Transient Hypoxia Extent Off Changjiang River Estuary due to Mobile Changjiang River Plume

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Abstract  Observed oxygen concentrations collected at discrete locations during research cruises were conventionally used to estimate spatial extents of bottom low-oxygen/hypoxic area. Yet observed oxygen concentrations were often not quantitatively representative of spatial patterns in instantaneous oxygen concentrations in coastal oceans, especially when the bottom hypoxia was transient. Over the Changjiang River estuary and its adjacent sea, research cruises could easily be longer than the time scale of variability of bottom hypoxia extent. The Changjiang River plume is extremely mobile due to changes in wind magnitude and direction, and the redistribution of this freshwater cap strongly regulates vertical stratification on which bottom hypoxia formation depends. A high-resolution ecosystem model was developed, which successfully reproduced observed temperature, salinity, and bottom oxygen concentration. This model suggested fast response of bottom oxygen to vertical stratification evolution (generally ~6–50 hr) and a transient spatial extent of summer bottom hypoxia off the Changjiang River estuary. Comparisons between observed and modeled oxygen concentrations implied that the hypoxic area calculated from dissolved oxygen at discrete locations often had possible errors and the estimated magnitude of hypoxic area which depended on the chronological order of observations. Therefore, it is risky to estimate the spatial extent of hypoxic area based on observations exclusively, and the relevant quantification of annual hypoxia area trend is also questionable. Integration of quasi-simultaneous observations is required to advance the understanding of oxygen dynamics, to minimize observational uncertainties. The development of skillful ecosystem models that profit from ample observations and have the power to reproduce dissolved oxygen is indispensable.

Plain Language Summary  Oxygen concentrations collected during research cruises are conventionally used to estimate bottom low-oxygen/hypoxic area. Research cruises over Changjiang River estuary and the adjacent sea generally take 1–3 weeks; however, the time scale of variability of bottom hypoxic area is much shorter. Thus, observed oxygen concentration is often not quantitatively representative of instantaneous oxygen concentration for this region, and the estimated hypoxic area during a cruise is often biased. A qualified ecosystem model suggests fast response of bottom oxygen to vertical stratification evolution (generally 6–50 hr) and transient spatial extent of summer bottom hypoxia. Changjiang River plume is extremely mobile due to changes in wind magnitude and direction, and the redistribution of this fresh cap strongly regulates vertical stratification on which bottom hypoxia formation and sustain depend. Wind-induced fresh water redistribution and the consequent evolution of vertical stratification are proved to drive short-time changes of bottom oxygen via controlling air-sea exchanges. We propose that ample observation is needed to advance understanding of realistic oxygen dynamics. To minimize biases and to exhibit bottom hypoxia condition in perspective, development of skillful ecosystem models that profit from the ample observation and have the power to reproduce is indispensable.

1. Introduction

Massive anthropogenic nutrient loads lead to coastal eutrophication, which has been well-explained to be contributive to the development of coastal hypoxia (Conley et al., 2009; Diaz & Rosenberg, 2008; Rabalais et al., 2014). Impacts of human activities on coastal regions have worsened in the past few decades, with consequences such as growth in coastal hypoxia sites (Breitburg et al., 2018; Vaquer-Sunyer & Duarte, 2008) and intensified severity of existing hypoxia sites (Breitburg et al., 2018). Oxygen depletion and hypoxia formation in coastal regions have been a growing problem worldwide, with detrimental effects that alter or interrupt ecosystem functions, such as acidification (Cai et al., 2011), degradation of biodiversity (Levin &
Breitburg, 2015), compression or loss of habitat (Stramma et al., 2012), shrinking of fish stocks, and even resilience (Levin & Breitburg, 2015). With continuously increasing nutrient loads, coastal hypoxia is most likely to worsen in the foreseeable future. East China Sea (e.g., D. Li et al., 2002; H. Wang, Dai, et al. 2016; Wei et al., 2007; J. Zhang et al., 2016), North Gulf of Mexico (e.g., Feng et al., 2012; Hetland & DiMarco, 2008; Rabalais, Turner, Sen Gupta, Boesch, et al., 2007; W. Zhang et al., 2015), and Chesapeake Bay (e.g., Bever et al., 2013, 2018; M. Li et al., 2016; Scully, 2010, 2013; Shen et al., 2013) are among the typical systems that are strongly influenced by massive nutrient loads introduced by riverine inputs.

The Changjiang River flows passed multiple mega cities in East China and then merges into the East China Sea through delta outlets. The huge amount of freshwater input facilitates the stabilization of the water column and strengthens vertical stratification. Mechanisms controlling the formation and extent of bottom hypoxia have been investigated based on observations (e.g., H. Wang, Dai, et al., 2016; Wei et al., 2007; Z. Zhu et al., 2011; J. Zhu et al., 2016), as well as numerical modelings (e.g., X. Chen et al., 2015; J. Zheng et al., 2016; F. Zhou, Chai, et al., 2017). Seasonal hypoxia formation and its spatial extent off the Changjiang River estuary are a multifactor controlled phenomenon, which are closely linked with nutrient loads (K. Wang, Chen, et al., 2016), wind speed and direction (Ni et al., 2016; B. Wang et al., 2017; J. Zheng et al., 2016), properties of the Kuroshio subsurface water, magnitude of freshwater discharge (J. Zheng et al., 2016), and other qualities such as topography (D. Li et al., 2002) and tide (X. Chen et al., 2015; Z. Zhu et al., 2017). Combining the stratification effect with the simultaneously introduced nutrients to promote ecosystem production and give rise to hypoxia off the estuary.

Generally, the balance between oxygen consumption that caused by organic matter decomposition and oxygen replenishment determines dissolved oxygen concentration at the bottom. Vertical stratification acts to inhibit surface-bottom oxygen exchange, facilitating oxygen depletion. Multiple dynamic processes, characterized by different time scales, confluence off the estuary to promote energetic plume dynamics and can easily redistribute the fresh plume water. The mobile Changjiang River plume, often considered as water shoreward of 310-psu isohaline in this study (e.g., W. Zhang et al., 2015), regulates the strength of vertical stratification.

J. Chen et al. (2017) collected nearly all the available summer oxygen data from 1998 through 2013 from existing studies and illustrated estimated bottom hypoxia extents. The details and corresponding references were listed in Table 1 of J. Chen et al. (2017). These research cruises took 1–3 weeks accordingly, and the estimated (based on observations) bottom hypoxic areas were different in magnitude as well as geographic location from year to year. The reader is referred to J. Chen et al. (2017) and its references for more details regarding observation information.

The contradiction between long durations of research cruises and the evolutions of the Changjiang River plume implied that the estimated hypoxia extents from observations might be different from their instantaneous distributions. In this study, a comprehensive, high-resolution ecosystem model was used to quantify the time scale of transient bottom hypoxia extent, to identify the dynamical mechanisms controlling this short-time evolution in summer, and to investigate if an uncertainty of estimated hypoxic area based on observation exists. This model is identified to have the ability to reproduce observed temperature, salinity, and dissolved oxygen concentration successfully. The spatial extent of summer bottom hypoxia off the Changjiang River estuary can be rather transient due to frequent redistribution of Changjiang River plume and the consequent evolution of vertical stratification. The oxygen budget is calculated based on model output to evaluate the relative importance of each source/sink or interface flux term during the evolution of bottom oxygen concentration. Analysis suggests that to estimate hypoxia spatial extent based on observations collected over week(s) can be risky.

2. Methodology

2.1. Observation

In situ observational measurements presented here were obtained aboard the R/Vs Haijian 47/49, Kexue III, and Beidou during several cruises from 2011 to 2013. A summary of the cruises with start and end dates is given in Table 1. Vertical profiles of salinity and temperature were obtained using a Seabird SBE 25 conductivity temperature depth/rosette system during the National Science Foundation of China Sharing Cruises in 2012 and 2013 (data published in Wu et al., 2018). All hydrographic sensors were periodically factory calibrated.
Table 1
Research Cruises During Years 2011–2013 Referred to in This Study

<table>
<thead>
<tr>
<th>Cruise number and season</th>
<th>Time</th>
<th>Research vessel</th>
<th>Measured property</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Summer</td>
<td>11–29 August 2011</td>
<td>R/V Beidou</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>2 Spring</td>
<td>6–14 March 2012</td>
<td>R/V Haijian 47/49</td>
<td>Temperature/salinity</td>
</tr>
<tr>
<td>3 Summer</td>
<td>14–18 July 2012</td>
<td>R/V Haijian 47/49</td>
<td>Temperature/salinity</td>
</tr>
<tr>
<td>4 Spring</td>
<td>4–20 March 2013</td>
<td>R/V Kexue III</td>
<td>Temperature/salinity</td>
</tr>
<tr>
<td>5 Spring</td>
<td>8–16 May 2013</td>
<td>R/V Beidou</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>6 Summer</td>
<td>6–28 August 2013</td>
<td>R/V Beidou</td>
<td>Dissolved oxygen</td>
</tr>
<tr>
<td>7 Summer</td>
<td>17–28 August 2013</td>
<td>R/V Kexue III</td>
<td>Temperature/salinity</td>
</tr>
</tbody>
</table>

to account for and correct long-term sensor drift. Discrete dissolved oxygen concentration measurements were obtained using a conventional Winkler titration (Bryan et al., 1976) of water samples during cruises off the Changjiang River estuary and the adjacent East China Sea in 2011 and 2013 (data published in Z. Zhu et al., 2017). Depths for the collection of water samples were decided at each location on the basis of the recorded conductivity temperature depth profile, which usually included a surface sample (approximately 2–3 m underneath the free surface), a bottom sample (3–5 m above the seabed), samples both above and below the pycnocline, and additional samples accordingly in consideration of the water column depth. Note that the dynamic tracers and oxygen concentration from different cruises were used here since we do not have the access to the rest part of the observed data.

2.2. Model Description

A comprehensive, high-resolution ecosystem model is used in this study, which includes a hydrodynamic model configured with the Regional Ocean Modeling System and a nitrogen cycle model (Fennel et al., 2013) extended to include dissolved inorganic phosphorus (DIP; Laurent et al., 2017). The hydrodynamic model domain (Figure 1) encompasses the entire Bohai Sea, Yellow Sea, East China Sea, and part of the Japan Sea and deep region offshore. The model application described in this paper was adapted from a previously calibrated and validated ECOM-si application (Wu et al., 2011, 2014). The black square in Figure 1 marks the region of interest, and the magenta star marks the river boundary in the model. This Regional Ocean Modeling System-based model has 30 vertical layers, with a minimum water depth of 3 m and a maximum slightly greater than 7,000 m. The horizontal resolution is <500 m in the upper estuary, ~1 km in the plume near-field region, and ~2 km and up further. This model initiated from rest and was forced with surface momentum and heat fluxes from the European Center for Medium-Range Weather Forecasts, freshwater flux from the Changjiang River, and current and tide at the open boundary. The initial and open boundary conditions for physical component are extracted from World Ocean Atlas and Simple Ocean Data Assimilation, respectively.

The biological model is a nitrogen, DIP cycle model based on Laurent et al. (2017) which includes two species of dissolved inorganic nitrogen (nitrate, NO3, and ammonium, NH4), DIP (phosphate, PO4), one functional phytoplankton group (Phy), chlorophyll (Chl) as a separate state variable, one functional zooplankton group (Zoo), two pools of detritus representing large, fast-sinking particles (LDet) and suspended, small particles (SDet), and dissolved oxygen as a state variable. The equation of dissolved oxygen conservation is given as

$$\frac{\partial O_x}{\partial t} = -[(u \frac{\partial O_x}{\partial x} + v \frac{\partial O_x}{\partial y} + w \frac{\partial O_x}{\partial z})] + \left( \frac{\partial}{\partial x} (K_H \frac{\partial O_x}{\partial x}) + \frac{\partial}{\partial y} (K_V \frac{\partial O_x}{\partial y}) \right) + \frac{\partial}{\partial z} (K_v \frac{\partial O_x}{\partial z}) + PP + WCR + Nitrif + F_{SDet} + F_{Air-sea}.$$  

Equation (1)

Ox represents dissolved oxygen concentration (mmol/m³); the first two terms on the right-hand side are advection and diffusion-induced oxygen changes. In these terms x, y, and z represent the two horizontal coordinates and the vertical coordinate, respectively; u, v, and w represent velocity components in x, y, and z coordinates, respectively; Kh and Kv are the horizontal and vertical diffusivities (m²/s), respectively. The term PP is primary production

$$PP = \mu_{max}(T) f(E) \left( \frac{L_{NO3}}{L_N} R_{NO3:NO3} + \frac{L_{NH4}}{L_N} R_{NO2:NH4} \right) min(L_N,L_P) Phy.$$  

Equation (2)
Figure 1. This figure shows the entire model domain and the region of interest (squared in black). The red points mark measurement locations for cruises 2, 3, 4, and 7 in Table 1, while the blue crosses mark measurement locations for cruises 1, 5, and 6; the isobath shown are 10, 20, 30, 40, and 50 m. The integrated historical hypoxia extent (adopted from F. Zhou, Chai, et al., 2017) is marked in green.

$\text{WCR} = -R_{\text{O}_2}, \begin{pmatrix} l_{\text{B}M, \text{Zoo}} + l_{\text{B}p} \frac{\text{Phy}^2}{K_p + \text{Phy}^2} \beta \text{Zoo} + \rho_{\text{SD}, \text{Det}} + \rho_{\text{LD}, \text{Det}} \end{pmatrix}, \tag{3}$

and $\text{Nitrif}$ stands for oxygen consumption due to nitrification

$\text{Nitrif} = -\delta \text{NH}_4^+.$ \tag{4}

where $\mu_{\text{max}} = \mu_0 \times 1.066^\gamma$ (Eppley, 1972) is the maximum growth rate of phytoplankton (day$^{-1}$), and $f(E) = \alpha E \sqrt{\mu_{\text{max}}^2 + \alpha^2 E^2}$ (Evans & Parslow, 1985) is light limitation, and the light function $E$ is parameterized to take account light attenuation caused by high turbidity in the upper estuary

$E = \text{PAR} \times \frac{1 - e^{-\Delta z}}{\Delta z}, \tag{5}$

where $\Delta z = \Delta z \times (\text{AttSW} + \text{AttChl} \times \text{Chl} + \Delta z \times \text{AttSed})$; $\Delta z$ is the thickness of a layer. $\text{AttSed}$ is parameterized light attenuation caused by sediment. Upper estuary is extremely turbid due to the huge amount of sediment flux from the Changjiang River, and $\text{AttSed} = 0.6(h < 10 \text{ m}); 0.4(10 \text{ m} < h < 25 \text{ m}); 0.1(h > 25 \text{ m})$. The list of biological parameters is presented in Table 2.

$F_{\text{SOC}}$ and $F_{\text{air} - \text{sea}}$ are the oxygen fluxes across the bottom and the air-sea interface, respectively. The biological model specifies sediment oxygen demand (SOD) as a negative flux of oxygen at the seafloor based on bottom temperature and oxygen concentrations, which was proposed by Hetland and DiMarco (2008)

$\text{SOD} = 6.0 \left[ \text{Ox m}^{-2} \text{day}^{-1} \right] \times 2^{7/10.0^\circ C} \times \left[ 1 - \exp\left( -\frac{\text{Ox}}{30.0 \mu \text{M Ox}} \right) \right], \tag{6}$

gas exchange across the air-sea interface (in units of mmol$\cdot$O$_2$$\cdot$m$^{-2}$) is parameterized as

$F_{\text{air} - \text{sea}} = \frac{\nu K_{O_2}}{\Delta z} (\text{Ox}_{\text{sat}} - \text{Ox}), \tag{7}$

where $\nu K_{O_2}$ is the gas exchange coefficient for oxygen, and $\text{Ox}_{\text{sat}}$ is oxygen concentration at saturation. The readers are referred to Laurent et al. (2017) for equations and elaborate explanation of the biological model. The initial and climatological open boundary conditions for biological components are extracted from World Ocean Atlas.
Table 2
Parameters, Values, and Units of the Biological Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_0 )</td>
<td>0.59</td>
<td>Phytoplankton growth rate at 0 °C</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.025</td>
<td>Initial slope of the instantaneous growth rate versus light curve</td>
<td>(W m(^{-2}))(^{-1}) day(^{-1})</td>
</tr>
<tr>
<td>( k_p )</td>
<td>2</td>
<td>Phytoplankton ingestion half saturation concentration</td>
<td>(mmol N m(^{-3}))(^{2})</td>
</tr>
<tr>
<td>( h )</td>
<td>0.2</td>
<td>Nitrification rate</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.75</td>
<td>Assimilation efficiency</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>( l_{BM} )</td>
<td>0.1</td>
<td>Excretion rate due to basal metabolism</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( l_{E} )</td>
<td>0.1</td>
<td>Maximum rate of assimilation related excretion</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( r_{SD} )</td>
<td>0.3</td>
<td>Remineralization rate of suspended detritus N</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( r_{LD} )</td>
<td>0.01</td>
<td>Remineralization rate of large detritus N</td>
<td>day(^{-1})</td>
</tr>
<tr>
<td>( R_{O_2: NO_3^-} )</td>
<td>8.625</td>
<td>( \text{O}_2 ) produced per mol of ( \text{NO}_3^- ) assimilated during photosynthesis</td>
<td>mmol( \text{O}_2 )(mmol( \text{NO}_3^- ))(^{-1})</td>
</tr>
<tr>
<td>( R_{O_2: NH_4^+} )</td>
<td>6.625</td>
<td>( \text{O}_2 ) produced per mol of ( \text{NH}_4^+ ) assimilated during photosynthesis</td>
<td>mmol( \text{O}_2 )(mmol( \text{NH}_4^+ ))(^{-1})</td>
</tr>
<tr>
<td>AttSW</td>
<td>0.08</td>
<td>Light attenuation due to seawater</td>
<td>m(^{-1})</td>
</tr>
<tr>
<td>AttChl</td>
<td>0.06</td>
<td>Light attenuation due to chlorophyll</td>
<td>(mg Chl m(^{-2}))(^{-1})</td>
</tr>
<tr>
<td>AttSed</td>
<td>Model description</td>
<td>Light attenuation due to sediment</td>
<td>m(^{-1})</td>
</tr>
</tbody>
</table>

2.3. The Use of Modeled and Observed Data

This ecosystem model initiated in January 2009, and a 5-year simulation was conducted with 3-hourly model output. Model output was analyzed since 2011 to ensure adequate time to finish spin up completely. Three-hourly temperature, salinity, density, oxygen, nitrate, and chlorophyll were directly recorded from the model. The performances of the hydrodynamic model were evaluated via comparing with in situ measurements before oxygen analysis. Values from cruises 2, 3, 4, and 7 in Table 1 are the observed dynamical tracers considered in this study, and the red points in Figure 1 denote the measurement locations. The blue crosses in Figure 1 denote locations of dissolved oxygen measurement from cruises 1, 5, and 6 in Table 1.

The corresponding modeled values for all observations were obtained for model-data comparisons during model evaluation. Modeled data for year 2011 and oxygen concentration from cruise 1 were subsequently analyzed in details. All observations from cruise 1 (66 stations in total) were first labeled sequentially in chronological order during plan-view comparisons of bottom oxygen. Then a “reversed order chronologically” was introduced, which means modeled oxygen values were extracted at the measurement locations but in the reversed order of observation chronologically. Such that modeled oxygen for location 66 was picked at the first cruise time on 14 August, and this went sequentially till the modeled oxygen value for location 1 was picked at the last cruise time on 29 August. Modeled bottom hypoxic area was defined as the sum of the area of all grid cells in the region of interest that characterized by oxygen concentration no more than 2 mg/L.

The Brunt-Väisälä frequency, \( N \), is often used to denote the strength of stratification (Brunt, 1927), which is defined as

\[
N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z} \tag{8}
\]

where \( g = 9.8 \text{ m/s}^2 \) is the gravitational acceleration; \( \rho_0 \) is the background or reference density (1,027 kg/m\(^3\)); \( \rho \) is seawater density. Brunt-Väisälä frequency was calculated based on modeled data, and the maximum value, \( N_{\text{max}}^2 \), of a profile was used here to quantitatively represent the strength of bulk stratification. Additionally, the pycnocline was defined as the location where vertical stratification maxima occurred for a profile.

The oxygen budget was calculated via quantifying all seven terms in equation (1) based on model results. Except for interface fluxes, air-sea flux, and SOD, other sinks and sources were depth-integrated for both the upper and lower water column. The upper layer budget was defined as the integration of layers above the main pycnocline for each term, while the lower layer budget was defined as the integration of layers below the main pycnocline for each term. Air-sea flux was considered as a term in the upper layer budget, while SOD was considered as a term in the lower layer budget. Plan views and time series of variables for year 2011 were analyzed based on model results. Thirty-three-hour moving average (i.e., low-pass filter) was done for long-term (months) time series analysis with the purpose of filtering out high frequency variabilities caused
Figure 2. Model-data point-to-point comparisons for (a) temperature, the solid black line is the linear fit. (b) Salinity, the solid black line is the linear fit. Red points represent surface values, and blue points represent bottom values. (c) Temperature-salinity scatter comparisons, ”*” and ”.” represent observed and modeled values, respectively. Orange represents surface values in spring; cyan represents bottom values in spring; red represents surface values in summer; and blue represents bottom values in summer. RMSE = root-mean-square error.

3. Results

3.1. Model Evaluation

Statistically point-to-point comparisons of temperature and salinity are extended in Figures 2a and 2b to assess the model accuracy. Points generally distribute along the diagonal, with root-mean-square error \( RMSE = 1.66 \) °C for temperature and \( RMSE = 2.22 \) psu for salinity. The solid black lines are the linear fits with a slope of 0.92 for temperature and 1.01 for salinity. These discrete points indicate the model adequately in reproduced individual observed temperature/salinity values for meeting the objectives of this study. Considering the highly variable temperature and salinity around the Changjiang River plume fronts, such a model performance was decent and comparable to previous studies (e.g., Wu et al., 2011, 2014).

In addition, the salinity-temperature scatter diagram in Figure 2c illustrates that this model was also capable of successfully reproducing observed water masses as a whole, such as the Kuroshio subsurface intrusion (\( RMSE = 1.80 \) °C for temperature and \( RMSE = 1.11 \) psu for salinity) and the Changjiang River plume (\( RMSE = 1.14 \) °C for temperature and \( RMSE = 3.36 \) psu for salinity). The Kuroshio subsurface intrusion approaches its maximum north reach in summer. This intrusion, characterized by high salinity and temperature ranging from 17 to 25 °C (L.; Li et al., 2007; P. Zhou, Song, et al., 2017), was detected at the bottom during these research cruises (blue circles in the green polygon as shown in Figure 2c); the model successfully reproduced this intrusion signature (blue stars). Comparisons between the red circles and stars indicate that the Changjiang River plume, characterized by high temperature and low salinity at the surface (Y. Zheng et al., 2009; J. Zhu et al., 2003), was also successfully reproduced by the model. These could be considered representative of the model ability to reproduce observed measurements over the region of interest in a statistical sense. Therefore, the hydrodynamic model was reliable in reproducing the dynamical tracers.

To assess the biological model ability, observed oxygen concentrations are compared with modeled values in Figure 3. Figure 3a shows point-to-point comparisons for all three cruises, with \( RMSE = 0.95 \) mg/L. Similar to dynamical tracer comparisons, points in Figure 3a generally distribute along the diagonal although some split out slightly, while Figure 3b shows the histogram of observed values minus modeled values. Figure 3c shows the interpolation of observed bottom \textbackslash oxygen concentrations during cruise 1; Figure 3d is the interpolation of the corresponding (at the closest vicinity of a measurement location and time) modeled values, and observations are superimposed. All measurements from cruise 1 are numbered in observed order chronologically.

The model captured the spatial pattern of observed bottom oxygen and the geographic location of low oxygen, as well as the value of each measurement. The low bottom oxygen was located within 122–124°E, 30–32°N during this cruise. The estimated low-oxygen (lower than 2.6 mg/L) area based on observation during cruise 1 was 5,922.8 km² (Figure 3c), while the corresponding low-oxygen area based on model was 7,290.0 km² (Figure 3d). The biological model reproduced observed oxygen concentration, establishing the model ability in representing realistic oxygen concentration.
Figure 3. (a) Model-data point-to-point comparison of bottom dissolved oxygen for cruises 1, 5, and 6; (b) histogram of observed oxygen concentration minus modeled oxygen concentration; (c) observed bottom dissolved oxygen for cruise 1; (d) modeled bottom dissolved oxygen corresponding to cruise 1, observations are superimposed in "•" and numbered in chronological order. BO = bottom oxygen; RMSE = root-mean-square error.

3.2. Changjiang River Plume, Vertical Stratification, and Bottom Oxygen

Figure 4 shows nine evolution stages of the modeled surface salinity from 27 July to 11 August 2011. Simultaneous winds are superimposed for all stages, indicating the occurrence of a strong wind event during this time. Typhoon 11 in 2011 occurred 26 July to 9 August and influenced the East China Sea on 5 through 7 August. The strong wind event in Figure 4 was the consequence of this typhoon. The northward wind on 27 July facilitated offshore extent of the Changjiang River plume, which consequently strengthened offshore stratification and promoted a large area of bottom hypoxia. By 3 August, the Changjiang River plume (31-psu isohaline) reached as far as 125°E offshore, yet northward wind halted. The upper layer around the black point was still strongly influenced by freshwater. The Changjiang River plume responded to wind forcing almost immediately and retreated as westward wind strengthened. By 7 August, freshwater had been pushed westward hugging the coast, and the black point was on the offshore edge of Changjiang River plume (31-psu isohaline). Wind switched to weak and northward on 8 August, and this was when the slightly offshore relaxation of Changjiang River plume started. Although not always as strong as a typhoon influence, similar wind-induced, short time scale changes of freshwater distribution occurred frequently in the summer over the region.

Modeled 3-hourly surface salinity fronts (31-psu isohaline) for August 2011 in Figure 5a illustrated the mobile distribution of the Changjiang River plume. Figure 5b shows modeled oxygen concentration along the selected transect on 27 August 2011. Hypoxic water is constrained by the white isoline. The multicolored isohaline marks the location of the pycnocline, which isolated the upper and lower layers of water via inhibiting surface-bottom oxygen exchanges. Figures 5c and 5e show the plan views of modeled surface nitrate and chlorophyll concentrations, respectively. Nitrate generally followed the Changjiang plume water distribution and fertilized coastal regions. However, shoreward of 25-m isobath, the massive nutrient support barely
promoted primary productivity, because the gigantic sediment flux from Changjiang River causes extremely high turbidity at shallow regions which induces light attenuation. Therefore, primary producer blooms are inhibited due to light limitation at shallow regions, and the chlorophyll concentration is generally low (Figures 5e and 5f).

Plan views of vertical stratification maxima based on model output are shown in Figures 6a and 6b, note that shallow regions associated with light limitation are blanked. The multicolored isohaline in Figures 6a and 6b indicates the offshore extent of Changjiang River plume for 15 and 27 August 2011, respectively. Strong vertical stratification was confined within the freshwater envelope associated with Changjiang River plume. Strong stratification inhibited surface-bottom oxygen exchange; hence, bottom oxygen depletion and formation of hypoxia often occurred under strong stratification (Figures 6c and 6d). Plan views demonstrate that strong stratification was phase-locked with the plume water, and bottom low-oxygen (hypoxia) was colocated with strong stratification.

Thirty-three-hour moving averaged time series of surface salinity, vertical stratification maxima, and bottom oxygen for year 2011 were analyzed in Figure 7. Figure 7a shows evolutions of surface salinity for the three locations marked in Figure 6d. Points within (1) and beyond (2 and 3) the near-field river plume were selected for comparisons. Seasonal variabilities of surface salinity for points 2 and 3 were modest, only a freshening occurred in summer which was most likely when the elevated river discharge reached its offshore-extent maxima. In Figure 7b, the corresponding vertical stratification maxima evolution for these two points show
modest magnitudes as well as their variabilities. A peak in vertical stratification maxima occurs under the freshening of surface salinity in summer. These two points were beyond the influence of Changjiang River plume; they were selected as references with the purpose of emphasizing the frequent salinity variabilities for point 1, which was in the near-field of Changjiang River plume. Surface freshwater redistribution occurred frequently all year round; vertical stratification responded to surface salinity evolution almost immediately, and its maximum value peaked in summer when the extremely freshwater at surface enhanced surface-bottom salinity differences.

Figure 7d shows time series of bottom oxygen concentrations, and spectrum analysis for points 1, 2, and 3 showed seasonal variability (83.3 days), semimonthly variability (15.4 days), weather band (8.03 days), and even shorter time scale variabilities (ranging from 1.3 to 6.9 days) due to the complex dynamics over the shelf. The seasonal variability was linked with oxygen saturation (temperature related); bottom oxygen was generally high in winter/spring and low in summer/early fall. The semimonthly variability resulted from neap-spring tidal cycle. Tide-induced stratification effect was most likely the reason controlling bottom oxygen via regulating vertical exchanges, which was in agreement with what X. Chen et al. (2015) concluded. Short time scale variability occurred in summer and fall frequently, most likely caused by wind-induced stratification evolution. Figure 7c shows the time rate of bottom oxygen change; positive values represent replenishment via mixing, and negative values represent depletion due to the establishment of strong vertical stratification. The bottom oxygen change rate ranged \(-0.037\) to \(-0.042\) mg/L/hr (Figure 7c), in agreement with the observed \(-0.026\) to \(-0.032\) mg/L/hr in the geographic vicinity (read from Figure 3 in Ni et al., 2016).

3.3. Oxygen Budget

Oxygen budget for point 1 was then calculated based on model results, and Figure 8 shows time series of 33-hr moving averaged calculations. Figure 8a shows time series of wind over this point; Figure 8b illustrates surface salinity and the consequent vertical stratification condition; Figure 8c shows time series of all seven
Figure 6. This figure shows two stages of calculated vertical stratification maxima and simultaneous bottom oxygen concentration in August 2011 (time format in “Year Month Day Hour”). The multicolored isolines are identical isohaline in (a) and (c) and (b) and (d). The superimposed arrows represent simultaneous wind.

Terms in the oxygen budget; Figures 8d and 8e show time series of the upper layer budget and the lower layer budget, respectively; and Figure 8f shows time series of bottom oxygen concentration.

The periodic advection-induced oxygen change was a consequence of tidal oscillation. Although this had trivial influence on short-time bottom oxygen variability (Figures 8c and 8f), this tide-induced advection may also contribute to the semimonthly variability of bottom oxygen. Short-time bottom oxygen variability was dependent on vertical processes. Water column respiration and SOD were oxygen sinks (negative values) and generally temperature-related; their time series showed seasonal variability with relatively high values occurring during the summer. Primary production-induced oxygen change showed typical seasonal variability. A secondary bloom occurred in spring when temperature warmed; the annual peak occurred in summer with sufficient nutrient and sunlight supplies. The primary production peak decreased when nutrients were mostly consumed, and primary production rose slightly in early fall (dark blue line in Figure 8c). Nitrification-induced oxygen change was trivial and neglectable.

Air-sea flux represented oxygen exchange at the air-sea interface; positive values indicated net gain of oxygen from the atmosphere, while negative values indicated degassing due to photosynthetic production. Air-sea flux-induced oxygen change was dual-controlled by the strength of vertical stratification and the bottom versus surface oxygen difference. Vertical stratification within the three magenta squares were similarly weak due to the retreat of freshwater caused by sharp changes in wind magnitude and direction (Figure 8a). Yet the corresponding strong mixing did not trigger a high level of air-sea flux in late May, because bottom oxygen was relatively high then (Figures 8c and 8f). In contrast, bottom oxygen concentrations in August and September were low; the reoxygenation of the bottom water caused large air-sea fluxes from the atmosphere to the surface layer (Figures 8c and 8f).

Figure 9 zooms into the second magenta square as shown in Figure 8 to further investigate short-time evolution of bottom oxygen. Note that the magnitudes of air-sea flux and diffusion in Figure 9 are slightly different from Figure 8, because Figure 8 shows 33-hr moving averaged calculations while Figure 9 shows
calculations based on 3-hourly results. Figure 9a shows wind conditions at point 1 during this time; the river plume extended over the shelf. Strong vertical stratification (Figure 9b) established on 4 August because of the offshore extent of the Changjiang River plume driven by previously northward wind; there was a corresponding drop of bottom oxygen (Figure 9e) lagged by 48 hr. The subsequently strengthened wind (typhoon 11) broke down vertical stratification and facilitated air-sea exchange via diffusion (Figure 9d). Bottom low-oxygen conditions disappeared quickly, in 26.1 hr, after the break down of strong vertical stratification.

4. Discussion: Spatial Extent of Bottom Low Oxygen

Figure 4 illustrates that the highly mobile freshwater was predominantly redistributed by wind. Red isolines denoted the modeled bottom hypoxic area, and the corresponding nine stages of bottom oxygen concentrations evolved rapidly following freshwater redistributions. In addition, Figure 6 illustrates the consistency of geographic locations of surface freshwater, strong vertical stratification, and bottom low oxygen/hypoxia. With a typical vertical viscosity $K_v \sim 0.03 \, \text{m}^2/\text{s}$ during mixing, the time scale of vertical mixing and the consequent surface-bottom oxygen exchange within 60-m isobath is $\tau = (K_v/H^2)^{-1} \sim 6-50 \, \text{hr}$. For instance, mixing time scale for point 3 (shown in Figure 6d) on 7 August was 27.9 hr, which is much shorter than research cruises generally take. Thus, regulated by the wind (Wu et al., 2014), model results suggested that the mobile Changjiang River plume controlled the short-time evolution of vertical stratification with a time scale of $\sim 6-50 \, \text{hr}$. Hence, the frequent stratification evolution was the ultimate control of transient bottom hypoxia from a physics point of view.

Oxygen budget calculations and time series analysis combined to successfully explore detailed vertical processes during bottom oxygen evolution (Figures 8 and 9). Typhoon-induced wind event was identified to be the dynamic mechanism controlling the short-time bottom oxygen evolution during this time. Strong wind could break down vertical stratification and facilitate air-sea exchange via diffusion. Although not as strong as typhoon event, strong wind events with magnitude and direction changing occurred frequently in summer (Figure 8a). Thus, high variability in wind magnitude and direction can induce frequent stratification evolution,
which is a leading factor that facilitates the transient characteristics of bottom hypoxia extent in summer off the Changjiang River estuary.

Evolution of the modeled hypoxic area during dates of cruise 1 was calculated after demonstrating the transient characteristics of bottom hypoxia extent. Figure 10a is identical to Figure 3d, while Figure 10b shows modeled oxygen extracted from the model in the reverse time order as the observations were collected; observations were superimposed for comparison. Figure 10c shows modeled, daily-averaged bottom hypoxic areas over the date range of cruise 1, as well as the list of observational measurements that each day accomplished during cruise 1. Figure 10d shows the time series of modeled bottom hypoxic area over the date range of cruise 1. Modeled bottom hypoxia expanded northward and eastward starting 14 August 2011; hypoxia extent had completely evolved and enlarged in a week by 21 August 2011, and the evolution continued till 25 August 2011. Hypoxic area expanded from 3,230 to 5,000 km² in 5 days, to 17,350 km² in the following 6 days, and then gradually faded to 11,366 km² in the following 4 days. The mean, median, and standard deviation of modeled hypoxic area over the date range of cruise 1 were 9,343.7, 8,928.8, and 5,280.4 km², respectively. This indicates that the possible error of cruise-based data-estimated hypoxic area could be as large as its own magnitude.

During a research cruise, the observed bottom low-oxygen/hypoxic area can be changing, and the estimated hypoxic area can vary dependent on the spatial and temporal sequence of the observations. In addition, Figure 10c illustrates that the spatial extent of bottom low-oxygen/hypoxia could vary over hours or a couple of days. During the exact same dates, a cruise that collected measurements as per the reversed chronological order of cruise 1 might have detected very different bottom oxygen concentration. Figure 10a is representative of the realistic oxygen condition during cruise 1, while Figure 10b is representative of realistic oxygen

Figure 8. Oxygen budget ($10^9$ mmol/hr, equivalent to $3.2 \times 10^{10}$ mg/hr) for point 1 as shown in Figure 6d is calculated and time series of (a) simultaneous wind; 33-hr moving averaged (b) surface salinity (psu) and vertical stratification maxima; (c) all seven terms in oxygen budget; (d) upper layer budget; (e) lower layer budget; and (f) bottom oxygen concentration. SOD = sediment oxygen demand; PP = primary production; WCR = water column respiration.
Figure 9. This figure zooms into the second magenta square as shown in Figure 8 to show detailed ventilation processes. Three-hourly time series of (a) simultaneous wind; (b) vertical stratification; (c) air-sea flux induced oxygen change ($\times 10^9$ mmol/hr); (d) diffusion induced oxygen change ($\times 10^9$ mmol/hr); and (e) bottom oxygen concentration.

Seasonal bottom hypoxia off the Changjiang River estuary is transient due to frequent wind events in the summer; hence, it is rather risky to quantify bottom hypoxic area based only on observational measurements. Analysis here suggests a possible error of up to 100% of the estimated hypoxic area using cruise 1 data. This can be a common problem for regions undergoing transient hypoxia. Bottom oxygen responded to vertical stratification with a lag of $\sim$6–50 hr; with such a short time scale, it is rather difficult to obtain synoptic realistic hypoxia spatial extents based on in situ observations exclusively, since conventional research cruises over the shelf in this study region usually took 1–3 weeks. With these relatively long sampling times, the chronological order of observation could strongly influence the estimated hypoxic area. Therefore, conclusions regarding annual or seasonal variabilities of hypoxia extent based on episodic, discontinuous observations should be made with care and with a detailed understanding of the potential uncertainty in the estimates. More complete methods incorporating models and cruise-based data are required to better evaluate the bottom hypoxia extent off the Changjiang River estuary.

Factors controlling oxygen replenishment are key to the formation, sustainment, and spatial/vertical extent of bottom hypoxia for a region. Short-time evolution of the summer hypoxia in some regions may not be as significant as off the Changjiang River estuary, for instance, bottom hypoxia over the North Gulf of Mexico is strongly regulated by the Mississippi River system (Hetland & DiMarco, 2008; Rabalais, Turner, Sen Gupta, Platon, et al., 2007; W. Zhang et al., 2015). Wind is weak and upwelling-favorable during summer (Cochrane & Kelly, 1986; Nowlin et al., 2005); freshwater discharge is trapped on the Louisiana shelf to intensify the stratification and inhibit the exchange of oxygen-rich surface water to subpycnocline waters (Bianchi et al., 2010; Hetland & DiMarco, 2008; Wiseman et al., 1997). In contrast, the Changjiang River estuary and the adjacent sea are affected by monsoon, and the short-time variability of wind occurs more frequently. Bever et al. (2018) used two continuously sampled oxygen profiles to estimate hypoxic volume for the Chesapeake Bay. These
daily-averaged profiles were considered to be more accurate in providing the estimations than the bimonthly cruise data because of the high-frequency changes in oxygen concentration under the variable wind direction and magnitude. Rabouille et al. (2008) stated that the residence times of bottom water are 11, 95, and 3–5 days for the regions adjacent to the Changjiang River estuary, Mississippi River estuary, and Pearl River estuary, respectively. The shorter the bottom water residence time, the harder for bottom hypoxia to form and be maintained. Thus, the uncertainty of estimated hypoxic area based on conventional research cruises can be a common issue for regions that are influenced by frequent changes in wind direction or magnitude, short residence time of bottom water, or strong diffusion.

Although studied for over a decade, sharing of resources and collaborations are still limited regarding seasonal hypoxia in this region. Breitburg et al. (2018) emphasized the importance of observation sufficiency and ecosystem model skills in investigating hypoxia. It is critical to integrate knowledge, resources, and experiences to advance understanding of this topic. Such collaborative researches are capable of collecting more quasi-simultaneous observations, the means by which to have more insights into realistic bottom hypoxia conditions over the shelf. A well-performing ecosystem model is indispensable in providing continuous dissolved oxygen evolution spatiotemporally. Ample observations will also facilitate the improvement of comprehensive ecosystem models via optimizing model equations, parameterizations, boundary, and other conditions. Thus, the robust approach is to develop a comprehensive system with ample observations and high-resolution ecosystem models. Oxygen dynamics is the fundamental driver of the oceanic ecosystem quality and is essential to other shelf biogeochemical dynamics. Therefore, this study can have important implications on further biogeochemical researches.

5. Conclusions

The topic of bottom hypoxia dynamics and its spatial extent off the Changjiang River estuary was revisited, based on observations collected during several research cruises and a comprehensive, high-resolution ecosystem model. So far, many models treated Changjiang River as a point source. This simplification clearly alters the Changjiang River plume extent on which vertical stratification and the consequent bottom hypoxia fundamentally depend. In addition, light attenuation at shallow regions was often neglected in previous studies, which resulted in artificial algal blooms near the river mouth and shrank nutrient supply to the offshore regions. The high-resolution model in this study eliminated both issues and reproduced observed dynamic tracers and oxygen concentration successfully.

The relationships between surface salinity, vertical stratification, and bottom oxygen concentration were analyzed. Vertical stratification responded to wind-induced redistribution of the Changjiang River plume almost immediately and bottom low oxygen colocated with strong stratification. The time series of wind,
salinity, stratification, and bottom oxygen proved that short-time bottom oxygen evolution was predominantly attributable to stratification evolution caused by wind-induced freshwater redistribution. Calculations of oxygen budget indicated that short-time bottom oxygen evolution was predominantly vertical processes dependent, and the relevant air-sea oxygen flux approached bottom via diffusion during mixing event.

The analysis of modeled bottom oxygen concentration identified a 6- to 50-hr response time to wind-induced freshwater redistribution (ultimately a stratification effect) via mixing with a lag of ~6–50 hr. Thus, the estimated spatial extents of bottom hypoxia during conventional research cruises could be uncertain, and the magnitude of the errors depended on the chronological order of the observations. The efficient approach to minimize these uncertainties is to integrate more qualified observations, aiming to explore more insights into realistic oxygen concentration and to facilitate the development of skillful ecosystem models. Therefore, the combination of a more robust observation management system and better ecosystem models is required to determine the realistic size of the low oxygen concentration areas in this region.

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