see our response to comment #2.

23. Page 8, line 13: This sentence seems to indicate that this estimation is not straightforward only in river dominant estuaries. How about tide dominant estuaries, which can also be impacted by local and remote source and sink processes? P9, line 8: What does “Cont” stand for? Continuous? I would think “Base” or “Reference” or “Realistic” might be better descriptions of this simulation.

Response:

The estimation is not straightforward in the tide dominant estuaries either. According to our results, the oxygen supplied by re-aeration can penetrate to the bottom waters through the vertical diffusion (see section 4.1 in Wang et al. (2017) and also P15 line 13-18 in the original manuscript). It follows that in a tide dominant estuary, the tide-induced mixing can facilitate the penetration. In the revised manuscript, we have modified the sentence as below:

"However, in a river and tide dominated estuary such as the PRE, this estimation is not straightforward because of the spatial connections of each source and sink process occurring in different locations."

The 'Cont' meant a control case. As suggested, we have renamed 'Cont' as 'Base' simulation in our revised manuscript.

24. Section 2.3: The text is not clear here. Are the concentrations of DO and nutrients reduced in all 8 rivers, or only the Humen? Also it is not clear whether the concentrations of DO and nutrients in the experiments are set to what is predicted in 2050, or are simply increased by 50%. In reality, the concentrations in 2050 will depend on management decisions which are very difficult to predict. I think it's best to state here that you increased/decreased the concentrations by 50%, and if you want to convince the reader that these are representative of 2050 and 1970 respectively, then bring this up in the discussion. Please provide the concentrations of DO and nitrate (as an example nutrient) used in each of these experiments. More detail is needed here. If freshwater flows stay the same, this should be stated.

Response:

The riverine inputs of DO, nutrients, and particulate organic carbon are reduced in all 8 rivers. In RivNtr+50% simulation, we increased the nutrient loading by 50% in all 8 rivers, which is close to the increase in nutrient loading in 2050 predicted by Strokal et al., (2015). As suggested, we have provided more details about the numerical experiments in the section 2.3 of our revised manuscript.

25. P11, line 19: Remove HFZ acronym since it is not used elsewhere. Please define the hypoxic frequency zone more quantitatively since this is used throughout the text. Where exactly is this? It's hard for the reader to know. Does it change in time?

Response:

We removed the HFZ acronym in the revised manuscript as suggested. The high frequency zone is defined in page 13-14 in our revised manuscript as below:

“The high frequency zone here is defined as the area encompassed by the 10% isoline of July-August averaged hypoxic frequency and is denoted by the white contour in Figure 8.”

We have depicted the high frequency zone with white lines in Figure 8 in the revised manuscript. The high frequency zone remains unchanged in time in our model simulation.

26. P11, line 23: The word “additionally” should come before “occurs” since hypoxia also occurs on the shelf.

Response:

Revised as suggested.

27. P13, line 9: Also list percent changes in hypoxia area and volume, as was done above.

Response:

Revised as suggested. In page 14 of the revised manuscript, we say:

“As a result, the hypoxic area and hypoxia volume only increase by about 10% in the RivNtr-50% simulation in relative to the Base simulation”

28. P13, line 22: Considering using PRE acronym earlier. (It hasn’t been used much since very early in the manuscript.)

Response:

Revised as suggested.

29. P14, line 14: Aren’t there two POC simulations/experiments, not three?

Response:

Here we meant the two POC simulations and the Cont simulation (renamed as Base simulation as suggested). As shown in table 1 in our revised manuscript, we have two POC simulations with increased or decreased riverine inputs of particulate organic carbon by 50%. We have clarified it in our revised manuscript as below:

"The two POC simulations and the Base simulation have identical physical processes and hence same temperature limitation."

30. P14, line 24: In the results, it would make sense to discuss Figure 7 (the "Cont" results) before the sensitivity experiment results, rather than inside the section 2.3 sensitivity experiment section.

Response:

We think the reviewer meant section 3.3 instead of section 2.3 of the original manuscript here. In the section 3.3 of our original manuscript, we found that changing the riverine inputs of particulate organic carbon could affect the re-aeration by changing the sediment oxygen demand and water column production (WCP). This finding leads to the discussion of Figure 7 (Figure 9 in the revised manuscript) which is to demonstrate the mechanisms of how the sediment oxygen demand influence the surface re-aeration quantitatively. Therefore we would like to keep the current presentation flow.

31. P14, line 25: The figure shows 0.53, not 0.55?

Response:

Right the value should be 0.53. We have corrected it in the revised manuscript as below:

"First, the SOD consumes bottom DO by 0.53 mg L^{-1} day^{-1} and decrease the upward advective DO fluxes reaching the upper layer by 0.34 mg L^{-1} day^{-1}."

32. P15, line 1: How does the reader compute 0.13 from Figure 7?

Response:

We have more detailly described the calculation in our revised manuscript as below:

"As shown in Figure 8, the SOD can affect the DO concentrations in the upper layer indirectly through the interactions with the vertical advection, the vertical diffusion, and the horizontal advection as explained below. First, the SOD consumes bottom DO by 0.53 mg L^{-1} day^{-1} and decrease the upward advective DO fluxes reaching the upper layer by 0.34 mg L^{-1}

day^{-1}. Second, the deoxygenation induced by SOD can increase the vertical DO gradient and facilitate the downward vertical diffusion of oxygen by 0.02 mg L^{-1} day^{-1} from the upper layer. Finally, the decreased upper DO concentrations affect the horizontal outfluxes of DO and ultimately result in a higher net horizontal advective flux by 0.21 mg L^{-1} day^{-1}. Consequently, the net effect of the SOD on the upper DO is 0.15 mg L^{-1} day^{-1}. which causes a decline of 2.22 mg L^{-1} in DO concentrations in the surface layer. "

In our original manuscript, we ignored the interactions between the sediment oxygen demand and the vertical diffusion to get 0.13 mg L^{-1} day^{-1}.

33. P15, line 2: Based on equation 8, I would think the dark blue DO bar would equal the sum of all the other bars, but this doesn't seem to be the case? Why is this?

Response:

The sediment oxygen demand (SOD) is a sink for the oxygen and therefore there is a negative sign in front of the DO_{SOD} in equations (1), (3), (7)-(9), and (13) in the section 2.1 and 2.2. However, in the other sections we did not include the negative sign in DO_{SOD}, where DO_{SOD} has positive value and represents the amount of oxygen removed by the sediment oxygen demand. Accordingly, the equation should be $\Delta DO = \Delta DO_{BC} + \Delta DO_{REA} + \Delta DO_{WCP} - \Delta DO_{SOD}$ (Dark blue bars = light blue bars + green bars + orange bars - yellow bars in the Figure 5 b-c). We have corrected the equations (1), (3), (8)-(9) in the revised manuscript to be consistent for the sign of DO_{SOD}.

For example, compared with the 'Cont' simulation (now renamed as the Base simulation), decreasing the riverine inputs of particulate organic carbon in RivPOC-50% will weaken the SOD and lead to a decrease in the magnitude of DO_{SOD} (the removal of oxygen caused by the SOD). That means the bottom DO will be increased by 0.51 mg L^{-1} (decrease in DO_{SOD} but increase in DO). In addition, decreasing the POC inputs weakens the light attenuation and facilitates the primary productivity, leading to an increase of bottom DO by 0.3 mg L^{-1} (increase in DO_{WCP}). At the same time, the decrease in riverine POC inputs will weaken the re-aeration and decrease the bottom DO by 0.22 mg L^{-1} (increase in DO_{REA}). Combining all of these processes, the bottom DO will be elevated ultimately by 0.51+0.3-0.22=0.59 mg L^{-1}.

34. P15, line 11: It is important to qualify the 217km2 statistic by saying that this is true only for a July/August average in 2006. This is not true for other months of the year, and we don't know whether this is true for other years.

Response:

We removed this sentence in the revised manuscript. We have clarified that this result is based on the July-August 2006 elsewhere in our revised manuscript.

35. P15, line 15: DO_REA is not a term that your readers will be familiar with (unless they have read this paper carefully). This paper will have a greater impact if this could be reworded such that processes are mentioned, i.e. discuss the re-aeration of surface water via air-sea flux (in units of oxygen per unit time), rather than DO_REA.

Response:

The text in P15, line 15 of the original manuscript meant the oxygen supplied by the re-aeration can penetrate to the bottom waters and compensate the oxygen loss caused by other processes. In our original manuscript, we did not use the word 're-aeration' (in units of oxygen per unit time) because re-aeration is the air-sea flux of oxygen occurring at the air-sea interface, which does not guarantee to penetrate to the bottom waters.

We agree that the term DO_{REA} is not familiar to readers, so we defined the key variables more clearly (e.g. DO_{BC}, DO_{WCP}, DO_{SOD}, and DO_{REA}) in the revised manuscript and list their definition in Table A1 in the revised manuscript.

36. P15, line 19: Again where is the hypoxic frequency zone? Where is "the west of the lower estuary"? Also, make it clearer that this is a result of Wang et al. (2017) and not of this paper.

Response:

Please see the response to comment 25 for the high hypoxic zone. Here we have clarified that this is the result based on Wang et al. (2017) and we moved this sentence to section 4.3 in our revised manuscript. The west of the lower estuary is represented by the red box in the new Figure 8d.

37. P15, lines 4-8: This is a very interesting result! But unfortunately this paper does not show any statistics on water column respiration, so this is not clear. Please separate out the

various terms inside WCP so the reader can see specifically that water column respiration is not large here.

Response:

Please see our response to the comment 4.

38. P16, line 15: I don't think the authors mean the residence time of the Mississippi River, which extends a great distance, well up into the continent of North America. Do you mean the shelf plume area? This section would be much stronger if the authors compared all three systems mentioned here: the GoM, Chesapeake Bay and the PRE.

Response:

Here we meant the residence time of bottom waters in the hypoxic zone of the shelf. The residence time of 95 days is cited from the Rabouille et al., (2008) where they compared the hypoxia in four different river systems (i.e. The Yangtz river, the Mississippi River, the Pearl River, and the Rhone River).

We have compared the three hypoxic systems (i.e. the Chesapeake Bay, the northern Gulf of Mexico (NGOM), and the PRE) to explain why the hypoxia in PRE is most sensitive to the riverine input of particulate organic carbon (P16 line 3-18 of original manuscript). The main differences between the three hypoxic systems are summarized in Table r1, which has been included as the Table 3 in the revised manuscript. As we discussed in the manuscript, in contrast to the NGOM and the Pearl River Estuary, the water column respiration induced by excess nutrients is the dominant oxygen depletion process in the Chesapeake Bay. As a result, the hypoxia in the Chesapeake Bay is very sensitive to the nutrient loading. In the NGOM and the PRE, the dominant roles of the sediment oxygen demand have been reported in many previous studies based on both observational (Murrell and Lehrter, 2011; Yin et al., 2004) and modelling studies ((Yu et al., 2015b; Zhang and Li, 2010). Hypoxia in the NGOM can be well simulated with appropriate parameterization of SOD while neglecting the water column processes (Yu et al., 2015a). However, in the NGOM, the particulate organic carbon (POC) produced by phytoplankton (autochthonous POC) is the major contribution to the sediment oxygen demand. While in the PRE, the riverine input of POC (allochthonous POC) is the dominant source. The differences in relative contributions of allochthonous POC versus autochthonous POC between the NGOM and the PRE are thereafter discussed in the revised manuscript.

Table r1. A summary of characteristics of hypoxia among three systems (i.e. Chesapeake Bay, northern Gulf of Mexico, and Pearl River Estuary)

	WCR dominant	SOD dominant	
		autochthonous POC dominant	**allochthonous POC dominant**
Chesapeake Bay	✓		
Northern Gulf of Mexico		✓	
Pearl River Estuary			✓

39. P16: Rather than discussing terrestrial vs. marine POC, I think it would be clearer to discuss autocthonous vs. allochthonous POC. "Marine POC" sounds as if it comes from outside the hypoxic zone from the ocean, but I don't think this is what is meant?

Response:

We have revised the terms as suggested in our revised manuscript. We had attempted to use the terrestrial POC and marine POC to represent the POC delivered from the river network and produced by the phytoplankton, respectively.

40. P16, line 22: Is July-August a wet or dry season?

Response:

The July-August are typical wet seasons with the monthly averaged river discharges over 20,000 m^3 s^{-1}. We have stated it in the section 3.1 of the revised manuscript to explain why we focused on July-August 2006:

"Another motivation of focusing on July and August is that these two months are among the typical wet seasons in the PRE (Figure 4b), which is in line with our study on the effects of riverine inputs."

41. Section 4.1: This section needs to describe more completely the difference in marine vs. terrestrial POC in the PRE vs. Gulf of Mexico. Why does terrestrial POC not impact hypoxia? Just because that the POC entering from the river is relatively small and sinks out before making it al the way to the shelf? Or is there something specifically different about the terrestrial matter entering from the Mississippi compare to that being delivered to the PRE? Is this a residence time issue? Is the terrestrial source more important in the PRE because the nutrient inputs are quite low, compared to what they are in the Gulf of Mexico? What about in the Chesapeake Bay?

Response:

More discussions on the differences in the PRE and the Northern Gulf of Mexico (NGOM) have been included in the section 4.2 of the revised manuscript:

"The different POC sources in the NGOM and the PRE might be explained by their distinct physical and biogeochemical processes (Table 4). Firstly, the relative magnitudes of autochthonous versus allochthonous POC are different in the two hypoxic systems. The allochthonous inputs of POC in the NGOM and PRE are at the same magnitude: 3.8×10^6 t yr^{-1} (Wang et al., 2004) and 2.5×10^6 t yr^{-1} (Zhang et al., 2013), respectively. However, the autochthonous inputs in the two systems are different. According to our model results, the primary productivity in the PRE is 310.8 ± 427.5 mg C m^{-2} day^{-1}, which is within the range of 183.9~1213 mg C m^{-2} day^{-1} reported by Ye et al., (2014). However, the observed primary productivity in the NGOM ranges from 330 to 7010 mg C m^{-2} day^{-1} (Quigg et al., 2011), the upper range of which is much higher than that in the PRE. The relatively lower primary productivity in the PRE is a result of the stronger phosphorus limitation (DIN:DIP ratio of 126 in the PRE versus 33 in the NGOM, respectively) and the light shading effects of high suspended sediment concentrations. The dominant role of the allochthonous POC in highly turbid estuaries have been reported in previous studies (Fontugne and Jouanneau, 1987; Middelburg and Herman, 2007). Secondly, fates of the allochthonous POC in the two systems are different due to the difference in the residence time between the systems. In the

PRE, the residence time is 3~5 days during the wet season, which is much shorter than in the NGOM (~95 days). It follows that the allochthonous POC cannot be degraded completely and hence can significantly fuel the SOD in the PRE. The difference in surface salinity distribution can also be used to explain the different relative roles of allochthonous POC in the two hypoxic systems. Previous studies have suggested a good correlation between the relative contributions of allochthonous POC and the salinity, namely the contributions of allochthonous POC generally decrease as salinity increases seaward (Fontugne and Jouanneau, 1987; Middelburg and Herman, 2007). Similar correlations have also been reported in the PRE (Yu et al., 2010) and NGOM (Wang et al., 2004). The surface salinity in the high hypoxia frequency zone varies between 0 to 10 psu during the wet season based on our model results, while the surface salinity in the hypoxic zone of the NGOM is saltier than 24 psu even in the wet season according to the results from a well-validated physical model in Yu et al. (2015a). This implies a more important role of allochthonous POC in the PRE than in the NGOM. Finally, compositions of the allochthonous POC are different in the two hypoxic systems. Zhang and Li (2010) mentioned that contributions of labile POC to the allochthonous POC are higher in the PRE than in the NGOM."

Unlike the PRE and the NGOM, the hypoxia in the Chesapeake Bay is more controlled by the water column respiration instead (Hong and Shen, 2013). And the hypoxia is sensitive to the nutrient loading. It follows that the autocthonous POC is more important than the allochthonou POC to the hypoxia formation. One possible reason is probably the relatively long residence time in the Chesapeake Bay (180 days (Du and Shen, 2016)), which allows the complete degradation of the allochthonou POC before entering the hypoxic zone."

42. P17, line 17: Isn't the same likely to occur in Chesapeake Bay? This might be a very interesting discussion point here.

Response:

Here we compared the Pearl River Estuary with the northern Gulf of Mexico to demonstrate that the high re-aeration in the Pearl River Estuary is due to the high sediment oxygen demand and shallow waters. Extended discussions on the Chesapeake Bay are largely limited by the lack of observations and relevant studies on the re-aeration. To our knowledge, few studies have mentioned the direction (source vs. sink) or the magnitude of re-aeration in the Chesapeake Bay. According to our results, we can speculate qualitatively that the strong water column respiration may enhance the re-aeration in the Chesapeake Bay.

As suggested, we have included a brief discussion on the Chesapeake Bay at the end of the section 4.3 of our revised manuscript.

Figures:

43. Figure 1: The figures do not look to be italicized (as it says in the caption). Fig 1b does not add any significant information to what appears in Fig 1a. In Fig 1c "grids" should be "grid". The Fig 1a caption should note that this is a bathymetric map.

Response:

We have modified the caption in the revised manuscript.

We would like to keep Figure 1b that shows the computational cross-sections of 1-D model. In the revised manuscript, we have stated the purposes of showing Figure 1a and Figure 1b.

We have replaced 'grids' with 'grid' in Figure 1c and revised the caption of Figure 1a as suggested.

44. Figure 3: The text refers to 3a and 3b, but the left panel is not marked (b), and there is no reference to (b) in the caption.

Response:

We have added the missing (b) in the left panel. We also added the reference to (b) in Figure 3.

Figure 5: The y-axes in (b)-(d) should specify that these are "Changes in concentration", not concentrations themselves. Also, (b)-(d) should have same y-range to make it easier for the reader to compare all three figures.

Response:

Revised as suggested.

45. Figure 6: Please label figures (a)-(e) and provide captions for each. What is the white line? Axes are not labeled.

Response:

We have provided captions for each panel in the revised manuscript. The white line in Figure 6 (new Figure 8 in revised manuscript) denotes the high frequency zone. We also added the information in the revised manuscript. Labels have been added to the axes in Figure 6.

46. Figure 7: This figure is a little confusing, because one would expect that the vertical diffusion out of box 1 would represent the vertical diffusion into box 2. I gather the net diffusion arrows are shown, but maybe it would make more sense to show the middle layer as having a +0.02 diffusion into the middle layer at the top, and a -0.17 diffusion out of the middle layer at the bottom? But why doesn't this equal 0.48? Maybe I'm confused because this is only DO_SOD, and not total oxygen? Wouldn't this be a more enlightening figure if all the DO fluxes were shown here?

Response:

Yes, fluxes shown in Figure 7 (new Figure 9 in the revised manuscript) represent the net fluxes of $-DO_{SOD}$. The purpose of Figure 7 is to explain how the sediment oxygen demand can affect the surface re-aeration. Other DO fluxes can be seen in Figure 11 and Figure 12 in our previous study (Wang et al., 2017). In our revised manuscript, we made a statement of the purpose of Figure 7 and referred other DO fluxes to Wang et al. (2017).

As suggested, we also modified the Figure 7 to show the influx and outflux separately. The new figure which will be used in the revised manuscript is shown here. The negative values represent the outfluxes and the positive values represent the influxes. Take the vertical diffusion (red arrows) as an example, the outflux from the upper layer is 0.02 mg L^{-1} day^{-1}. Considering the mass conservation, the mass of DO (in unit of mg) leaves from the upper layer should be equal to the mass enters the lower layer. As we mentioned in our original manuscript (P14 line 22-23), volume of the middle layer is three times as large as the upper and bottom layers. Therefore, the influx into the middle layer should be $0.02/3 \approx 0.01$ mg L^{-1} day^{-1}. As analogy to the upper-middle layer, the outflux from the middle layer should be one thirds of the influx into the bottom layer ($0.48/3 \approx 0.16$ mg L^{-1} day^{-1}). Since the influx and outflux of the middle layer are -0.01 and 0.16 mg L^{-1} day^{-1}, respectively, the net flux is 0.15 mg L^{-1} day^{-1} as was shown in the Figure 7 in our original manuscript.

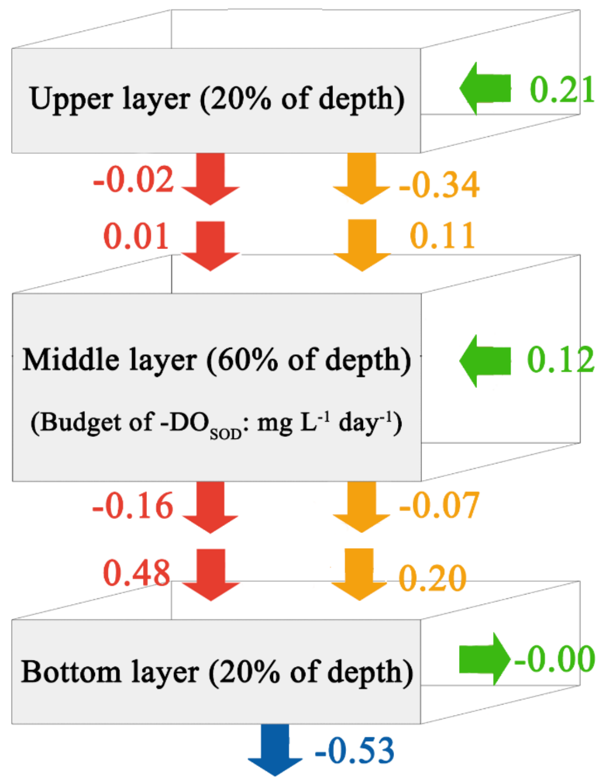

Figure r2. Budget of $-DO_{SOD}$ for the upper layer, middle layer, and bottom layer in the Pearl River Estuary for the 'Cont' case (has been renamed as Base case in the revised manuscript).

English language comments:

Throughout, "organic matters" should be changed to "organic matter". And similarly "dissolved matters" should be "dissolved matter".

P 4, line12 – processes should be process
P6, Line 26 – transportation should be transport
P7, line 7 – delete "here" and "as"
P8, line 16 – should be "interacting"
Page 12, line 1: "further" should be "farther"

P14, line 17: should be “ layer, exerting a strong constraint”

P15, line 14: supply should be supplies

P15, line 24: most should be “more”

P16, line 5: should be “are the most important processes”

Response:

Thank you for the detailed comments. We have modified them as suggested in our revised manuscript.

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Impacts of anthropogenic inputs on the hypoxia and oxygen dynamics in the Pearl River Estuary

Bin Wang [1,3], Jiatang Hu [1,2,*], Shiyu Li [1,2,*], Liuqian Yu[3], Jia Huang [1]

[1] School of Environmental Science and Engineering, Sun Yat-Sen University, Guangzhou, 510275, China
[2] Guangdong Provincial Key Laboratory of Environmental Pollution Control and Remediation Technology, Guangzhou 510275, China
[3] Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada

Correspondence to: Jiatang Hu (hujtang@mail.sysu.edu.cn), Shiyu Li (eeslsy@mail.sysu.edu.cn)

Abstract. In summer, the Pearl River Estuary (PRE) experiences hypoxia, largely driven by the high input of freshwater with low dissolved oxygen (DO) and abundant nutrients and particulate organic carbon from the Pearl River network. In this study, we used a well-validated physical-biogeochemical model together with a DO species tracing method to study the responses of hypoxia and oxygen dynamics to the anthropogenic perturbations of riverine inputs (i.e. DO, nutrients, and particulate organic carbon) in July-August 2006. Model results showed that hypoxia in the PRE was most sensitive to riverine inputs of particulate organic carbon, followed by DO concentrations and nutrients. Specifically, a 50% decrease (increase) in riverine input of particulate organic carbon led to a 47% decrease (64% increase) in hypoxic area, with the sediment oxygen demand and water column production being the two most important processes contributing to the changes in DO concentration. Changes in the riverine inputs of DO and nutrients had little impacts on the simulated hypoxia because of the buffering effects of re-aeration (DO fluxes across the air-sea interface), i.e. the re-aeration responded to the changes in surface apparent oxygen utilization (AOU) associated with river-induced variations of oxygen source and sink processes. The PRE features shallow waters (with averaged depth of 10 m) where oxygen provided by the re-aeration could penetrate to bottom waters via vertical diffusion and largely offset the changes in DO contributed by other oxygen source and sink processes. This study highlights the importance of re-aeration in reducing hypoxia variability in shallow estuaries.

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1. Introduction

Recent decades have seen a decline in dissolved oxygen (DO) concentrations in most of the coastal oceans because of intensifying anthropogenic disturbances, leading to an increase in the occurrence and intensity of hypoxic conditions (Diaz and Rosenberg, 2008). Relations between the riverine nutrient loading and the hypoxic conditions (DO<2mg L^{-1}) have been well documented in many coastal hypoxic systems such as the Changjiang Estuary (Li et al., 2011; Ning et al., 2011), the Chesapeake Bay (Du and Shen, 2015; Hagy et al., 2004), and the northern Gulf of Mexico (NGOM) (Forrest et al., 2011; Justić et al., 2003). The classic paradigm for explaining the relations is that excessive nutrient inputs to the coastal oceans stimulate the high primary productivity there, and the subsequent decomposition of the organic matter in the bottom water consumes significant amount of DO that leads to hypoxia. As a result, nutrient reduction has been proposed to alleviate hypoxia in many hypoxic systems (e.g., the Chesapeake Bay (Scavia et al., 2006) and the NGOM (Justić et al., 2003)). Recent years have also seen an increasing number of studies showing that climate variation contributes to the spreading hypoxia in coastal oceans. The climate variation can change the ocean circulation or the vertical stratification to alter the balance between the oxygen source and sink processes (Rabalais et al., 2010). A modeling study conducted in the Chesapeake Bay has shown the good correlations between the climate variation, stratification, and the observed DO (Du and Shen, 2015). In addition, the global warming, as a symptom of climate variation, is another factor that can enhance the hypoxia. For example, Laurent et al. (2018) predicted a prolonged and more severe hypoxia in the northern Gulf of Mexico under a projected future (2100) climate state where the global warming leads to reduction in oxygen solubility and increased stratification.

（Position of Figure 1）

The Pearl River Estuary (PRE) is located on the Pearl River Delta (Figure 1a) and has a drainage area of 452,000 km^2. Previous studies have reported some summer hypoxic events in the PRE and explored the underlying mechanisms. Yin et al. (2004) suggests that stratification and estuarine circulations are two primary processes controlling the hypoxia in the PRE. Rabouille et al. (2008) compares the hypoxic conditions among four hypoxic systems and demonstrates the significance of tidal mixing to break hypoxia in the PRE. Zhang and Li (2010) further suggests that the contributions of biogeochemical processes to hypoxia in the PRE are also important. By conducting the oxygen balance analysis, they show that sediment oxygen demand (SOD) is the dominant sink for oxygen. A more recent study by Wang et al. (2017) further points out that the balance of oxygen in the PRE is mainly controlled by the source and sink processes occurring in local and adjacent waters, among which the re-aeration (DO fluxes across the air-sea interface) and SOD determine the spatial distributions and durations of hypoxia in the PRE.

As a distinct river-dominated estuary, the PRE receives 3.3×10^{11} m^3 yr^{-1} of freshwater (Ou et al., 2009; Zhang and Li, 2010) along with a large amount of nutrients from the Pearl River network (Figure 1a), i. e. 5.6×10^5 t yr^{-1} of dissolved inorganic nitrogen (DIN) and 9.9×10^3 t yr^{-1} of dissolved inorganic phosphorus (DIP) (Hu and Li, 2009). Both dissolved inorganic nitrogen and phosphorus loadings have increased by about 60% from 1970 to 2000 and is predicted to increase by two times in 2050 due to the fast-growing agriculture and urbanization (Strokal et al., 2015). Understanding the response of hypoxia and oxygen dynamics to the changes in nutrient loading in the PRE is hence valuable for hypoxia prediction and management.

In addition to the nutrient loading, the particulate organic carbon (POC) are another important form of anthropogenic inputs that influence the hypoxia in the estuary (~2.5×10^6 t yr^{-1} from the Pearl River network (Zhang et al., 2013)). The POC can fuel the SOD when deposited and mineralized in the sediment layers, which has been found to dominate the DO depletions within the bottom waters of the PRE (Yin et al., 2004; Zhang and Li, 2010). In coastal systems the POC are often derived from the dead phytoplankton (Green et al., 2006), while in the PRE the POC mainly originate from the riverine inputs (Ye et al., 2017; Yu et al., 2010). This suggests the importance of studying the impact of riverine POC on hypoxia in the PRE.

In some cases, the hypoxia may also be induced by the advection of low-oxygen waters (Grantham et al., 2004; Montes et al., 2014; Wang, 2009; Wang et al., 2012). For example, Wang (2009) demonstrates that the hypoxia development in the Changjiang estuary is largely due to the Taiwan Warm Current bringing low–oxygen waters to the hypoxic zone. As to the PRE, the impact of riverine input of low-oxygen waters on hypoxia is also worth investigation considering the large amount of river discharge entering the estuary and that there has been hypoxia observed in its upper reaches (He et al., 2014).

Collectively the previous studies show that both natural and anthropogenic processes greatly contribute to hypoxia in the PRE. Understanding the respective roles of these two types of processes is important to faithfully predict future hypoxic events under the enhanced human activities and climate variations, which is useful for designing effective management strategies to prevent or remediate the hypoxic conditions in the PRE.

Here we focus on the role of human activities, i.e. different anthropogenic inputs, on hypoxia and oxygen dynamics in the PRE, whereas the role of natural processes will be reported in our future works. Specifically, we explore the impacts of varying anthropogenic inputs (riverine nutrients, POC, and DO) on hypoxia and oxygen dynamics in the PRE by using a three-dimensional (3D) coupled physical-biogeochemical model. The DO species tracing method introduced in Wang et al., (2017) is applied to isolate the effects of each oxygen source and sink process and to elucidate their interactions in this shallow and river-dominated estuarine system.

2. Method

2.1 Model description and validation

2.1.1 Model description

Physical model

Our physical model is a 1D-3D coupled model which incorporates the Pearl River network and the PRE (see Figure 1b, c for locations) into a single framework to resolve the dynamic interactions between these two regions (Hu and Li 2009). This coupled model was firstly developed with the biological and sediment models for the Pearl River-Estuary system to study the water, nutrients, and sediment flux budgets between the river network and estuary (Hu and Li 2009; Hu et al. 2011). Thereafter, it was extended to study the hypoxia (Wang et al. 2017) and the nutrient fluxes across the water-sediment interface (Liu et al., 2016) in the PRE.

The coupled model uses a so-called explicit coupling approach to incorporate the 1D model for the Pearl River Network and the 3D model for the PRE through the eight outlets (including Humen, Yamen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen, and Yamen; see Figure 1a for their locations). At each time step, the 3D model is forced by the simulated river discharges from the 1D model, and as a feedback, sends its simulated water levels at eight outlets to the 1D model as the downstream boundary conditions for the next time step. More detailed descriptions of the model methodology can be referred to Hu and Li (2009).

The cross-sectional integrated 1D model solves the Saint Venant equations of mass and momentum conservation by using a Preissmann implicit scheme and an iterative approach in the well-mixed river network. Figure 1b shows that the Pearl River Network is discretized into 1726 computational cross-sections, 189 nodes (interactions between the different river branches), five upper boundaries (i.e. Shizui, Gaoyao, Shijiao, Laoyagang, and Boluo), and eight lower boundaries (the eight outlets). The upper boundaries of the 1D model are specified by the real-time observations of river discharges or water levels. The lower boundaries use the simulated water levels from the 3D model. Initial conditions are set to be zero for water levels and velocities and model time step is 5 seconds.

The 3D model is based on the Estuaries and Coastal Ocean Model with Sediment Module (ECOMSED; HydroQual Inc. (2002)) that has been extensively used to study the hydrodynamics in estuaries. The model has 183x186 horizontal grid cells with a resolution ranging from 400 m inside the Lingdingyang Bay to 4 km near the open boundaries (Figure 1c), and has 16 terrain-following sigma layers with refined resolution near the surface and bottom layers. The horizontal mixing is parameterized by a Smagorinsky-type formula (Smagorinsky, 1963) and the vertical mixing is calculated by the Mellor-Yamada level 2.5 turbulent closure model (Mellor and Yamada, 1982). The 3-D model is forced by the 6 hourly winds and 3 hourly surface heat fluxes from the ERA-interim (the Interim ECMWF Re-Analysis, http://www.ecmwf.int/en/research/climate-reanalysis/era-interim). Three open boundaries are specified by a monthly averaged profile of salinity and temperature (Hu and Li, 2009). Tides are introduced at the open boundaries using the water levels from the Oregon State University Tidal Data Inversion Software (OTIS). Freshwater inputs from the Pearl River network to the estuary use the river discharges simulated by the 1-D model.

The physical model is run from 1 November 2005 to 31 December 2006. More detailed descriptions and configurations can be found in Hu et al. (2011) and Wang et al. (2017).

Biogeochemical model

The biogeochemical model is the Row-Column AESOP model (RCA; HydroQual Inc. (2004)) that solves the mass balance equations for 26 state variables involved in five interactive cycles (i.e. the nitrogen cycle, the phosphorus cycle, the carbon cycle, the silicon cycle, and the oxygen dynamics). Interactions between these state variables with atmosphere and sediment are illustrated in Figure 2.

(Position of Figure 2)

The equation of DO (mg O_2 L^{-1}) is given by:

$$\frac{\partial DO}{\partial t} + u\frac{\partial DO}{\partial x} + v\frac{\partial DO}{\partial y} + w\frac{\partial DO}{\partial z} - \frac{\partial}{\partial x}\left(E_x\frac{\partial DO}{\partial x}\right) - \frac{\partial}{\partial y}\left(E_y\frac{\partial DO}{\partial y}\right) - \frac{\partial}{\partial z}\left(E_z\frac{\partial DO}{\partial z}\right) = WCP + REA - SOD \quad (1)$$

where x and y represent the horizontal coordinates and z the vertical coordinate; u, v, and w (m s^{-1}) represent velocity components in x, y, and z coordinates, respectively; and E_x, E_y, and E_z (m s^{-2}) are dispersion coefficients. The velocity components and dispersion coefficients are computed by the physical model.

The term *WCP* represents the gross DO production rates in the water column (mg O_2 L^{-1} day^{-1}), hereafter the water column production, which is the combination of photosynthesis, respiration, nitrification, and oxidation. Detailed equations for each component of the water column production can be seen in the Appendix A. According to the DO budget analysis in Wang et al. (2017), the photosynthesis and respiration are two major oxygen source and sink processes in the water column. Considering that photosynthesis and respiration are both closely and directly correlated to the phytoplankton dynamics, they have the similar distributions and responses to the external forcing. We therefore use the water column production to represent the net effects of water column on the DO and hypoxia.

The term *REA* represents the re-aeration (mg O_2 L^{-1} day^{-1}) at the air-sea interface, given as:

$$REA = k_a\theta_a^{T-20}(DO_{sat} - DO) \quad (2)$$

where DO_{sat} represents the DO concentration at saturation (mg O_2 L^{-1}) which is dependent on salinity and temperature; k_a is the surface mass transfer coefficient (day^{-1}); and θ_a is a temperature coefficient (dimensionless). Values for these parameters can be seen in Table A2.

The term *SOD* represents the sediment oxygen demand (mg O_2 L^{-1} day^{-1}) at the water-sediment interface and Δz represents thickness of the respective bottom grid cell (m).

$$SOD = \frac{s(DO - DO_{\mathrm{sed}})}{\Delta z} \quad (3)$$

where s represents the transfer coefficient between the sediment and overlying water (m day^{-1}); DO_{sed} represents DO concentrations (mg O_2 L^{-1}) in the sediment layers. In the RCA, a sediment flux module is incorporated to simulate the depositional flux of particulate organic matter (i.e. particulate organic carbon, particulate organic nitrogen, and particulate organic phosphate), the diagenesis processes in the sediment, and the transport of nutrients and DO from the sediment to the overlying water (Figure 2). Detailed descriptions about the sediment flux module can be seen in the Appendix B.

The simulation period for our biogeochemical model is the same as the physical model. Initial conditions were obtained from a two-month spin-up simulation which was repeated for three times to reach a steady state. River boundary conditions of biogeochemical variables were derived from the monthly observations in 2006 collected by the State Oceanic Administration (including nutrients and DO) and from a previous study (including different classes of dissolved organic carbon, particulate organic carbon, dissolved organic nitrogen, particulate organic nitrogen, dissolved organic phosphorus, and particulate organic phosphorus) (Liu et al., 2016). The open boundary conditions of biogeochemical variables were specified following Zhang and Li (2010).

2.1.2 Model validation

The physical-biogeochemical model has been validated against available observations during the July of 1999 in Hu and Li (2009) and July-August 2006 in Wang et al. (2017). We briefly summarize the validation results in 2006 below.

Being the coupling interface between the 1D model and the 3D models, the eight outlets serve as the lower boundaries of the 1D model and the river boundaries of the 3D model. It follows that the simulation of eight outlets is of great importance to the robustness of the 1D-3D coupled model. Model-data comparisons of water levels were conducted for eight stations including six outlets (i.e. Jiaomen, Hengmen, Modaomen, Jitimen, Hutiaomen, Yamen) and two other stations (i.e. Zhuhai and Wanshan) in Wang et al. (2017), with locations of the stations in their Figure 3. The normalized root-mean-square difference (RMSD) of water levels falls within 0.30 of the standard deviation of the observations and the correlation coefficient between the simulated and observed water levels exceeds 0.95. This indicates that the coupled physical model is able to resolve the interactions between the river network and the estuary well. In addition, the tidal variations and the spring-neap tidal cycles in the PRE are well reproduced.

The PRE is characterized by the large extended river plume in the summer. Therefore, the model simulated salinity and temperature fields were validated against 146 profiles of salinity and temperature collected by estuary-wide monitoring cruise. The comparisons show small normalized RMSDs (both <0.60 of standard deviations of observations) and high correlations (>0.90 for salinity and >0.80 for temperature) between the model and observations, indicating that the coupled physical model is robust to reproduce the broad-scale features and intra-seasonal patterns of the main hydrodynamic features in the PRE.

For validation of biogeochemical fields, the simulated DO concentrations were validated against 53 oxygen profiles collected at 4 different cruises and distributed estuary-wide. The point to point comparisons show that the simulated DO concentrations agree well with observations, with the normalized RMSD below 0.8 standard deviation of the observations and the vast majority (85%) of the normalized errors falling within 1 standard deviation of the observations. Model-data comparisons of bottom DO concentrations further show that the model is able to reproduce the spatial distribution of the observed bottom DO and hypoxia. We have also assessed model skills in resolving source and sink processes associated with DO concentration. We found that the simulated spatial distributions and magnitudes of the re-aeration, respiration, and the SOD rates are similar with those of previous observational studies (see Table 3 in Wang et al. (2017)). The simulated chlorophyll-a, primary productivity and particulate organic carbon, which largely determine the respiration and the SOD rates (Zhang and Li, 2010), are also consistent with historical estimations. This suggests that our model is able to reproduce the oxygen dynamics properly.

In short, the model validation in Wang et al. (2017) indicate that our physical-biogeochemical model is robust to simulate the hydrodynamics and biogeochemical cycles in the PRE and is skillful in simulating summer hypoxia in 2006.

2.2 **The DO species tracing method**

The DO exhibits non-conservative behavior during the mixing in the estuary because of the oxygen source and sink processes described in Section 2.1.1 (Figure 3a). As shown in Figure 3b, the DO concentrations are controlled by both the conservative (represented by the theory mixing curve) and the non-conservative effects (represented by the shading areas). The conservative effects are associated with physical advection and diffusion, while the non-conservative effects are due to the oxygen source and sink processes (i.e. re-aeration, the water column production, and the SOD). Quantifying the relative contributions of the respective effect is important to understand the DO dynamics during the mixing in the estuary. In a 0-D system, the non-conservative effects can be easily estimated as the products of time intervals and rates of corresponding source and sink processes. However, in a river and tide dominated estuary such as the PRE, this estimation is not straightforward because of the spatial connections of each source and sink process occurring in different locations. To address this problem, the DO species tracing method (referred to as the physical modulation method in Wang et al. (2017)) was introduced and implemented in our previous study to investigate the mechanisms of hypoxia in the PRE. By dividing the DO into different DO species, the tracing method can track the DO contributed by different source and sink processes. For example, Wang et al. (2017) found that about 28% of surface DO supplied by the re-aeration penetrated to the bottom waters and hence modulated the hypoxia in the PRE. In this study, the DO species tracing method is used to track contributions of each source and sink process to the DO dynamics and hypoxia under the different riverine inputs scenarios. Interactions between the oxygen source and sink processes will be investigated as well.

The DO species tracing method is incorporated into the biogeochemical model by explicitly including four numerical oxygen species as model tracers to track the DO contributed by the lateral boundary conditions (DO_{BC} (mg O_2 L^{-1})), air-sea re-aeration (DO_{REA} (mg O_2 L^{-1})), water column production (DO_{WCP} (mg O_2 L^{-1})), and SOD (DO_{SOD} (mg O_2 L^{-1})), respectively (Table A1). Equations of the four numerical oxygen species are given as below:

$$\frac{\partial DO_{\mathrm{BC}}}{\partial t} + tran(DO_{\mathrm{BC}}) = 0 \quad (4)$$

$$\frac{\partial DO_{\mathrm{REA}}}{\partial t} + tran(DO_{\mathrm{REA}}) = REA \quad (5)$$

$$\frac{\partial DO_{\mathrm{WCP}}}{\partial t} + tran(DO_{\mathrm{WCP}}) = WCP \quad (6)$$

$$\frac{\partial DO_{\mathrm{SOD}}}{\partial t} + tran(DO_{\mathrm{SOD}}) = SOD \quad (7)$$

and

$$DO = DO_{\mathrm{BC}} + DO_{\mathrm{REA}} + DO_{\mathrm{WCP}} - DO_{\mathrm{SOD}} \quad (8)$$

$$tran(DO) = tran(DO_{\mathrm{BC}}) + tran(DO_{\mathrm{REA}}) + tran(DO_{\mathrm{WCP}}) - tran(DO_{\mathrm{SOD}}) \quad (9)$$

where $tran$ represents the physical transport processes, i.e. the advection $(u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z})$ and diffusion $(-\frac{\partial}{\partial x}\left(E_{\mathrm{x}}\frac{\partial}{\partial x}\right) - \frac{\partial}{\partial y}\left(E_{\mathrm{y}}\frac{\partial}{\partial y}\right) - \frac{\partial}{\partial z}\left(E_{\mathrm{z}}\frac{\partial}{\partial z}\right))$; *REA* (mg O_2 L^{-1} day^{-1}), *WCP* (mg O_2 L^{-1} day^{-1}), and *SOD* (mg O_2 L^{-1} day^{-1}) are the re-aeration, water column production, and SOD, which represent the net effects of the air-sea interface, the water column, and the water-sediment interface on the oxygen, respectively. Values of these terms are obtained from the biogeochemical model at each time step.

(Position of Figure 3)

According to the Eq. 4, the DO_{BC} concentrations are only controlled by the advection and diffusion. By assigning the initial conditions and lateral boundary conditions of DO_{BC} the same as those for DO, the mixing curve of DO_{BC} will overlap the theory mixing curve shown in Figure 3b. It follows that the DO_{BC} represents the conservative effects, while the DO_{REA}, DO_{WCP}, and DO_{SOD} that include oxygen source or sink term represent the non-conservative effects.

The Eqs. 8 and 9 suggest that the DO concentration and its transport flux equal the sum of the concentrations and transport fluxes of the four DO species, respectively, the validity of which has been tested and confirmed in Wang et al. (2017). They show that there is little discrepancy between the DO concentrations calculated by Eq. (9) and Eq. (1), with 97% of the differences within the range of -2%~6% of the averaged DO concentrations. The hourly time series of domain-averaged DO calculated by the DO species tracing method also agree well with that calculated by the biogeochemical model with the R-square coefficient > 0.99 and the regression slope close to 1:1. In addition, the horizontal advective fluxes, vertical advective fluxes, and vertical diffusive fluxes calculated by the tracing method are found to agree well with the respective fluxes calculated by the biogeochemical model, indicating that the tracing method is able to satisfactorily reproduce the physical transport processes of DO.

2.3 Model experiments

We conducted three groups of sensitivity experiments to study the response of hypoxia and oxygen dynamics to different scenarios of riverine inputs. Each group has two simulations, where the concentration of one type of the riverine inputs at eight river outlets is decreased and increased by 50%, respectively. These simulations are named as Base, RivDO-50%, RivDO+50%, RivNtr-50%, RivNtr+50%, RivPOC-50% and RivPOC+50%, with the basic information of each simulation presented in Table 1.

（Position of Table 1）

The Base simulation uses the realistic riverine inputs as mentioned in Section 2.1.1. In the Base simulation, the DO concentration in the Humen outlet, the largest river outlet in the PRE, is set to 4 mg L^{-1} based on observations nearby. The RivDO-50% simulation where DO concentration from the eight outlets is decreased by 50% represents the scenario where hypoxia has developed in the Humen outlet, which has been reported in previous studies (e.g. He et al., 2014). In contrast, the RivDO+50% simulation, where the DO concentration from the eight outlets is increased by 50% to be close to that from the open boundaries, represents the scenario where the riverine input of DO is free from the anthropogenic impact. As to nutrient simulations, the RivNtr+50% and RivNtr-50% simulations increase and decrease nutrients concentrations from all eight outlets by 50%, respectively. The resulting riverine inputs in the two simulations will be close to the scenarios in 2050 and 1970 as reported by Strokal et al. (2015). Note that in the nutrient simulations, the concentrations of all nutrients (including dissolved silica, dissolved inorganic phosphorus, ammonia nitrogen, and nitrite and nitrate nitrogen) are set to vary at the same percentage that the effects of different combinations of changes in nutrients are not considered here. The hydrodynamic conditions are identical in all experiments.

The hypoxic extent in different simulations is quantified by the expected hypoxic area and hypoxic volume:

$$Hypoxic\ area = \sum p * \Delta s \tag{10}$$

$$Hypoxic\ volume = \sum p * \Delta v \tag{11}$$

where Δs, Δv, and p are the area, the volume, and the hypoxic frequency of each grid cell. The hypoxic frequency p is calculated by:

$$p = \frac{N_{\mathrm{h}}}{N_{\mathrm{s}}} * 100\% \tag{12}$$

where N_{h} is the number of hours when hypoxia occurs, and N_{s} is the total number of hours. In this study, the threshold of hypoxia is defined as 3 mg L^{-1} (Luo et al., 2008; Rabalais et al., 2010).

3. Results

3.1 Hypoxia in the Pearl River Estuary

As shown in Figure 4, the hypoxia in the PRE starts to develop in April, peaks in August, and disappears in October, which is highly correlated (R^2=0.91) with the annual cycle of total river discharges with a time lag of one month. Figure 5 shows the model simulated DO distributions and hypoxic frequency in the bottom layer during the May-October. In May, the hypoxia is confined to the upstream of the Modaomen sub-estuary. In June, the bottom DO declines along the west coast of the PRE and the hypoxia starts to develop near the Gaolan island (see Figure 1 for its location). The hypoxia extends eastward to near the Hengqin Island in July and August. After August, the hypoxia retreats westward and almost disappears in October. Unlike the large spatial extent of hypoxia observed in the Changjiang Estuary (Wang, 2009; Wang et al., 2012) and the NGOM (Rabouille et al., 2008), the hypoxia in the PRE is confined to a small area as a result of the SOD and the re-aeration (Wang et al., 2017).

In 2006, oxygen observations are only available in July and August, which have demonstrated the occurrence of hypoxia. No observations are available for validating the model simulated hypoxia in other months. We have collected and analyzed the oxygen observations from 1993 to 2009. However, the available observations are insufficient to resolve the annual cycle of the hypoxia in the PRE. To our knowledge, there are currently few studies on the annual cycle of hypoxia in the PRE due to the scarcity of observations. Discussions in this study therefore focus on the hypoxia in July-August when the distinct hypoxia was both observed and simulated by the model. Another motivation of focusing on July and August is that these two months are among the typical wet seasons in the PRE (Figure 4b), which is in line with our study on the effects of riverine inputs.

（Position of Figure 4）

（Position of Figure 5）

3.2 Response of hypoxia and oxygen dynamics to riverine DO inputs

Figure 6 shows the comparisons of bottom DO concentrations and hypoxic frequency during July-August for different DO simulations. In the RivDO-50% simulation, the spatial distribution of bottom DO is similar to that in the Base simulation except that hypoxia additionally occurs near the river outlets due to the inputs of low-oxygen waters from the upstream river network (Figure 6b, e). We have also examined the impact of reducing riverine DO in region farther away from the river outlets by excluding the hypoxic region near the river outlets. In this case the expected hypoxic area in RivDO-50% is only 2% higher than that in the Base simulation while the hypoxic volume is 26% higher (Figure 7a), indicating that the thickness of hypoxic water is greatly increased in RivDO-50%. In contrast, the RivDO+50% simulation yields higher bottom DO concentrations, leading to reductions of hypoxic area and volume by 23% and 30%, respectively (Figure 7a).

（Position of Figure 6）

(Position of Figure 7)

(Position of Figure 8)

Figure 7b, c, d further shows the changes in each DO species averaged over the bottom layer of the high frequency zone for different simulations in relative to the Base simulation. The high frequency zone here is defined as the area encompassed by the 10% isoline of July-August averaged hypoxic frequency and is denoted by the white contour in Figure 8. To provide more insights into the response of different oxygen species to riverine inputs, the spatial distributions of DO_{BC} and DO_{REA} in the bottom water are shown in Figure 8. Differences in DO_{WCP} and DO_{SOD} concentrations between simulations are much smaller and hence omitted here.

Halving the riverine DO inputs in the RivDO-50% simulation yields lower DO_{BC} concentrations but higher DO_{REA} in the bottom water (Figure 7b and Figure 8). The decrease in DO_{BC} concentrations is largely balanced by the increase in DO_{REA} concentration in RivDO-50% simulation, which ultimately reduces the magnitude of changes in hypoxic extent responding to the reduced riverine DO input. In the contrary, the RivDO+50% simulation leads to higher DO_{BC} concentrations (Figure 7b and Figure 8c) but lower DO_{REA} in the bottom water (Figure 7b and Figure 8f), which together reduces the net increase in bottom DO (Figure 7b).

The re-aeration buffering effects can be explained by the surface apparent oxygen utilization (AOU, the difference between the actual DO concentration and its saturation at a known temperature and salinity). As shown in Eq. (2), the re-aeration is a function of surface AOU. Halving the riverine DO inputs decreases the DO concentrations in entire water column and therefore increases the surface AOU, which ultimately results in an increase in re-aeration rate. In our model simulations, the surface domain-averaged saturated DO concentration is ~7.42 mg L^{-1}, while the surface domain-averaged DO concentration in the Base and RivDO-50% simulations are 6.81 and 6.57 mg L^{-1}, respectively. The surface AOU for the RivDO-50% simulation is 39% higher than that for the Base simulation, which is consistent with the 38% increase in re-aeration rate for the RivDO-50% simulation.

3.3 Response of hypoxia and oxygen dynamics to riverine nutrient inputs

As shown in Figure 7a, perturbing riverine nutrient inputs by 50% has relatively weak impact on hypoxic extent (changes are within 10%). Among all the oxygen sink and source processes, the water column production and re-aeration are the two that are most sensitive to variations in nutrient inputs. Halving the nutrient inputs by 50% in the RivNtr-50% simulation remarkably reduces the primary productivity and water column production rates, which in turn increases the surface AOU that facilitates the re-aeration. The increase in DO_{REA} to the bottom water via vertical diffusion offsets ~60% of the total DO loss associated with the reduced nutrient inputs in the high hypoxic frequency zone (Figure 7c). As a result, the hypoxic area and hypoxia volume only increase by about 10% in the RivNtr-50% simulation in relative to the Base simulation. In contrast, the RivNtr+50%

simulation yields higher water column production and lower re-aeration rate, with the changes of the two balance each other, and hence only leads to 4% and 6% decreases in hypoxic area and hypoxic volume, respectively in relative to the Base simulation.

3.4 Response of hypoxia and oxygen dynamics to riverine POC inputs

As shown in Figure 7, perturbing the riverine inputs of POC by 50% leads to significant changes in DO concentrations and hypoxic extent. In the RivPOC-50% simulation, the DO concentration increases by 0.56 mg L^{-1} in the high hypoxic frequency zone and the hypoxic area and hypoxic volume decrease by 50% and 64%, respectively. In the contrary, RivPOC+50% simulation leads to significant decrease in the DO concentration, causing an extension of hypoxic area by 64% and a doubling of hypoxic volume (Figure 7a).

As to oxygen dynamics, the RivPOC-50% simulation leads to significant decline in the SOD rate (Figure 7d), and increase in the water column production rate (Figure 7d) as a result of the lower inputs of POC weakening the light attenuation in PRE. The combination of lower SOD and higher water column production rates increases oxygen concentration by 0.81 mg L^{-1} in the bottom waters of the high hypoxic frequency zone (Figure 7d). However, decreasing the riverine inputs of POC in the RivPOC-50% simulation simultaneously weakens the re-aeration due to the decreased surface AOU. As a result, nearly 27% of the increased DO concentrations is offset by the decreased re-aeration in the high hypoxic frequency zone. In contrast, increasing the riverine inputs of POC in the RivPOC+50% simulation increases the SOD rates but weakens the water column production rates, which consequently reduces bottom water oxygen; nevertheless, 26% of the oxygen loss is offset by the enhanced re-aeration in this simulation.

To understand the impacts of changing the riverine inputs of POC on the water column production rates, we further examine how phytoplankton growth responds to varying riverine inputs of POC. The equation for the phytoplankton growth rate G_{P} (day^{-1}) can be written as:

$$G_{\mathrm{P}} = G_{\mathrm{Pmax}} \cdot G(T) \cdot G(I) \cdot G(N) \tag{14}$$

where G_{Pmax} represents the maximum growth rate at the optimum conditions (day^{-1}); $G(T)$, $G(I)$, and $G(N)$ represent the limitations by temperature, light, and the nutrients, respectively. These limitation coefficients are non-dimensional scale values ranging from 0 to 1, with 0 representing no growth and 1 no limitation. The two POC simulations and the Base simulation have identical physical processes and hence same temperature limitation. Table 2 shows that changing the riverine inputs of POC has little impact on nutrient limitation but leads to large variations in light limitation, suggesting that the riverine inputs of POC can significantly affect the phytoplankton growth through light shading effects.

(Position of Table 2)

Considering the important role of re-aeration in POC simulations, we further quantify how re-aeration responds to the SOD by conducting a diagnostic analysis of DO_{SOD} in July and August (Figure 9). Three vertical layers are defined: the upper layer (top 20% of the water column), middle layer (middle 60% of the water column), and bottom layer (20% of the water column above the sediment). Note that horizontal diffusion is omitted in the diagnostic analysis because its magnitude is much smaller than other terms. Diagnostic analysis of other DO species can be seen in Figures 11 and 12 of Wang et al. (2017). As shown in Figure 8, the SOD can affect the DO concentrations in the upper layer indirectly through the interactions with the vertical advection, the vertical diffusion, and the horizontal advection as explained below. First, the SOD consumes bottom DO by 0.53 mg L^{-1} day^{-1} and decrease the upward advective DO fluxes reaching the upper layer by 0.34 mg L^{-1} day^{-1}. Second, the deoxygenation induced by SOD can increase the vertical DO gradient and facilitate the downward vertical diffusion of oxygen by 0.02 mg L^{-1} day^{-1} from the upper layer. Finally, the decreased upper DO concentrations affect the horizontal outfluxes of DO and ultimately result in a higher net horizontal advective flux by 0.21 mg L^{-1} day^{-1}. Consequently, the net effect of the SOD on the upper DO is 0.15 mg L^{-1} day^{-1}. which causes a decline of 2.22 mg L^{-1} in DO concentrations in the surface layer. Figure 9 shows contributions of the SOD and the water column production rates to the changes of surface DO. The positive values of $\Delta(-DO_{SOD})$ and $\Delta(DO_{WCP})$ represent the increased DO concentrations due to the decrease of the SOD and increase of the water column production, respectively. In the RivPOC-50% simulation, decreasing the POC inputs decreases the SOD rate but increases the water column production rate, which in combine increase the DO concentrations in the surface layer. As a result, the re-aeration in the RivPOC-50% simulation is weakened, especially in the west of the lower estuary (Figure 10a).

(**Position of Figure 9**)

(**Position of Figure 10**)

4. Discussion

4.1 Comparability of hypoxia in 2006

In this study, we performed a series of numerical experiments together with the application of DO species tracing method to study the effects of different anthropogenic inputs on hypoxia and oxygen dynamics in the PRE. This study is the first attempt to quantitatively estimate the interactions between each DO source and sink processes (e.g. DO buffering effects) under the anthropogenic perturbations in the PRE. The year 2006 was selected because the distinct hypoxia was observed, and the available observations are relatively more abundant than in other years. In addition, it is a wet year with the annual averaged total river discharge over 10,000 m^3 s^{-1} (interannual variations of total discharges during 1999-2010 in the PRE can be seen in Figure s1 in the supplement). Discussions are only focus on the hypoxia in July and August of 2006 when oxygen observations are available. However, conclusions drawn here should be applicable to other years because previous studies have reported similar locations and spatial extents of hypoxia in other years (Lin et al., 2001; Zhang and Li, 2010). The mechanisms underlying hypoxia of summer 2006 found here are also consistent with previous studies on hypoxia in this region, such as the strong re-aeration (Zhang and Li, 2010), the dominance of the SOD (Yin et al., 2004; Zhang and Li, 2010), and the important contributions of the allochthonous POC (Hu et al., 2006; Yu et al., 2010).

4.2 Relative contributions of different anthropogenic inputs

Numerical experiments show that the hypoxia in the PRE is more sensitive to the riverine inputs of POC rather than the nutrient loading (Figure 6a). This is distinct from other hypoxic systems such as the Chesapeake Bay (Hagy et al., 2004) and the NGOM (Justić et al., 2003) that have observed close relation between nutrient loading and hypoxia. We attribute this to the different characteristics of hypoxia in these systems (Table 3). In the Chesapeake Bay, the dominant oxygen sink leading to hypoxia is the water column respiration, which is associated with high primary productivity stimulated by the excessive nutrient loading (Hong and Shen, 2013). In contrast, the bottom water DO depletions are dominated by the SOD in the NGOM (Murrell and Lehrter, 2011; Yu et al., 2015b) and the PRE (Yin et al., 2004; Zhang and Li, 2010). Hypoxia in the NGOM can be well simulated with appropriate parameterization of SOD while neglecting the water column processes (Yu et al., 2015a).

However, the relative contributions of autochthonous POC (i.e. the POC generated by settling of phytoplankton after death) versus allochthonous POC to the SOD are different in the NGOM and the PRE. In the NGOM, the autochthonous POC serves as the major source of POC (Green et al., 2006), which means increasing the nutrient loading can facilitate the SOD by increasing the depositional fluxes of dead phytoplankton and ultimately promote the formation of hypoxia. In the PRE, the relative contributions of autochthonous versus allochthonous POC inputs to the SOD and hypoxia have long been a topic of debate. Some studies suggest that allochthonous POC dominate in wet seasons due to the high river discharges (Ye et al., 2017; Yu et al., 2010), while others argue that autochthonous inputs can also play an important role (Guo et al., 2015; Su et al., 2017). Previous studies (Guo et al., 2015; Hu et al., 2006; Ye et al., 2017) show that the ratios of allochthonous POC to autochthonous POC have distinct spatial and seasonal variabilities in the PRE. Generally, the allochthonous contributions dominate inside the estuary and gradually decrease seaward as the impact of the river discharges weakens (Hu et al., 2006; Jia and Peng, 2003). In our study, the high hypoxic frequency zone is near the Modaomen sub-estuary which receives high depositional fluxes of allochthonous POC. Therefore, the allochthonous inputs have dominant contributions to the SOD and summer hypoxia in the high hypoxic frequency zone.

（Position of Table 3）

The different POC sources in the NGOM and the PRE might be explained by their distinct physical and biogeochemical processes (Table 4). Firstly, the relative magnitudes of autochthonous versus allochthonous POC are different in the two hypoxic systems. The allochthonous inputs of POC in the NGOM and PRE are at the same magnitude: 3.8×10^6 t yr^{-1} (Wang et al., 2004) and 2.5×10^6 t yr^{-1} (Zhang et al., 2013), respectively. However, the autochthonous inputs in the two systems are different. According to our model results, the primary productivity in the PRE is 310.8±427.5 mg C m^{-2} day^{-1}, which is within the range of 183.9~1213 mg C m^{-2} day^{-1} reported by Ye et al., (2014). However, the observed primary productivity in the NGOM ranges from 330 to 7010 mg C m^{-2} day^{-1} (Quigg et al., 2011), the upper range of which is much higher than that in the PRE. The relatively lower primary productivity in the PRE is a result of the stronger phosphorus limitation (DIN:DIP ratio of 126 in the PRE versus 33 in the NGOM, respectively) and the light shading effects of high suspended sediment concentrations. The dominant role of the allochthonous POC in highly turbid estuaries have been reported in previous studies (Fontugne and Jouanneau, 1987; Middelburg and Herman, 2007). Secondly, fates of the allochthonous POC in the two systems are different due to the difference in the residence time between the systems. In the PRE, the residence time is 3~5 days during the wet season, which is much shorter than in the NGOM (~95 days). It follows that the allochthonous POC cannot be degraded completely and hence can significantly fuel the SOD in the PRE. The difference in surface salinity distribution can also be used to explain the different relative roles of allochthonous POC in the two hypoxic systems. Previous studies have suggested a good correlation between the relative contributions of allochthonous POC and the salinity, namely the contributions of allochthonous POC generally decrease as salinity increases seaward (Fontugne and Jouanneau, 1987; Middelburg and Herman, 2007). Similar correlations have also been reported in the PRE (Yu et al., 2010) and NGOM (Wang et al., 2004). The surface salinity in the high hypoxia frequency zone varies between 0 to 10 psu during the wet season based on our model results, while the surface salinity in the hypoxic zone of the NGOM is saltier than 24 psu even in the wet season according to the results from a well-validated physical model in Yu et al. (2015a). This implies a more important role of allochthonous POC in the PRE than in the NGOM. Finally, compositions of the allochthonous POC are different in the two hypoxic systems. Zhang and Li (2010) mentioned that contributions of labile POC to the allochthonous POC are higher in the PRE than in the NGOM.

(Position of Table 4)

4.3 The importance of re-aeration in PRE

Model results also highlight the importance of re-aeration in regulating DO dynamics and hypoxia migration in the PRE. On the one hand, based on our previous study applying the same physical-biogeochemical model and tracing method as here (Wang et al., 2017), the re-aeration together with the SOD are the most important process controlling DO dynamics. Nearly 28% of the surface DO_{REA} can reach the bottom layer, exerting a strong constrain on the spatial extent and duration of hypoxia in the PRE. When turning off the re-aeration, the high SOD will lead to a persistent hypoxia covering an area of over 3,000 km^2 in the PRE. On the other hand, the re-aeration responds rapidly to the perturbations of riverine inputs, which moderates the DO changes impacted by the perturbations. A conceptual diagram of these processes is illustrated in Figure 10. Compared with other hypoxic systems, the re-aeration in the PRE is of great importance because of the shallow topography and the strong re-aeration, which enable the surface oxygen supplied by re-aeration to penetrate to the bottom water. Re-aeration thus can greatly influence spatial migration of hypoxia under the perturbations of riverine inputs in the PRE. Furthermore, the shallow topography in the PRE allows the bottom SOD to indirectly affect the surface DO by decreasing the upward DO advective fluxes, which also facilitates strong re-aeration in the PRE. As we have described in section 3.3, the bottom SOD can lead to a decrease in surface DO concentrations by 2.22 mg L^{-1}. If turning off the SOD, the surface AOU would change from 0.61 to -1.61 mg L^{-1}, causing a change of re-aeration from 0.55 mg L^{-1} day^{-1} to -1.45 mg L^{-1} day^{-1}. This indicates that the SOD could shift the role of re-aeration from a strong oxygen sink to a strong source.

(**Position of Figure 11**)

One counter-example to the shallow PRE is the NGOM, where the hypoxic zone is deeper such that the surface water and bottom hypoxic water is detached. Also, the observed SOD varies from 0.06 to 0.70 g m^{-2} day^{-1} in the summer season in the NGOM (Murrell and Lehrter 2011), which is much lower than those in the PRE (0.72~3.89 g m^{-2} day^{-1}; Chung et al. (2004)). These characteristics together with the supersaturated DO concentrations in the surface water due to the high primary productivity make the re-aeration primarily an outgassing process in the NGOM (Yu et al., 2015b).

In the other hypoxic system, the Chesapeake Bay as described earlier, extended discussion on the importance of re-aeration is limited by a lack of observations and relevant studies of re-aeration. Nevertheless, according to our results, we can speculate that the re-aeration might be quite important in the Chesapeake Bay because the strong water column respiration can draw down the surface DO concentrations and enhance the re-aeration. However, the penetration of the oxygen supplied by re-aeration to the bottom layer is hard to be estimated without applying the DO species tracing method like our study or method similar in the Chesapeake Bay. In general, more relevant studies are required to examine the role of the re-aeration on hypoxia in the Chesapeake Bay.

5. Conclusion

This study uses a physical-biogeochemical model to simulate the DO dynamics and hypoxia in the PRE and investigate their responses to anthropogenic perturbations in riverine inputs. Model results based on simulation in 2006 shows that the hypoxia in the PRE starts in April, peaks in August, and disappears in October. Perturbing riverine inputs has strong impacts on DO dynamics and hypoxia. The hypoxic extent in the PRE is most sensitive to riverine input of particulate organic carbon, followed by oxygen and nutrients. This is different from other hypoxic systems (i.e. NGOM and Chesapeake Bay) because of the distinct physical and biogeochemical features in the PRE, i.e. the shallow topography, high water exchange rates and dominance of the SOD for DO depletions within bottom waters.

Model results also highlight the importance of re-aeration on hypoxia, which has strong buffering effects on the oxygen dynamics in the PRE. River-induced changes in source and sink processes can trigger an opposite shift in re-aerations by altering the surface AOU. In turn, the re-aeration can moderate the DO changes and hypoxia shifts responding to the changes in the oxygen source and sink processes. The important role of re-aeration in the PRE is due to the shallow waters and strong SOD in the estuary. Firstly, because of the shallow topography, the SOD can affect the surface DO indirectly by decreasing the surface AOU and consequently shifting re-aeration from an oxygen sink to a strong source process. Secondly, the shallow waters enable the oxygen supplied by the re-aeration in to diffuse to bottom waters and compensate the DO loss by the SOD.

Appendix A: Each component of water column production

The water column production (WCP) used in this study represents the net effects of water column on DO, which is a combination of the photosynthesis, respiration, nitrification, and oxidation:

$$WCP = Phot - Resp - Nitrif - Oxid \qquad (A1)$$

The first term *Phot* represents the photosynthesis (mg O_2 L^{-1} day^{-1}):

$$Phot = \left[\alpha_{\mathrm{OC}} \cdot \alpha_{\mathrm{NH_4}} \cdot G_{\mathrm{P}} \cdot P_{\mathrm{c}} + \left(\alpha_{\mathrm{NO_{23}c}}\right) \cdot \left(1 - \alpha_{\mathrm{NH_4}}\right) \cdot G_{\mathrm{P}} \cdot P_{\mathrm{c}}\right] \qquad (A2)$$

where α_{OC} represents oxygen to carbon ratio (mg O_2:mg C), $\alpha_{\mathrm{NH_4}}$ represents the phytoplankton's preference for ammonium uptake (dimensionless), G_{P} represents specific phytoplankton growth rate (day^{-1}) which is dependent on the temperature, light, and nutrients (including NO2+NO3, NH4, PO4, Si, see Eq. (14)), P_{c} represents phytoplankton biomass (mg C L^{-1}), and $\alpha_{\mathrm{NO_{23}c}}$ represents oxygen to carbon ratio for nitrate uptake (mg O_2:mg N).

The term *Resp* represents the respiration (mg O_2 L^{-1} day^{-1}):

$$Resp = \alpha_{\mathrm{OC}} \cdot k_{\mathrm{PR}}(T) \cdot P_{\mathrm{c}} \qquad (A3)$$

where the $k_{\mathrm{PR}}(T)$ represents the temperature-dependent respiration rate (day^{-1}).

The term *Nitrif* represents the nitrification (mg O_2 L^{-1} day^{-1}):

$$Nitrif = 2 \cdot \alpha_{ON} \cdot k_{14,15}\theta_{14,15}^{T-20} \cdot NH_4 \cdot \frac{DO}{K_{nitri} + DO} \qquad (A4)$$

where α_{ON} represents the oxygen-to-nitrogen ratio (mg O_2:mg N), $k_{14,15}$ represents the nitrification rate at 20 °C (day^{-1}), $\theta_{14,15}$ represents the temperature coefficient (dimensionless), and K_{nitri} represent the half saturation constant for oxygen limitation (mg O_2 L^{-1}).

The term *Oxid* represents the oxidation of dissolved organic carbon, and dissolved sulfide (mg O_2 L^{-1} day^{-1}):

$$Oxid = \alpha_{OC} \cdot \left[k_{20,0}\theta_{20,0}^{T-20} \cdot RDOC + k_{21,0}\theta_{21,0}^{T-20} \cdot LDOC \cdot \frac{LDOC}{K_{LDOC} + LDOC} + k_{22,0}\theta_{22,0}^{T-20} \cdot ReDOC \cdot \frac{ReDOC}{K_{LDOC} + ReDOC} + k_{23,0}\theta_{23,0}^{T-20} \cdot ExDOC \cdot \frac{ExDOC}{K_{LDOC} + ExDOC}\right] \cdot \frac{P_c}{K_{Pc} + P_c} \cdot \frac{DO}{K_{DO} + DO} + k_{O_2^*}\theta_{O_2^*}^{T-20} \cdot O_2^* \cdot \frac{P_c}{K_{Pc} + P_c} \cdot \frac{DO}{K_{DO_{O_2^*}} + DO} \qquad (A5)$$

where $k_{20,0}$, $k_{21,0}$, $k_{22,0}$, $k_{23,0}$, and $k_{O_2^*}$ represent the oxidation rates of refractory dissolved organic carbon (RDOC), labile dissolved organic carbon (LDOC), reactive dissolved organic carbon (ReDOC), algal exudate dissolved organic carbon (ExDOC), and dissolved sulfide at 20 °C (day^{-1}); $\theta_{20,0}$, $\theta_{21,0}$, $\theta_{22,0}$, $\theta_{23,0}$, and $\theta_{O_2^*}$ represent the temperature coefficient (dimensionless); K_{LDOC} represents the Michaelis constant for LDOC (mg C L^{-1}); K_{Pc} represents the half-saturation constant for phytoplankton limitation (mg C L^{-1}); K_{DO} and $K_{DO_{O_2^*}}$ represent the half-saturation constant for DO limitation (mg O L^{-1}). More detailed information of these variables and parameters can be seen in Table A1 and Table A2.

(position of Table A1)

(position of Table A2)

Appendix B: Sediment flux module

In this study, a sediment flux module is used to receive the depositional fluxes of particulate organic carbon, particulate organic nitrogen, and particulate organic phosphorus, which are collectively referred to as particulate organic matter, from the overlying water. After that, the diagenesis of particulate organic matter will occur in the sediment and produce soluble end-products. The fluxes of nutrients and SOD across the water-sediment interface will be determined by the differences in the dissolved concentrations between the resulting sediment and overlying water combined with the transfer coefficient.

In the sediment flux module, particulate organic matter is classified into three G classes (G1: reactive, G2: refractory, and G3: inert) with the different reaction rates. The kinetic equation for diagenesis is:

$$H\frac{dG_i}{dt} = -k_{Gi}\theta_{Gi}^{T-20}G_iH + J_{Gi} \qquad (B1)$$

where H is the depth of sediment (m), G represents the particulate organic carbon, the particulate organic nitrogen, or the particulate organic phosphorus (mg L^{-1}), subscript i represents the i^{th} G class (i=1, 2, 3), k_{Gi} represents the corresponding reaction rate (day^{-1}), θ_{Gi} represents the temperature coefficient (dimensionless), and J_{Gi} represents the depositional fluxes of Gi from the overlying water (g m^{-2} day^{-1}).

After the deposition and diagenesis, further reactions of organic matter (including particulate organic carbon, dissolved organic carbon, particulate organic nitrogen, dissolved organic nitrogen, particulate organic phosphorus, and dissolved organic phosphorus) will occur in both aerobic layer (denoted as layer 1) and anaerobic layer (denoted as layer 2). The mass balance equations can be expressed as a general form:

$$H_1\frac{dC_{T1}}{dt} = K_{L01}(f_{d1}C_{T1} - C_{d0}) + w_{12}(f_{p2}C_{T2} - f_{p1}C_{T1}) + K_{L12}(f_{d2}C_{T2} - f_{d1}C_{T1}) - K_1H_1C_{T1} + J_{T1} \quad (B2)$$

$$H_2\frac{dC_{T2}}{dt} = -w_{12}(f_{p2}C_{T2} - f_{p1}C_{T1}) - K_{L12}(f_{d2}C_{T2} - f_{d1}C_{T1}) - K_2H_2C_{T2} - w_2C_{T2} + J_{T2} \qquad (B3)$$

where the subscript 0, 1, 2 represent the overlying water, the aerobic layer, and the anaerobic layer, H_1 and H_2 represent the thickness of aerobic layer and anaerobic layer (m), respectively, C_{T1} and C_{T2} represent the total concentrations (mg L^{-1}) in aerobic layer and anaerobic layer, respectively, C_{d0} represents the dissolved concentrations (mg L^{-1}) in the overlying water, f_{d1} and f_{d2} represent the dissolved fractions in aerobic layer and anaerobic layer (dimensionless), respectively, f_{p1} and f_{p2} represent the particulate fractions in aerobic layer and anaerobic layer (dimensionless), respectively, K_{L01} represents the transfer coefficient between the overlying water and aerobic layer (m day^{-1}), K_{L12} represents the transfer coefficient between the aerobic layer and anaerobic layer (m day^{-1}), K_1 and K_2 represent the first-order decay rate of in the aerobic layer and anaerobic layer (day^{-1}), respectively, w_{12} represents the particle mixing rate between the aerobic layer and anaerobic layer (m day^{-1}), w_2 represents the sedimentation rate out of the anaerobic layer (m day^{-1}), J_{T1} and J_{T2} represent the total influxes for each class of particulate organic matter into the aerobic layer and anaerobic layer (g m^{-2} day^{-1}), respectively.

Fluxes of nutrients and DO across the water-sediment interface can be represented as:

$$J = s(C_{water} - C_{sed}) \qquad (B4)$$

where s represents the transfer coefficient (m day^{-1}), C_{water} and C_{sed} represent the concentrations of nutrients and DO in the water and sediment (mg m^{-3} day^{-1}), respectively.

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Table list

Table 1. Overview of model experiments

Experiments	Description
Base	Forced by the riverine inputs of monthly observed DO, nutrients and particulate organic carbon concentration from 2006 collected by the State Oceanic Administration
DO simulations	
RivDO-50%	Same as Base simulation except the riverine DO inputs are decreased by 50%
RivDO+50%	Same as Base simulation except the riverine DO inputs are increased by 50%
Nutrients simulations	
RivNtr-50%	Same as Base simulation except the riverine nutrients inputs are decreased by 50%
RivNtr+50%	Same as Base simulation except the riverine nutrients inputs are increased by 50%
POC simulations	
RivPOC-50%	Same as Base simulation except the riverine inputs of particulate organic carbon are decreased by 50%
RivPOC+50%	Same as Base simulation except the riverine inputs of particulate organic carbon are increased by 50%

Table 2. Comparisons of nutrient limitation and light limitation on the growth of phytoplankton for Base and two POC simulations. Values are averaged over the bottom layer of the PRE. The lower values represent the stronger limitation.

	Base	**RivPOC-50%**	**RivPOC+50%**
Nutrient limitation	0.81±0.09	0.80±0.09	0.82±0.09
Light limitation	0.21±0.15	0.25±0.16	0.18±0.14

Table 3. A summary of characteristics of hypoxia among three systems (i.e. Chesapeake Bay, northern Gulf of Mexico, and PRE). Abbreviation WCR represents the water column respiration which is the sum of respiration, nitrification, and oxidation.

	WCR dominant	**SOD dominant**	
		Autochthonous POC dominant	**Allochthonous POC dominant**
Chesapeake Bay	√		
NGOM		√	
PRE			√

Table 4. A summary of the differences in physical and biogeochemical processes associated with the relative contributions of autochthonous versus allochthonous POC between the PRE and NGOM

	Period	PRE	NGOM
Allochthonous POC input ($t\ yr^{-1}$)	Annual	2.5×10^{6} [a]	3.8×10^{6} [b]
Primary productivity ($mg\ m^{-2}\ day^{-1}$)	Summer	183.9–1,213 [c]	330-7,010 [d]
DIN loading ($t\ d^{-1}$)	Annual	1531 [e]	1955 [e]
DIP loading ($t\ d^{-1}$)	Annual	27 [e]	133 [e]
DIN:DIP (mol:mol)	Annual	126 [e]	33 [e]
Residence Time (d)	Summer	3-5 [f]	~95 [f]

[a] Zhang et al. (2013); [b] Wang et al. (2004); [c] Ye et al. (2014); [d] Quigg et al. (2011); [e] Hu and Li (2009);
[f] Rabouille et al. (2008)

Tabel A1. List of state variables in the water quality model (RCA) and the DO species tracing method

variables	Description (unit)
DO	Dissolved oxygen (mg O_2 L^{-1})
DO_{sat}	Saturated DO concentrations (mg O_2 L^{-1})
DO_{sed}	DO concentrations in the sediment (mg O_2 L^{-1})
DO_{BC}	DO species which is contributed by lateral boundary condition (mg O_2 L^{-1})
DO_{REA}	DO species which is contributed by re-aeration (mg O_2 L^{-1})
DO_{WCP}	DO species which is contributed by water column production (mg O_2 L^{-1})
DO_{SOD}	DO species which is contributed by sediment oxygen demand (mg O_2 L^{-1})
O_2^*	Dissolved oxygen equivalent (mg O_2 L^{-1})
P_{c}	phytoplankton biomass (mg C L^{-1})
RDOC	refractory dissolved organic carbon (mg C L^{-1})
LDOC	labile dissolved organic carbon (mg C L^{-1})
ReDOC	reactive dissolved organic carbon (mg C L^{-1})
ExDOC	algal exudate dissolved organic carbon (mg C L^{-1})
Gi	Concentrations of particulate organic carbon, particulate organic nitrogen, or particulate organic phosphorus in i^{th} G class (mg L^{-1})
C_{d0}	dissolved concentrations in the overlying water (mg L^{-1})
C_{T1}	total concentrations in aerobic layer (mg L^{-1})
C_{T2}	total concentrations in anaerobic layer (mg L^{-1})
C_{water}	concentrations of nutrients and DO in the water (mg L^{-1})
C_{sed}	concentrations of nutrients and DO in the sediment (mg L^{-1})

Table A2. Main parameters and constants for the water quality model (RCA)

parameters	Description (unit)	values
α_{OC}	oxygen to carbon ratio (mg O_2:mg C)	32/12
$\alpha_{\mathrm{NO_{23}c}}$	oxygen to carbon ratio for nitrate uptake (mg O_2:mg C)	12/14
α_{ON}	oxygen-to-nitrogen ratio (mg O_2:mg N)	32/14
$k_{14,15}$	nitrification rate at 20 °C (day^{-1})	0.08
K_{nitri}	half saturation constant for oxygen limitation (mg O_2 L^{-1})	1.0
$k_{20,0}$	oxidation rates of refractory dissolved organic carbon at 20 °C (day^{-1})	0.009
$k_{21,0}$	oxidation rates of labile dissolved organic carbon at 20 °C (day^{-1})	0.1
$k_{22,0}$	oxidation rates of reactive dissolved organic carbon at 20 °C (day^{-1})	0.1
$k_{23,0}$	oxidation rates of algal exudate dissolved organic carbon at 20 °C (day^{-1})	0.35
$k_{\mathrm{O_2^*}}$	oxidation rates of dissolved sulfide at 20 °C (day^{-1})	0.08
K_{LDOC}	Michaelis constant for LDOC (mg C L^{-1})	0.1
K_{Pc}	half-saturation constant for phytoplankton limitation (mg C L^{-1})	1.0
K_{DO}	half-saturation constant for DO limitation (mg O L^{-1})	0.2
$K_{\mathrm{DO_{O_2^*}}}$	half-saturation constant for DO limitation in oxidation of dissolved sulfide (mg O L^{-1})	0.2
θ_{a}	temperature coefficient for re-aeration (dimensionless)	1.024
$\theta_{14,15}$	temperature coefficient for nitrification (dimensionless)	1.045
$\theta_{20,0}$	the temperature coefficient for oxidation rates of refractory dissolved organic carbon (dimensionless)	1.08
$\theta_{21,0}$	the temperature coefficient for oxidation rates of labile dissolved organic carbon (dimensionless)	1.08
$\theta_{22,0}$	the temperature coefficient for oxidation rates of reactive dissolved organic carbon (dimensionless)	1.08
$\theta_{23,0}$	the temperature coefficient for oxidation rates of algal exudate dissolved organic carbon (dimensionless)	1.047
$\theta_{\mathrm{O_2^*}}$	the temperature coefficient for oxidation rates of dissolved sulfide (dimensionless)	1.08

Figure caption

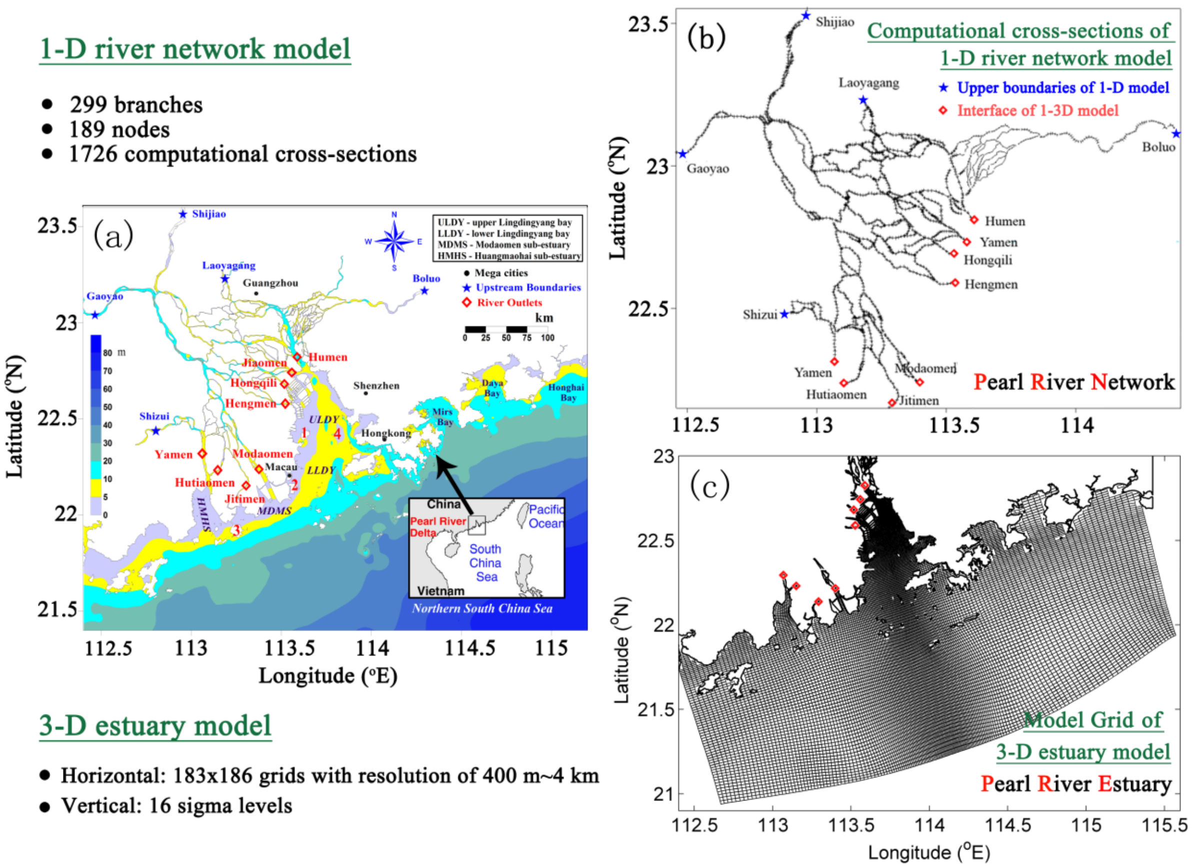

Figure 1 (a) A bathymetric map showing the Pearl River Network and the Pearl River Estuary, (b) computational cross-sections for the 1-D river network model, and (c) the model grid for 3-D estuary model. Red numbers in Figure 1a represent islands which are not marked on the map: 1-Qi'ao island; 2-Hengqin island; 3-Gaolan island; and 4-Inner Lingding island.

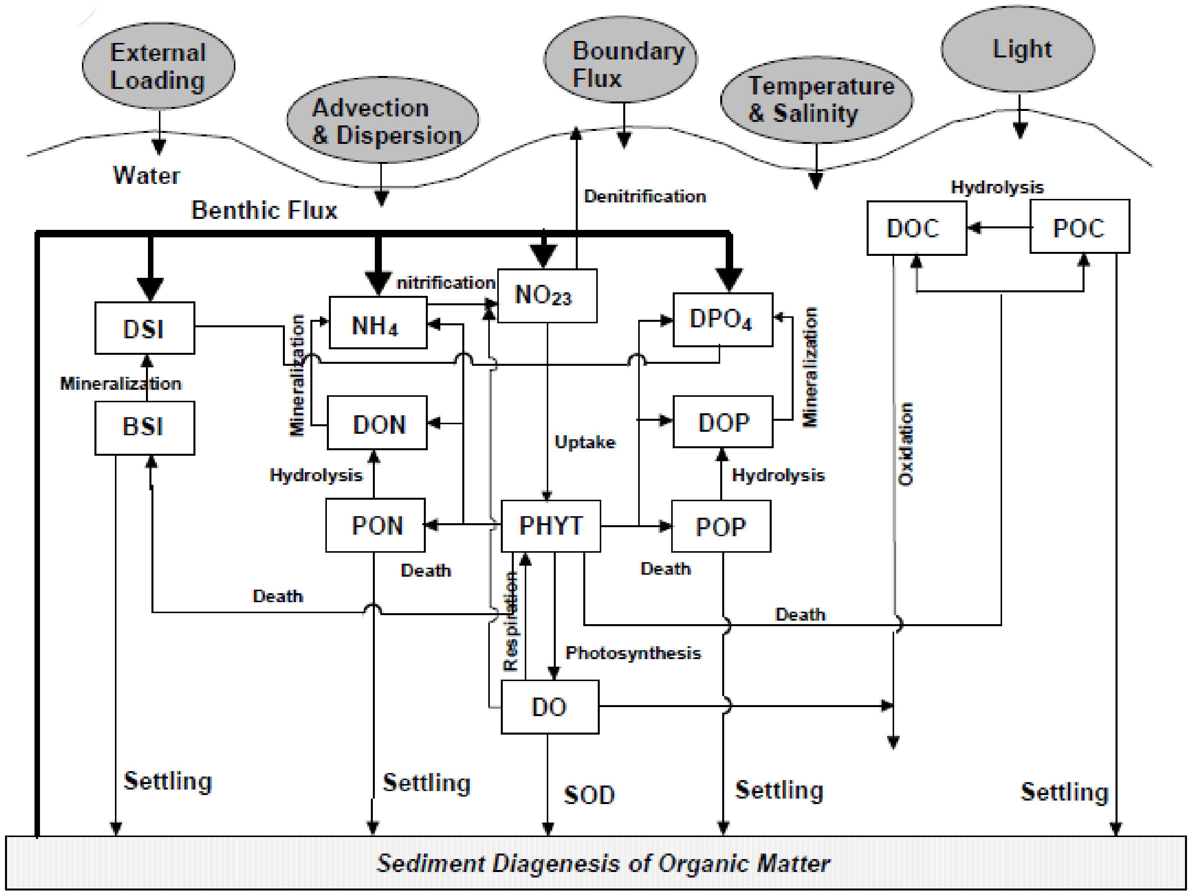

Figure 2 Conceptual framework for RCA model with a sediment flux module (Zhang and Li, 2010). DO represents dissolved oxygen; PHYT represents phytoplankton; POC represents particulate organic carbon; DOC represents dissolved organic carbon; NH_4 represents ammonia nitrogen; NO_{23} represents nitrite and nitrate nitrogen; PON represents particulate organic nitrogen; DON represents dissolved organic nitrogen; DPO_4 represents dissolved inorganic phosphorus; POP represents particulate organic phosphorus; DOP represents dissolved organic phosphorus; DSi represents dissolved silica; BSi represent biogenic silica; and SOD represents sediment oxygen demand.

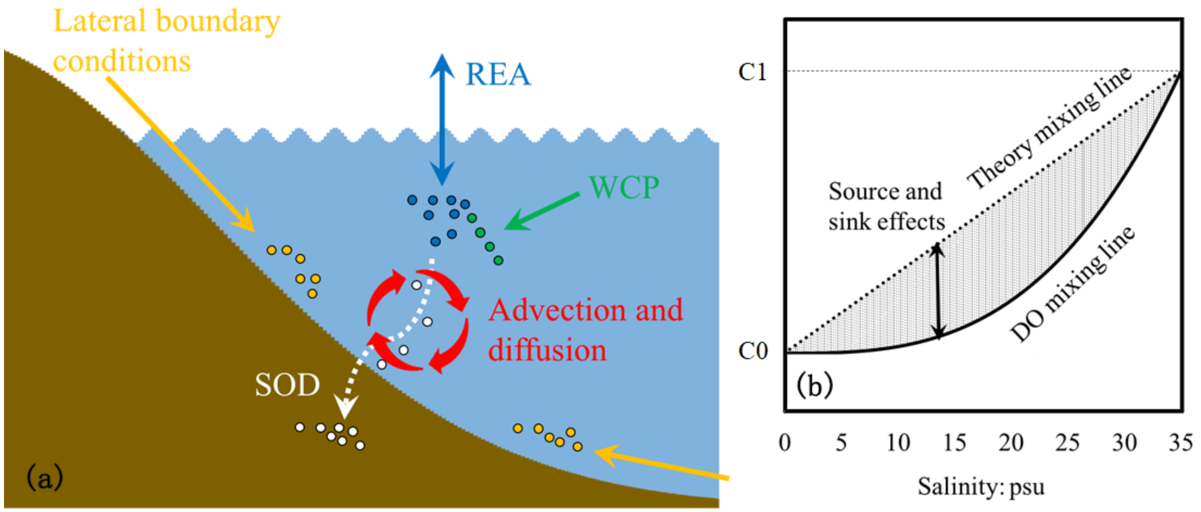

Figure 3 (a) The schematic diagram illustrating the mixing process of dissolved oxygen in the estuary and (b) the schematic plot for dissolved oxygen versus salinity (the solid black curve line) during the mixing in the estuary. C1 represents the concentrations in sea water, while C0 represents the concentrations in river water.

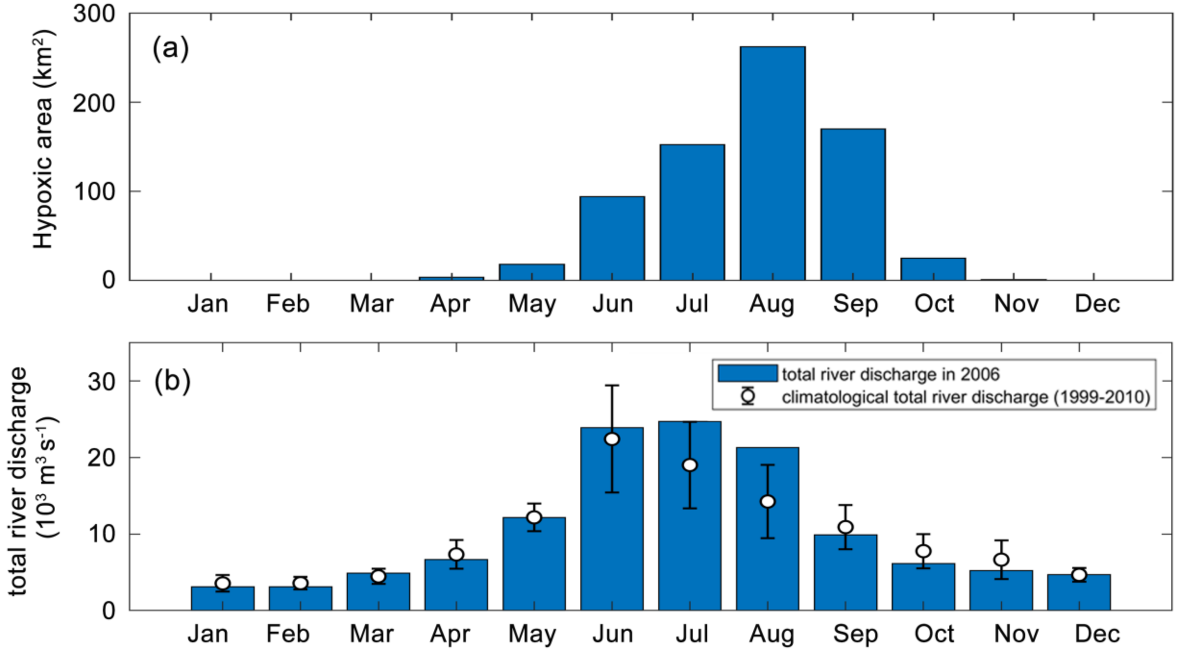

Figure 4. (a) Annual cycles of the model simulated monthly hypoxic area in 2006 of the PRE, (b) annual cycle of the total river discharges in 2006 (blue bars) and during 1999-2010 (error bars represent a standard deviation around the climatological mean values).

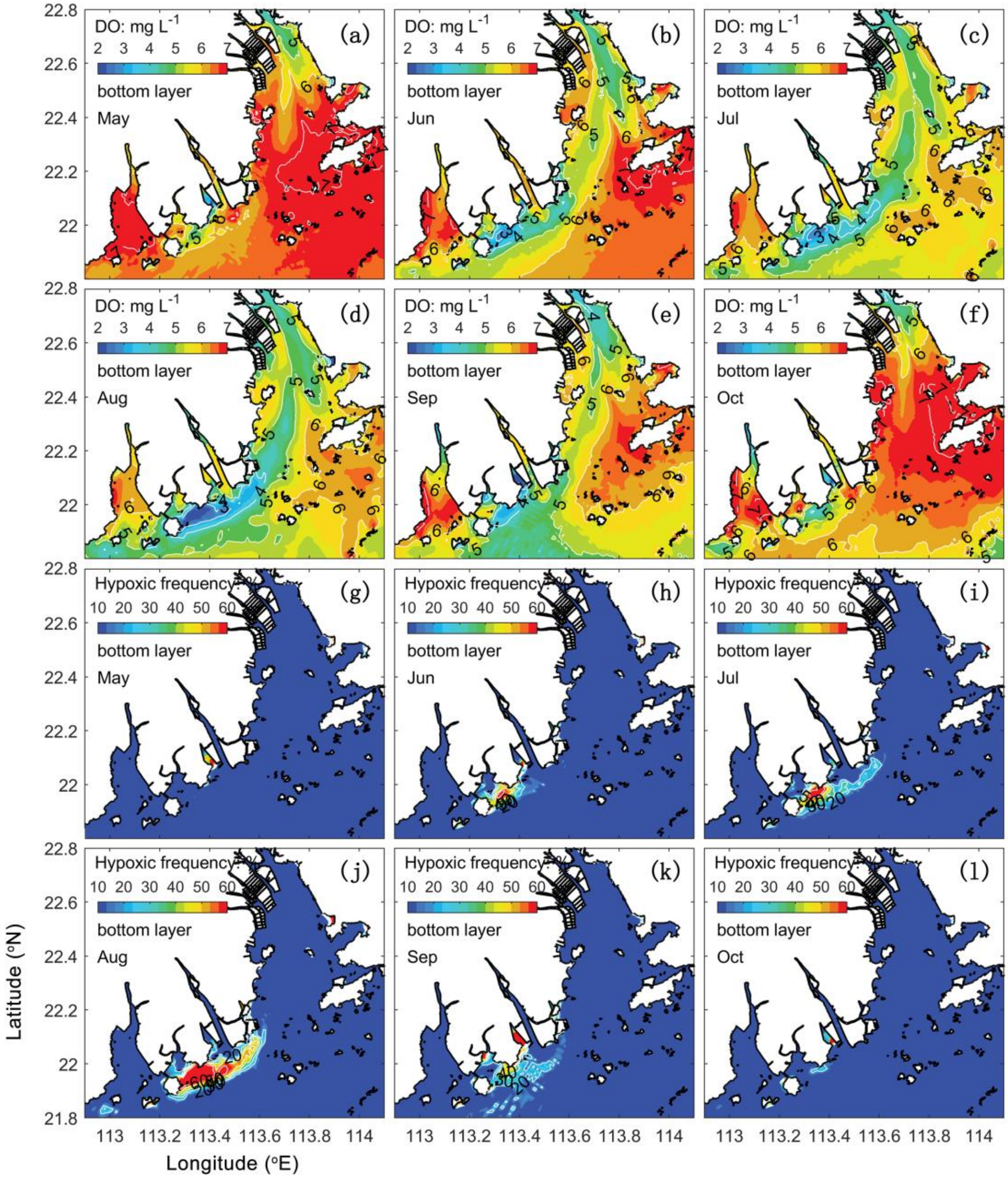

Figure 5. Spatial distributions of bottom DO (a~f) and hypoxic frequency (g~l) during the May-October. The hypoxia is defined as DO concentraion below 3 mg L^{-1}.

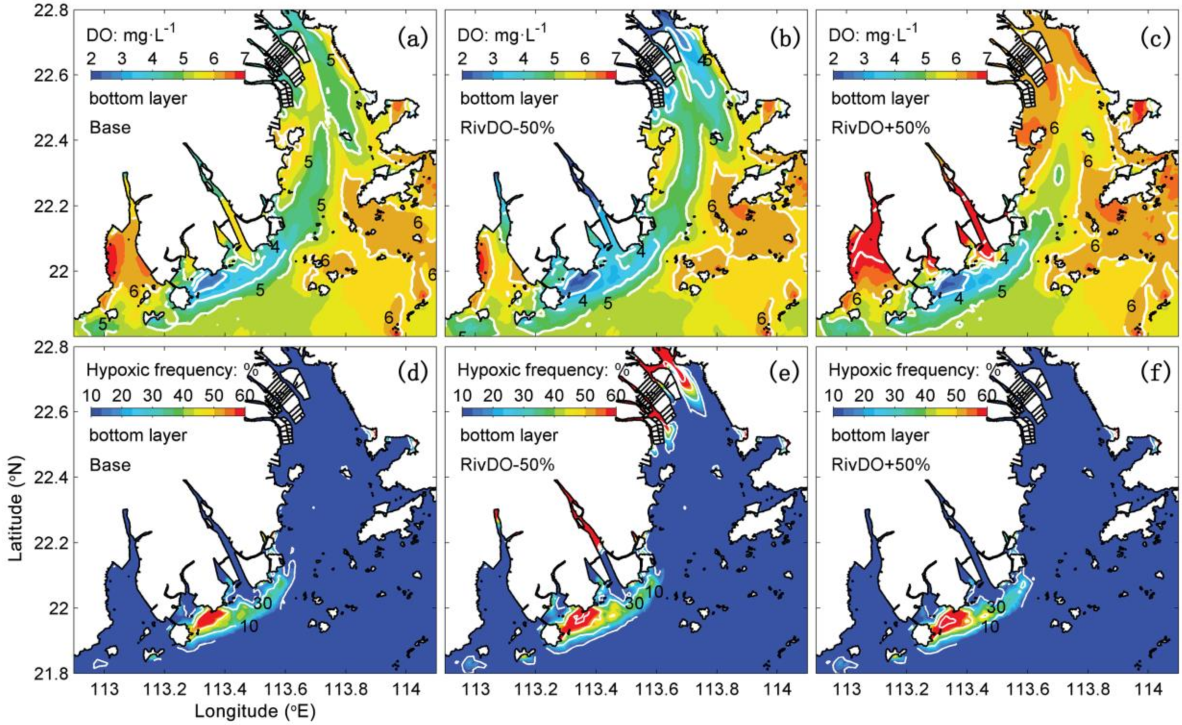

Figure 6 Spatial distributions of DO concentrations (a, b, c) and hypoxic frequency (d, e, f) in the bottom layer for DO concentration simulations. The DO concentration is averaged over July and August 2006.

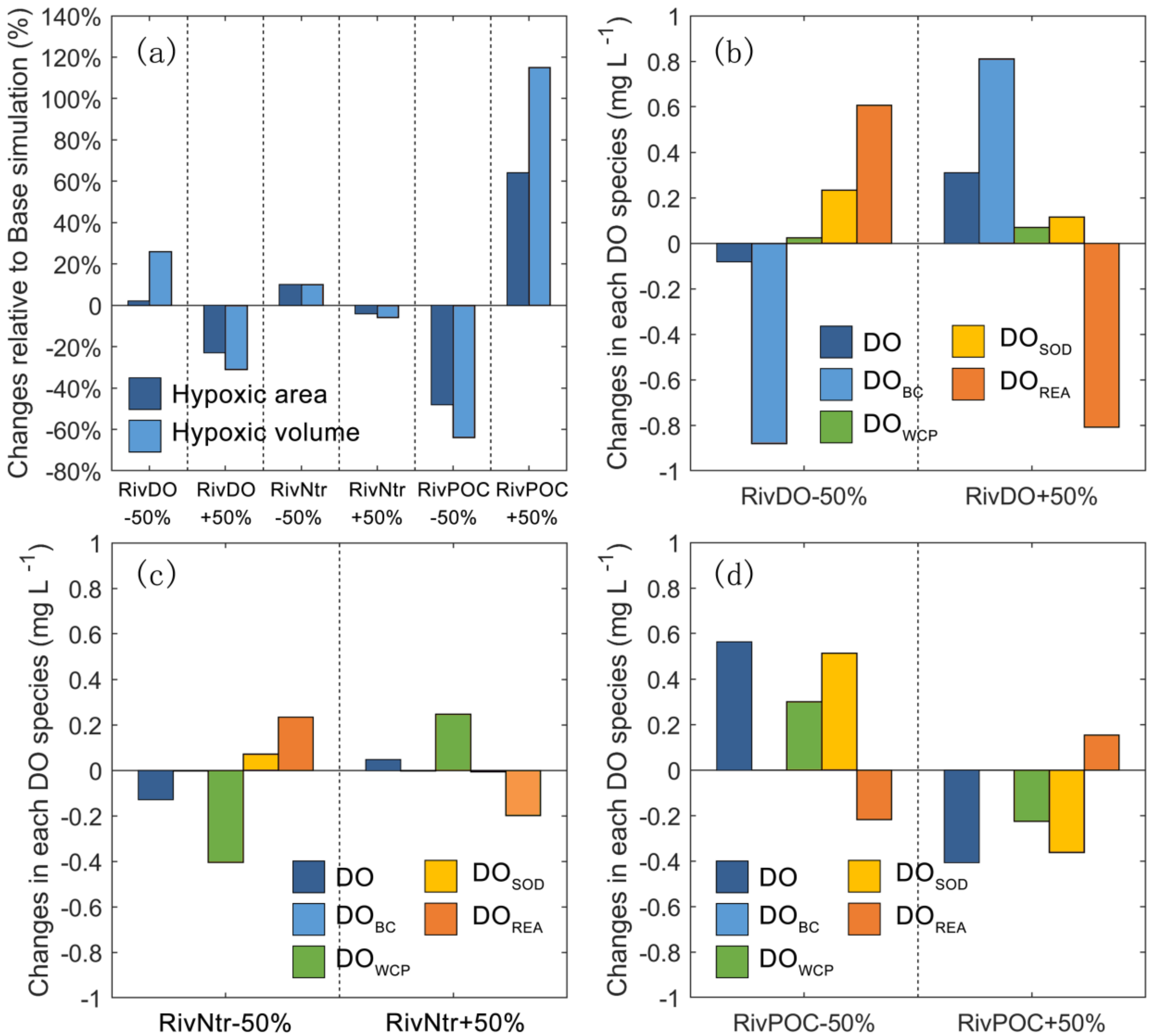

Figure 7 The percentage changes of the hypoxic area and hypoxic volume in each simulation in relative to the Base simulation (a). The changes of each DO species averaged over the high hypoxic frequency zone (denoted as the white contour in Figure 6) in DO simulations (b), nutrient simulations (c), and POC simulations (d) in relative to the Base simulation.

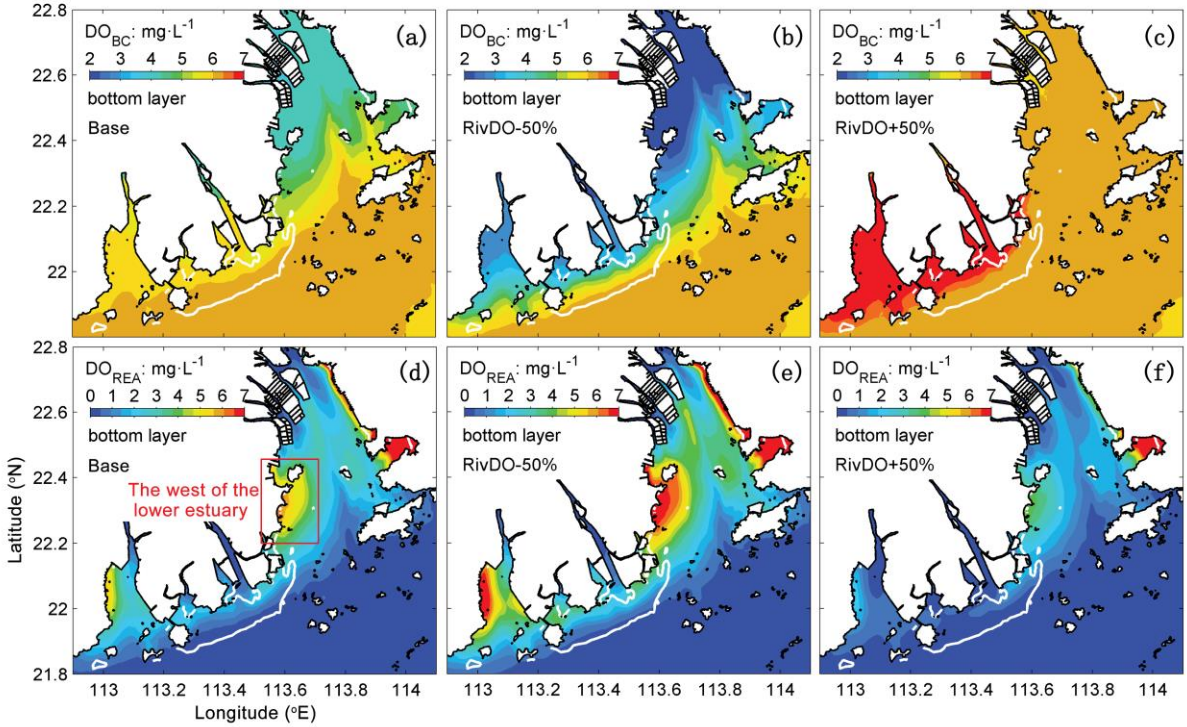

Figure 8 The spatial distribution of DO_{BC} (a, b, c) and DO_{REA} (d, e, f) concentrations at the bottom layer for three DO simulations. The white contour represents the high frequency zone, and the red box represents the west of the lower estuary.

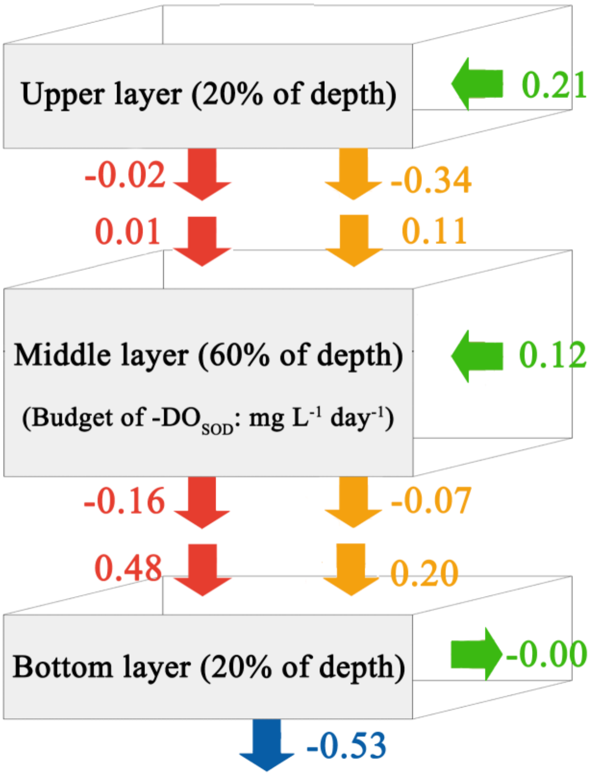

Figure 9 Budget of $-DO_{SOD}$ for the upper layer, middle layer, and bottom layer in the PRE for the Base simulation. Blue arrows represent sediment oxygen demand, red arrows represent the vertical diffusion, orange arrows represent vertical advection, and green arrows represent horizontal advection. Positive values mean the source effects while the negative values mean the sink effects of the sediment oxygen demand on DO concentrations. (unit: mg L^{-1} day^{-1})

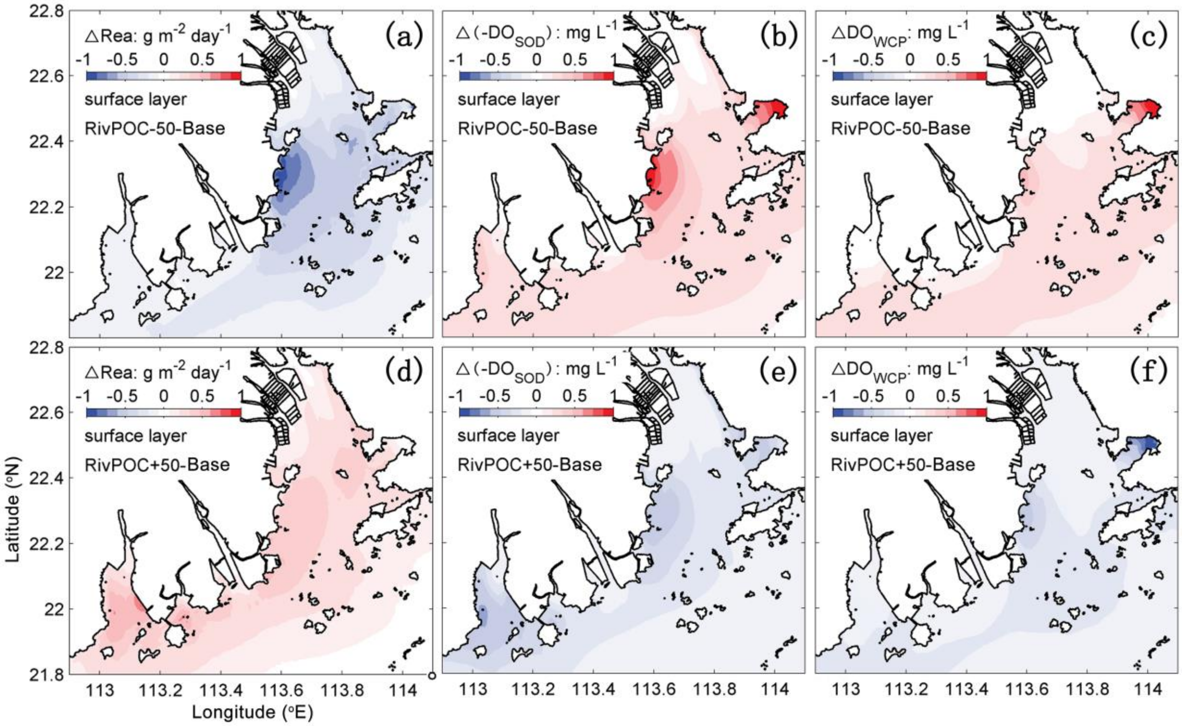

Figure 10 The changes in air-sea re-aeration rates (a, d), -DO_{SOD} (b, e), and DO_{WCP} (c, f) concentrations in the surface layer with respect to the Base simulation (model-Base). Positive values of ΔRea, $\Delta(-DO_{SOD})$ and ΔDO_{WCP} concentrations represent higher re-aeration rates, higher DO concentrations caused by the changes of the sediment oxygen demand rate and the water column production rate, respectively.

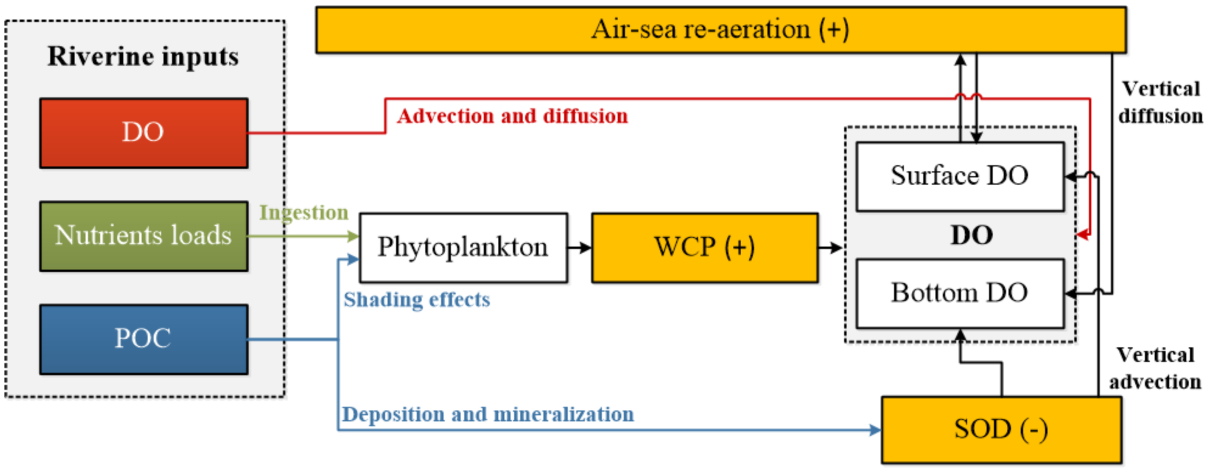

Figure 11 Conceptual schematic of the oxygen dynamics in response to riverine inputs in the PRE. The white boxes represent the state variables in the water column, the orange boxes represent the source and sink processes associated with the oxygen dynamics. The positive signs represent the sources while the negative signs represent the sinks for DO concentrations.