Responses to Anonymous Referee #1
Below the review is reproduced in black font and our responses interspersed in blue.

Comments:

In overall, the authors have answered to reviewers requests. The discussion has been reworked, and new sections added (3.1 model validation, 3.2.3 Physical drivers of intra-seasonal variability in hypoxia) as well as new figures.

Thank you to the authors for having proceeded to an additional simulation with repeated annual forcing. The results of the extra figure show indeed no trend in the model behavior or budget. This fully answers to one of my main concern.

Concerning the data-model comparison, the other main concern, shared by other reviewers, a new section has been added (3.1). Unfortunately, these are mostly text already present in the supplement of the previous version, and new text referring to the (already existing) supplement figures.

Reply: We are not quite sure what the Reviewers concern is and how to respond to this comment. Unfortunately, the other two Reviewers of the previous manuscript version commented that model-data comparisons were not provided even though they were in the Supplement. By moving the relevant text to the main manuscript (and adding additional model-data comparisons for nutrients) we believe that these previous concerns were addressed in the first revision. Furthermore, we had addressed the previous comment by this Reviewer about the color choices. No further action was taken.

The main answer to the data-model comparison request is that data are missing. Which may be true. Still, this is not completely satisfying in the sense that the model produces detailed time series of many variables, and that the inter-annual and intra-seasonnal variability are discussed in depth, while the model "validation" is made at punctual parameters (data availability).

Reply: We agree with the Reviewer that more data would be excellent, but obviously can only compare the model to the data that are available. In section 3.1, we have provided extensive model data-comparisons and accompanying statistical metrics using all the data that are available (incl. *in situ* measurements of oxygen, nitrate, T & S, and satellite measurements of SST and chlorophyll). Also, it is exceedingly rare that detailed time series of intra-seasonal and interannual variability are collected, both for coastal regions as well as for the open ocean (aside from very few time series locations). Nonetheless, models are routinely developed and used for coastal regions and provide useful insights. We also note that the Reviewer explicitly states in the next comment that "the model skills are reasonably good" which is greatly appreciated.

Both in introduction (line 117) and discussion (line 511), the authors write that "a 6-year simulation was performed and validated". I disagree with this too strong sentence. I agree that the model skills are reasonably good. But the model has not been "validated" over the 6 years. This is important : after section 3.1, only model results are presented. In Figure 3, the model is evaluated on "static" features. In figures 4 and further, model results are discussed in their "dynamics". For non- modelers, this may be confusing. Still I appreciate the work.

Reply: We have removed four occurrences of "validate" (one in the Abstract, one in the Intro, one on Section 3.1, and one in the second paragraph of the Discussion), but left the subsection title of 3.1 as "Model validation", left "We implemented and validated …" in the first sentence of the Discussion, and the term "validation" in the second sentence of the Conclusions for the following reasons. We wonder whether the Reviewer's disagreement with our statement that "the model was validated" is a misunderstanding about the meaning of the word validate. We are using this term consistent with the dictionary to refer to "the process of checking the validity or accuracy of (something)" as is common in the modelling literature. A more comprehensive scientific definition of the term is given by Dee (1995, p.4) according to which validation refers to "the process of formulating and substantiating explicit claims about the applicability and accuracy of computational results, with reference to the intended purposes of the model as well as to the natural system it represents" (Dee, 1995, p. 4). We believe we have done that and hence feel justified in using the term.

Nevertheless, if the Reviewer and Editor insist that we should not use this word at all, we can replace it by "quantitative model-data comparisons were carried out" (this would apply to three remaining occurrences in the manuscript).

Dee, D. P., A Pragmatic Approach to Model Validation, in Quantitative Skill Assessment for Coastal Ocean Models, pp. 1–13, American Geophysical Union (AGU), 1995, section: 1, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/CE047p0001.

Many values of your results have changed since previous submission : maximum hypoxic extent in section 3.2, all values in the table of Oxygen budget in supplement. Idem for correlation coefficients in Figure S7 (previously Figure S6). Is the reason a change in the region definition, or any change in the conducted simulations or the model parameterization itself ? Sorry, I did not find any explanation in the answers to the three reviewers. It is probably of minor importance, but it would be better to clarify.

Reply: This is correct. The reason is that we repeated all simulations with a minor update to the riverine nutrient input data (note the author contributions where we explicitly state: "For the manuscript revision, AL reran the model simulation…"). The results were not affected in any qualitative way, but the detailed numbers have changed a little as the Reviewer correctly observed. More specifically, the update of the riverine nutrient brings the phosphate and nitrate loads in agreement with in-situ nutrient measurements in the estuary (which only became available to us after the first version of the manuscript was submitted) and is described in Section 2.2 where we state:

> "*Monthly nutrient loads of NO3 and PO4 from the Changjiang are from the Global-NEWs Model (Wang et al., 2015) but were adjusted by multiplicative factors of 1.20 and 1.66, respectively, to ensure a match between simulated and observed nutrient concentrations in the CE (see July and Aug 2012 in Figure 2).*"

Supplement :
Figures from the supplement have been improved for visibility of color dots.

In Figure S7 (previously Figure S6), the model-data comparison of Surface Chlorophyll, surprisingly, the plot for February has disappeared. This was one of the less favorable !

Reply: We appreciate the comment about improved colors. Remotely sensed chlorophyll in February tends to overestimate actual conditions probably due to high suspended particulate matter concentrations on the inner shelf resulting from the strong East Asian monsoon, which was also mentioned in previous version of Supplement. Therefore, the comparison in February is less meaningful, and has been removed in the new version to make the text more concise. No further action taken.

Responses to Anonymous Referee #2
Below the review is reproduced in black font and our responses interspersed in blue.

Comments:

Thank you for the work that you have done on the manuscript since the last version. The manuscript has improved, I do however think that it is still in need of major revisions before a potential publication.

Reply: We appreciate the Reviewer's comment that the manuscript has improved but were alarmed and disappointed to see a degradation in the Reviewer's scores from Good, Fair, Good for the initial version to Fair, Fair, Poor for the revised version. We are puzzled by this not only because the Reviewer stated that the manuscript has improved, but also because the Reviewer's comments, which we appreciate, are mostly of editorial nature and asking for clarifications rather than raising any flaws in the study or analysis, at least in our reading. Nevertheless, we value the constructive suggestions for further improvement and the opportunity to clarify the intended scope and contributions of our study.

Major comments:

1. In the introduction you already mention other studies that have investigated the oxygen dynamics in this region, and that they have found that the oxygen consumption, the wind and stratification are important drivers behind. It is not clear to me what new knowledge that you study brings in to this. To clarify this, please develop your discussion of your findings in perspective to these studies in your manuscript.

Reply: The previous studies we mention in the Introduction are by Chen et al. (2015a, b), Zheng et al. (2016) and Zhou et al. (2017). They differ from ours as follows:

- Chen et al. (2015a, b) used a very restricted domain and no biological model (as stated in the Intro).
- Zheng et al. (2016) used a simple nitrogen model but did not explicitly investigate the role of nutrient inputs in hypoxia generation.

We state explicitly in the Intro referring to these two studies: "*These previous modeling studies focused on the response of hypoxia to physical factors only and did not address seasonal evolution and interannual variations of hypoxia or the influence of variability in biological rates*."

- The study by Zhou et al. (2017) is the most sophisticated of the prior studies, but their model did not include sediment oxygen consumption, which is now known to be an important driver of hypoxia in the ECS. Their study also did not investigate to what degree hypoxia variability is driven by variations in river input or wind forcing.

Again, we state this explicitly in the Intro: "*Zhou et al. (2017) analyzed the seasonal evolution of hypoxia and the importance of the Taiwan Warm Current and Kuroshio intrusions as a nutrient* *source using an advanced coupled hydrodynamic-biological model. However, the baseline of their model does not include sediment oxygen consumption…*"

We reformulated the last paragraph of the Introduction to concisely state the objectives of the study by adding: "*We performed and assessed a 6-year simulation of the ECS, and use the model results here to identify the main factors driving hypoxia variability on interannual and intra-seasonal timescales in the simulation. More specifically, we investigate the role of interannual variations in riverine input of nutrients and freshwater versus intra-seasonal variations in coastal circulation and mixing. We also present an oxygen budget to quantify the relative importance of SOC and the influence of lateral advection of oxygen."*

We would like to add that despite the previous work referred to above, no comprehensive explanation of the main factors driving hypoxia variability has been put forward as of yet.

Lastly, the most important contributions of this study are listed below (and emphasized in bold font) with an explanation as to why they are important and how they are spelled out in the Discussion:

1. **Variability in river inputs of freshwater partly explains year-to-year variations in hypoxia but variability in DIN loads does not.** This is a surprising and interesting finding. In other river-dominated hypoxic regions (e.g. the Gulf of Mexico and Chesapeake Bay) FW and DIN loads are highly correlated and DIN is used to predict hypoxic extent. We say in the third paragraph of the Discussion: "*Interannual variability in hypoxic area is partly explained by variations in annual FW input… there is a strong and significant negative correlation between mean bottom oxygen in August and annual FW input.*" And in the fourth paragraph of the Discussion: "*Surprisingly, DIN load is not correlated with FW input, hypoxic area, and mean bottom oxygen in August*"
2. **Short-term variability in hypoxia is strongly related to the spatial extent of the freshwater plume.** To the best of our knowledge, such relationship has not been shown for other coastal regions. It is interesting because observing the surface plume is easier than observing bottom oxygen concentrations, hence this relationship holds promise for developing predictions based on the surface plume extend which can be observed remotely. We also showed how plume distribution is affected by upwelling-favorable and downwelling-favourable winds. Eighth paragraph of the Discussion: "*Intra-seasonal variability in hypoxic conditions is significantly related to the extent of the FW plume which is partly explained by variations in riverine FW input but strongly modulated by coastal circulation and mixing… Wind direction has a notable effect on the geographic distribution of hypoxia. Southerly, upwelling-favorable winds lead to a more widespread eastward extension of the FW plume… Northerly, downwelling-favorable winds create a coastally trapped southward jet that moves FW southward and constrains the plume close to the coast."*
3. **High-wind events explain hypoxia reduction events on the short term and partly explain year-to-year variability.** While high-wind events have previously been implicated when explaining short-term reoxygenation events, we show for the first time that these can also explain differences in hypoxia from year to year. We provide two examples of pairs of years (2010 and 2012; 2009 and 2013) where riverine freshwater

and DIN inputs were similar but hypoxic conditions markedly different and show that this is explained by differences in the occurrence of high-wind events during the hypoxic season. Ninth paragraph of the Discussion: "*Wind strength turned out to be one of the dominant factors in hypoxia evolution. … The frequency of high-wind events during summer explains the differences in hypoxic area between 2010 and 2012 (Figure 10) and 2009 and 2013 (Figure S8). In 2009 and 2010 there were only few high-wind events during summer while 2012 and 2013 experienced a sequence of storms that led to partial reoxygenation of the water column throughout the summer and thus impeded the development of hypoxia.*"

4. **Our oxygen budget further corroborates the importance of SOC for hypoxia generation and shows that it is important to include this in hypoxia models for the region.** We note that our model is the first to do so. We say in the third to last paragraph: "*SOC is the dominant oxygen sink in the subsurface. The relative importance of WOC and SOC had not previously been quantified for this region due to lack of concurrent WOC and SOC observations and lack of models that realistically account for both processes.*"
5. **The oxygen budget also shows that lateral transport switches from an oxygen sink in spring to an oxygen source in summer.** The role of lateral transport as an oxygen source has not been previously discussed. We state in the last paragraph of the Discussion: "*The finding that lateral oxygen transport can act as a net source to subsurface water is also new. On seasonal scales, oxygen advection in the subsurface varies from an oxygen sink in spring to a source in summer, especially in the southern hypoxic region, implying that the Taiwan Warm Current becomes an oxygen source when oxygen is depleted in the hypoxic region. This aspect was neglected in previous studies which only emphasized the role of advection as an oxygen sink promoting hypoxia formation (Ning et al., 2011; Qian et al., 2015).*"
6. Furthermore, we would also like to emphasize again that our model is more comprehensive than previous models for the ECS (stated explicitly in the first paragraph of the Discussion) and thus forms the basis for useful follow-up studies: Grosse et al. (2020) is based on this model and was published earlier this year. Another follow-up study by Laurent et al. is to be submitted. We also have received requests from Chinese researchers whether we can share this model with them.

2. You need to develop your mechanistic explanation of the variations in hypoxia. You find that the extent of the freshwater plume and the primary (organic matter) production /oxygen consumption are important controlling factors. But, are these linked? Does the freshwater plume stabilize the water column in a way that promotes primary production? Or is it just that the stratification and primary production contribute separately to the variability in the oxygen? Have you considered a link with the load of riverine organic matter? (I cannot find it in the manuscript)?

Reply: We believe that we have laid out a logical sequence of questions that are answered in subsections 3.2.1 to 3.2.3 to address our overarching research objective of explaining variations in hypoxia. They are:

In section 3.2.1: Do year-to-year variations in nutrient load and FW input from the Changjiang explain interannual variability in hypoxic conditions? The answers are, yes, partly for freshwater, and no, not at all for DIN loads.

In section 3.2.2: Do low-oxygen conditions correlate with biological rates on shorter (intra-seasonal) timescales? If yes, what drives variations in biological rates? The answers are yes, but there is a lot of variability that must be due to something else (which turns out to be circulation and mixing in the next subsection) to the first question and mostly the extent of the freshwater plume to the second question.

In section 3.2.3: What role does coastal circulation (upwelling versus downwelling) and mixing play? The answers are 1) coastal circulation plays a big role in determining whether the plume (and thus hypoxia) is broad and extends northeastward or whether it is narrowly contained along the coast in southward direction, and 2) vertical mixing during high wind events is important in driving short-term and interannual variations in hypoxia.

In answer to the specific questions posed by the reviewer:

1) You find that the extent of the freshwater plume and the primary (organic matter) production /oxygen consumption are important controlling factors. But, are these linked? Yes, we state this in section 3.2.2 (2nd paragraph from the end) where we say*: "Mechanistically, the presence of a large FW plume not only affects hypoxia by increasing vertical stratification and thus inhibiting vertical supply of oxygen to the subsurface but also because PP and respiration is larger in the plume. Large FW plumes stimulate more widespread biological production and thus oxygen consumption."*
2) Does the freshwater plume stabilize the water column in a way that promotes primary production? Or is it just that the stratification and primary production contribute separately to the variability in the oxygen? They both contribute and cannot be separated.
3) Have you considered a link with the load of riverine organic matter? (I cannot find it in the manuscript)? No, because organic matter inputs are much smaller than inorganic nutrient inputs. Also see comment below.

3. A revision of the structure of the text/study, might also help the reader to understand what new knowledge your study bring to the community:

Suggestions for the abstract:

You do not need to write that the model was validated reproduces the observed temporal and spatial variability in the abstract. If you use the model for process studies, the reader already assumes that the model has been/ is evaluated in the study.

Reply: Since the model validation makes up a considerable fraction of this manuscript and because it is likely that not every reader assumes that a validation has been performed, we prefer to leave this statement in the abstract.

You start by wrtiting that the interannual variations in hypoxic extent is partly explained by.... Start instead by describing the main mechanism behind, i.e. the spatial extent of the freshwater plume. Describe why it is important for the hypoxic extent. Then you can go on writing that the extent of this plume is mainly dependent on the wind, and to a lesser extent on the freshwater discharge.

Reply: We have revised the abstract a bit in response to this comment. We would like to point to our response to comment 2 above in making a case that we have laid out a logical structure for our manuscript and follow the same structure for the abstract.

Suggestions for the structure of the study:

In the way your manuscript is currently written, you are dealing both with intra-seasonal and interannual time scales, and it feels like you do not fully go into either of them and sometimes mixing them up (I think you will see from my minor comments that this is a bit confusing to me). Wouldn't it be better to focus on one of these time scales? If you choose to focus on interannual time scales, you could in the end do one budget for annual means. I think that your budget analysis is very nice and provides useful information. With this one you more directly (compared to correlations) see the contributions from different processes. For example you see that, apart from oxygen consumption, the vertical fluxes of oxygen are important for the bottom oxygen. This you could link to the wind events that you also are looking into. One idea could be to do budgets for different years, and then you will see how much the vertical mixing (wind) and the oxygen consumption contribute to the hypoxic conditions for each year?
Maybe you could even start your manuscript with this budget, and thereafter dig into the different terms to get a more mechanistic understanding behind? For example, the vertical mixing can be influenced by both freshwater input and wind events, and oxygen consumption is related to the input/production of organic matter, which can also be influenced by freshwater input through a stabilization of the water column, or input of riverine organic matter.

Reply:

Regarding the suggestion to only focus on interannual or intra-seasonal variations: We do not believe that focussing only on interannual or only on intra-seasonal variations could be done in a satisfying manner because, as we show in this study, both time scales are linked. Interannual variations cannot be solely explained by year-to-year variations of the drivers. We show that short-term wind events, when occurring in sequence during the summer can result in big interannual differences (see comments above about 2010 versus 2012 and 2009 versus 2013, two pairs of years where riverine freshwater and DIN inputs were similar but hypoxic conditions markedly different, and we show that differences in the occurrence of high-wind events explain this).

Regarding the suggestion to include interannual budgets: We have already done this in the first round of revisions in response to a comment from this Reviewer. See Figure 11 where the small bars show each of the 6 years, and Table S2 which reports the numbers for each of the 6 years.

Regarding the suggestion to start with the budget analysis: We believe we have laid out a logical sequence of questions that we address in order (see our response to comment 2). We prefer to leave it this way.

Would it be possible for you to focus on one measure of hypoxia, i.e. either hypoxic extent or oxygen concentration? As it is now you are switching between these in the manuscript which makes it confusing for the reader.

Reply: Hypoxic extent and oxygen concentration are very different metrics. Hypoxic extent is a high-level scalar metric commonly used to convey the severity of hypoxic conditions in one simple number that can easily be compared for different years and even different regions. It explicitly includes the spatial extent of hypoxic conditions. Oxygen concentration is a local measure that is useful and needed when drilling down on process details. We do need both in order to discuss the processes we wish to elucidate in this manuscript. We believe that the overwhelming majority of readers will be able to grasp the difference between hypoxic extent and oxygen concentration. We also note that in the existing literature on coastal hypoxia both are typically used in the same paper.

4. Is the division into two regions necessary? In the end it seems like the governing processes are similar in these two regions (Figure 12)?

Reply: It is known from observations that there are two distinct centers of recurring hypoxic conditions: the northern core is located just to the east of the CE and Hangzhou Bay and the southern core to the southeast of Hangzhou Bay, and thus the existing literature on hypoxia off the CE distinguishes between the two cores. Our model also simulates these two distinct cores (indicated by the dark red areas and demarcated by the innermost thin isolines in Figure 4 d). Furthermore, we show that in our simulation, hypoxic conditions occur at much lower rates of primary production and sediment oxygen consumption in the southern region than in the northern region (Figure 6). This is explained in the manuscript in section 3.2. We feel that these differences, as well as precedent in the existing literature justify distinction between the two. We also cannot think of any drawback to distinguishing between the two and therefore prefer to keep it.

Minor comments:

- section 2.2: you write on lines 168-169 that you include riverine organic matter in the model. But you do not describe what values you use for concentration in the rivers.

Reply: We added the following to our text on river sources in section 2.2:

"Due to a lack of data on organic matter loads, river load concentrations of SDet and LDet and RDOM were assumed conservatively at 0.5, 0.2 and 15 mmol N m^{-3}*, respectively."*

- l74: Change "Freshwater discharge reaches the minimum" to "Freshwater discharge from the Changjiang River reaches the minimum"

Reply: We presume the Reviewer refers to line 52 and have made the suggested change there. On line 74 we talk about the Taiwan Warm Current and make no mention of freshwater discharge. On line 174 we talk about biogeochemical processes in the sediment, not freshwater.

- line 187: add "river" after Changjiang

Reply: We have removed all occurrences of "River" after "Changjiang" because of Copernicus journal conventions. Note that the companion paper to this study was published earlier this year (https://www.biogeosciences.net/17/2701/2020/bg-17-2701-2020.pdf) and in it the publisher's copy editors removed all occurrences of "River" after "Changjiang" because "jiang" means river in Chinese.

- section 3.1: you need to explain what all the correlations you write about in there are based on, is it spatial correlation, or temporal correlation? If it is spatial correlations, are these correlations enough to say that your model reproduces the dynamics on intra-seasonal and interannual timescales?

Reply: In response to the first question, we have clarified what each correlation is based on, i.e. monthly climatology in the case of SST, spatial correlation if only one monthly field is used, e.g. for satellite chl, and all data points in space and time for correlation coefficients involving *in situ* data. We now refer to the latter as overall correlations.

With regard to the 2nd question, we are very careful throughout the manuscript to not overstate the results of our validation exercise. For example, in section 3.1, we conclude by saying: "*Together, these comparisons show that the model is able to reproduce important aspects of the physical-biogeochemical dynamics in the study region.*" In the abstract we say: "*The model [..] reproduces the* ***observed*** *temporal and spatial variability of physical and biological properties including bottom oxygen.*" We feel that this is a defensible statement as we have shown the observed variability is reproduced.

line 232: you have to define "hypoxic" somewhere in the manuscript. Either here or in the methodology section.

Reply: Hypoxia is defined in the first sentence of the Introduction.

- figure 4a) add legend

Reply: We added the necessary information to the caption.

- lines 232-43: please describe if this is this in agreement with observations?

Reply: Comparisons using all the available observations were conducted and described in section 3.1. Here, in section 3.2.2, we are describing model results that cannot readily be compared against observations. For example, it is not possible to compare the maximum spatial extent, the integrated spatial extent, or the detailed phenology of hypoxia to observations because there aren't sufficient observations to derive these metrics. As Figure 4 shows, there is significant short-term variability. The value of a reasonably accurate model is that it can elucidate these patterns that cannot be obtained by observations. No action taken.

- section 3.2.1: Have you looked at the relation with the load of riverine organic matter?

Reply: We haven't analyzed relationships with riverine input of organic matter because these are significantly smaller than the inorganic loads. On average, the organic N load of all the rivers combined amounts to only 10% of the total N load.

- Figure 4: It is confusing that you put the variable that you are investigating both on the y-axis and the x-axis. I would be consistent all over the subplots and keep one axis for you variable of investigation.

Reply: We presume the Reviewer is referring to Figure 5 not Figure 4. We are not sure what the Reviewer means by "the variable that you are investigating" because all the variables that are included in these correlations are variables we are investigating. We understand that this figure contains a lot of information and have attempted to organize this as best as possible. For example, in each column the x-axes are the same across all three rows. No action taken.

- line 278: refer to figure 4d) after low-oxygen zone

Reply: This sentence refers to Figure 5 not Figure 4. Since it is the first sentence referring to Figure 5 it is intended to set out the general purpose of this figure. We refer to each panel individually in the sentences that follow. No action taken.

- line 278: you need to describe somewhere how you calculate the plume area. You have written two different definitions in the table and figure 4. Please correct this and put also somewhere in the text how you define it.

Reply: We had used two different definitions for the plume in Fig 5 and Table 1 but agree that it would be better to use the same definition throughout. Accordingly, we have updated figure panel 5g. We also have added the definition of plume area in the text as: "*defined as the horizontal extent of surface water with salinity less than 29.*"

- line 303: change "riverine inputs" to "riverine inputs of nutrients" or "riverine inputs of nutrients and organic matter", if you also have looked at that.

Reply: We are referring to riverine inputs of nutrients and FW and have stated this explicitly now.

- Figure 6: I would remove this figure, I do not think that you need it for your story. It is enough that you argue in the text for your choice of separation of the domain into two different zones. Alternatively you could put it in a supplementary material.

Reply: We believe that the figure is instructive in illustrating the differences between the northern and southern zones. We note that this Reviewer himself/herself questioned the need to distinguish between the two subregions (see major comment 4 above). This figure shows why it is important to do so, hence we prefer to keep it. No action taken.

- line 339-340: I do not think that you can argue that because the annual FW input is correlated with the annual mean extent of the freshwater plume, the daily plume extent can be used as a measure of daily freshwater input. On these shorter time scales the wind have a larger influence.

Reply: We are not arguing that the daily extent of the freshwater plume is a measure of daily freshwater input. This comment is misrepresenting our sentence, which states: "daily plume extent can be used as a measure of **FW presence.**" We simply make the statement that the spatial extent of the FW plume is a simple measure of FW presence. No action taken.

- What new information does figure 7 come with in addition to figure 5? I see that they are considering different time scales. If the main processes acting at smaller time scales are similar to those on longer time scales, it is enough that you make a note on that in the text.

Reply: Figure 5 addresses the question whether year-to-year variations in nutrient load and FW input from the Changjiang explain interannual variability in hypoxic conditions. In other words, Figure 5 is about the degree to which interannual variations in riverine inputs are related to year-to-year variations of various properties. Figure 7 builds on this and addresses the question of what drives biological rates on intra-seasonal timescales. Figure 7 also shows that, even though the correlations between oxygen concentration and biological rates are significant, there is a lot of variability, thus motivating the next question to be addressed, which is about the role of atmospheric forcing disrupting a closer correlation between biological rates and oxygen concentration. We do not believe just a note in the text would be satisfactory to most readers. No action taken.

- Figure 8: I think that this one goes more under interannual variability, as you look at variations between years.

Reply: We have removed this Figure because it is not essential to the interpretation of our results.

- Figure 9: Have you calculated this based on the whole simulation period?

Reply: Yes. We have added "*averaged over all days during the 6-yr simulation*" to the caption to make this clearer.

- section 3.3: why do you calculate the budget only for March to August?

Reply: We had presented March to August only because these are the months were oxygen decreases. We have now extended the budget to cover the period from March to November in Figure 11.

A numerical model study of the main factors contributing to hypoxia and its interannual and intra-seasonal variability off the Changjiang Estuary

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Abstract

A three-dimensional physical-biological model of the marginal seas of China was used to analyze interannual and intra-seasonal variations in hypoxic conditions and identify the main processes controlling their generation off the Changjiang Estuary. The model was compared against available observations and reproduces the observed temporal and spatial variability of physical and biological properties including bottom oxygen. Interannual variations of hypoxic extent in the simulation are partly explained by variations in river discharge but not nutrient load. As riverine inputs of freshwater and nutrients are consistently high, promoting large productivity and subsequent oxygen consumption in the region affected by the river plume, wind forcing is important in modulating interannual and intra-seasonal variability. Wind direction is relevant because it determines the spatial extent and distribution of the freshwater plume which is strongly affected by either upwelling or downwelling conditions. High-wind events can lead to partial reoxygenation of bottom waters and, when occurring in succession throughout the hypoxic season, can effectively suppress the development of hypoxic conditions thus influencing interannual variability. An oxygen budget is presented and shows that sediment oxygen consumption is the dominant oxygen sink below the pycnocline and that advection of oxygen in the bottom waters acts as an oxygen sink in spring but becomes a source during hypoxic conditions in

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summer especially in the southern part of the hypoxic region, which is influenced by open-ocean intrusions.

1. Introduction

In coastal seas, hypoxic conditions (oxygen concentrations lower than 2 mg L^{-1} or 62.5 mmol m^{-3}) are increasingly caused by rising anthropogenic nutrient loads from land (Diaz & Rosenberg, 2008; Rabalais et al., 2010; Fennel and Testa, 2019). Hypoxic conditions are detrimental to coastal ecosystems leading to a decrease in species diversity and rendering these systems less resilient (Baird et al., 2004; Bishop et al., 2006; Wu, 2002). Hypoxia is especially prevalent in coastal systems influenced by major rivers such as the northern Gulf of Mexico (Bianchi et al., 2010), Chesapeake Bay (Li et al., 2016), and the Changjiang Estuary (CE) in the East China Sea (Li et al., 2002).

The Changjiang is the largest river in China and fifth largest in the world in terms of volume transport, with an annual discharge of 9×10^{11} m^3 $year^{-1}$ via its estuary (Liu et al., 2003). The mouth of the CE is at the confluence of the southeastward Yellow Sea Coastal Current and the northward Taiwan Warm Current (Figure 1). Hydrographic properties in the outflow region of the CE are influenced by several different water masses including fresh Changjiang Diluted Water, relatively low-salinity coastal water, more saline water from the Taiwan Warm Current, and high-nutrient, low-oxygen water from the subsurface of the Kuroshio (Wei et al., 2015; Yuan et al., 2008). The interactions of these water masses together with wind forcing and tidal effects lead to a complicated and dynamic environment.

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Freshwater (FW) discharge by the Changjiang reaches its minimum in winter when the strong northerly monsoon (dry season) prevails and peaks in summer during the weak southerly monsoon (wet season) resulting in a large FW plume adjacent to the estuary. Along with the FW, the Changjiang delivers large quantities of nutrients to the East China Sea (ECS) resulting in eutrophication in the plume region (Li et al., 2014; Wang et al., 2016). Since the 1970s, nutrient load has increased more than twofold with a subsequent increase in primary production (PP) in the outflow region of the estuary (Liu et al., 2015). Hypoxia off the CE was first detected in 1959 and, with a spatial extent of up to 15,000 km^2, is among the largest coastal hypoxic zones in the world (Fennel & Testa, 2019). Although no conclusive trend in oxygen minima has been observed (Wang, 2009; Zhu et

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al., 2011), hypoxic conditions are suspected to have expanded and intensified in recent decades (Li et al., 2011; Ning et al., 2011) due to the increasing nutrient loads from the Changjiang (Liu et al., 2015).

It is generally accepted that water-column stratification and the decomposition of organic matter are the two essential factors for hypoxia generation, and this is also the case for the shelf region off the CE (Chen et al., 2007; Li et al., 2002; Wei et al., 2007). High solar radiation and FW input in summer contribute to strong vertical stratification which is further enhanced by near-bottom advection of waters with high salinities (> 34) and low temperatures (< 19 °C) by the Taiwan Warm Current. The resulting strong stratification inhibits vertical oxygen supply (Li et al., 2002; Wang, 2009; Wei et al., 2007). At the same time, high organic matter supply fuels microbial oxygen consumption in the subsurface (Li et al., 2002; Wang, 2009; Wei et al., 2007; Zhu et al., 2011). It has also been suggested that the Taiwan Warm Current brings additional nutrients contributing to organic matter production (Ning et al., 2011) and that the low oxygen concentrations (~ 5 mg L^{-1}) of the Taiwan Warm Current precondition the region to hypoxia (Ning et al., 2011; Wang, 2009).

While observational analyses suggest that hypoxia off the CE results from the interaction of various physical and biogeochemical processes, quantifying the relative importance of these processes and revealing the dynamic mechanisms underlying hypoxia development and variability require numerical modeling (Peña et al., 2010). Numerical modeling studies have proven useful for many other coastal hypoxic regions such as the Black Sea northwestern shelf (Capet et al., 2013), Chesapeake Bay (Li et al., 2016; Scully, 2013), and the northern Gulf of Mexico (Fennel et al., 2013; Laurent & Fennel, 2014).

Models have also been used to study the hypoxic region of the CE. Chen et al. (2015a) used a 3D circulation model with a highly simplified oxygen consumption parameterization (a constant consumption rate) to investigate the effects of physical processes, i.e. FW discharge, and wind speed and direction, on the dissipation of hypoxia. Chen et al. (2015b) examined the tidal modulation of hypoxia. The model domain in these two previous studies was relatively limited encompassing only the CE, Hangzhou Bay and the adjacent coastal ocean but did not cover the whole area affected by hypoxia (Wang, 2009; Zhu et al., 2011). Zheng et al. (2016) employed a nitrogen cycle model coupled with a 3D hydrodynamic model to examine the role of river discharge, wind speed and direction on hypoxia, and

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also emphasized the physical controls. These previous modeling studies focused on the response of hypoxia to physical factors only and did not address seasonal evolution and interannual variations of hypoxia or the influence of variability in biological rates.

More recently, Zhou et al. (2017) analyzed the seasonal evolution of hypoxia and the importance of the Taiwan Warm Current and Kuroshio intrusions as a nutrient source using an advanced coupled hydrodynamic-biological model. However, the baseline of their model does not include sediment oxygen consumption (SOC), which is thought to be a major oxygen sink in the hypoxic region off the CE (Zhang et al., 2017) and other river-dominated hypoxic regions including the northern Gulf of Mexico (Fennel et al. 2013, Yu et al. 2015a,b). Zhou et al. (2017) acknowledged the importance of SOC based on results from a sensitivity experiment but did not quantify its role in hypoxia generation.

Here we introduce a new 3D physical-biological model implementation for the ECS that explicitly includes nitrogen and phosphorus cycling and SOC. The model is a new regional implementation for the ECS of an existing physical-biogeochemical model framework that has been extensively used and validated for the northern Gulf of Mexico (Fennel et al., 2011, 2013; Laurent et al., 2012; Laurent and Fennel, 2014; Yu et al., 2015b; Fennel and Laurent, 2018). The hypoxic zones in the northern Gulf of Mexico and off the CE have similar features including the dominant influence of a major river (Changjiang and Mississippi), a seasonal recurrence every summer, a typical maximum size of about 15,000 km^2, documented P-limitation following the major annual discharge in spring and a significant contribution of SOC to oxygen sinks in the hypoxic zone (Fennel and Testa 2019).

We performed and assessed a 6-year simulation of the ECS, and use the model results here to identify the main factors driving hypoxia variability on interannual and intra-seasonal timescales in the simulation. More specifically, we investigate the role of interannual variations in riverine inputs of nutrients and FW versus intra-seasonal variations in coastal circulation and mixing. We also present an oxygen budget to quantify the relative importance of SOC and the influence of lateral advection of oxygen. A companion study by Grosse et al. (2020) uses the same model to quantify the importance of intrusions of nutrient-rich oceanic water from the Kuroshio for hypoxia development off the CE.

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2. Model description

2.1. Physical model

The physical model used in this study is based on the Regional Ocean Modeling System (ROMS; Haidvogel et al., 2008) and was implemented for the ECS by Bian et al. (2013a). The model domain extends from 116°E to 134°E and from 20°N to 42°N (Figure 1), covering the Bohai Sea, the Yellow Sea, the ECS, part of the Japan Sea and the adjacent northwest Pacific, with a horizontal resolution of 1/12° (about 10 km) and 30 vertical layers with enhanced resolution near the surface and bottom. The model uses the recursive Multidimensional Positive Definite Advection Transport Algorithm (MPDATA) for the advection of tracers (Smolarkiewicz and Margolin, 1998), a third-order upstream advection of momentum, and the Generic Length Scale (GLS) turbulence closure scheme (Umlauf & Burchard, 2003) for vertical mixing.

The model is initialized with climatological temperature and salinity from the World Ocean Atlas 2013 V2 (WOA13 V2) (Locarnini et al., 2013; Zweng et al., 2013), and is forced by 6-hourly wind stress, and heat and FW fluxes from the ECMWF ERA-Interim dataset (Dee et al., 2011). Open boundary conditions for temperature and salinity are prescribed from the monthly climatology (WOA13 V2), and horizontal velocities and sea surface elevation at the boundaries are specified from the monthly SODA data set (Carton & Giese, 2008). In addition, eight tidal constituents (M2, S2, N2, K2, K1, O1, P1 and Q1) are imposed based on tidal elevations and currents extracted from the global inverse tide model data set of TPXO7.2 of Oregon State University (OSU, Egbert & Erofeeva, 2002). At the open boundaries, Chapman and Flather conditions are used for the free surface and the barotropic velocity, respectively, and the radiation condition for the baroclinic velocity. Eleven rivers are included in the model. FW discharge from the Changjiang uses daily observations from the Datong Hydrological Station (DHS; www.cjh.com.cn). Since daily observations are not available for the other rivers, we prescribed monthly or annual climatologies (Liu et al., 2009; Tong et al., 2015; Zhang, 1996).

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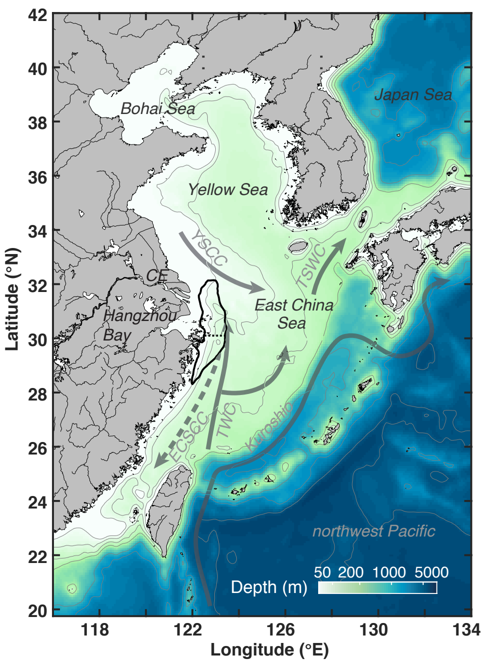

Figure 1. Bathymetry of the model domain with 30, 50, 100, 200, 1000, 2000 and 5000 m isobaths. The black outline near the Changjiang Estuary (CE) and Hangzhou Bay indicates the zone typically affected by low-oxygen conditions (dotted line shows separation between northern and southern zones). Solid grey arrows denote currents present throughout the year (Kuroshio; TWC: Taiwan Warm Current; YSCC: Yellow Sea Coastal Current). The dashed grey arrow indicates the direction of the wintertime East China Sea Coastal Current (ECSCC) which flows in the opposite direction to summertime flow.

2.2. Biological model

The biological component is based on the pelagic nitrogen cycle model of Fennel et al. (2006, 2011, 2013) and was extended to include phosphate (Laurent et al., 2012; Laurent & Fennel, 2014) and riverine dissolved organic matter (Yu et al., 2015b). The model includes two forms of dissolved inorganic nitrogen (DIN), nitrate (NO3) and ammonium (NH4), phosphate (PO4), phytoplankton (Phy), chlorophyll (Chl), zooplankton (Zoo), two pools of detritus, suspended and slow-sinking small detritus (SDet) and fast-sinking large detritus (LDet), and riverine dissolved organic matter (RDOM). Here, riverine dissolved and particulate organic nitrogen enter the pools of RDOM and SDet, respectively. The remineralization rate of RDOM is an order of magnitude lower than that of SDet to account for the more refractory nature of the riverine dissolved organic matter (Yu et al., 2015b).

At the sediment-water interface, SOC is parameterized assuming "instantaneous remineralization," i.e. all organic matter reaching the sediment is remineralized instantaneously and oxygen is consumed due to nitrification and aerobic remineralization at the same time. In the "instantaneous remineralization", all phosphorus is returned to the water column as PO4 while a constant fraction of fixed nitrogen is lost due to denitrification. All biogeochemical model parameters are given in Table S1 in the Supplement. A more detailed model descriptions can be found in the Supplement to Laurent et al. (2017).

Light is vertically attenuated by chlorophyll, detritus and seawater itself. In addition, to account for the effects of colored dissolved organic matter (CDOM) and suspended sediments, which show relatively high values near the coast and in the river plume (Bian et al., 2013b; Chen et al., 2014), a light-attenuation term dependent on water depth and salinity is introduced which yields higher attenuation in shallow areas and in the FW plume.

Initial and boundary conditions for NO3, PO4 and oxygen are prescribed using the World Ocean Atlas 2013 (WOA13) climatology (Garcia et al., 2013a,b). A small positive value is used for the other variables. NO3 is nudged towards climatology in the northwest Pacific at depth > 200 m. Monthly nutrient loads of NO3 and PO4 from the Changjiang are from the Global-NEWs Model (Wang et al., 2015) but were adjusted by multiplicative factors of 1.20 and 1.66, respectively, to ensure a match between simulated and observed nutrient concentrations in the CE (see July and Aug 2012 in Figure 2). Nutrient loads in other rivers are based other published climatologies (Liu et al., 2009; Tong et al., 2015; Zhang, 1996). Due to a lack of data on organic matter loads, river load concentrations of SDet and LDet and RDOM were assumed conservatively at 0.5, 0.2 and 15 mmol N m^{-3}, respectively.

We performed an 8-year simulation from 1 January 2006 to 31 December 2013, with 2006-2007 as model spin up and 2008-2013 used for analysis. Model output was saved daily.

3. Results

3.1. Model validation

Model output is compared with observations of simulated surface and bottom temperature, salinity, current patterns and strength, surface chlorophyll, surface nitrate and bottom oxygen. The model reproduces remotely sensed spatial and temporal SST patterns (NOAA AVHRR) very well (Figure S1) with an overall correlation coefficient, i.e. considering all climatological monthly mean SST fields interpolated to the model grid, of 0.98. Simulated surface and bottom salinity also show similar spatial and seasonal patterns as available *in situ* observations (Figures S2 and S3) with overall correlation coefficients, i.e. using all surface and all bottom data points, of 0.77 and 0.84, respectively. Simulated surface and bottom temperature, when compared with available *in situ* data (Figures S4 and S5), are also consistent with the observations with overall correlation coefficients of 0.96 and 0.93.

The simulated current systems in the ECS and YS show typical seasonal variations as follows (see also Figure S6). In winter, currents mainly flow southward on the Yellow Sea and ECS shelves driven by the northerly wind. In contrast, the East China Sea Coastal Current and the Korean Coastal Current flow northward in summer. The Kuroshio is

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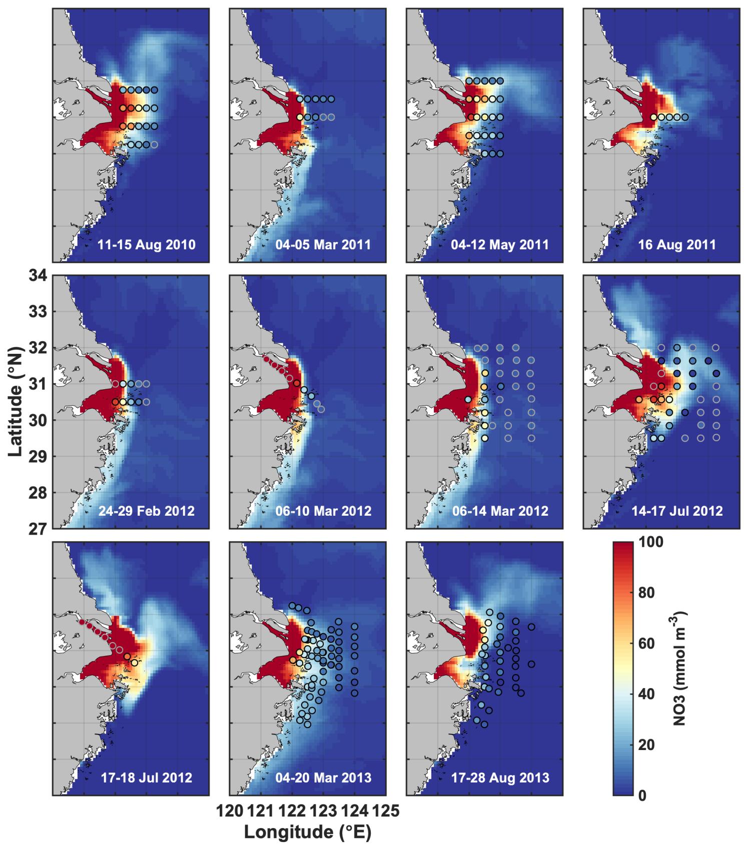

Figure 2: Simulated surface nitrate (colored map) shown for the day that marks the mid-point of the cruise dates (given in each panel) the compared to observations (dots) during 11 cruises from 2011 to 2013.

stronger in summer than in winter. The model captures the seasonal pattern of the current system and resolves currents in the ECS and Yellow Sea (also see Grosse et al. 2020).

Simulated monthly averaged (2008-2013) surface chlorophyll concentrations in May, August and November are compared with satellite-derived fields (MODIS-Terra) and agree well with spatial correlation coefficients of 0.77, 0.94 and 0.64, respectively (Figure S7).

Simulated surface nitrate concentrations are shown in comparison to *in situ* observations in Figure 2 and agree well with an overall correlation coefficient of 0.84. Observations in March and July of 2012 show strongly elevated concentrations in the CE and a sharp gradient in the vicinity of the estuary's mouth that are well represented by the model. Likewise, simulated and observed bottom oxygen distributions are compared in Figure 3 and agree reasonably well overall with an overall correlation coefficient of 0.71 although the model underestimates observed low-oxygen conditions in July of 2011 and 2013 and August 2013.

Together, these comparisons show that the model is able to reproduce important aspects of the physical-biogeochemical dynamics in the study region.

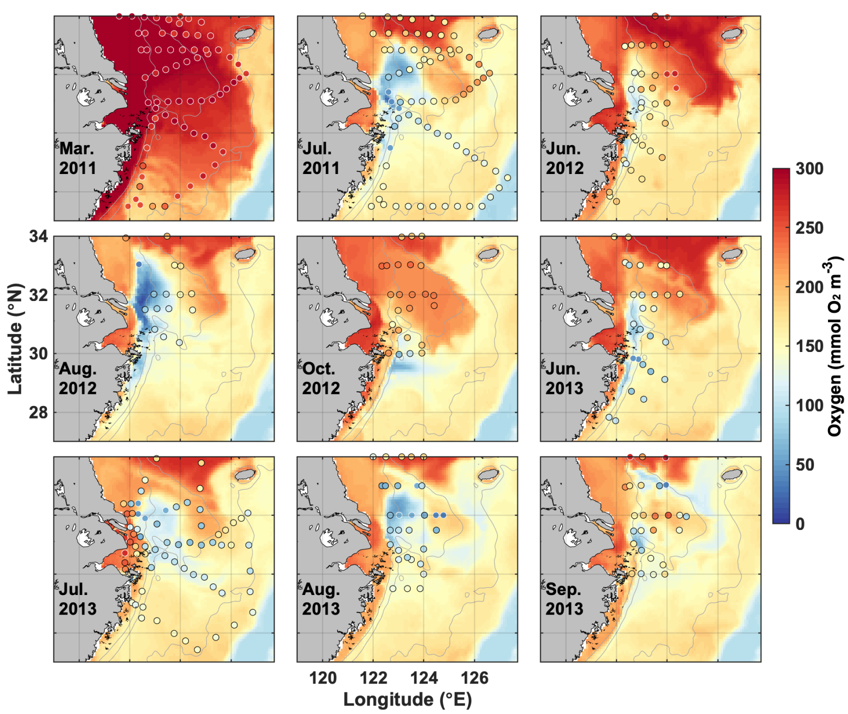

Figure 3. Simulated bottom oxygen (colored map) shown for the day that marks the mid-point of the cruise dates compared with observations (dots) during nine cruises from 2011 to 2013.

3.2. Simulated oxygen dynamics

First, we describe the timing and distribution of simulated bottom-water oxygen off the CE to set the stage for our investigation into the drivers underlying hypoxia variability. The model simulates annually recurring hypoxic conditions with a typical seasonal cycle where bottom waters are well-oxygenated until April/May, hypoxic conditions establish in June or July, become more pronounced in August, and disperse in October or November (Figure 4a, c). However, the model also simulates significant interannual variability in timing and extent of hypoxia over the 6-year simulation period (Figure 4b, c). The years with largest maximum hypoxic extent are 2010 (20,520 km^2), 2009 (16,660 km^2), 2012 (13,930 km^2) and 2008 (12,720 km^2) while the simulated hypoxic extent is much smaller (<5,000 km^2) in 2011 and 2013. The ranking is similar when considering the time-integrated hypoxic extent (Figure 4b). The year with the largest maximum and integrated hypoxic extent

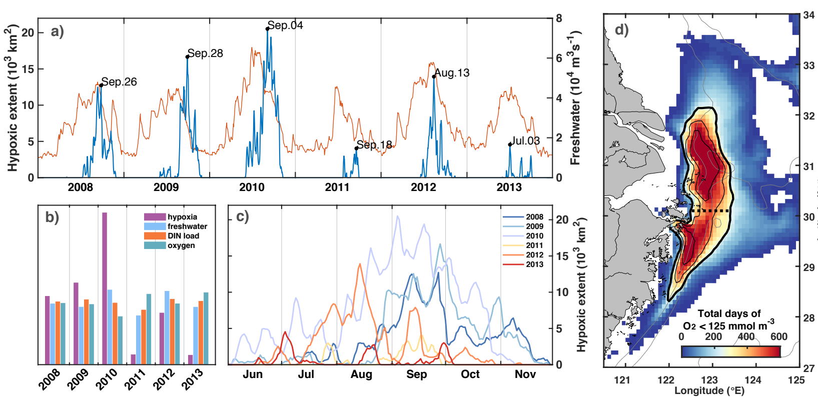

Figure 4. a) Time series of freshwater discharge (thin red line) and simulated hypoxic extent (thick blue line) with peaks specified by date. b) Annual comparison of normalized time-integrated hypoxic extent, freshwater discharge, and DIN load, and summer-mean bottom oxygen concentration. c) Evolution of simulated hypoxic extent by year. d) Frequency map of number of days when bottom oxygen concentrations were below 125 mmol m^{-3} (4 mg/l). The black isolines indicate 240, 360 and 480 days (or 40, 60 and 80 days per year). The thick solid line indicates the region we refer to as the typical low-oxygen zone and the dashed line shows the demarcation between its northern and southern regions.

(2010) also has the highest peak discharge (Figure 4a) and highest annual FW discharge (65,400 m^3 s^{-1}), although the annual discharge in 2008 and 2012 is not much smaller than in 2010.

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The region where low-oxygen conditions are most commonly simulated is indicated by the frequency map in Figure 4d, which shows the total number of days in the 6-year simulation when bottom oxygen concentrations were below 125 mmol m^{-3} (or 4 mg/l), i.e. twice the hypoxic threshold. It is known from observations that there are two centers of recurring hypoxic conditions: the northern core is located just to the east of the CE and Hangzhou Bay and the southern core to the southeast of Hangzhou Bay. The model is consistent with these observations and simulates two distinct core regions of low-oxygen conditions centered at 31°N and 29.3°N. The northern core region is larger than the southern core region (9,050 km^2 for a threshold of 80 days per year of < 4 mg/l compared to 5,230 km^2). We will refer to the region defined by a threshold of 40 days of < 4 mg/l of per year (solid black line in Figure 1 and 4d) as the "typical low-oxygen zone" for the remainder of the manuscript and demarcate the northern and southern sections by 30.1°N latitude (dashed line in Figures 1 and 4d).

There are marked differences in the phenology of simulated hypoxic extent (Figure 4c). Among the four years with largest hypoxic areas, hypoxia establishes relatively late (mid-August) and lasts long (into November) in 2008 and 2009. In contrast in 2012, hypoxic conditions establish earlier (June), are most pronounced in August and are eroded by mid-October. In 2010, the year with the largest peak extent, hypoxia establishes already at the beginning of June and is maintained until the end of October, leading to the largest time-integrated hypoxia by far among the 6 years (Figure 4b). In all years there are times when hypoxic extent decreases rapidly.

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In the following sections, we explore the drivers underlying these interannual and intra-seasonal variations, specifically the contribution of year-to-year variations in nutrient loads and FW inputs from the Changjiang, and the potential reasons for intra-seasonal variability in hypoxia by assessing the role of biological processes and physical forcing.

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3.2.1 Interannual variations in hypoxia

The first question we address is: Do year-to-year variations in nutrient load and FW input from the Changjiang explain interannual variability in hypoxic conditions? We do this by investigating correlations of time-integrated hypoxic area, average PP, total oxygen consumption (OC) by respiration, SOC, and bottom oxygen in the typical low-oxygen zone (Figure 5 a-f). We also consider the correlation between the spatial extent of the FW plume, defined as the horizontal extent of surface water with salinity less than 29, and annually integrated FW input and DIN load (Figure 5 g-i).

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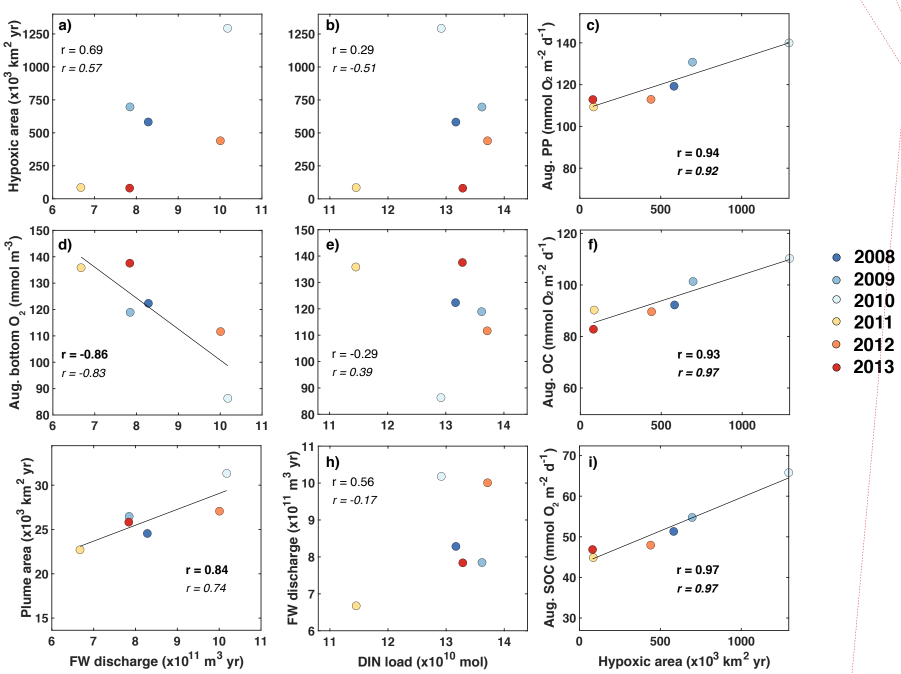

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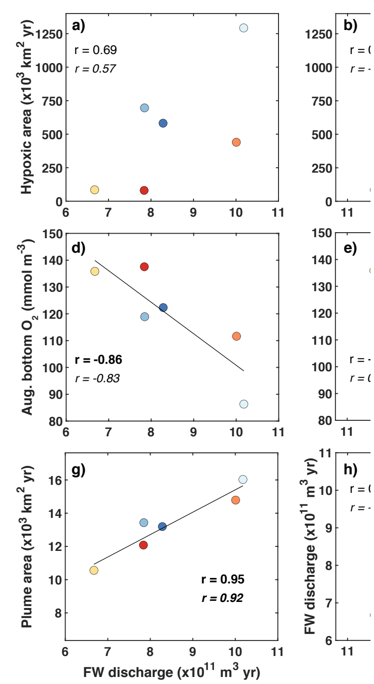

Figure 5. Correlations of time-integrated hypoxic area, average primary production, respiration an bottom oxygen in the typical low-oxygen zone in August, and the spatial extent of the FW plume (define here as the area with surface salinity smaller than 29) with annually integrated FW input and DIN loa Correlation coefficients are given for all 6 years and, in italic font, after excluding year 2011. Significant correlations are shown in bold font and linear regressions indicated by the black line whenever the correlation is significant at $p<0.05$.

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There is a significant negative correlation between annual FW input and mean bottom-water oxygen concentration in the low-oxygen zone of -86% and a weaker, statistically insignificant positive correlation of 69% between annual FW input and integrated hypoxic area (Figure 5a, d). This indicates that variations in FW input at least partly explain variability in hypoxic conditions. Perhaps surprisingly, there is no convincing correlation between annual FW input and annual DIN load (Figure 5h). Although the correlation coefficient is 56% when all 6 years are considered, the correlation reverses to -17% when the low-flow year 2011 is excluded and neither of these correlations is statistically significant. As expected, there is a strong positive correlation of 84% between the annual FW input and time-integrated plume area (Figure 5g). Plume area can thus be interpreted as a proxy of FW input.

In contrast to the positive correlations between FW input and hypoxia, and FW input and bottom oxygen, correlations between the annual DIN load with integrated hypoxic area and mean bottom-water oxygen are much weaker and insignificant (Figure 5b, e). This implies that interannual variations in DIN load do not lead to year-to-year variations in hypoxia. However, the correlations between integrated hypoxic area and mean rates of PP and OC (especially SOC) in August are significant and strong at 94% and 93% (97%), respectively (Figure 5c, f, i). The high correlation between hypoxic area and OC is primarily driven by SOC. Clearly, biological processes are important drivers of hypoxia and contribute to its interannual variability, but they do not appear to result from variations in DIN load. More relevant are variations in FW load, which explain interannual variations in hypoxia at least partly.

Clearly, other factors than riverine inputs of nutrients and FW must be contributing to interannual variations. For example, the years 2010 and 2012 both had very similar FW input and DIN load but differed in severity of hypoxia (Figure 5a, b). Likewise, the years 2009 and 2013 were very similar in terms of FW input and DIN load, but very different in hypoxic extent. Next, we investigate the potential reasons for intra-seasonal variability in hypoxia, i.e. the processes leading to the differences in hypoxia phenology in Figure 4c.

Deleted: As mentioned above, there is significant interannual variation in hypoxic extent in the 6-year simulation (Figure 4a, b, c). The years with the largest time-integrated hypoxic events are 2010, 2009 and 2008 followed by 2012 with the fourth largest hypoxic extent. In 2011 and 2013, hypoxic conditions were much less severe than in the other 4 years. Freshwater (FW) input and nutrient load are less variable with the largest FW inputs in 2010 and 2012 and the lowest in 2011. In an attempt to explain the interannual variations in hypoxia, we consider first the role of riverine FW inputs and nutrient loads. More specifically, we investigate correlations of time-integrated hypoxic area, average primary production (PP), total oxygen consumption (OC) by respiration, sediment oxygen consumption (SOC) and bottom oxygen in the typical low-oxygen zone, and the spatial extent of the FW plume with annually integrated FW input and DIN load (Figure 5).¶

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3.2.2 Biological drivers of intra-seasonal variability in hypoxia

In the previous subsection, we identified biological rates as important drivers of low-oxygen conditions on interannual timescales but unrelated to variations in riverine DIN load. Here we attempt to elucidate what drives variations in biological rates and low-oxygen conditions on intra-seasonal scales by addressing the following two questions. Do low-oxygen conditions correlate with biological rates on these shorter timescales? If yes, what drives variations in biological rates?

For this analysis it seems prudent to distinguish between the northern and southern hypoxic regions for the following reasons. The bathymetry in the northern zone is slightly deeper than in the southern zone (median depth of 28.5 m versus 24.6 m) and several biological rates with direct relevance to oxygen dynamics are different between the two zones (Figure 6). During the summer months (June to September), PP, oxygen consumption in the water column (WOC=OC-SOC), and SOC are larger in the northern zone with medians of 124 compared to 77.0 mmol O_2 m^{-2} d^{-1} for PP, of 43.1 versus 35.9 mmol O_2 m^{-2} d^{-1} for WOC, and 49.3 versus 27.3 mmol O_2 m^{-2} d^{-1} for SOC. During hypoxic conditions, PP and SOC are also notably larger in the northern zone with medians of 151 versus 107 mmol O_2 m^{-2} d^{-1} for PP and 69.9 versus 50.4 mmol O_2 m^{-2} d^{-1} for SOC. In the water column, the difference is reversed and WOC larger in the southern than the northern zone (52.9 versus 46.7 mmol O_2 m^{-2} d^{-1}). Because of these different characteristics, we consider the northern and southern zones of the typical low-oxygen region separately.

First, we explore whether significant relationships exist between daily biological rates and bottom-water oxygen by determining the correlations of daily averaged rates of PP, OC and SOC with daily mean bottom oxygen concentration (Figure 7 and Table 1).

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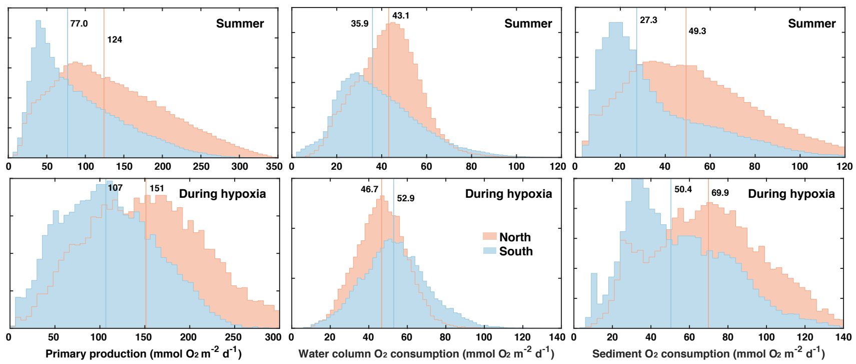

Figure 6: Histograms primary production and water-column and sediment respiration during the summer months (June to September) and during hypoxic conditions in the northern and southern parts of the typically hypoxic zone. Medians are indicated by vertical lines.

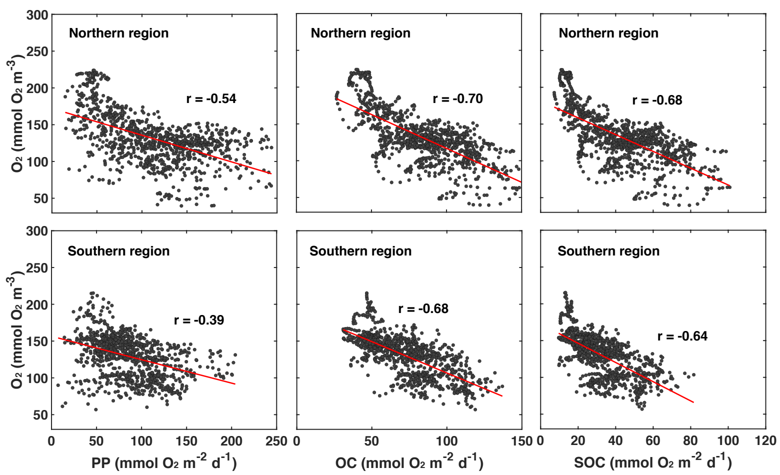

Figure 7. Correlations of daily averaged rates of PP, OC and SOC plotted with daily mean bottom oxygen concentration in the northern and southern regions of the low-oxygen zone in summer. The correlations are all significant. Correlation coefficients and slope and intercept of linear regressions (indicated by red lines) are given in Table 1.

Moved down [3]: , and the presence of FW in the two zones. Since annual FW input is highly correlated with the extent of the FW plume (see Figure 5g), daily plume extent can be used as a measure of FW presence and compared to daily rates of PP, OC, SOC, and bottom oxygen.

Relationships between bottom oxygen (mmol m^{-3}) in northern region and											
PP (mmol O_2 m^{-2} d^{-1})			OC (mmol O_2 m^{-2} d^{-1})			SOC (mmol O_2 m^{-2} d^{-1})					
r	a	b	r	a	b	r	a	b			
-0.54	-0.36	172	-0.70	-0.92	209	-0.68	-1.14	181			
Same for the southern region											
-0.39	-0.32	157	-0.68	-0.85	192	-0.64	-1.30	172			
Relationships between plume area (10^3 km^2; defined by surface salinity < 29) in northern region											
PP (mmol O_2 m^{-2} d^{-1})			OC (mmol O_2 m^{-2} d^{-1})			SOC (mmol O_2 m^{-2} d^{-1})			Bottom oxygen (mmol m^{-3})		
0.62	6.04	47.6	0.49	2.48	57.7	0.51	2.05	22.0	-0.56	-3.74	171
Same for the southern region											
0.43	3.78	64.6	0.56	3.18	57.8	0.43	1.50	24.7	-0.49	-3.52	149

Table 1. Correlation coefficients and parameters of a linear model fit (of the form y=ax+b) between

Indeed, daily PP, OC, and SOC are all significantly and negatively correlated with bottom-water oxygen. This confirms that local production of organic matter and the resulting biological oxygen consumption are important for hypoxia development and that variations in these rates partly explain variations in low-oxygen conditions. However, it is also obvious that variability around the best fit is large (Figure 7).

The next question is: What drives variations in the biological rates? Since the annual correlations presented in the previous section indicate that variability in annual FW input partly explains interannual variability in hypoxia, we consider whether FW variability is related to variations in biological rates. Using daily plume extent as a measure of FW presence and comparing it to daily rates of PP, OC, SOC, and bottom oxygen, we find that bottom oxygen and biological rates are significantly correlated with the extent of the FW plume with correlation coefficients ranging from 43% to 62% (Table 1). In other words, variability in the extent of the FW plume explains roughly half of the variability in biological rates. Mechanistically, the presence of a large FW plume not only affects hypoxia by increasing vertical stratification and thus inhibiting vertical supply of oxygen to the subsurface but also because PP and respiration is larger in the plume. Large FW plumes stimulate more widespread biological production and thus oxygen consumption.

Since annual FW input is highly correlated with the extent of the FW plume (see Figure 5g), variability in its extent is partly due to variations in riverine input, but coastal circulation and mixing processes must be playing a role as well. Next, we analyze the impact of the underlying physical drivers.

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3.2.3 Physical drivers of intra-seasonal variability in hypoxia

We focus our analysis of physical drivers on wind direction and wind strength, and their relation to FW plume location and extent because the latter has already been identified as an explanatory variable for interannual variations in the previous section.

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Wind direction is relevant because for most of June, July, and August winds blow predominantly from the south, but switch to predominantly northerly winds between the second half of August and the end of September. As a result of the northward, upwelling favorable winds in the early summer, the FW plume is spread offshore and overlaps primarily with the northern zone. After the switch to mostly southward, downwelling-favorable directions, the FW plume moves southward, becomes more contained near the coast, and grows in its southward extent as it is transported by a coastal current. Wind direction has a demonstrable impact on PP and the extent of the FW plume as shown in Figure 8 for the month of September. Especially in the northern region, PP and plume extent are notably larger during southerly winds when the FW plume is more spread out, than during northerly winds when the plume is more restricted within the coastal current.

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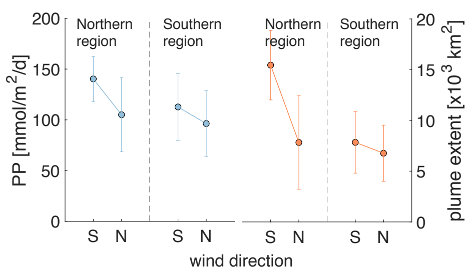

Figure 8. Mean PP and FW plume extent in the northern and southern regions averaged over all days during the 6-yr simulation with north and south wind (i.e. when direction is +/- 45˚ of true north or south) and wind strength >0.03 Pa for in September.

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Wind strength is relevant because storm events can erode vertical stratification and thus lead to resupply of oxygen to bottom waters due to vertical mixing. We investigated the effect of wind strength on bottom oxygen, hypoxia, and the extent of the FW plume by first inspecting time series of these variables (Figure S8). We isolated all event during the

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months June to September and, in Figure 10, show the corresponding changes in wind stress, mean bottom oxygen in the northern and southern zones, and the extent of the FW plume. We diagnosed these events as follows. First, we identified all days when the wind stress exceeded 0.12 Pa. Then we detected the minima in wind stress adjacent to the high-wind days by searching for minima in wind stress within 3 days prior and 3 days after the high-wind days. The periods within these minima are used as analysis period for each wind event. In four instances the wind stress exceeded the threshold within 5 days of a previous wind event. Those subsequent high-wind events were combined into one. We identified the minimum in bottom oxygen (maximum in FW plume area) at the beginning of the event and the maximum in oxygen (minimum in FW area) after the maximum in wind stress was reached.

Figure 9a illustrates rapid increases in wind stress typically within 2 to 4 days. The only exceptions are the 4 events where two storms occurred in rapid succession and the combined event lasted longer (up to 8 days) until maximum wind stress was reached. The year with the most wind events is 2013 (with 8 in total including one of the combined long-lasting event). The year with the least events is 2010 (2 events) followed by 2009 (3 events). Most of these events resulted in notable increases in mean bottom oxygen, typically by 10 to 30 mmol m^{-3}, but up to 100 mmol m^{-3} in 2010 in the southern zone (Figure 9b). In the rare cases where bottom oxygen did not increase or slightly decreased, bottom oxygen was already elevated before the wind event. The wind events strongly affected the extent of the FW plume (Figure 9c) by mixing the FW layer with underlying ocean water. The effects were largest when the FW plume was most expansive. This analysis shows the significant role of storm events in disrupting the generation of low-oxygen conditions and ventilating bottom waters.

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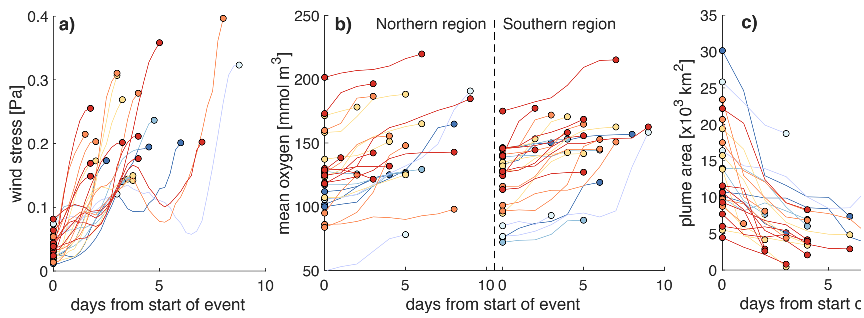

Figure 9. Evolution of a) wind stress, b) bottom mean oxygen in the northern and southern regions, and c) extent of the FW plume during high-wind events. These events are defined by wind stress exceeding 0.12 Pa.

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In section 3.2.1 above, we noted that while the years 2010 and 2012 had very similar FW input and DIN load, 2010 had a much larger hypoxic area. Likewise, the years 2009 and 2013 were very similar in terms of FW input and DIN load, but 2009 had a much larger hypoxic area. It now becomes obvious that the frequency and severity of high-wind events explains the differences in both cases.

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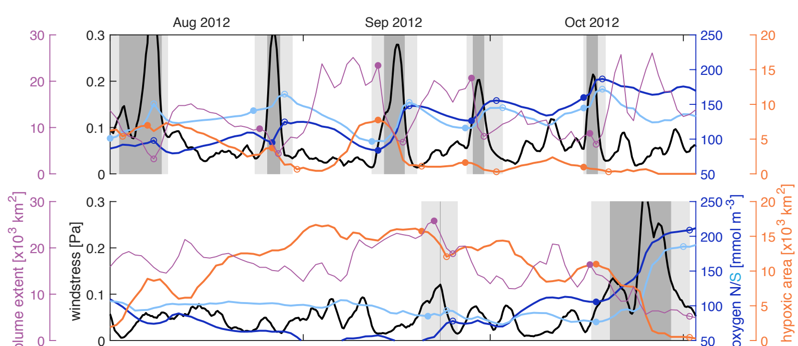

Figure 10. Wind stress (black), mean bottom oxygen in the northern and southern zones (dark and light blue), total hypoxic extent (orange), and FW plume extent (purple) throughout August, September and October of 2010 and 2012. The filled and open circles indicate a variables' value at

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the beginning and after high-wind events. High-wind days/events are indicated by the dark/light gray shading.

Figure 10 shows the wind stress, mean bottom oxygen in the northern and southern zones, and total hypoxic extent and FW plume extent in 2012 and 2010. In 2012, there were 5 high-wind events during the months of August, September, and October that all coincided with increases in bottom oxygen, decreases in hypoxic extent when a hypoxic zone was established at the beginning of the event, and decreases in FW plume extent. Inspection of the evolution of bottom oxygen is especially instructive. While bottom oxygen concentrations declined during periods with average or low wind, they were essentially reset at a much higher level during each wind event. Whenever the FW plume was extensive at the beginning of a high-wind event, it was drastically reduced during the event. In 2010, bottom oxygen was at similar levels to 2012 at the beginning of August but dropped to low levels throughout August, especially in the northern zone, and remained low with widespread hypoxia until a major wind event in the second half of October ventilated bottom waters. Except for a very short event in the second half of September, there were no high-wind events from August until mid-October in 2010.

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The differences in hypoxia in 2009 and 2013 can also be explained by the frequency and intensity of high-wind events. In 2013, there were 8 high-wind events from July to October that led to an almost continuous ventilation of bottom waters while in 2009 there were only 3 such events during the same period (Figure S8). Low to average winds from mid-August to early October of 2009 coincided with a decline in bottom oxygen and establishment of an expansive hypoxic zone throughout most of September.

These analyses show that wind direction and strength play an important role in determining the location of the hypoxic zone (i.e. northern versus southern region) and the extent and severity of hypoxic conditions.

3.3 Oxygen budgets for the northern and southern regions

In order to further investigate the roles of physical and biological processes in regulating hypoxia, oxygen budgets were calculated from daily model output for the period from March to November for the northern and southern hypoxic regions. Considering that hypoxic conditions occur near the bottom, we evaluate an oxygen budget not only for the

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whole water column but also for its lower portion which typically becomes hypoxic. To account for variations in the thickness of the hypoxic layer, which tends to be thicker in deeper waters (similar to observations by Ning et al., 2011), we include the bottommost 12 layers of our model grid. Because of the model's terrain-following vertical coordinates, the thickness of these 12 model layers varies with total depth. The terms considered in the budget are air-sea flux, lateral physical advection and diffusion, vertical turbulent diffusion (for the subsurface budget only), PP, WOC (including respiration and nitrification), and SOC. Each term was integrated vertically over the whole water column and also over the bottom-most 12 layers and then averaged for the northern and southern regions for each month (Figure 11). We also report these terms for the months during which oxygen decreases (March to August) in Table S2.

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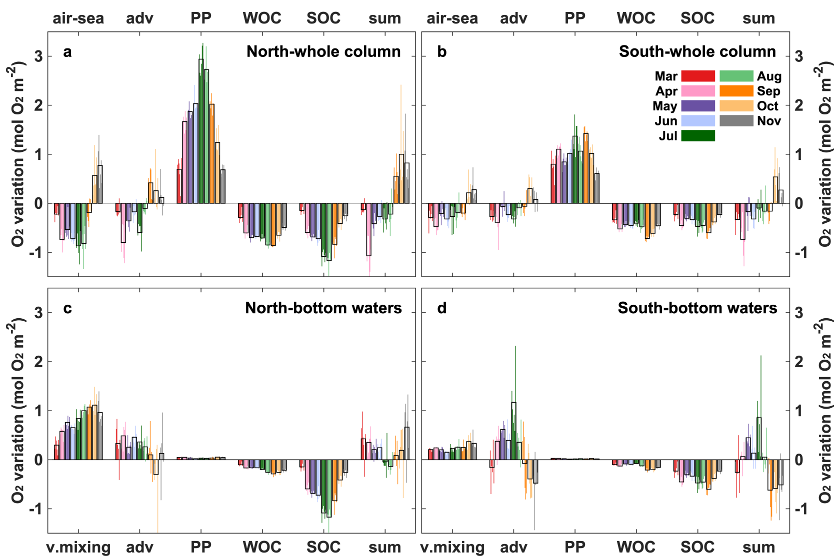

Figure 11. Monthly averaged (2008-2013) oxygen budgets for the whole water column and subsurface water from March to November in the northern and southern hypoxic regions. Adv represents lateral advection and lateral diffusion which is comparatively small, while v.mixing represents vertical turbulent diffusion, which is only relevant for the subsurface budget. Thin color bars represent individual years whereas the black bars are the 6-year average.

For the whole water column (Figure 11a, b), biological processes (PP, WOC, and SOC) greatly exceed physical processes (air-sea exchange and advective transport) in affecting oxygen. PP is always greater than the sum of WOC and SOC in the whole column indicating autotrophy in spring and summer. Advection is negative, acting as an oxygen sink and offsetting 21% of PP on average in the northern and southern regions. Of the two biological oxygen consumption terms (WOC and SOC), WOC accounts for half of total respiration. Negative air-sea flux indicates oxygen outgassing into the atmosphere and is due to photosynthetic oxygen production and decreasing oxygen solubility. However, since hypoxia only occurs in the subsurface, the subsurface budget below is more instructive.

When considering only subsurface waters (Figure 11c, d), the influence of PP decreases markedly, accounting for less than 2% of that in the whole water column. Vertical turbulent

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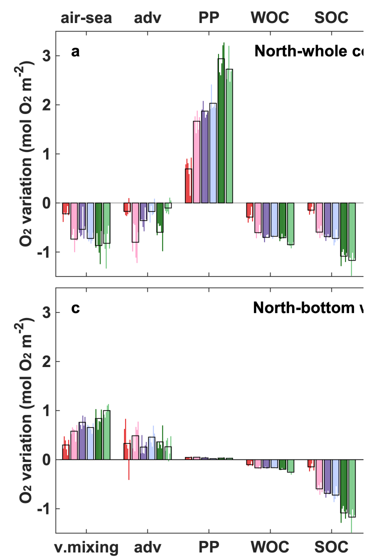

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diffusion acts as the largest oxygen source in the subsurface layer. SOC is the dominant oxygen sink accounting for 80% of the total biological oxygen consumption. As photosynthetic oxygen production increases gradually from spring to summer (Figure 12a, b) WOC and SOC also increase as they are closely associated with photosynthetically produced organic matter. Vertical oxygen diffusion tends to covary with PP, implying an oxygen gradient driven by photosynthetic oxygen production in the upper layer. Lateral advection of oxygen is negative in March only (early in the hypoxic season) mainly in the southern region but becomes positive later. This suggests that early in the hypoxic season, import of low-oxygen water contributes to hypoxia generation but advection switches to an oxygen source later. Overall, oxygen sources and sink terms are similar in the northern and southern regions.

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4. Discussion

We implemented and validated a state-of-the-art physical-biological model for the ECS. The implementation is based on a model that was previously developed and extensively used for the northern Gulf of Mexico (Fennel et al. 2011, Laurent et al. 2012, Yu at al.2015b), a region that is similar to the ECS in that it receives large inputs of FW and nutrients from a major river and develops extensive, annually recurring hypoxia (see Table 1 in Fennel and Testa (2019). Our model is more comprehensive than previous models for the ECS.

A 6-year simulation was performed and compared to available observations. The model faithfully represents patterns and variability in surface and bottom temperature and salinity, surface chlorophyll and nitrate distributions, bottom oxygen, and correctly simulates the major current patterns in the region (see Section 3.1 and Supplement). We thus deem the model's skill as sufficient for the analysis of biological and physical drivers of hypoxia generation presented here.

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The model simulates annually recurring hypoxic conditions but with significant interannual and intra-seasonal variability and marked differences in phenology of hypoxic conditions from year to year (Figure 4a, b, c). Interannual variability in hypoxic conditions is much larger than variations in FW input, nutrient load, and bottom oxygen concentrations (Figure 4b) because small variations in oxygen can lead to large changes in hypoxic area when bottom oxygen is near the hypoxic threshold. Interannual variability in hypoxic area is partly explained by variations in annual FW input, consistent with previous studies (Zheng et al., 2016; Zhou et al., 2017). While the correlation between time-integrated hypoxic area and FW input is insignificant, there is a strong and significant negative correlation between mean bottom oxygen in August and annual FW input (Figure 5). Annual FW input is also correlated strongly and significantly with the annually integrated spatial extent of the FW plume, which is a useful metric for extent of the region directly influenced by riverine inputs which induce strong density stratification and high productivity.

Surprisingly, DIN load is not correlated with FW input, hypoxic area, and mean bottom oxygen in August (Figure 5). This is in contrast to the northern Gulf of Mexico where DIN load is highly correlated with both FW input and nutrient load and frequently used as a predictor of hypoxic extent (Scavia et al. 2017; Laurent and Fennel 2019). However, the lack of correlation between hypoxia and DIN load in the ECS should not be interpreted as biological processes being unimportant in hypoxia generation, just that variations in DIN load do not explain year-to-year differences. In fact, hypoxic area and biological rates (i.e. mean August PP, OC, and SOC) are strongly and significantly correlated (Figure 5), emphasizing the dominant role of biological oxygen consumption. The fact that riverine variations in DIN load do not seem to have an effect suggests that riverine nutrient inputs are large enough to saturate the region with nutrients, similar to the northern Gulf of Mexico where small reductions in nutrient load have a relatively small effect (Fennel and Laurent 2018).

Variations in riverine FW input only partly explain interannual variations in hypoxia. For example, the years 2010 and 2012 had similar FW inputs and DIN loads but the hypoxic area was 4 times larger in 2010 than 2012 (Figure 5a). Similarly, 2009 and 2013 had the same FW inputs and nutrient loads but 2009 experienced extensive hypoxia while there was almost none in 2013. In order to elucidate these differences, we investigated biological and physical drivers of intra-seasonal variability.

In the ECS, two distinct zones of low oxygen have been observed (Li et al., 2002; Wei et al., 2007; Zhu et al., 2016, 2011). The model simulates these two zones, referred to as the northern and southern zones, consistent with observations (Figure 4d) and with

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generally higher PP and SOC in the northern zone (Figure 6). Because of these differences we treated the two zones separately in our analysis of intra-seasonal drivers.

We found daily biological rates (i.e. PP, OC, SOC) to be significantly correlated with bottom oxygen in both zones, but with relatively large variability around the best linear fit (Figure 7). The biological rates and bottom oxygen are also significantly correlated with the extent of the FW plume (Table 1). Again, these results emphasize the dominant role of biological oxygen consumption, and its relation to riverine inputs, in hypoxia generation but leave a significant fraction of the variability unexplained.

Intra-seasonal variability in hypoxic conditions is significantly related to the extent of the FW plume which is partly explained by variations in riverine FW input but strongly modulated by coastal circulation and mixing. Their influence is elucidated by our analysis of the effects of wind direction and strength on hypoxia. Wind direction has a notable effect on the geographic distribution of hypoxia. Southerly, upwelling-favorable winds lead to a more widespread eastward extension of the FW plume with elevated PP and vertical density stratification (Figure 8). Northerly, downwelling-favorable winds create a coastally trapped southward jet that moves FW southward and constrains the plume close to the coast. A similar behavior has been described for the northern Gulf of Mexico (Feng et al., 2014).

Wind strength turned out to be one of the dominant factors in hypoxia evolution. We identified high-wind events and showed that whenever bottom oxygen is low, a high-wind event will lead to a partial reoxygenation of bottom waters and decrease hypoxic extent (Figure 9). The impact of high-wind events is also visible in the extent of the FW plume, which is drastically reduced during high winds because FW is mixed. The frequency of high-wind events during summer explains the differences in hypoxic area between 2010 and 2012 (Figure 10) and 2009 and 2013 (Figure S8). In 2009 and 2010 there were only few high-wind events during summer while 2012 and 2013 experienced a sequence of storms that led to partial reoxygenation of the water column throughout the summer and thus impeded the development hypoxia.

We calculated oxygen budgets for the northern and southern regions considering the whole water-column and the near-bottom layer only. The subsurface budget is particularly useful in providing insights into when and where lateral advection amplifies or mitigates hypoxia and illustrates that SOC is the dominant oxygen sink in the subsurface. The relative

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importance of WOC and SOC had not previously been quantified for this region due to lack of concurrent WOC and SOC observations and lack of models that realistically account for both processes. The budget for the whole water column is less useful because it is dominated by the oxygen sources, sinks and transport in the surface layer, which does not experience hypoxia and thus is not relevant.

The importance of SOC in our model is consistent with recent observational studies in the ECS. SOC on the coastal shelves in the Yellow Sea and ECS has been estimated to range from 1.7 to 17.6 mmol O_2 m^{-2} d^{-1} (mean rate of 7.2 mmol O_2 m^{-2} d^{-1}) from April to October except August by Song et al. (2016), and from 9.1 to 62.5 mmol O_2 m^{-2} d^{-1} (mean of 22.6 ± 16.4 mmol O_2 m^{-2} d^{-1}) from June to October in Zhang et al. (2017). Simulated SOC in the typical low-oxygen zone falls within the range observed by Zhang et al. (2017) with a mean rate of 20.6 ± 19.2 mmol O_2 m^{-2} d^{-1} between April and October. Based on observations, Zhang et al. (2017) already suggested that SOC is a major contributor to hypoxia formation in below-pycnocline waters, which is further corroborated by our model results. It is also consistent with the modelling study of Zhou et al. (2017), who did not include SOC in the baseline version of their model but showed in a sensitivity study that inclusion of SOC simulates hypoxic extent more realistically. Our results are in line with findings from the northern Gulf of Mexico hypoxic zone where WOC is much larger than SOC below the pycnocline, while SOC is dominant in the bottom 5 m where hypoxia occurs most frequently in summer (Quiñones-Rivera et al., 2007; Yu et al., 2015b).

The finding that lateral oxygen transport can act as a net source to subsurface water is also new. On seasonal scales, oxygen advection in the subsurface varies from an oxygen sink in spring to a source in summer, especially in the southern hypoxic region, implying that the TWC becomes an oxygen source when oxygen is depleted in the hypoxic region. This aspect was neglected in previous studies which only emphasized the role of advection as an oxygen sink promoting hypoxia formation (Ning et al., 2011; Qian et al., 2015). The Taiwan Warm Current originates from the subsurface of the Kuroshio northeast to Taiwan Island, and thus represents an intrusion onto the continental shelves from the open ocean (Guo et al., 2006). In addition to oxygen advection, nutrients are transported supporting PP on the ECS shelves (Zhao & Guo, 2011; Grosse et al., 2020). The intrusion of the Taiwan Warm Current and the Kuroshio accompanied by relatively cold and saline water, and

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nutrient and oxygen transport, is thought to influence hypoxia development (Li et al., 2002; Wang, 2009; Zhou et al., 2017) but no quantification of the relative importance has occurred until now (see companion paper by Grosse et al., 2020, using the same model).

5. Conclusions

In this study, a new 3D coupled physical-biological model for the ECS was presented and used to explore the spatial and temporal evolution of hypoxia off the CE and to quantify the major processes controlling interannual and intra-seasonal oxygen dynamics. Validation shows that the model reproduces the observed spatial distribution and temporal evolution of physical and biological variables well.

A 6-year simulation with realistic forcing produced large interannual and intra-seasonal variability in hypoxic extent despite relatively modest variations in FW input and nutrient loads. The interannual variations are partly explained by variations in FW input but not DIN load. Nevertheless, elevated rates of biological oxygen consumption are of paramount importance for hypoxia generation in this region, as shown by the high correlation between hypoxic area, bottom oxygen, and biological rates (PP, OC, SOC) on both annual and shorter time scales.

Other important explanatory variables of variability in hypoxia are wind direction and strength. Wind direction affects the magnitude of PP and the spatial extent of the FW plume, because southerly, upwelling favorable winds tend to spread the plume over a large area while northerly, downwelling-favorable winds push the plume against the coast and induce a coastal current that contains the FW and moves it downcoast. Wind strength is important because high-wind events lead to a partial reoxygenation whenever bottom oxygen is low and can dramatically decrease the extent of the FW plume. The frequency of high-wind events explains some of the interannual differences in hypoxia, where years with similar FW input, nutrient load, and mean rates of oxygen consumption have display very different hypoxic extents because high-wind events lead to partial reoxygenation of bottom waters.

A model-derived oxygen budget shows that SOC is larger than WOC in the subsurface of the hypoxic region. Lateral advection of oxygen in the subsurface switches from an oxygen sink in spring to a source in summer especially in the southern region and is likely

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associated with open-ocean intrusions onto the coastal shelf supplied by the Taiwan Warm Current.

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Code/Data Availability: The ROMS model code is available at http://myroms.org. NOAA AVHRR and MODIS-Terra are available at https://www.nodc.noaa.gov/SatelliteData/ghrsst/ and http://oceancolor.gsfc.nasa.gov/. The model results are available on request to the authors.

Author Contributions: The manuscript is based on HZ's PhD thesis (in Chinese). CB implemented the physical model. HZ added the biological component, performed model simulations, and wrote the first version of the manuscript with input from KF and AL. For the manuscript revision, AL reran the model simulation, AL and KF performed additional analyses, and KF revised the text with input from all co-authors.

Competing Interests: The authors declare they have no competing interests.

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