Impacts of increasing dissolved inorganic nitrogen discharged from Changjiang on primary production and seafloor oxygen demand in the East China Sea from 1970 to 2002

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ABSTRACT

In recent years, benthic hypoxia has been observed in the outflow region of the Changjiang River in the East China Sea. Because the nitrogen input to the Changjiang watershed, mainly from human activities, has increased by 3 fold in the last four decades and the nitrogen load had grown exponentially, it is speculated that anthropogenic nutrients may be responsible for the hypoxia in the East China Sea shelf. We employ a coupled 3-D physical–biogeochemical model of the East China Sea to investigate how the changing Changjiang nutrient loads from 1970 to the end of 2002 may have impacted on primary production in the water column and the seafloor oxygen demand (SOD) on the seafloor. The model predicts an average value of 437 mgC m⁻² d⁻¹ for primary production and 10.0 mmol O₂ m⁻² d⁻¹ for SOD for the ECS shelf over the entire modeling period. The model results compare reasonably with observations during the period from December 1997 to October 1998. Responding to the increase of the Changjiang DIN loading by a factor of ~2.4, the modeled primary production in the East China Sea shelf has increased by 17%, and the modeled SOD by 22%. In the inner shelf, where the impact is the strongest, the SOD increases by 30%. We are able to identify areas of potential hypoxia using two criteria: SOD > 30 mmol O₂ m⁻² d⁻¹ and water depth < 25 m. The maximum area of potential hypoxic region in any month of a year has increased dramatically after 1991; the change appears related to the Changjiang DIN loads from May to July that showed a sudden increase after 1990. The responses in potential hypoxic area are more pronounced than the increases in DIN (dissolved inorganic nitrogen) loads, suggesting strong nonlinear effect in the development of hypoxia, which warrants further investigation. It is cautioned that the SOD calculation was based on the Redfield C/N ratio, but the actual C/N ratio may deviate from it. Direct observations of the sediment oxygen consumption are needed to validate our modeling approach. We also assessed the potential impacts of particulate organic matter from Changjiang by introducing a load of reactive particulate nitrogen (PN), which was assumed proportional to DIN based on estimated yields in the watershed. The modeled impacts on primary productivity and SOD are significant, but more accurate quantification of the monthly PN load and better characterization of its reactivity are required for better assessment.

1. Introduction

The global human population has increased by 1–2% annually during the last few decades reaching a current population of 7 billion. The marginal seas in the western North Pacific Ocean are bordered by some of the most densely populated coastal planes (e.g., the Changjiang Delta) and megacities (e.g., Shanghai) in the world. Biogeochemical cycles in these marginal seas are strongly influenced by input of anthropogenic nutrients via river runoffs (e.g., Yan et al., 2010) and aerosol dispersion (e.g., Kim et al., 2011).

The East China Sea is arguably one of the most impacted marginal seas by human activities because of some large rivers, including Changjiang, emptying into it. Material loading in Changjiang is one of the largest in the world as it is carried in a mean annual runoff over 928 km³ (Liu et al., 2008; Liu et al., 2008; Zhang, 2002), carrying more than 4.68 × 10⁶ tons yr⁻¹ of sediments (Huang et al., 2001) and a large amount of nutrients (75 Gmol N yr⁻¹, 0.8 Gmol P yr⁻¹ and 94 Gmol Si yr⁻¹) into the ECS (Zhang, 2002). It has been demonstrated that the rich supply of nutrients makes significant contribution to the high primary productivity in the East China Sea (Liu et al., 2010a).
Dispersal of the Changjiang discharge varies seasonally (Lee and Chao, 2003). In summer the Changjiang Plume has a bimodal distribution (Beardsley et al., 1985). Forced by the southerly monsoon in summer, the current off the river mouth is diffuse and the river plume disperses seaward (Liu et al., 2010b). Under the northerly monsoon in winter, the plume follows a narrow coastal jet, i.e., CCC, extending southward (Lee and Chao, 2003). The sediments discharged from Changjiang causes rich sediment deposition in the inner shelf near the river mouth and along the coast south of the Changjiang river mouth (Su and Huh, 2002). It has been suggested that the re-suspension of sediments near the river mouth under strong northerly-northeasterly monsoon in winter may suppress phytoplankton growth (Gong et al., 2003).

Along the shelf edge of the ECS is the encroaching Kuroshio. The intrusion of the subsurface Kuroshio Water provides a rich supply of nutrients onto the ECS shelf (Liu et al., 2000). Besides Kuroshio, the mostly northward flow from the Taiwan Strait also feeds waters to the ECS (Jan and Chao, 2003), but its nutrient loading is rather limited due to the oligotrophic nature of the warm water from the northern South China Sea (Liu et al., 2010c).

The purpose of this study is to investigate the impacts of the increasing load of dissolved inorganic nitrogen (DIN) on the primary production of the East China Sea and the seafloor oxygen demand (SOD) from 1970 to the end of 2002. For the first time, we are to compare the modeled chlorophyll distributions of the specific years with shipboard observations and remotely sensed data from the SeaWIFS. We compare the modeled and observed primary production results from the same period of time. Such comparisons help us assess the reliability of our model and needs for improvement. We hope that the modeling approach can lead to a better understanding of the environmental changes in the East China Sea, especially, the processes related to the recurring hypoxia off the Changjiang river mouth (Zhu et al., 2011).

### 2. Observations

For model validation we have used data obtained by Gong et al. (2003) on four cruises in the East China Sea (Table 1). Seawater samples were collected using the Rossette sampler (General Oceanic Inc., USA) with Teflon-coated GoFlo bottles (General Oceanic Inc., USA) mounted on the CTD assembly. Water samples for nutrient measurements were placed in 100 mL polypropylene bottles and frozen immediately with liquid nitrogen. Nitrate and nitrite were analyzed by the standard pink azo dye method adapted for flow injection analyzer (Morris and Riley, 1963; Pai et al., 1990; Strickland and Parsons, 1972). The algal pigments retained on GF/F filters were extracted in 90% acetone and the extract was measured with a fluorometer, Turner 10-AU-005 (Gong et al., 2000; Parsons et al., 1984; Welschmeyer, 1994). The precision of the measurement represented by the standard deviation of repeated analyses was better than ±0.3 μM for nitrate and nitrite, and ±0.1 μg L⁻¹ for Chl-a.

Water samples for the primary productivity measurements were prescreened through a 200 μm mesh and inoculated with 10 μCi NaH¹⁴CO₃ before incubation. The P–E curve was done by incubation for 2 h at 9 light levels, namely, 2200, 2002, 1386, 968, 506, 264, 132, 66 and 0 μE m⁻² s⁻¹. Samples were in duplicate or triplicate at each light level. Subsequently, the samples were filtered through GF/F filters (Whatman 25 mm) under low vacuum (<100 mm Hg). After treatment with 0.5 mL of 2 N HCl overnight, the total activity on the filters was counted in a liquid scintillation counter (PACKARD 2700TR). Primary productivity at each depth (PP(z)) was calculated with the photosynthetic parameters obtained from the P–E curve (Jassby and Platt, 1976). Detailed account of the method was reported by Gong et al. (2003).

### 3. Model description

#### 3.1. Hydrodynamic model

The coupled physical–biogeochemical model, which was developed for the investigation of primary production in the East China Sea (Liu et al., 2010a), is used for this study. It is based on a circulation model for marginal seas of the western Pacific Ocean (Lee and Chao, 2003), which has been amended with tidal forcing (Lee and Liu, 2013). The circulation model, a generalization of Semtner (1974) to include a free sea surface, solves for three-dimensional velocities, sea level, temperature, and salinity. The model domain (Fig. 1) extends from 23°N to 41°N and from 116°E to 134°E with a horizontal resolution of 1/6° and 33 levels in the vertical. The top layer, subject to sea level fluctuations, is 5 m thick on average. Moving down the water column, the layer thickness increases at the rate of 17.85% per level with the maximum basin depth reaching 6018 m. The model resolves depth-averaged flows and sea level with a time step of 8 s. The remaining motion, temperature, salinity and biogeochemical tracer concentrations are resolved with a coarser time step of 400 s.

For the tidal motion, we impose tidal elevations and currents on open boundaries using the result from a 2-D barotropic tide model with 1/12° resolution (Hu et al., 2010). Their tide-induced sea level contains 6 tidal constituents (P1, O1, K1, N2, M2 and S2),

\[
\mathbf{S} = \sum_{n=1}^{6} f_n \mathbf{S}_n \cos(\omega_n t + (\mathbf{V}_0 + \mu) + \theta_n),
\]

where \(f_n\) is the nodal factor, \(\omega_n\) is the frequency, \(\mathbf{V}_0\) is the initial phase angle of equilibrium tides, \(\mu\) is the nodal angle and \(\theta_n\) is the phase lag of tidal constituents. Assuming linearity (Dean and Dalrymple, 1984; Pugh, 1987), corresponding tidal currents are

\[
\mathbf{U} = (\mathbf{gD}) \sum_{n=1}^{6} f_n \mathbf{S}_n \cos(\omega_n t + (\mathbf{V}_0 + \mu) + \theta_n),
\]

where \(\mathbf{D}\) is the undisturbed water depth on open boundaries and \(\mathbf{g}\) is the gravitational acceleration.

The modeled ocean is initially motionless with prescribed distributions of January climatological temperature and salinity fields of WOA2005 (http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html). The ocean is subsequently forced by the monthly mean wind stress data from NCEP/DOE Reanalysis (http://nomad3.ncep.noaa.gov/ncep_data/). All these data are interpolated from the original resolution to fit the model grid. Following Sarmiento and Bryan (1982), we weakly nudge the modeled temperature and salinity toward monthly climatological temperature and salinity fields of WOA2005. Inflows and outflows through open ocean boundaries are specified at their climatological positions. Justifications for the choice of monthly transport values (Table 2) were given by Lee and Chao (2003). Monthly Changjiang discharges containing dissolved inorganic nitrogen are prescribed for the spin-up for one model year as in Liu et al. (2010c). Following the spin-up model runs with actual forcings from 1970 to the end of 2002, the period coincides with that of the available data (Fig. 2) of monthly Changjiang discharge and concentration of dissolved inorganic nitrogen (Yan et al., 2010). The actual forcings include

### Table 1

<table>
<thead>
<tr>
<th>Cruise no.</th>
<th>Date of the cruise</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORI-515</td>
<td>Mar. 16–Mar. 27, 1998</td>
</tr>
<tr>
<td>ORI-532</td>
<td>Oct. 21–Nov. 5, 1998</td>
</tr>
</tbody>
</table>
monthly data of wind stress, short-wave radiation (for photosynthesis), sea surface temperature (SST, for temperature nudging) and the Changjiang discharge. The wind stress and SST data are taken from NCEP/DOE Reanalysis I (http://rda.ucar.edu/datasets/ds090.0/) for the period from 1970 to 1978 and from NCEP/DOE Reanalysis II (http://rda.ucar.edu/datasets/ds091.0/) for the period from 1979 to 2002. The short-wave radiation data are taken from NCEP/DOE Reanalysis I.

For the model run of 1970 the monthly forcings of that year are used to drive the model twice following the spin-up, resulting in a total run of three model years. For the following years the model runs are driven first with monthly forcings of the previous year and then of that year. For the model run of 1971 as an example, the model runs for three years with the climatology monthly forcings for the first year, those of 1970 for the second year and those of 1971 for the third year. The results of the third model years are used for analysis in this study. For baseline runs without riverine nutrient input, the model is run with the same Changjiang discharges as the regular runs, but the DIN concentration is set to zero.

3.2. Changjiang discharge and nitrogen loading

The data of Changjiang River discharge (Fig. 2a) and the dissolved inorganic nitrogen (DIN, referring to \( \text{NO}_3^- \), \( \text{NO}_2^- \) and \( \text{NH}_4^+ \)) concentrations (Fig. 2b) have been compiled and used to drive the biogeochemical model in this study. The Changjiang River discharge data were taken from the national key hydrological station—Datong Hydrological Station (DHS, 117°11'E and 30°46'N), the DHS presents the upstream limit of the estuary that is free from both tidal effects and

![Bathymetry map of the East China Sea with contours of 50 m, 100 m and 200 m. The orange box indicates the survey area of Gong et al. (2003). The heavy solid lines represent open ocean boundaries of the model domain.](image)

Table 2

Mean monthly transports at open boundaries. Positive values indicate inflows and negative values outflows. All transports are in units of Sv.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taiwan Strait</td>
<td>0.5</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>2.2</td>
<td>2.3</td>
<td>2.3</td>
<td>2.4</td>
<td>2.4</td>
<td>1.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Kuroshio Inflow</td>
<td>22</td>
<td>22</td>
<td>22.5</td>
<td>23</td>
<td>24</td>
<td>23.5</td>
<td>23.5</td>
<td>28</td>
<td>28</td>
<td>22</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Tsushima Straits</td>
<td>-2.27</td>
<td>-1.89</td>
<td>-1.75</td>
<td>-1.89</td>
<td>-2.28</td>
<td>-2.8</td>
<td>-3.32</td>
<td>-3.71</td>
<td>-3.85</td>
<td>-3.71</td>
<td>-3.33</td>
<td>-2.8</td>
</tr>
</tbody>
</table>
urban effluents of the nearby city (Yan et al., 2010). The section of the Changjiang River above the DHS drains about 94% of the total watershed and delivers more than 95% of the water (Yan et al., 2003).

The data of DIN concentrations (Fig. 2b) in the river discharge at the DHS were calculated from the total input of nitrogen from diffuse sources based on the Global-NEWS model, and validated with monitoring data of DIN at the DHS (Yan et al., 2010). Total diffuse input of nitrogen included chemical fertilizer input, manure input, N₂ fixation, atmospheric nitrogen deposition, nitrogen removal by crop harvest, river and reservoir nitrogen removal processes, and the watershed export fraction (Dumont et al., 2005; Mayorga et al., 2010). Most diffuse inputs and socioeconomic data sets were obtained from China Statistical Year books (Chinese National Bureau of Statistics, 1980–2003) at the provincial level. When adequate input data were not available from regional sources, the spatially distributed inputs compiled for global applications by the Global NEWS Millennium Ecosystem Assessment project were used (e.g., Seitzinger et al., 2010).

Measured DIN loading was obtained as follows:

\[ \text{DIN}_{\text{load}} = Q \times C \]  

\[ (3) \]

\( \text{DIN}_{\text{load}} \) is DIN loading at DHS, Gmol kg N yr⁻¹; Q is measured Changjiang River discharge at DHS, 10 m³ yr⁻¹; C is measured DIN concentration, measured at DHS, μmol L⁻¹. N concentration of nitrate and ammonia from the basin is calculated based on the 33-year unpublished data at DHS from the annual hydrologic reports of China (1970–2003). Water sampling and nitrate analysis were described in Yan et al. (2003). By using the one-way ANOVA to evaluate the possible system errors caused by the shift of analytical methods for the time series during the period, we found there is no significant difference for measured DIN concentrations and fluxes during the period (α = 0.05). Therefore, the shift in methods should not have a negative effect on the quality of the data.

Aside from DIN load, Changjiang also carries considerable amount of particulate nitrogen (PN), which may also impact the biogeochemical processes in the receiving water body. In order to investigate how important the impact could be, we conducted a numerical experiment by introducing the PN load of Changjiang in the model. The Global NEWS (Nutrient Export from Watersheds) group reported average PN yield of the Changjiang watershed to be 0.2 ton km⁻² yr⁻¹ (Beusen et al., 2005), which is about 62% of the DIN yield, 0.328 ton km⁻² yr⁻¹ (Dumont et al., 2005), estimated by the same group. Because the monthly estimates of PN load are not available, we assumed that the monthly PN load was proportional to the DIN load with the same ratio as the aforementioned yields. While the highly degraded organic matter from soils is probably a major source of particulate organic matter in Changjiang (Wu et al., 2007), the riverine PN may only be partially reactive. Because the particulate amino acid accounts for 50% of PN in Changjiang river water and may reach 60% or more in the estuary (Wu et al., 2007), we assume 60% of the PN load is reactive and may take part in the biogeochemical processes represented by the model.

3.3. Biogeochemical model

In this study we conducted three numerical experiments to investigate how the Changjiang nitrogen loads may influence the biogeochemical conditions of the ECS shelf. The first was driven by monthly loads of DIN, the second was run without the Changjiang nitrogen load, and the third one was driven by monthly loads of DIN and PN. They are designated as CJ-DIN, No-CJN, and CJ-DIN + PN.

The biogeochemical model, which follows Liu et al. (2002, 2007, 2010c), has four core compartments: dissolved inorganic nitrogen (DIN), phytoplankton (Phy), zooplankton (Zap) and detritus (Det) with a variable chlorophyll-to-nitrogen ratio (R) in phytoplankton. Consequently, chlorophyll (Chl) is also set as a state variable, which is expressed in units of mg m⁻³. All other biogeochemical variables are expressed in terms of nitrogen concentration (mmol N m⁻³). The chlorophyll-to-nitrogen ratio depends on light and DIN availability (Doney et al., 1996; Liu et al., 2007).

The biogeochemical model is coupled to the physical model with the same spatial and temporal resolution. The time-dependent change of a biogeochemical tracer is determined first by physical (advection and diffusion) processes and then by biogeochemical (production and consumption) processes. Detritus sinks with a velocity of 10 m d⁻¹ relative to the vertical movement of water. Governing equations for...
biogeochemical tracers are described in Liu et al. (2002). Table 3 lists the values of biogeochemical parameters; all values follow Liu et al. (2010a).

We initialize the DIN distribution by interpolating the 1-degree annual mean field of nitrate from the WOA2005 (http://www.nodc.noaa.gov/OC5/WOA05/pr_woa05.html) to the model grid. SeaWiFS data (Level 3 Monthly Standard Mapping Image: http://daac.gsfc.nasa.gov/data/dataset/SEAWIFS/01_Data_Products/index.html), averaged over the 1998–2003 period, provides the initial field of chlorophyll concentration in surface waters. The vertical profile of chlorophyll follows the Eumali initial profile (Evans and Garçon, 1997); see http://ads.smr.uib.no/gofs/inventory/Toulouse/index.htm. A chlorophyll/phyptoplankton ratio of 1.59 dictates the initial phytoplankton field. The initial fields of zooplankton and detritus were calculated from the phytoplankton field under the assumption of constant ratios of 1/10 for zoooplankton/phytoplankton and 1/1.42 for detritus/phytoplankton; these choices are consistent with how Evans and Garçon (1997) derives the Eumali initial conditions for zooplankton and large detritus.

For the model computation, advection of biogeochemical tracers uses the upstream-differencing scheme following Sarmiento et al. (1993). If the ocean stratification becomes gravitationally unstable in the vertical direction, biogeochemical tracers are subject to the same convective adjustment as in temperature and salinity. All equations of biogeochemical processes are solved in the top 14 layers (0 m–140 m); all biogeochemical materials are assumed to have zero transport across the water–sediment boundary except the detritus (Det). The detritus that reaches the bottom is assumed to convert to DIN instantly, but 14% of the regenerated DIN is eliminated due to consumption by benthic denitrification (Fennel et al., 2006; Liu et al., 2007).

Because carbon is not directly simulated in the model, the monthly primary production is calculated from the uptake rate of DIN by phytoplankton multiplied by the Redfield C:N ratio of 106/16, which is temporally averaged over the entire month. The monthly SOD is calculated from the flux of detrital organic nitrogen that hits the seafloor; the organic nitrogen flux is converted to organic carbon flux with the same C:N ratio and then converted to oxygen demand by the O2/C ratio of 138/106, which was also averaged over the entire month.

### 4. Model results

We illustrate the model results from the run CJ-DIN first by showing the modeled distributions of DIN, chlorophyll and vertically integrated primary production (IPP) in the same months of the ship board observations by Gong et al. (2003). For the chlorophyll distributions we also include the monthly chlorophyll concentration derived from remotely sensed ocean color data by SeaWiFS for the same months for comparison. Then we present the time series of spatially averaged monthly model output of the same variables from the three model runs, namely, CJ-DIN, No-CJN and CJ-DIN + PN. Because the focus of this study is the continental shelf of the East China Sea, we present the model results for the region from 118°E to 128°E and from 25°N to 35°N. By doing so, we also avoid the model results near the domain boundaries.

#### 4.1. Nutrient distribution

**Fig. 3** shows the modeled distribution of sea surface DIN (SSDIN) in the East China Sea for the months corresponding to ship board observations, which are shown for comparison. The model driven by the monthly Changjiang discharge with monthly varying DIN concentration successfully reproduces the high SSDIN core in the Changjiang river plume off the river mouth. It also generates the strong cross-shelf gradients of SSDIN all year round. The core of high SSDIN near the river...
Fig. 3. Comparisons of DIN distribution in the East China Sea shelf from the model run, CJ-DIN (left panels), and field observations (right panels, Gong et al., 2003) for [a] December 1997, [b] March 1998, [c] July 1998, and [d] October 1998. The contours indicate the isobaths of 50 m, 100 m and 200 m.
mouth resembles the observations, but the extension of the core in the inner shelf does not reach as far away from the river mouth as the observed. It has been shown before that the Changjiang river plume could be as thin as 10 m or less in the peripheral area of the plume (Gong et al., 1996). The model with a minimum vertical resolution of 5 m may not be fine enough to resolve the plume behavior precisely.

The Kuroshio that flows hugging the shelf break dominates the SSDIN distribution in the outer shelf. The modeled SSDIN distributions do reproduce the seasonally varying, moderate SSDIN concentration (1–3 μM) area, covering major portions of the mid and outer shelves in all seasons. It is noted that the modeled SSDIN gradients appear smoother than the observations. The overly smoothed gradients may

Fig. 4. The same as Fig. 3 except for comparisons of chlorophyll distribution. Data are from the model run, CJ-DIN (left panels), field observations (middle panels, Gong et al., 2003) and SeaWiFS (right panels) for (a) December 1997, (b) March 1998, (c) July 1998, and (d) October 1998.
have resulted from the model grid and the horizontal diffusivity employed for better numerical stability. Better spatial resolution is probably needed for more realistic simulation of the SSDIN distribution. It is worth mentioning that no data nudging is used for the simulation of the DIN field. The modeled SSDIN distributions, though do not match precisely the observed spatial patterns, they nevertheless reflect the reduced nutrient levels as a result of phytoplankton uptake. This suggests that the model has captured the essential physical and biogeochemical processes controlling nutrient dynamics in the East China Sea shelf.

4.2. Chlorophyll and primary production

Fig. 4 shows the modeled distribution of sea surface chlorophyll (SSChl) in the East China Sea for the months corresponding to shipboard observations, which are shown for comparison. Also shown are monthly images of SeaWiFS chlorophyll from the same months as the model results. For December 1997, the modeled SSChl values in the survey area, 0.2–1 mg m\(^{-3}\), are quite close to the observations (Fig. 4a). The observed SSChl distribution showed a south–north contrast with higher value in the south, but the model slightly overestimates SSChl in the northern part and slightly underestimates that in the offshore region in the southern part. By contrast, the SeaWiFS data are grossly overestimated in the zones off the Changjiang river mouth and along the coast, while those in the mid and outer shelves are comparable to observations. The rather patchy distribution of slightly elevated SSChl in the offshore region of the SeaWiFS image, which has a spatial resolution of 9 km, suggests the observational stations were too few to catch the patchiness. The modeled SSChl in the region off the shelf is similar to that from the SeaWiFS.

For March 1998, the modeled SSChl values are slightly overestimated in comparison with the observations (Fig. 4b). The observed SSChl values showed a rather narrow range from 0.3 to 1.2 mg m\(^{-3}\). The modeled SSChl in the same area shows a slightly wider range, from 0.2 to 2 mg m\(^{-3}\). In the southern ECS just north of Taiwan, the modeled SSChl distribution reproduces the observations quite well. Over the shelf just off the Changjiang river mouth, the modeled SSChl exceeds the observations, especially near the river mouth and along the coast. The model’s prediction of elevated SSChl in the inner shelf near the Changjiang river mouth reflects the influence of the nutrient flux discharged from Changjiang. In reality, the observed SSChl in the coastal zone was low probably resulting from light limitation (Gong et al., 2003) due to colored dissolved organic matter (CDOM) or re-suspension of sediments driven by the stronger northeast monsoon that prevails from November to March. Because the model does not include CDOM or sediments, the shading effect from re-suspended sediments is lacking and remains to be implemented in the future. Similar to the previous case, the SeaWiFS data are grossly overestimated in the zones off the Changjiang river mouth and along the coast, while those in the mid and outer shelves are comparable to observations. The SeaWiFS SSChl again shows patchiness of elevated values in the offshore region. The modeled SSChl distribution shows a seaward decreasing trend across the shelf, resembling the SeaWiFS image, but the gradient is too gentle.

For July 1998 (Fig. 4c), the modeled SSChl near the Changjiang river mouth resembles that of observations, the model generally underestimates the SSChl in the inner shelf, in contrast to the previous two cases. The underestimation probably results from the insufficient dispersion of the high DIN plume along the coast to the south. On the other hand, the modeled SSChl (left panel of Fig. 4c) shows a zone of elevated value seaward from the Changjiang river mouth, which is outside the survey area, resembling the SeaWiFS image of July 1998 (right panel of Fig. 4c). Again the modeled SSChl distribution shows too gentle a seaward SSChl gradient across the shelf, as compared to the shipboard observation or the SeaWiFS image.

For October 1998 (Fig. 4d), the modeled SSChl concentrations are similar to the observation, while the modeled values are slightly underestimated in the region adjacent to the Changjiang river mouth. Both the model output and observations show gradual spatial variation without a distinct pattern. The SeaWiFS image shows gross overestimation in the zones close to the Changjiang river mouth and along the coast, whereas those in the mid and outer shelves are mostly similar to observations. However, the patchiness of the SeaWiFS data is absent in both the observation and modeled results due to insufficient spatial resolution.

Fig. 5 shows integrated primary production (IPP) in the top 100 m or the entire depth in areas with water depths shallower than 100 m. For December 1997 (Fig. 5a), the modeled IPP distribution in the survey area shows a range (50–400 mgC m\(^{-2}\) d\(^{-1}\)) similar to the observation, but the patterns differ somewhat. The modeled IPP distribution (left panel) shows a decreasing trend seaward across the shelf, whereas the observations (right panel) showed the lowest IPP off the Changjiang river mouth and low values (40–300 mgC m\(^{-2}\) d\(^{-1}\)) along the coast with a modest seaward increasing trend. The low IPP in the coastal zone reflects the shading effect of re-suspended sediments under strong northeast monsoon.

For March 1998 (Fig. 5b), the modeled IPP distribution resembles the pattern for the December case with slightly higher value, while the observation also showed a minimum, lower than 100 mgC m\(^{-2}\) d\(^{-1}\), off the Changjiang river mouth, resembling that for the December case. However, in the southern ECS just north of Taiwan, the modeled IPP distribution shows relatively high values (400–500 mgC m\(^{-2}\) d\(^{-1}\)) in areas immediately to the north of the Taiwan Strait and lower values (300 mgC m\(^{-2}\) d\(^{-1}\)) in the shelf region off northeast Taiwan. Such a seaward decreasing trend matches the observation quite well.

For July 1998 (Fig. 5c), the modeled IPP range (300–1000 mgC m\(^{-2}\) d\(^{-1}\)) overlaps with the major portion of the observations, but the observations showed stronger spatial variation with more extreme values. The modeled cross-shelf gradient is smoother than observations. The observed IPP reached more than 1200 mgC m\(^{-2}\) d\(^{-1}\) in the coastal zone, and dropped to as low as 200 mgC m\(^{-2}\) d\(^{-1}\) in the outer shelf. The modeled IPP in the Changjiang plume region off the river mouth is weaker than the observation.

For October 1998 (Fig. 5d), the modeled IPP shows the range of 150–500 mgC m\(^{-2}\) d\(^{-1}\) similar to observations, but the spatial pattern differs somewhat from the observed. The observations showed low values (150–300 mgC m\(^{-2}\) d\(^{-1}\)) in the coastal zone just north of Taiwan Strait, but the modeled IPP shows value around 300 mgC m\(^{-2}\) d\(^{-1}\) in the same area. On the other hand, the model output shows low IPP (down to less than 200 mgC m\(^{-2}\) d\(^{-1}\)) in the Kuroshio intrusion onto the shelf northeast of Taiwan, whereas the observations showed only slight drop of IPP to about 300 mgC m\(^{-2}\) d\(^{-1}\) near the edge of the survey area.

4.3. Comparisons of time series data: 1997–2002

Fig. 6a shows the time series of the monthly averages of modeled SSChl in the entire survey area of Gong et al. (2003) for the period from July 1997 to the end of 2002. For comparison the plot also shows the averaged SSChl from SeaWiFS for the same area from September 1997 to the end of 2002. The averaged SSChl from shipboard observations are shown for comparison, too. The modeled SSChl time series is close to the level of observed values in December 1997 and March 1998, but considerably lower than the observations in July and October 1998. The SeaWiFS time series matches the observation in July 1998 well and close to that observed in October 1998, but exceeds the observations significantly for the two earlier cruises.

Fig. 6b shows the time series of the monthly averages of modeled IPP in the whole survey area of Gong et al. (2003) for the same period as the SSChl time series. The modeled IPP time series matches the observations better than the SSChl; despite a slight overestimation, the IPP time series reveals a seasonal pattern resembling the observation closely.
For further comparison, we divide the East China Sea shelf into three zones, the inner, mid, and outer shelves, which are defined as the zones with water depths less than 50 m, 50–100 m and 100–200 m. Fig. 7a shows the comparisons of SSChl for the inner shelf, where the observed SSChl values were always higher than those observed in the mid and outer shelves. The modeled SSChl time series shows a range (0.5–1.7 mg m$^{-3}$) that matches with three of the observations in terms of magnitude (0.7–1.4 mg m$^{-3}$), but the timing is a little off. The observed spring bloom occurred later than the modeled bloom, probably because the re-suspension of sediments was blocking sun light in the early

Fig. 5. The same as Fig. 3 except for comparisons of primary production: [a] December 1997, [b] March 1998, [c] July 1998, and [d] October 1998.
spring, when the northeast monsoon was still strong. The modeled peak SSChl (1.7 mg m$^{-3}$) is considerably less than that (3.7 mg m$^{-3}$) observed. It is likely that the underestimation of the peak value is related to the timing of the modeled blooming, which is too early so that a significant fraction of the nutrient supply from the river discharge is consumed such that the remaining nutrient reserve is not sufficient to support the very strong peak of the bloom. As shown below the euphotic zone depth is probably limited to only a few meters in the inner shelf in winter and early spring due to strong light attenuation. Much of the nutrient stock below the shallow euphotic zone is reserved for the spring bloom, which occurs much later than that predicted by the model. This mismatch between model and reality probably is a major reason for the less than satisfactory model performance in simulating SSChl. The modeled DIN distribution for July 1998 (left panel of Fig. 4c) testifies to the lower DIN concentration than observations in the inner shelf, where the modeled high DIN area is considerably smaller than that observed.

The average SSChl time series from SeaWiFS for the inner shelf shows peak values later in the year, which agree with the scenario of delayed bloom, but the levels are much higher than observations, except in July 1998. The overestimation of the SeaWiFS chlorophyll is probably caused by the false signals from river discharged CDOM and the re-suspended sediments (IOCCG, 2000). According to Gong et al. (2007), the SeaWiFS chlorophyll data are higher than shipboard observations by a factor of 2 or more for the traditionally nutrient rich area in the ECS, namely, the inner shelf. It is well known that the standard SeaWiFS chlorophyll algorithm is only valid for “Case 1 waters”, but not for “Case 2 waters” (Carder et al., 1999; O’Reilly et al., 1998). One of the main problems is the interference from the strong absorption of CDOM in the blue band that overlaps with phytoplankton chlorophyll absorption (Mueller and Austin, 1995).

For the mid shelf, the modeled SSChl time series shows a range (0.55–1.1 mg m$^{-3}$) overlaps significantly with the observations (0.65–1.4 mg m$^{-3}$), but the timing of the peak value is too early and the peak value is too low, similar to that found for the inner shelf. However, in contrast to the inner shelf, the SeaWiFS time series of the mid shelf shows the range of SSChl much closer to the modeled values and observations. However, spikes of relatively high SSChl values occurred from time to time without a clear seasonal trend.

For the outer shelf, the modeled SSChl time series shows a range (0.35–0.8 mg m$^{-3}$) similar to that (0.45–0.9 mg m$^{-3}$) observed. By contrast, the modeled seasonal variation is quite close to that revealed from the SeaWiFS time series, while the observations did not show a clear seasonal trend. Because the SeaWiFS data for the outer shelf are probably free from interferences due to CDOM or suspended sediments, they are probably better representation of the real conditions.

The time series of modeled IPP show similar seasonal cycles as the modeled SSChl. For the inner shelf (Fig. 7d), the modeled range (300–680 mgC m$^{-2}$ d$^{-1}$) during the observation period falls within the observed range of 150–1030 mgC m$^{-2}$ d$^{-1}$, but the magnitude is much less than observations. During the period of prevailing north-east monsoon (November–March), the modeled IPP exceeds the observations considerably. This is in sharp contrast to the good fit of the modeled SSChl to the observed value (0.8 mg m$^{-3}$) in winter. The very low observed IPP in the inner shelf in winter and spring was apparently due to light shading by the turbid water, which was evidenced by the high light attenuation coefficient of 1 m$^{-1}$ or more (Gong et al., 2003). Under normal conditions, the euphotic zone depth could reach as deep as 75 m for an average chlorophyll concentration of 1 mg m$^{-3}$, but it could be reduced to only 8 m for water with light attenuation coefficient of 1 m$^{-1}$. Therefore, for the surface layer where there was enough light, the observed SSChl were close to the modeled values, but the very shallow euphotic zone limited phytoplankton growth and resulted in a much reduced IPP in reality.

For the mid shelf (Fig. 7e), the modeled IPP during the observation period shows a range (325–650 mgC m$^{-2}$ d$^{-1}$) similar to the observed range (250–580 mgC m$^{-2}$ d$^{-1}$). The modeled seasonality matches the observation reasonably well except the timing of the spring bloom is too early. For the outer shelf (Fig. 7e), the modeled IPP time series shows strong seasonality with a range (250–530 mgC m$^{-2}$ d$^{-1}$) encompassing the observed range (300–400 mgC m$^{-2}$ d$^{-1}$), while the observations do not show a clear seasonal trend.

The average values of modeled and observed IPP in the survey area over the same annual cycle are summarized in Table 4 for comparison. The averages for each zone of the shelf are also listed. The annual mean of observed IPP for the survey area is taken from the estimate of Gong et al. (2003). Those for different zones are estimated using similar approach for the time integration. For the modeled IPP, the annual mean is the mean of monthly IPP from November 1997 to October 1998. The modeled IPP values show slight overestimation as compared to observations. For the inner and outer shelves, the overestimation is within 14%; for the mid shelf the estimation is 31%. Overall the overestimation is 21% for the whole shelf (Table 4).


Fig. 8 shows the time series of spatially averaged model output of SSChl, IPP and the seafloor oxygen demand for the East China Sea shelf from 1970 to the end of 2002. The shelf is defined as the area with water depth less than 200 m within the domain of 118–128°E and 25–35°N. For each variable the averages over the inner, mid and outer shelves and over the entire shelf are presented. For SSChl the inner shelf shows the highest values over the mid and outer shelves. The averages over the entire shelf are close to the mid shelf averages.

Contrary to the trend shown by the SSChl values (Fig. 8a), the inner shelf does not show the highest IPP values (Fig. 8b), because IPP is an integrated value over a thickness of the water column and the inner shelf has the least thickness for integration. The lower SSChl values of the mid
and outer shelves are compensated by the greater thicknesses for integration. Consequently, the IPP values do not differ much in the three zones of the shelf (Table 4). The mean IPP over the whole shelf during the entire modeling period is 437 mgC m$^{-2}$ d$^{-1}$.

The seafloor oxygen demand (SOD), which is proportional to the detritus flux hitting the seafloor, shows different relationships from those of the IPP among the three shelf zones (Fig. 8c). While the IPP does not differ much from zone to zone, the detritus flux reaching the seafloor is inversely related to the water column depth due to degradation in the water column. Hence, other things being equal, the shorter the distance, the greater the detritus flux. Consequently the inner and mid shelves show the same level of mean SOD (Table 4), while the outer zone, where the water depths are the greatest, shows the lowest SOD.

Fig. 9 shows comparisons between output from the basic run, CJ-DIN, and the other two model runs, namely, No-CJN and CJ-DIN + PN. The top panel shows the monthly DIN loads of Changjiang and also the assumed PN loads, which are assumed proportional to the former. It is clear that, without Changjiang nitrogen load, both the primary production and seafloor oxygen demand in the ECS shelf are much reduced. The extra nitrogen load from riverine PN may significantly enhance primary productivity as well as seafloor oxygen demand (Fig. 9).

### Table 4

Summary of averaged values of IPP and sea floor oxygen demand (SOD) in the East China Sea shelf and its three zones over the entire modeling period from model run CJ-DIN. Also listed are averaged IPP values from model output and observations for the survey area of Gong et al. (2003), based on which the errors are estimated. IPP represents vertically integrated primary production in units of mgC m$^{-2}$ d$^{-1}$. The seafloor oxygen demand is in units of mmol O$_2$ m$^{-2}$ d$^{-1}$.

<table>
<thead>
<tr>
<th>Areas examined</th>
<th>Variables</th>
<th>Inner shelf (&lt;50 m)</th>
<th>Mid shelf (50–100 m)</th>
<th>Outer shelf (100–200 m)</th>
<th>Whole area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey area of Gong et al. (2003)*</td>
<td>Area (km$^2$)</td>
<td>49,376</td>
<td>102,027</td>
<td>36,972</td>
<td>188,375</td>
</tr>
<tr>
<td></td>
<td>IPP$_{meas}$</td>
<td>437</td>
<td>390</td>
<td>365</td>
<td>397</td>
</tr>
<tr>
<td></td>
<td>IPP$_{mod}$</td>
<td>501</td>
<td>511</td>
<td>406</td>
<td>482</td>
</tr>
<tr>
<td></td>
<td>(Nov. 1997–Oct. 1998) Estimated model error</td>
<td>+14%</td>
<td>+31%</td>
<td>+11%</td>
<td>+21%</td>
</tr>
<tr>
<td>ECS shelf</td>
<td>Area (km$^2$)</td>
<td>161,848</td>
<td>173,461</td>
<td>105,316</td>
<td>440,625</td>
</tr>
<tr>
<td></td>
<td>IPP$_{meas}$</td>
<td>387 ± 122</td>
<td>474 ± 100</td>
<td>401 ± 85</td>
<td>437 ± 102</td>
</tr>
<tr>
<td></td>
<td>SOD$_{meas}$</td>
<td>11.0 ± 4.1</td>
<td>11.0 ± 2.4</td>
<td>5.6 ± 1.4</td>
<td>10.0 ± 2.6</td>
</tr>
</tbody>
</table>

* See middle panels of Figs. 3 and 4.
5. Discussion

We first discuss the trends of modeled IPP and SOD over the modeling period with and without riverine nitrogen load in order to investigate the effects of the increasing Changjiang DIN load. Then we illustrate the relationship between riverine DIN load and the enhancements of IPP and SOD. Finally we explore the areas of intensive SOD, where hypoxia could potentially occur. Because the extra nitrogen load from riverine PN may exacerbate hypoxia, we examine how strongly the PN load may impact on the seafloor oxygen demand.

5.1. Trend of Changjiang DIN load and biogeochemical responses

We wish to explore whether the modeled IPP and SOD show significant increasing trends and whether the trends are attributable to the increasing DIN load of Changjiang. Fig. 9 shows the time series of Changjiang DIN loading (top panel) and biogeochemical responses of the East China Sea from 1970 to the end of 2002. The responses are represented by the monthly data of averaged IPP over the entire continental shelf (middle panel) and the averaged SOD over the inner shelf (bottom panel), where the impacts are probably the strongest. Also shown are output for model runs with the Changjiang DIN load set to zero. Linear regressions are done on all monthly data shown in Fig. 9. Some results are presented in the figure, while details are listed in Table 5.

Over the period from 1970 to 2002, the Changjiang DIN load increased significantly from a mean of 45 Gmol yr\(^{-1}\) to 108 Gmol yr\(^{-1}\) according to linear regression (Fig. 9a). During the same period, the model predicts that the average IPP has increased from 402 mgC m\(^{-2}\) d\(^{-1}\) to 472 mgC m\(^{-2}\) d\(^{-1}\), a significant increase by 17% (Fig. 9b). In contrast, the model run with no riverine nitrogen load predicts no significant increasing trend with values around 286–296 mgC m\(^{-2}\) d\(^{-1}\) (Table 5). This indicates that the increase in IPP is attributed to the increase in DIN loading, while other forcings do not cause significant changes. The enhancement of IPP due to riverine DIN in the East China Sea shelf accounts for 29% of the IPP in 1970 and 37% in 2002 (Table 5). The enhancement of IPP is most remarkable in the inner shelf, where the enhancement accounts for 54% of the IPP in 1970 and 62% in 2002 (Table 5).

Fig. 8. Time series of model run CJ-DIN output for different zones of the East China Sea shelf from 1970 to the end of 2002. [a] Sea surface chlorophyll, [b] Integrated primary production, and [c] Seafloor oxygen demand.

Fig. 9. Monthly variations of Changjiang DIN loading and the model predicted biogeochemical output of the model run, CJ-DIN (black curves) represented by spatially averaged monthly values. Also shown are results from the model runs of No-CJN (grey curves) and CJ-DIN + PN (dashed curves). The solid lines are linear regression fits for the output of CJ-DIN, and the dashed grey lines are those for No-CJN. The regression equations for the grey curves are not shown because they are not significant. (See text.) [a] The Changjiang DIN loading (solid curve) and potential contribution from reactive PN (dashed curve); [b] IPP in the whole shelf; and [c] Seafloor oxygen demand in the inner shelf.
been suspected whether primary production in the ECS shelf is limited by DIP. (e.g., Wong et al., 1998). Tseng et al. (2014) examined such a premise and concluded that P-limitation occurs in the periphery of the Changjiang river plume where the surface layer is strongly influenced by the oligotrophic surface water of the Kuroshio. In the main body of the river plume, P-limitation is alleviated by two processes: (1) amendment of DIP by entrainment of subsurface water beneath the plume, and (2) release of DIP from organic phosphorus due to the action of allochthonous alkaline phosphatase discharged from the river. The shelf water beneath the river plume mainly comes from intrusion of the Kuroshio subsurface water or the northward flow from the Taiwan Strait. Both are enriched in DIP relative to DIN (Liu et al., 2000; Wong et al., 1998). Therefore, it is reasonable to use the riverine DIN load to predict the enhancement of IPP in the main body of the Changjiang river plume in the inner shelf, where the enhancement is the strongest. For the outer shelf, where P-limitation may occur, the enhancement is quite limited. On the other hand, light limitation in the water column is a problem for the model performance in winter and early spring as mentioned earlier. The high turbidity as evidenced by the very high light attenuation coefficient (≥1 m⁻¹) observed in the inner shelf (Gong et al., 2003) under the strong northeast monsoon limits light penetration to only a few meters for phytoplankton growth. Our model needs the capability of simulating the light field in the water column with strong light attenuation.

5.2. Enhancement of primary production and oxygen consumption

We examine how the modeled primary production responds to variation in riverine nutrient loading plotting the enhancement of the yearly total primary production (TPP) in the ECS shelf vs. the DIN annual load (Fig. 10). The TPP is the integration of the IPP over shelf area of the East China Sea during an annual cycle. The enhancement of primary production is represented by the increment (ΔTPP) due to the riverine DIN load, which is the difference between the TPP with riverine DIN load and that (TPPo) without. In order to differentiate the effect on various zones of the shelf, the area integration is done separately for the shelf area with water depths less than 50 m (inner shelf), or 100 m (inner and mid shelves), or 200 m (whole shelf).

The enhancement of primary production by riverine nutrient load is strongest in the inner shelf (Fig. 10). While the inner shelf comprises 34% of the shelf area (Table 4), 58–73% of the enhancement occurs in the inner shelf in different years. Because the inner shelf is most sensitive to the DIN enhancement resulting from riverine DIN discharge, the estimated model errors, as derived according to that listed in Table 4, are plotted and compared to the enhancement (Fig. 10). It is clear that the enhancement is significantly larger than the model errors. By contrast, barely any enhancement occurs in the outer shelf, which accounts for 2.5% of the enhancement on average. In other words, most of the impact of riverine nutrient load on primary productivity occurs within the 100 m isobath. The enhancement of primary production responding to DIN loading follows a trend similar to that for the Michaelis–Menten kinetics:

\[
\Delta \text{TPP} = 1.91 \frac{Q_N}{(Q_N + 54.1)} \quad \text{for the inner shelf and}
\]

\[
\Delta \text{TPP} = 3.63 \frac{Q_N}{(Q_N + 89.9)} \quad \text{for the inner and mid shelf}
\]

Table 5

<table>
<thead>
<tr>
<th>Model runs</th>
<th>Variables</th>
<th>Intercept (at the beginning of 1970)</th>
<th>Slope (per year)</th>
<th>R</th>
<th>p</th>
<th>Regression predicted value at the end of 2002</th>
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<tr>
<td>CJ-DIN</td>
<td>DIN load</td>
<td>45 ± 21</td>
<td>1.89 ± 0.24</td>
<td>0.373</td>
<td>&lt;0.001</td>
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<td></td>
<td>IPPinner_sh</td>
<td>345 ± 55</td>
<td>2.56 ± 0.63</td>
<td>0.220</td>
<td>&lt;0.001</td>
<td>430</td>
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<tr>
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<td>IPPmid_sh</td>
<td>435 ± 45</td>
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<td>&lt;0.001</td>
<td>512</td>
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<td>IPPshelf</td>
<td>370 ± 42</td>
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<td>0.098</td>
<td>0.051</td>
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<td>IPPouter_sh</td>
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<td>2.12 ± 0.53</td>
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<td>&lt;0.001</td>
<td>472</td>
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<td>&lt;0.001</td>
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<td>0.013</td>
<td>5.9</td>
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<td>11.0</td>
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<td>IPPmid_sh</td>
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<td>0.257</td>
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<td>IPPouter_sh</td>
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<td>IPPshelf</td>
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<td>SODinner_sh</td>
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<td>SODouter_sh</td>
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<td>0.008 ± 0.007</td>
<td>0.060</td>
<td>0.237</td>
<td>5.3</td>
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<tr>
<td></td>
<td>SODshelf</td>
<td>5.5 ± 0.6</td>
<td>0.008 ± 0.007</td>
<td>0.060</td>
<td>0.234</td>
<td>5.8</td>
</tr>
</tbody>
</table>
5.3. Potential impacts of riverine reactive particulate matter

The potential biogeochemical effects of reactive particulate organic matter delivered by lateral transport from Changjiang are assessed from the output of the model run, CJ-DIN + PN (Fig. 9). Due to lack of monthly data, the PN load is assumed proportional to the DIN load. The uncertainty involved in this assumption renders this model run a sensitivity test. Although the reactive PN load varies following the DIN load, its behavior is simulated with the variable, DET or detrital organic nitrogen, which is different from the variable DIN. The reactive particulate organic matter discharged by Changjiang may disperse in the ECS shelf water, decompose to release DIN or sink to the seafloor and consume oxygen. The potential effects of the riverine PN are summarized in Table 6. It lists the averages of SSChl, IPP and SOD in the inner, mid and outer shelves and the whole shelf over the entire modeling period for the two model runs, CJ-DIN and CJ-DIN + PN. It also shows the percentage changes.

The effects are the strongest in the inner shelf. There the SSChl increases by about 9%, the IPP by 22% and SOD by 18%. By contrast, in the outer shelf, there is essentially no change in SSChl or IPP, but SOD still increases by 6%. Over the entire shelf, the SOD increases the most, by 8%. As the model run, CJ-DIN, overestimates IPP (Table 4), it is obvious that the extra nitrogen load from riverine PN tends to exacerbate the deviation. However, this does not rule out the possibility that riverine PN may be important to the ECS biogeochemistry. The model overestimation may not be due to the riverine load of nitrogen, but may originate from other sources, which warrant further investigation. On the other hand, better estimation of the riverine PN load and characterization of its reactivity are crucial to the better assessment of its environmental importance.

5.4. Chemical characteristics of POM and biogeochemical processes

Because the biogeochemical model is based on nitrogen, primary production is predicted from uptake of DIN instead of carbon fixation. The conversion depends on the C/N ratio of phytoplankton. Comprehensive surveys have been conducted to investigate the chemical characteristics of POM in the ECS (e.g., Hung et al., 2007; Zhu et al., 2006). According to Zhu et al. (2006) POM in the Changjiang Diluted Water (river plume), the ECS shelf outside the Changjiang river plume and the Kuroshio Water have mean C/N ratios of 6.59 ± 0.60, 7.57 ± 2.99 and 7.41 ± 1.00, respectively. According to results obtained on two summer surveys by Hung et al. (2007), POM in the ECS shelf has C/N ratio from 5.7 to 15.2 for

$$\Delta \text{TSOD} = 0.77Q\text{N}_\text{fl} / (Q\text{N}_\text{fl} + 63.2)$$  \quad \text{for the inner shelf} \quad (8)
$$\Delta \text{TSOD} = 1.29Q\text{N}_\text{fl} / (Q\text{N}_\text{fl} + 80.0)$$  \quad \text{for the inner-mid shelves combined} \quad (9)

where $\Delta \text{TSOD}$ is total seafloor oxygen demand in unit of (Tmol O$_2$ yr$^{-1}$) over the area specified.
the surface water, from 5.0 to 13.8 for the mid-depth water and from 5.5 to 17.4 for the bottom water, but the ΔPOC/ΔPN ratio, an indicator of freshly produced materials, is 6.18. Two surveys in the southern ECS in spring and autumn yielded the ΔPOC/ΔPN ratios of 6.67 and 6.37, respectively (Liu et al., 1995). The average ΔPOC/ΔPN ratio is 6.41 ± 0.25, which is quite close to the Redfield ratio of 6.63. However, if the observed average ΔPOC/ΔPN ratio is representative of the phytoplankton biomass, our model overestimates primary production by ~3%, which is much less than the estimated model error. This implies that the major error of the model is not the assumption of the Redfield ratio for the conversion from DIN uptake to carbon fixation.

The sea floor oxygen demand is calculated from the flux of detrital organic nitrogen (DET) that hits the sea floor based on the following reaction (Redfield et al., 1963):

\[
(\text{CH}_2\text{O})_{10}\text{(NH}_3)_{16}\text{H}_3\text{PO}_4 + 13\text{O}_2 = 10\text{6CO}_2 + 16\text{HNO}_3 + \text{H}_3\text{PO}_4 + 122\text{H}_2\text{O}
\]

The organic nitrogen flux is converted to oxygen demand by the O2/N ratio of 138/16. However, the actual sea floor oxygen demand depends on the average chemical composition of the particulate organic matter (POM) oxidized by aerobic respiration on seafloor.

There are at least two types of POM involved in this process: the autochthonous and the allochthonous POM. The former is the sinking POM produced in the euphotic zone by phytoplankton; the latter is the riverine POM transported laterally from the Changjiang estuary. For POM in Changjiang POM, Wu et al. (2007) reported the average C/N ratio, 7.7 ± 1.6. The same authors found particulate amino acids as an important component of the riverine POM, which is assumed to be the reactive POM in our model. Because particulate amino acids usually have low C/N ratio, the reactive fraction of riverine POM may have a lower C/N ratio than the bulk samples.

The C/N ratio is a good indicator of the average chemical composition of POM. Oxygen consumption during aerobic respiration may be calculated from the C/N ratio, if the chemical position of the POM takes the form shown in the following reaction:

\[
(\text{CH}_2\text{O})_{10}\text{(NH}_3)_{16}\text{H}_3\text{PO}_4 + a\text{O}_2 = 16\text{RCO}_2 + 16\text{HNO}_3 + \text{H}_3\text{PO}_4 + b\text{H}_2\text{O}
\]

where R is the C/N atomic ratio, \(a = 16(R + 2)\), and \(b = 16(R + 1)\). The oxygen consumption may be calculated from the consumption of detrital organic nitrogen (DET) multiplied by \(R + 2\).

If we use the mean C/N ratio observed by Zhu et al. (2006) instead of the Redfield ratio to calculate SOD for the autochthonous POM, the results would be essentially the same for the Changjiang river plume area, 14% higher for the shelf outside the plume and 12% higher for the Kuroshio region. However, if we use the average ΔPOC/ΔPN ratio for the calculation, because the freshly produced POM is most readily degradable during aerobic respiration, then the results would be 3% lower. If we use the mean C/N of the riverine POM observed by Wu et al. (2007) to calculate the SOD, the results would be 16% higher. However, the actual chemical composition of the reactive POM from Changjiang may have a lower C/N ratio, which would consume less oxygen during aerobic respiration. It is very difficult to precisely simulate...
the oxygen consumption during degradation of POM on the seafloor. The approach we take appears to be a reasonable approximation for the real process, but slight deviations within ±10% over all may occur in the estimation of SOD due to variation of the C/N ratio.

5.5. Areas of intensive seafloor oxygen demand

High sediment oxygen consumption, which is equivalent to seafloor oxygen demand in this study, and water column stratification are two main causes for the development of hypoxia in continental shelves (Fennel et al., 2013). Here we examine the variation of the area of high seafloor oxygen demand in order to identify the areas, where hypoxia could potentially develop. In the Texas–Louisiana shelf in the Gulf of Mexico, where hypoxia occurs in summer, the maximum flux of sediment oxygen consumption is temperature sensitive with a $Q_{10}$ value of 2:

$$F_{max} = 6.0 \times 2^{\frac{T-20}{10}}$$

where $F$ is in mmol O$_2$ m$^{-2}$ d$^{-1}$ and $T$ is temperature in centigrade (Hetland and DiMarco, 2008). The observed bottom water temperature in the hypoxic zone in the East China Sea shelf in August 2006 ranged from $20^\circ$C to $25^\circ$C (Zhu et al., 2011). Within such a temperature range, the range of $F_{max}$ value is estimated to be from 24 to 34 mmol O$_2$ m$^{-2}$ d$^{-1}$, which is quite close to that (30 mmol O$_2$ m$^{-2}$ d$^{-1}$) observed in the Texas–Louisiana shelf (Rowe et al., 2002). Hence, we use 30 mmol O$_2$ m$^{-2}$ d$^{-1}$ as the threshold for potential hypoxia in the East China Sea shelf. Aside from oxygen consumption, water column stratification is the other critical controlling factor for hypoxia (Fennel et al., 2013). Here we adopt a very simple criterion for stratification that the water depth must be deeper than 25 m as observed by Zhu et al. (2011). In the region shallower than 25 m, tidal mixing may be strong enough to weaken the stratification.

Fig. 12 shows the area with modeled SOD exceeding the threshold in the shelf with water depth greater than 25 m as predicted by the model of CJ-DIN and CJ-DIN + PN for July 1999. For comparison the hypoxic areas in August 1999 observed by Li et al. (2002) are plotted. Both model runs predict two potential hypoxic areas just off the Changjiang river mouth, resembling the observations that also showed two hypoxic areas. The areas of intensive SOD predicted by CJ-DIN + PN are larger than those by CJ-DIN as expected (Fig. 12). The southern potential hypoxic areas predicted by both models are smaller than the observed hypoxic area, but overlap significantly with the observed one. On the other hand, the model predicted secondary area is to the north of the Changjiang river mouth in both model runs, while the observed secondary area is to the south. The significant overlap between the major areas predicted by the models and the observed one indicates that the model has the skill to predict the approximate location and size of the area, where hypoxia may potentially develop. This also implies that the simple criteria adopted for the identification of potential hypoxic area are reasonable. The spatial deviation of model prediction from observations deserves discussion.

It appears that the model predicted areas of intensive SOD are skewed too much to the north as compared to observed hypoxic areas in 1999. However, hypoxic area to the north of the Changjiang river mouth did occur in August 2006 (Zhu et al., 2011). According to the compilation of Zhu et al. (2011), the major hypoxic area reported by Li et al. (2002) is the region of repeated hypoxia recurrences. The secondary hypoxic area to the south reported by Li et al. (2002) has never been observed hypoxic again. It is likely that the southwestern extension of the hypoxia was attributed to local effects, not accounted for by the model. For instance, the wind field used in the model is the monthly mean wind with a spatial resolution of about 1.9°. In reality, the local wind field could be quite variable both spatially and temporally such that the spatial distribution of intensive SOD may differ somewhat from the model prediction, which is driven by much smoothed wind forcing. In addition, the monthly mean wind in summer is usually a persistent southerly, which may drive the Changjiang river plume too much to the north. Improved spatial and temporal resolution may be required for more accurate prediction of the potential hypoxic areas.

It is noted that we compare the model prediction of SOD in July 1999 with the observations in August 1999. The reason is that hypoxia is a consequence of intensive oxygen consumption. Therefore, the period of high SOD should precede the occurrence of hypoxia. Further discussion on the temporal variation of areas of intensive SOD follows.

5.6. Temporal variation of potential hypoxic area

It is demonstrated above that we may identify areas of potential hypoxia using two criteria: (1) SOD > 30 mmol O$_2$ m$^{-2}$ d$^{-1}$ and (2) water depth > 25 m. Using the two criteria, we search through the model output to compile a list of occurrences of potential hypoxia and its area every month from 1970 to 2002. The results are summarized in Fig. 13 and compared to the Changjiang DIN loads.

According to the model prediction, the potential hypoxia occurs from April to the end of August. With increasing DIN load, potential hypoxia appears to last longer in later years. Both the average area and maximum area of potential hypoxia show variations corresponding to the variation of the DIN load, but the responses are apparently not linear. The yearly DIN load increased with a rather gentle trend, but the average area of potential hypoxia appears to have increased dramatically after the late 1980s. Moreover, the maximum area of potential hypoxia seems to have taken a sudden jump after the early 1990s. Because hypoxia occurs in summer, it is reasonable to assume that the average DIN load in the months from May to July is more relevant...
to hypoxia. The average May-to-July DIN load did show a sudden jump in 1990 (Fig. 13a). Starting from 1992, the maximum areas of potential hypoxia reaches 9000–21,000 km². It is noted that the May-to-July DIN load in 1992 was large but not exceptionally large, suggesting that other factors could be also important. The predicted areas of potential hypoxic region resemble the reported areas of hypoxia (5000–20,000 km²) between 1999 and 2003 (Zhu et al., 2011).

The sudden increase of the maximum area of potential hypoxia after 1992 may explain the more frequent reports of observed hypoxia in the East China Sea in the last two decades (Zhu et al., 2011). However, the observed events of hypoxia usually occurred from July to September with peaks in August. Our model predicted potential hypoxia occurs mostly from May to the end of August with peaks usually in June or July. Although it is reasonable to assume intensive oxygen consumption should precede hypoxia, only direct simulation of the oxygen concentration in the water body can verify this assumption.

The maximum areas of potential hypoxia predicted by the model run, CJ-DIN + PN, show considerable increments over the run without Changjiang PN load (Fig. 13). The predicted areas span the range from 15,000 km² to 23,000 km². The values are larger than the reported range but remain at about the same order of magnitude. The significant increases suggest the riverine PN could potentially contribute to exacerbation of hypoxia in the ECS shelf, but the actual PN load and its reactivity are critical to reliable assessment of the impact of riverine PN load.

As mentioned earlier, the timing of the modeled bloom of phytoplankton is too early in the year, especially in the inner shelf, where hypoxia occurs most frequently. It is likely that the development of potential hypoxia could also be too early as a consequence of the modeled early blooming. Proper treatment of the light field is required to improve the model performance on phytoplankton growth and the subsequent seafloor oxygen demand induced by the sinking detritus from the bloom. In addition, the benthic flux of oxygen consumption, namely, the SOD, is formulated as instantaneous remineralization of detrital organic matter, which is oversimplified (Fennel et al., 2013). A better treatment of the benthic oxygen consumption process, such as the formulation of Hetland and DiMarco (2008), is needed for better simulation of oxygen. However, the oversimplified treatment adopted for this study may do a reasonable job as suggested by Fennel et al. (2013). Therefore, the results of the model run, CJ-DIN + PN, reported here provide a reasonable assessment of the actual situation, whereas the CJ-DIN + PN may overestimate the impacts.

6. Summary and conclusions

Using monthly discharges and DIN loads of Changjiang from 1970 to the end of 2002 as the riverine forcing, we simulate the chlorophyll distribution, primary production and seafloor oxygen demand in the East China Sea with a three-dimensional coupled physical–biochemical model, driven by tides and monthly forcing of wind, solar radiation and sea surface temperature and climatological sea surface salinity. The model results compare reasonably well with observations during the period from December 1997 to October 1998. The model predicts a mean value of 437 mgC m⁻² d⁻¹ for primary productivity and 10.0 mmol O₂ m⁻² d⁻¹ for seafloor oxygen demand averaged over the East China Sea shelf during the entire modeling period. It is cautioned that the modeled primary production is overestimated by 21% as compared to observations.

From 1970 to 2002, the Changjiang DIN loading increased by a factor of ~2.4. Responding to this increase the modeled primary production in the East China Sea shelf has increased by 17%, and the modeled seafloor oxygen demand by 22%. In the inner shelf, which is defined as the area with water depth less than 50 m, the increase is 30%. By contrast, no significant increases are found in model output with Changjiang DIN load set to zero, suggesting that the increase in DIN load is the main cause for the increases in the modeled biological rates.

Using two criteria: (1) SOD > 30 mmol O₂ m⁻² d⁻¹ and (2) water depth > 25 m, we are able to identify areas of potential hypoxia. The maximum area of potential hypoxia in any month of the year has increased dramatically after 1991 from less than 7700 km² to mostly above 9000 km² with peak values around 21,000 km². The model predicted range overlaps with a major portion of the reported area of hypoxia (5000–20,000 km²) in the East China Sea shelf from 1999 to 2003. The change appears to be related to the Changjiang DIN loads from May to July that showed a sudden increase after 1990. However, the responses in potential hypoxic area are more pronounced than the increases in DIN load, suggesting nonlinear effect in the development of hypoxia.

We also did a sensitivity test to assess the potential impacts of the reactive particulate organic matter load carried by Changjiang by assuming the concentration of reactive particulate nitrogen (PN) to be 37.2% of DIN based on estimates of DIN and PN yields in the Changjiang watershed. The model results show that the potential impacts on primary productivity and SOD are quite significant. However, for more reliable assessment, we need more accurate quantification of the monthly PN load and better characterization of its reactivity.

Further improvement of the model is required to better simulate the biogeochemical conditions of the East China Sea. Proper simulation of the light field in the water column is necessary to account for the observed strong light attenuation in the inner shelf, especially in winter and early spring. Dissolved oxygen need be included as a state variable. Better treatment of benthic oxygen consumption should include more sophisticated representation of the oxygen flux at the water–sediment interface, which should take into consideration processes occurring within the sediment column. Finer model resolution and better temporal and spatial resolution of forcing functions, especially wind, are probably required to simulate fine features of biogeochemical conditions, such as hypoxia. As we have demonstrated the usefulness of the model in simulating seafloor oxygen demand in the East China Sea, we will conduct more numerical experiments to explore the nonlinear nature of the development of potential hypoxia in response to external forcings.

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