Hydrodynamic and biochemical impacts on the development of hypoxia in the Louisiana–Texas shelf Part 1: roles of nutrient limitation and plankton community

Yanda Ou[1] and Z. George Xue[1,2,3]

[1]Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA, 70803, USA.

[2]Center for Computation and Technology, Louisiana State University, Baton Rouge, LA, 70803, USA.

[3]Coastal Studies Institute, Louisiana State University, Baton Rouge, LA, 70803, USA

Correspondence to: Z. George Xue (zxue@lsu.edu)

Abstract. A three-dimensional coupled hydrodynamic–biogeochemical model with multiple nutrient and plankton functional groups was developed and adapted to the Gulf of Mexico to investigate the role of nutrients and the complexity of plankton community in dissolved oxygen (DO) dynamics. A 15-year hindcast was achieved covering the period of 2006–2020. Extensive model validation against *in situ* data demonstrates that the model was capable of reproducing vertical distributions of DO, spatial distributions of bottom DO concentration, as well as their interannual variations. Model results indicated that while nitrogen (N) limitation was more commonly found in the shallow (< 20 m) middle and west shelf, phosphorus (P) and silicon (Si) limitations could be more spreading on the shelf than previously reported. The seasonality of primary and secondary production exhibited a bi-peak (in late spring and early summer) pattern, which was contributed by both nanophytoplankton and the dominated diatom groups. DO consumption at the sediment layers was mostly contributed by zooplankton mortality and egestion processes. The plankton community in the water column in general, produced more DO than it consumed. In waters within 2 m above the bottom, there was a higher chance that DO consumption could exceed production. Nutrient limitation, interactions (competition, grazing, and predation behaviors) among plankton groups, and shifts in net DO contribution from the community (i.e., (photosynthesis - total respiration)/total biomass) complicated hypoxia development under different nutrient reduction strategies. Sensitivity tests indicate that a triple riverine nutrient reduction (N, P, and Si) of 60 % is needed to reach the goal of a 5000 km^2 hypoxic zone.

1 Introduction

The Louisiana–Texas (LaTex) shelf in the northern Gulf of Mexico (nGoM) has one of the most notorious recurring hypoxia in the world (bottom dissolved oxygen (DO) < 2 mg L^{-1}, Rabalais et al., 2002; Rabalais et al., 2007a; Justić and Wang, 2014). Regular mid-summer cruises since 1985 show that hypoxia usually first emerges in mid-May and persists through mid-September. The hypoxic zone can cover as big as 23,000 km^2 and has a volume of up to 140 km^3 (Rabalais and Turner, 2019;

65 Rabalais and Baustian, 2020). Although N is the ultimate limiting nutrient, P load reduction would also lead to a significant
66 reduction of the hypoxia area (Fennel and Laurent, 2018). Transient P limitation on the shelf (Laurent et al., 2012; Sylvan et
67 al., 2007) was deemed to be associated with the delayed onset and reduction of the hypoxia area. Sensitivity experiments of
68 hypoxia area reduction to different nutrient reduction strategies by Fennel and Laurent (2018) suggested that to meet the
69 hypoxic area reduction goal ($<$ 5,000 km^2 in a 5-year running average) set by the Hypoxia Task Force (2008), a dual nutrient
70 strategy with a reduction of 48 % of total nitrogen (N) and inorganic phosphorus (P) would be the most effective way.
71
72 Coastal eutrophication in the LaTex shelf leads to a high rate of microbial respiration and depletion of DO (Rabalais et al.,
73 2007b). Incubation studies in the LaTex shelf suggested that sediment oxygen consumption (SOC) accounted for 20$\pm$4 %
74 (Murrell and Lehrter, 2011) to 25$\pm$5.3 % (McCarthy et al., 2013) of below-pycnocline respiration, nearly 7-fold greater than
75 the corresponding percentage in waters overlying sediments (3.7$\pm$0.8 %, about 20 cm above sediments in McCarthy et al.,
76 2013). Incubation experiments indicated the SOC over the total respiration rate at sediments and overlying water was ~87 %
77 (McCarthy et al., 2013). The numerical study by Fennel et al. (2013) calculated the corresponding SOC fraction which reached
78 60 % when applying the water respiration rates of Murrell and Lehrter (2011) and sediment respiration rates of Rowe et al.
79 (2002). Another numerical study (Yu et al., 2015) also pointed out that in the LaTex shelf, oxygen consumption at the bottom
80 water layer was more associated with SOC rather than water column respiration. According to in-situ data and statistical
81 analysis, SOC could be estimated using the bottom temperature and DO concentration (e.g., Hetland and DiMarco, 2008).
82 Nevertheless, many numerical studies treated SOC only associated with the abundance of organic matter in the sediment (e.g.,
83 Justić and Wang, 2014; Fennel et al., 2006; 2011). For example, an instantaneous remineralization parameterization used by
84 Fennel et al. (2006, 2011) estimated SOC as a function of sediment detritus and phytoplankton. Using this scheme, Große et
85 al. (2019) found that the simulated SOC was supported by Mississippi N supply (51$\pm$9 %), Atchafalaya N supply (33$\pm$9 %),
86 and open-boundary N supply (16$\pm$2 %). However, the instantaneous parameterization tends to underestimate SOC at the peak
87 of blooms yet overestimate SOC after the blooms. In a realistic environment, there should be a lag between the blooms and
88 the peak SOC (Fennel et al., 2013). Recently, developments of coupled sediment–water models emphasized the importance of
89 biogeochemical processes in sediments on the SOC dynamics and evolution of bottom hypoxia in the shelf (Moriarty et al.,
90 2018; Laurent et al., 2016). However, coupled sediment–water models are computationally more expensive than a simplified
91 parameterization of SOC. Especially for long-term simulations and time-sensitive forecasts, it is crucial to balance the model's
92 efficiency with its complexity.
93
94 In addition to SOC and excess nutrient supply from the rivers, water column stratification also plays an important role in
95 regulating the variability of bottom DO concentration in the LaTex shelf. Strong stratification prohibits ventilation of DO and
96 thus results in reduced DO supply to the bottom water layer (Hetland and DiMarco, 2008; Bianchi et al., 2010; Fennel et al.,
97 2011, 2013, 2016; Justić and Wang, 2014; Wang and Justić, 2009; Feng et al., 2014; Yu et al., 2015; Laurent et al., 2018). On
98 the shelf, the Mississippi and the Atchafalaya plume introduces buoyancy, leading to a stable water column and weak DO

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Moved down [1]: Sensitivity experiments of hypoxia area reduction to different nutrient reduction strategies by Fennel and Laurent (2018) suggested that to meet the hypoxic area reduction goal ($<$ 5,000 km^2 in a 5-year running average) set by the Hypoxia Task Force (2008), a dual nutrient strategy with a reduction of 48 % of total nitrogen

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Moved down [3]: Cruises data in the nGoM indicated that diatoms accounted for ~50 to ~65 % (inner-shelf) and ~33 to ~64 % (mid-shelf) of chlorophyll a in winter and spring, and ~30 % to ~46 % (inner-shelf) during summer and fall, respectively (Chakraborty and Lohrenz, 2015). A field survey documented that the biovolume

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ventilation processes (Mattern et al., 2013; Fennel and Testa, 2019). Due to the different distances from major river mouths, the influence of freshwater-induced buoyancy would vary along the shelf. Moreover, the transports and deposition processes of organic matter are affected by the coastal along-shore current systems resulting in a SOC gradient across the shelf. For instance, Hetland and DiMarco (2008) pointed out that in the west of Terrebonne Bay, where stratification is usually weak, bottom hypoxia is mainly controlled by bottom respiration.

The phytoplankton blooms on the shelf result from both cyanobacteria and diatoms (Wawrik and Paul, 2004; Schaeffer et al., 2012; Chakraborty et al., 2017). In the Mississippi River plume, diatoms were found as the most diverse algal class accounting for over 42 % of all unique genotypes observed (Wawrik and Paul, 2004). Cruises data in the nGoM indicated that diatoms accounted for ~50 to ~65 % (inner-shelf) and ~33 to ~64 % (mid-shelf) of chlorophyll a in winter and spring, and ~30 % to ~46 % (inner-shelf) during summer and fall, respectively (Chakraborty and Lohrenz, 2015). A field survey documented that the biovolume contribution of diatoms to the total phytoplankton could be as high as 80 % and 70 % during the upwelling seasons in 2013 and 2014, respectively (Anglès et al., 2019). While a lot of existing studies indicated N and P were more limited than Si on the shelf (e.g., for cruises in 2004 in Quigg et al., 2011; for cruises in 2012 in Zhao and Quigg, 2014; for cruises in 1984, 1994, 2005, 2010, and 2011 in Turner and Rabalais, 2013), Si limitation has also been reported for both plume and shelf water. Based on cruises studies in the plume of the Mississippi River in 1992 and 1993, strong Si limitation in spring was found due to the increasing N:Si ratio in the Mississippi River water (Nelson and Dortch, 1996). Cruise measurements in 1987 and 1988 also suggested the likelihood of Si limitation, which sometimes overwhelmed the N limitation (Dortch and Whitledge, 1992).

Numerical studies for hypoxia in the LaTex shelf were developed mostly based on observations that emphasized N and P as limiting nutrients (e.g., Hetland and DiMarco, 2008; Fennel et al., 2006, 2011, 2013; Laurent et al., 2012; Laurent and Fennel, 2014; Fennel and Laurent, 2018; Justić et al., 2003; Justić et al., 2007; Justić and Wang, 2014; Große et al., 2019; Moriarty et al., 2018). In addition, most existing models utilized an over-simplified lower trophic level model (one phytoplankton + one zooplankton function group or only one phytoplankton group). The recycling of nutrients in water columns and the associated biogeochemical processes, which may be important to hypoxia evolution (e.g., in the Chesapeake Bay by Testa and Kemp, 2012), could be over-simplified. In this study, we aimed to 1) investigate the cycling of silicate and its contribution to the hypoxia evolution in the LaTex shelf; and 2) assess the impacts of the complexity of the plankton community on DO dynamics. We adapted and modified a coupled physical-biogeochemical model covering the entire Gulf of Mexico (GoM) by introducing the oxygen and P cycles to the North Pacific Ecosystem Model for Understanding Regional Oceanography (NEMURO, Kishi et al. 2007). The model has two phytoplankton and three zooplankton functional groups for a more comprehensive representation of the plankton community. We also modified the instantaneous remineralization parameterization by adding a conceptual sedimentary organic pool (represented by a sedimentary particulate organic N pool, PON_{sed}; Fig. 1) to allow the accumulation of organic matter in the sediment. The sedimentary organic matter pool in our study is supported by a complex

246 plankton community, including two phytoplankton and three zooplankton functional groups. The influence of the community
247 is represented in the biogeochemical processes in water columns and sediments and eventually be reflected in the bottom DO
248 variability.

249 **2 Methods**

250 **2.1 Coupled hydrodynamic–biogeochemical model**

251 We adapted the three-dimensional, free-surface, topography-following community model, the Regional Ocean Model System
252 (ROMS, version 3.7), on the platform of Coupled Ocean–Atmosphere–Wave–Sediment Transport (COAWST) modeling
253 system (Warner et al., 2010) to the GoM (Gulf–COAWST). ROMS solves finite difference approximations of Reynolds
254 Averaged Navier–Stokes equations by applying hydrostatic and Boussinesq approximations with a split explicit time-stepping
255 algorithm (Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005, 2009). The biogeochemical model applied is primarily
256 based on the NEMURO developed by Kishi et al. (2007). NEMURO is a concentration-based, lower-trophic-level ecosystem
257 model developed and parameterized for the North Pacific. The original NEMURO model has 11 concentration-based state
258 variables, including nitrate (NO_3), ammonium (NH_4), small and large phytoplankton biomass (PS and PL), small, large, and
259 predatory zooplankton biomass (ZS, ZL, and ZP), particulate and dissolved organic N (PON and DON), particulate silica
260 (Opal), and silicic acid ($Si(OH)_4$). NEMURO is known for its capability to distinguish ZS, ZL, and ZP and to provide a detailed
261 analysis of the dynamics of different functional groups. It was widely used in studies of plankton biomass on regional scales
262 (Fiechter and Moore 2009; Gomez et al., 2018; Shropshire et al., 2020). The embedded Si cycle permits the inclusion of a
263 diatom group (i.e., PL), the dominant phytoplankton group in the nGoM.

264 **2.2 Model modification**

265 In a recent effort, Shropshire et al. (2020) adapted and modified NEMURO to the GoM with five structural changes. (1) The
266 grazing pathway of ZL on PS was removed since, in the GoM, the PS group is predominated by cyanobacteria and
267 picoeukaryotes, which are too small for direct feeding by most mesozooplankton (i.e., ZL). (2) Linear function of mortality
268 was applied for PS, PL, ZS, and ZL, while quadratic mortality was used for ZP, accounting for predation pressure of unmodeled
269 predators, like planktivorous fish. (3) The ammonium inhibition term in the nitrate limitation function was no longer considered
270 exponentially but followed the parameterization by Parker (1993). (4) Light limitation on photosynthesis was replaced with
271 Platt et al.'s (1980) functional form, which was also implemented in the newer version of NEMURO. (5) Constant C: Chl ratio
272 was replaced with a variable C: Chl model according to the formulation by Li et al. (2010).

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274 However, neither the modified (Shropshire et al., 2020) nor the original (Kishi et al., 2007) NEMURO model considered P
275 and oxygen cycles. In this study, we introduced a P cycle into NEMURO, including three concentration-based state variables
276 as phosphate (PO_4), particulate organic P (POP), and dissolved organic P (DOP). The P limitation on phytoplankton growth

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286 was introduced using the Michaelis–Menten formula. In the NEMURO model, N serves as the common "currency", while P

287 and Si are converted to N using the Redfield ratio of P: N: Si=1: 16: 16. In the river-dominated LaTex shelf, inorganic and

288 organic nutrients are supplied mainly by rivers. In our model, riverine PO_4 (Fig. C1), DOP, and POP were prescribed based on

289 water quality measurements at river gages. When no measurement was available, the PO_4, DOP, and POP were approximated

290 using total nitrate+nitrite (NO_3+NO_2), dissolved organic N (DON), and particulate organic N (PON) measurements,

291 respectively, via the Redfield ratio of P: N=1: 16. We neglected the POP settling process but preserved these pools by

292 introducing the stoichiometric ratio between P and N instead. In other words, the sinking process of POP was implicitly

293 included by building linkages between PON and POP concentrations, as the sinking of PON was considered in the model.

294 Governing equations for P state variables were given according to Eqs. 1–3. Please also refer to the appendices for more details

295 on expressions of modified terms (Appendix A), state variables (Appendix Table B1), source and sink terms (Appendix Table

296 B2), and values of parameters (Appendix Table B4).

$$\frac{d(PO_4)}{dt} = (ResPSn + ResPLn) \cdot RPO4N$$
$$+ (DecP2N + DecD2N) \cdot RPO4N$$
$$+ (ExcZSn + ExcZLn + ExcZPn) \cdot RPO4N$$
$$- (GppPSn + GppPLn) \cdot RPO4N, \tag{1}$$

$$\frac{d(DOP)}{dt} = (DecP2D - DecD2N) \cdot RPO4N$$
$$+ (ExcPSn + ExcPLn) \cdot RPO4N, \tag{2}$$

$$\frac{d(POP)}{dt} = (MorPSn + MorPLn + MorZSn + MorZLn + MorZPn) \cdot RPO4N$$
$$+ (EgeZSn + EgeZLn + EgeZPn) \cdot RPO4N$$
$$- (DecP2N + DecP2D) \cdot RPO4N, \tag{3}$$

307 We further adapted the oxygen cycle developed by Fennel et al. (2006, 2013) to NEMURO for hypoxia simulations. However,

308 our model's biogeochemical processes are slightly different due to the different plankton functional groups considered. Sources

309 for oxygen are contributed by the photosynthesis of two phytoplankton functional groups, while the sinks are attributed to

310 respirations of two phytoplankton functional groups, metabolism of three zooplankton functional groups, light-dependent

311 nitrification (Olson, 1981; Fennel et al., 2006), aerobic decomposition of particulate and dissolved organic matter (measured

312 as PON, and DON, respectively), and SOC. Wanninkhof's (1992) parameterization was implemented for estimates of oxygen

313 air–sea flux. The biogeochemical dynamics of oxygen were adopted as follows (Eq. 4; also see detailed descriptions of

314 variables and parameters in Appendix A–B):

$$\frac{d(Oxyg)}{dt} = (rOxNO_3 \cdot GppNPS + rOxNH_4 \cdot GppAPS)$$
$$+ (rOxNO_3 \cdot GppNPL + rOxNH_4 \cdot GppAPL)$$

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$$- ResPSn \cdot [RnewS \cdot rOxNO_3 + (1 - RnewS) \cdot rOxNH_4]$$

$$- ResPLn \cdot [RnewL \cdot rOxNO_3 + (1 - RnewL) \cdot rOxNH_4]$$

$$- rOxNH_4 \cdot (ExcZSn + ExcZLn + ExcZPn)$$

$$- 2 \cdot Nit \cdot LgtlimN \cdot r$$

$$- rOxNH_4 \cdot (DecD2N + DecP2N) \cdot r$$

$$- SOC \cdot THK_{bot}, \tag{4}$$

A PON_{sed} pool due to vertical sinking processes of PON was introduced for parameterization of SOC. The SOC scheme (Fennel et al., 2006) is known as the instantaneous consumption of DO. As soon as the PON falls into the sediment bed, PON will be decomposed instantaneously. This scheme tends to underestimate SOC at the peak of blooms and to overestimate SOC after blooms since the lag in SOC demand is neglected (Fennel et al., 2013). We considered such temporal delays in SOC by introducing a PON_{sed} pool. A portion of sinking PON ends up with PON_{sed}, while the rest is buried (PON_{burial}) and is removed from the system. The parameterization is shown in the following. 1) Organic matter settling down at the conceptual sediment layer is remineralized at a temperature-dependent aerobic remineralization rate, K_{P2N}. 2) Sediment oxygen is consumed only in the oxidation of sedimentary organic matter (represented by PON_{sed}) and the nitrification of ammonium to nitrate (Fennel et al., 2006). 3) Oxygen consumption at the conceptual sediment layer directly contributes to oxygen concentration decreases only at the bottom water column. 4) Sediment denitrification is linearly related to SOC according to observational-based estimates by Seitzinger and Giblin (1996), but the relationship was modified by Fennel et al. (2006) with a slightly smaller slope of denitrification on SOC rate, i.e.,

$$denitrification\ (mmolN\ m^{-2}\ day^{-1}) = 0.105 \times SOC\ (mmolO_2\ m^{-2}\ day^{-1}), \tag{5}$$

5) Aerobic decomposition of PON_{sed}, sediment nitrification, and denitrification follow chemical equations according to (Fennel et al., 2006):

$$C_{106}H_{263}O_{110}N_{16}P + 106O_2 \leftrightarrow 106CO_2 + 16NH_4 + H_2PO_4 + 122H_2O, \tag{R1}$$

$$NH_4 + 2O_2 \rightarrow NO_3 + 2H + H_2O, \tag{R2}$$

$$C_{106}H_{263}O_{110}N_{16}P + 84.8HNO_3 \rightarrow 106CO_2 + 42.4N_2 + 16NH_3 + H_3PO_4 + 148.4H_2O, \tag{R3}$$
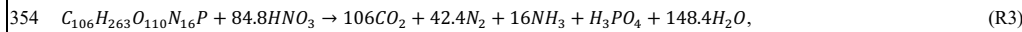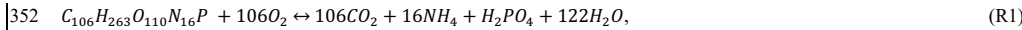
6) Nitrate produced in sediments (Eq. R2) is used for denitrification (Eq. R3). The linear assumption in 4) implicitly builds relationships among the reactions listed in assumption 5). Let's assume that the production rate of NH_4 by aerobic decomposition (Eq. R1) of organic matter is M mmol m^{-3} day^{-1}, and that the fraction of denitrification-produced CO_2 (Eq. R3) to the total CO_2 production (Eqs. R1 and R3) is x. According to the linear assumption abovementioned, the consumption rate of NO_3 during denitrification (Eq. R3) is proportional to the total consumption rate of O_2 in the sediment (Eqs. R1 and R2), yielding $\frac{84.8Mx}{16(1-x)} = 0.105 \times \left[\frac{106M}{16} + \frac{84.8Mx}{8(1-x)}\right]$ and further $x \approx 0.1425$. The oxygen consumption rate (Eq. 6) and organic matter

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393 consumption rate (Eq. 7) due to the coupled aerobic decomposition, nitrification, and denitrification processes can be obtained

394 by substituting the x value into the stoichiometric ratios according to Eqs. R1–R3.

395 $$Oxyg_{consumption} = \frac{106M}{16} + \frac{84.8Mx}{8(1-x)} = 8.3865M, \tag{6}$$

396 $$OM_{consumption} = \frac{M}{16} + \frac{Mx}{16(1-x)} = 0.0729M, \tag{7}$$

397 Accordingly, the SOC and consumption rate of PON_{sed} are given, respectively as follows:

398 $$SOC = Oxyg_{consumption} \cdot THK_{bot} = 8.3865M \cdot THK_{bot}, \tag{8}$$

399 $$PON_{sed\,consumption} = 16 \cdot OM_{consumption} \cdot THK_{bot} = 1.1662M \cdot THK_{bot}, \tag{9}$$

400 where,

401 $$M = \frac{PON_{sed} \cdot VP2N_0 \cdot exp(K_{P2N} \cdot TMP)}{THK_{bot}}, \tag{10}$$

402 $$THK_{bot} = thickness\ of\ bottom\ water\ column, \tag{11}$$

403

404 We further added light inhibition on the nitrification (Olson, 1981) and oxygen dependency on nitrification and aerobic

405 decomposition. These parametrizations were applied following descriptions by Fennel et al. (2006, 2013). For the oxygen-

406 dependent term, an oxygen threshold was specified below which no aerobic respiration or nitrification occurred. Detailed

407 equations were listed in Appendix A. The structure of the newly modified NEMURO model was shown in a schematic diagram

408 in Fig. 1.

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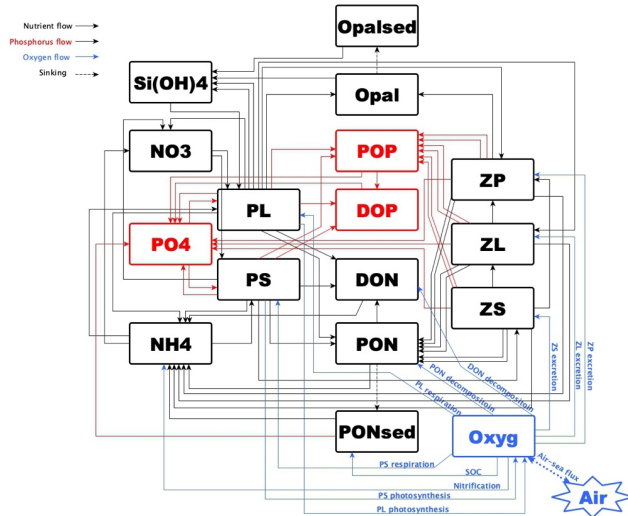
421 **Figure 1. Schematic diagram of the modified NEMURO model. Note that the P flow and the oxygen flow are two newly added flows**
422 **to the original NEMURO model.**

423 **2.3 Model set-ups**

424 The coupled model was applied to the GoM using Arakawa C-grid with a horizontal resolution of ~5 km (Fig. 2a). There are
425 334 and 357 interior rho points in the east-west and north-south directions, respectively. The model includes 36 sigma layers
426 vertically. The wetting and drying scheme (Warner et al., 2013) was implemented for a more accurate representation of shallow
427 water. The computational time step (i.e., baroclinic time step) was set to 240 seconds while the number of barotropic time
428 steps between each baroclinic time step was set to 30. Model hindcast was carried out from 1 August 2006 to 26 August 2020
429 with the first 5 months as a spin-up period. Model results were output on a daily interval at UTC 00: 00.
430

431 The physical model set-ups largely followed an earlier Gulf–COAWST application (Zang et al., 2018, 2019, 2020). Open
432 boundaries were set at the south and east forced by daily water level, horizontal components of 3-D current velocity, horizontal
433 components of depth-integrated current velocity, 3-D water salinity, and 3-D water temperature derived from the Hybrid
434 Coordinate Ocean Model (HYCOM) global analysis products (Bleck and Boudra, 1981; Bleck, 2002) with data assimilated
435 via the Navy Coupled Ocean Data Assimilation system (Cummings, 2005; Cummings and Smedstad, 2013; Fox et al., 2002;
436 Helber et al., 2013). For lateral boundary conditions, we utilized Chapman implicit for free surface and water level (Chapman,
437 1985), Flather for depth-integrated momentum (Flather, 1976), gradient for mixing total kinetic energy, and mixed radiation-
438 nudging conditions for 3-D momentum, temperature, and salinity (Marchesiello et al., 2001). The nudging time steps for the
439 mixed radiation-nudging condition were set to 1 day for inflows and 30 days for outflows. The boundary nudging technique
440 was performed at the computational grids along the open boundary. The boundary condition types for passive biological and
441 chemical tracers (i.e., PS, PL, ZS, ZL, ZP, NO$_3$, NH$_4$, PON, DON, Si(OH)$_4$, opal, PO$_4$, POP, DOP, and Oxyg) were all
442 prescribed as radiation.
443

444 Initial conditions for water level, horizontal components of 3-D current velocity, horizontal components of depth-integrated
445 current velocity, 3-D water salinity, and 3-D water temperature were provided by the same HYCOM products as well. Initial
446 conditions for concentrations of NO$_3$, PO$_4$, and Si(OH)$_4$ were interpolated from measurements provided by the World Ocean
447 Database (WOD, Boyer et al., 2018). Initial conditions for DO concentration were given by World Ocean Atlas (WOA, Garcia
448 et al., 2018). At the sediment layer, PON$_{sed}$, PON$_{burial}$, opal$_{sed}$, and opal$_{burial}$ were initialized as 0.1 mmol m^{-3}. Other biological
449 and chemical tracers were initialized as 0.1 mmol m^{-3} due to the lack of observations.
450

451 Atmospheric forcings, including surface wind velocity at 10 m height above sea level, net longwave radiation flux, net
452 shortwave radiation flux, precipitation rate, air temperature 2 m above sea level, sea surface air pressure, and relative humidity
453 2 m above sea level, were derived from the National Centers for Environmental Prediction (NCEP) Climate Forecast System
454 Reanalysis (CFSR) 6-hourly products (for years prior to 2011, Saha et al., 2010) and NCEP CFS Version 2 (CFSv2) 6-hourly

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460   products (for years starting from 2011, Saha et al., 2011) with a horizontal resolution of ~35 km and ~22 km, respectively. In

461   our model, 63 rivers were considered as horizontal point source forcings along the coastal GoM. They were split into 280

462   points (red dots in Fig. 2a) sources transporting time-varying salinity (nearly zero), temperature, 3-D horizontal momentum

463   (based on the magnitude of river discharges), nutrients (NO_3, NH_4, PO_4, $Si(OH)_4$, PON, DON, POP, and DOP; Fig. C1), and

464   DO to the computational domain. Locations of river point sources of the Mississippi and the Atchafalaya Rivers were shown

465   as red dots in Fig. 2b. For reconstructions of time series of river forcing terms, we composed measurements from various

466   sources, including U.S. Geological Survey (USGS) National Water Information System (NWIS), National Oceanic and

467   Atmospheric Administration (NOAA) Tides and Currents System (TCS), NOAA National Estuarine Research Reserve System

468   (NERRS), and Mexico National Water Commission (CONAGUA, for rivers in Mexico's territory). Daily averaged river

469   discharges were given based on measurements by USGS NWIS and CONAGUA. The magnitude of river discharges was

470   multiplied by 1.4 to account for adjacent watershed areas and the lateral inflow of tributaries (Warner et al., 2005). River

471   temperature and salinity time series were reconstructed from measurements by USGS NWIS, NOAA TCS, and NOAA

472   NERRS. River nutrient concentrations were provided monthly by USGS NWIS and NOAA NERRS and were extended to

473   daily time series with values in the corresponding months. Riverine DO concentration was set to be a constant (258 mmol m^{-3}

474   ) assuming that riverine DO was saturated at 25 °C under 1 atm. Besides, tidal forcings were introduced in the hydrodynamic

475   model taking into account of influences of tidal elevations and tidal currents. There were 13 tidal constituents considered in

476   the model including M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, and MN4.

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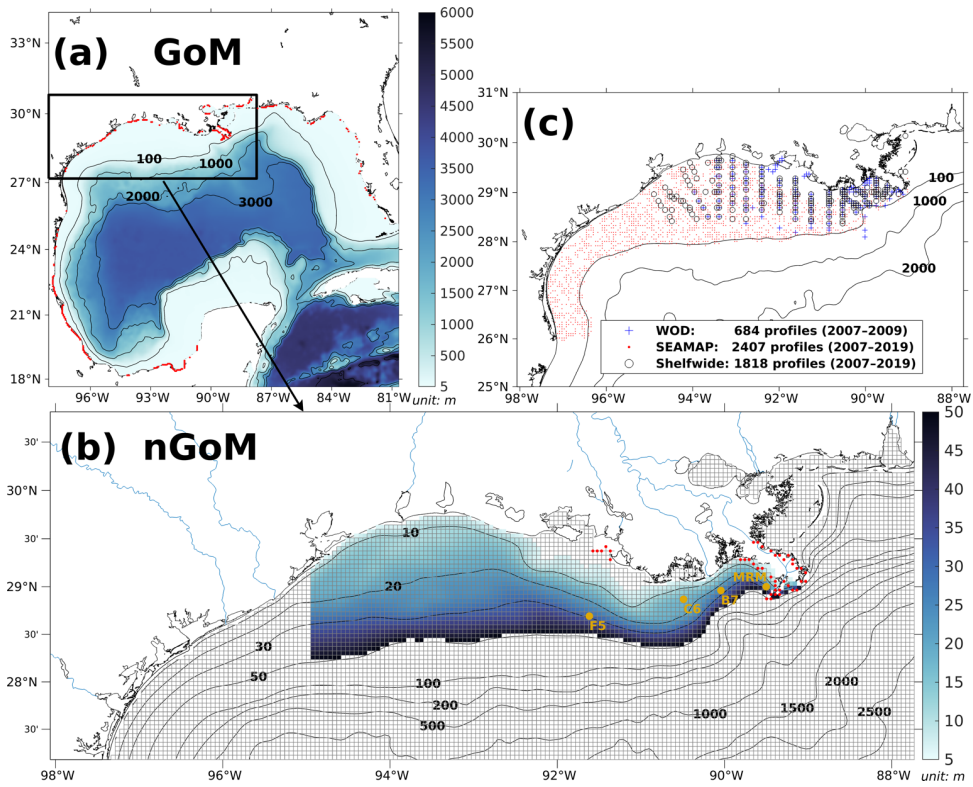
Figure 2. (a) Bathymetry of the entire domain of the Gulf–COAWST, (b) zoom-in bathymetry plot of the northern Gulf of Mexico (nGoM), and (c) locations of observed inorganic nutrient and DO profiles derived from WOD, SEAMAP, and NOAA's shelf-wide cruises. In (a), locations of river point sources are denoted by red dots. In (b), only bathymetry between 6 and 50 m was mapped with colors; computational meshes were split by solid grey lines; main river channels are denoted by solid blue curves; locations of river point sources of the Mississippi and the Atchafalaya Rivers are indicated by red dots; sampling locations for SOC and overlaying water respiration measurements by McCarthy et al. (2013) are denoted by dark yellow dots.

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3 Biogeochemical model validations

3.1 Available measurements

In this section, biogeochemical model validations were conducted for inorganic nutrient concentration profiles (i.e., NO_3, PO_4, and $Si(OH)_4$), ratios of diatom and total phytoplankton, SOC, DO concentration profiles, spatial distributions of bottom DO

	Deleted: ratios of SOC and overlaying water respiration,

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concentration, and temporal variability of the hypoxic area against multiple field and lab data sets. Validation of the hydrodynamic model can be found in Zang et al. (2019).

Inorganic nutrient concentration profiles from WOD were used for model validation. WOD measurements cover the period from 11 January 2007 to 5 July 2009 including 478 NO_3 profiles, 409 PO_4 profiles, and 217 $Si(OH)_4$ profiles. The diatom percentage of total phytoplankton was derived from measurements by Chakraborty and Lohrenz (2015) and Schaeffer et al. (2012). The SOC measurements were from an incubation study (McCarthy et al., 2013). Available DO concentration profiles were obtained from the NOAA-supported mid-summer shelf-wide cruises and Summer Groundfish Survey in GoM supported by Southeast Area Monitoring and Assessment Program (SEAMAP) conducted annually by the Gulf States Marine Fisheries Commission. The shelf-wide cruises provided 1818 measured profiles with 85140 available records from 2007 to 2019. There were at least 83 DO profiles for each summer (June–August, except 2016) from the shelf-wide cruise observations. The selected SEAMAP DO dataset covers a time range from 2007 to 2019 with measurements including 2407 profiles with 77415 sampled records. Locations of the selected profiles from different archives were shown in Fig. 2c. Summer measurements by the shelf-wide cruises were used to validate spatial patterns of bottom DO concentration and time series of summer hypoxic areas. Estimated hypoxic areas by the cruises are available from 2007 to 2020 with a range from 5,480 km^2 to 22,720 km^2.

3.2 Nutrients concentration profiles

Modeled results showed good agreements with WOD nutrient profiles (Fig. 3a, 3c, and 3e, averaged every 2 m from the surface to 50 m depth) in terms of vertical distribution and magnitudes. The surface waters were rich in NO_3 (Fig. 3a) but oligotrophic in PO_4 (Fig. 3c) and $Si(OH)_4$ (Fig. 3e), indicating possibly high diatom productivity (Table 1) and possible P or Si limitation in the photic zone. Previous numerical studies did not provide comparisons for nutrient profiles in the shallow LaTex shelf region but focused more on the validation for surface nutrient concentration. Although surface nutrients are important for plankton blooms, the nutrient concentration at other water layers is also critical in affecting the shelf production dynamics. The simulated profiles were linearly interpolated to the observed depth for point-to-point comparisons. Biases were summarized and shown against the distance to the Mississippi River mouth (Fig. 3b, 3d, and 3f). An overall overestimation of NO_3 was found, especially around the mouths of the Mississippi River (distances<70 km), where most of the biases were between ± 50 mmol m^{-3}. Biases around the Atchafalaya River mouth (distances between 250 to 260 km) were detected negatively with a wider range than that around the Mississippi River mouth. In other locations, most NO_3 biases are within ± 25 mmol m^{-3}. There is no pronounced overestimation or underestimation detected for the PO_4 biases, which are mostly within ± 1 mmol m^{-3}, except for waters around the Mississippi River mouth. The PO_4 biases ranged from -3 to -2 mmol m^{-3} for profiles close to the mouth (distances < 16 km). Slight underestimation was found in the $Si(OH)_4$ concentration biases, especially for profiles around the Atchafalaya River mouth (distances = 211 km). Most of the $Si(OH)_4$ biases ranged from -20 to 5 mmol m^{-3} and were smaller than the magnitude of the NO_3 biases. Mean NO_3 concentrations from the Mississippi and Atchafalaya Rivers were 99 ± 34 mmol m^{-3} (mean ± 1sd) and 66 ± 29 mmol m^{-3}, respectively. Mean riverine PO_4 concentrations were 2.7

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575 ± 0.7 mmol m^{-3} and 2.3 ± 0.7 mmol m^{-3}, respectively, and mean riverine Si(OH)$_4$ concentrations were 118 ± 23 mmol m^{-3} and

576 116 ± 21 mmol m^{-3}, respectively. The nutrient concentrations bias between simulations and observations is acceptable,

577 considering the possible transient influence from the riverine nutrient loads during a survey.
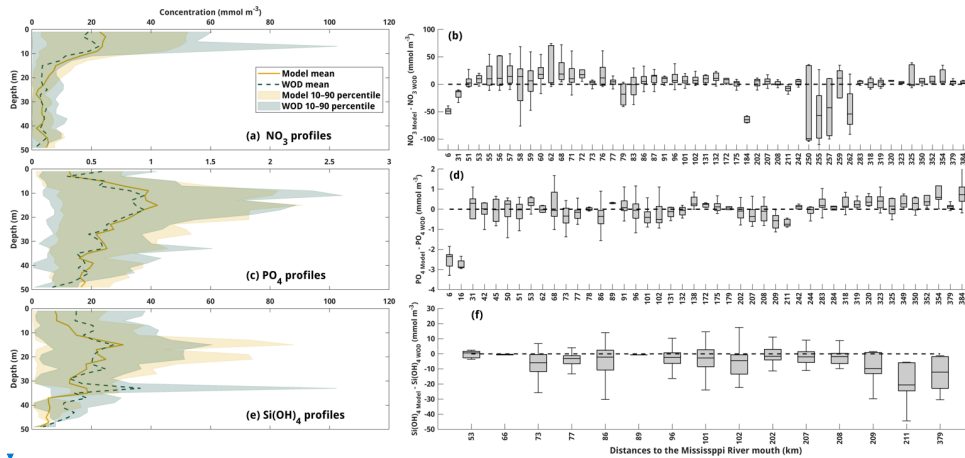
578

579 **Figure 3. Profile comparisons between model hindcasts and WOD measurements for concentrations of (a)–(b) NO₃, (c)–(d) PO₄, and**
580 **(e)–(f) Si(OH)₄. Box charts on the right-hand side show the minimums, maximums, first quartiles, third quartiles, and medians of**
581 **the concentration differences between the hindcast and measured profiles.**

582 **3.3 Diatom ratios**

583 Both measured and model-simulated Si(OH)$_4$ profiles suggested strong diatom productivity in the photic zone (Fig. 3e). Cruise

584 observations confirmed that the LaTex phytoplankton community is dominated by the diatom group (Schaeffer et al., 2012;

585 Chakraborty and Lohrenz, 2015). Regional averages (Fig. C2 in Appendix C), vertical averages (only the surface, middle, and

586 bottom layers were chosen), and monthly averages were applied to the concentration ratio of diatom and total phytoplankton

587 according to the sampled locations, sampled layers, and sampled months, respectively, of the cruise studies by Schaeffer et al.

588 (2012) and Chakraborty and Lohrenz (2015). The modeled ratios well reproduced the measured ones in terms of magnitudes,

589 monthly variability, and cross-shelf variability (Table 1). During the cruise periods in 2008, the range of modeled diatom

590 percentage (79% to 99%) matched well with the measurements (79% to 88%) except for June 2008, when underestimations

591 were found. In 2009, our model results agreed well with the measurements in inner shelf waters but overestimated the

592 measurements in the mid-shelf regions, especially in the summer and fall of 2009. The measured percentages exhibited salient

593 monthly variations with higher values in winter and spring and low ones in summer and fall. In the cross-shelf direction, the

594 phytoplankton community shifted from a highly diatom-dominated one in the inner shelf waters to a less diatom-dominated

595 one in the mid-shelf waters, especially in summer. Such patterns were well captured by our model.

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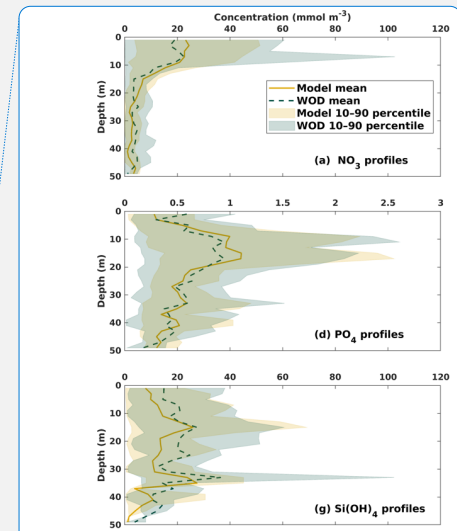
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Table 1. Comparison of simulated (mean±1SD) and measured (mean±1SD in parentheses) diatom percentage of the total phytoplankton. Note that the statistics for the simulated percentages were conducted based on concentration values and averaged over the cruise months and over given regions that cover the cruise sampling locations (Fig. C2). The measured percentages by Schaeffer et al. (2012) (for measurements in 2008) were calculated based on biovolume values, while those by Chakraborty and Lohrenz (2015) (for measurements in 2009) were given by chlorophyll *a* attributed to different phytoplankton groups.

	Diatom/total phytoplankton × 100%	
	Inner shelf	Midshelf
February 2008	99±4 (88±16)	
April 2008	99±2 (71±16)	
May 2008	79±39 (79±22)	
June 2008	29±42(85±10)	
January 2009	60±29 (66±21)	57±14 (47±14)
April 2009	50±33 (59±14)	51±19 (33±29)
July 2009	41±33 (40±13)	33±24 (13±16)
October–November 2009	50±33 (46±14)	38±19(19±17)
March 2010	49±35 (50±14)	52±26 (64±12)

614

3.4 SOC rates

616 Modeled SOC rates were compared against the laboratory incubation by McCarthy et al. (2013) at five shelf sites (location see

617 the Fig. 1 in that paper) using sediment and water samples collected during six cruises (i.e., July 2008, September 2008, January

618 2009, August 2009, May 2010, and May 2011). The modeled SOC was averaged over the cruise months for four shelf sites

619 (i.e., F5, C6, B7, and MRM; Fig. 2b). Our model could well capture the SOC magnitude. The model generally overestimated

620 the SOC at sites F5 and C6 except for January 2009 and May 2010 at site C6 and underestimated SOC at sites B7 and MRM

621 (except for August 2009) (Fig. 4). The largest overestimations were found on September 2008 when measurements were

622 carried out shortly after Hurricanes Gustav and Ike. These measurements tended to provide a low SOC but a high water column

623 respiration, possibly induced by the mixing incurred by storms. Note that the model results shown in Fig. 4 were averaged

624 over an entire month because no exact cruise date information was reported by McCarthy et al. (2013).

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(a) Site F5 / (c) Site B7 — SOC (umol m⁻² h⁻¹) for Sep 2008, Jan 2009, Aug 2009, May 2010, May 2011

Figure 4. Comparison of modeled and measured SOC (unit: μmol m^{-2} h^{-1}) at four LaTex shelf sites (Fig. 2b). Note that the measurements are provided by McCarthy et al.'s (2013) incubation study.

3.5 DO profiles

Both simulated and observed DO profiles were averaged for different depth ranges (Fig. 5) and compared against normalized depths ranging from 0 (surface) to 1 (bottom). The observed DO vertical structures were well captured by the model, with the 10–90 percentiles of modeled DO overlapping the measured ones well. We noticed the model tended to overestimate the observed DO by ~ 1 mg L^{-1} on average, especially in lower water columns for profiles with greater depths, which can be ascribed to the model's relatively coarse vertical resolution in deeper waters. The vertical coordinate transformations and vertical stretching functions applied to the model provided a finer resolution around the surface and relatively coarse ones around the bottom (1 to 2 m for each layer), while the shelf-wide and SEAMAP measurements were almost equally distributed along the vertical direction. We noted our model was less biased against the SEAMAP than the shelf-wide data as the latter sometimes has several measurements within one meter. In shallow waters (6–15 m), DO was somewhat more overestimated around the surface than in layers below (Fig. 5a and 5d). ROMS tends to overmix the water column in shallow water regardless of the vertical mixing parameterizations chosen (Robertson and Hartlipp, 2017). Despite the slight overestimations of DO profiles, our model results provided similar and even better performances than previous numerical studies. For example, DO concentration biases against profile measurements in Yu et al. (2015) were within 2 mg L^{-1}.
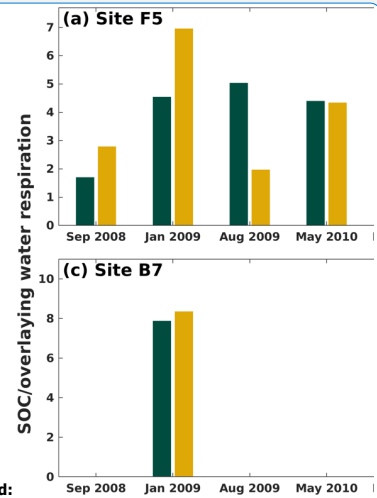
Deleted: Figure 5. Comparison of modeled and measured (McCarthy et al., 2013) ratios of SOC/overlaying water respiration at four LaTex shelf sites.¶

Deleted: Both simulated and observed DO profiles were averaged every 2 m from the surface to 50 m depth (Fig. 6a, 6c, and 6e). The observed DO vertical structures, such as the "zigzag" shape in the WOD profiles and "C" shape in the shelf-wide and SEAMAP profiles, were well captured by the model. The 10–90 percentile of modeled DO overlap the measured ones. Probability histograms of relative bias between the model and measurements reveal that the model overestimated the measured DO (Fig. 6b, 6d, and 6f). There were 45% (27%) of the WOD DO samples were overestimated (underestimated) by 50%. When compared to the shelf-wide cruise measurements, the probability histogram of the relative bias showed a bell-shaped distribution with a peak around zero. 28 %, 44 %, and 66 % of observations were misestimated by ±10 %, ±20 %, and ±50 %, respectively (Fig. 6d). Our model seemed to agree well with SEAMAP data. There were 36% (20%), 50% (26%), and 61% (31%) of records being overestimated (underestimated) by 10%, 20%, and 50%, respectively (Fig. 6f). ¶ ... [3]

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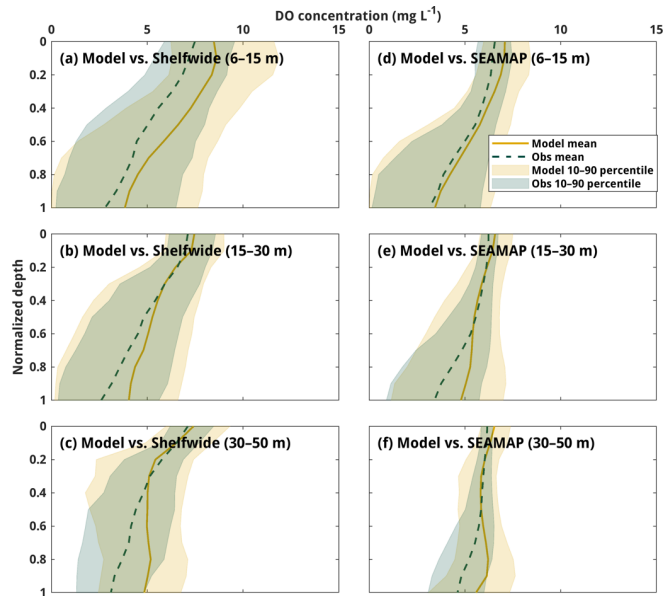
Figure 5. Comparisons of DO profiles between model hindcasts and measurements by (a–c) NOAA's shelf-wide cruises and (d–f) SEAMAP. The normalized depths of 0 and 1 represent the surface and bottom, respectively.

721

3.6 Spatial distributions of bottom DO and temporal variability of hypoxic area

As the annual NOAA shelf-wide cruises were conducted from the east shelf to the west in the summer, the model simulated bottom DO was resampled following the cruise periods. For example, if the westmost location of the cruise is 90°W on day 1, the simulated bottom DO concentration over the east of 90°W on that day is extracted. On the following day, if the westmost location of the cruise is 91°W, the simulation between 91°W and 90°W on day 2 is extracted, and so forth. All the extracted frames were blended to reconstruct the spatial distribution of simulated bottom DO concentration during the summer cruise period. Simulated results outside the LaTex shelf and over the deep (> 50 m) and shallow (< 6 m) water regions were excluded since observations were unavailable. Model results showed a good agreement with the observations in terms of interannual variability and spatial extent of bottom hypoxic waters (Fig. 6). The spatial distribution of the hypoxic regions varied over different summers. For example, the hypoxic area was small and was primarily restricted to nearshore (<20 m) regions during the summers of 2007, 2009, 2010, 2012, 2014, and 2018. The size of the hypoxic zone was more prominent and extended offshore in 2008, 2011, 2013, and 2019. The spatial dispersion of hypoxic waters occurred mostly over the west of the LaTex

15

747 shelf, where bathymetry gradients were gentle. Over the eastern shelf, the hypoxic water was mostly constrained within a

748 narrow belt. In the meantime, the western and eastern hypoxic waters were not always merged but were separated at around

749 91 °W (e.g., 2007, 2010, 2012, 2014, 2017, and 2018). These results suggested that the hypoxia development on the LaTex

750 shelf was complex and generally followed the bathymetry and distances from the major river mouths.

751

752 The daily time series of the size of the hypoxic zone was calculated over the LaTex shelf (6–50 m; Fig. 7). There was a good

753 agreement between simulated hypoxia zone size and that captured by the shelf-wide cruises in terms of variability and

754 magnitude. The overall R^2 was found as 0.47 and varied yearly (Table 2). The 5-year running R^2 increased from 0.02 for the

755 first 5-year period (2007–2010) to 0.91 for the last 5-year period (2015–2020, excluding 2016). The lower R^2 before 2010

756 could be attributed to the coarse resolution of the atmospheric forcings (~ 35 km, CFSR). Since 2011, CFSRv2 provided

757 forcings with a higher resolution of 22 km. Underestimations were found in 2007, 2010, 2012, and 2014 with a root-mean-

758 squared error (RMSE) of 9988 km^2, while minor underestimations were simulated in 2008, 2017, 2018, and 2020 (RMSE=4862

759 km^2). The model tended to slightly overestimate the measurements in other summers of interest (i.e., 2009, 2011, 2013, 2015,

760 and 2019; RMSE=2132 km^2). Nevertheless, those biases were acceptable considering the relative sporadic converges of cruise

761 data.

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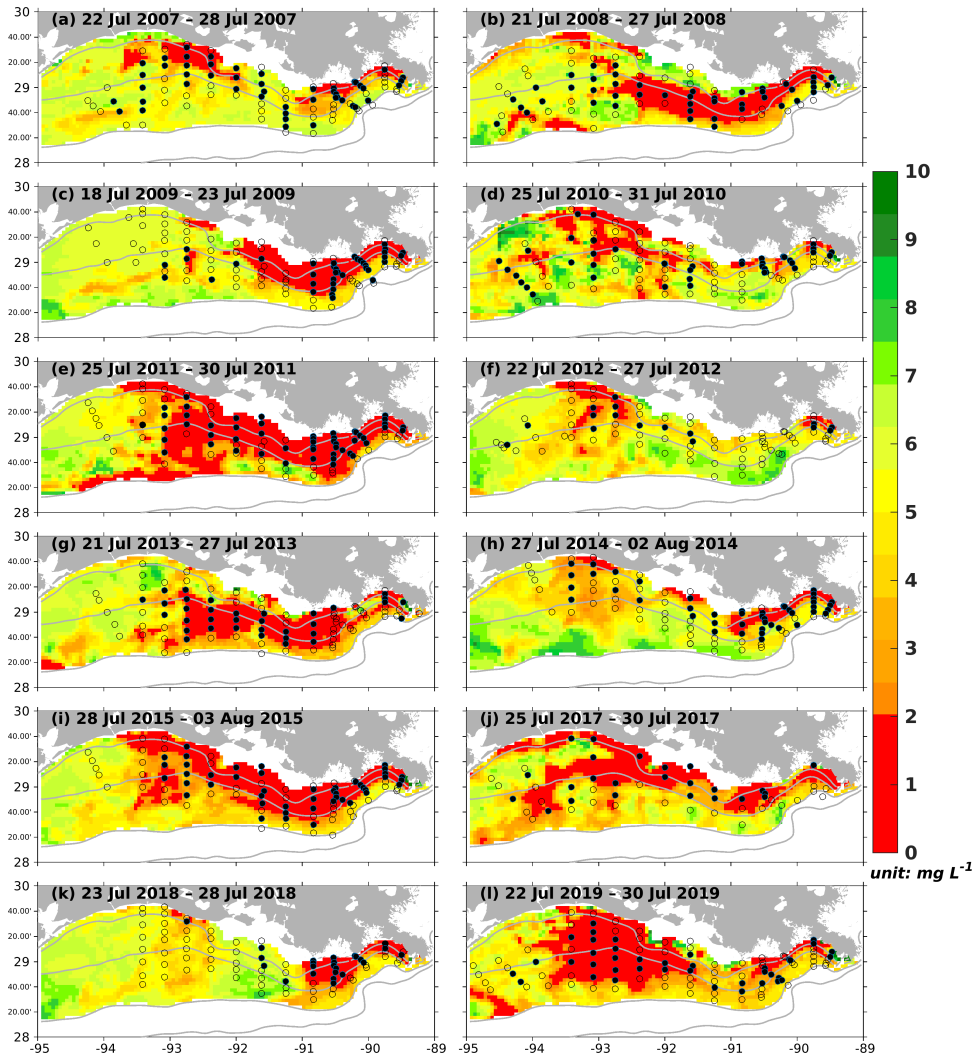
Figure 6. Modeled summer bottom DO concentration (colored patches) and NOAA's summer shelf-wide hypoxia observations (black dots and open circles). The black dots and the open circles are indicators of observed bottom hypoxia and normoxia, respectively. The solid grey lines indicate bathymetry of 10, 20, 50, and 100 m, respectively.

17

The figure shows 13 stacked panels (a–m) plotting hypoxic area (km²) versus days for years 2007–2020 (except 2016). Each panel labels:

(a) 2007 — Model : 6682 km²; Shelf-wide : 20480 km²
(b) 2008 — Model : 14630 km²; Shelf-wide : 21764 km²
(c) 2009 — Model : 9227 km²; Shelf-wide : 8240 km²
(d) 2010 — Model : 7990 km²; Shelf-wide : 18400 km²
(e) 2011 — Model : 22148 km²; Shelf-wide : 17680 km²
(f) 2012 — Model : 2497 km²; Shelf-wide : 7480 km²
(g) 2013 — Model : 15181 km²; Shelf-wide : 15120 km²
(h) 2014 — Model : 4393 km²; Shelf-wide : 13080 km²
(i) 2015 — Model : 17290 km²; Shelf-wide : 16760 km²
(j) 2017 — Model : 18205 km²; Shelf-wide : 22720 km²
(k) 2018 — Model : 4335 km²; Shelf-wide : 7040 km²
(l) 2019 — Model : 19227 km²; Shelf-wide : 18000 km²
(m) 2020 — Model : 1487 km²; Shelf-wide : 5480 km²

Y-axis: Hypoxic area (km²); X-axis: Days (1 to 361).

Figure 7. Comparison of the hypoxic area (in km²) between model simulations and shelf-wide cruise observations from 2007 to 2020 (except 2016). The pink patches denote the cruises periods while the solid black lines represent the measured hypoxic area.

18

781 **Table 2. The overall (2007–2020) and 5-year running R^2 of summer hypoxic area between model simulations and shelf-wide**
782 **measurements. Note that the comparison in the year 2016 was excluded due to the lack of measurement.**

Year ranges	R^2	Year ranges	R^2
2007–2020 (overall)	0.47	2011–2015	0.82
2007–2011	0.02	2012–2017	0.75
2008–2012	0.39	2013–2018	0.71
2009–2013	0.41	2014–2019	0.73
2010–2014	0.44	2015–2020	0.91

783

784 **4 Results**

785 **4.1 Nutrient limitation**

786 Riverine nutrient loads from the Mississippi and Atchafalaya Rivers were calculated based on measurements from the USGS
787 NWIS. During the investigated period (2007–2020), the riverine N:P ratio was higher than 16:1 during spring and reached its
788 minimum in summer. Riverine N:Si ratio fluctuated around 1:1 and was slightly higher in late spring and summer than in other
789 seasons (Fig. 8). The rivers transported excessive inorganic N and Si to the shelf but much less P when compared to the
790 Redfield ratio of N:P:Si=16:1:16. Ratios of integrated nutrient concentration in the shelf (Fig. 8) suggested that P was usually
791 limited in spring when compared to N and Si. In most summers, Si limitation might be more important in regulating
792 phytoplankton production than N limitation (N:Si>1:1) and P limitation (Si:P<16:1).

793

Nutrient limitation could vary among different phytoplankton species with different efficiencies in nutrient uptakes. In our model, the Si limitation was modeled only for the PL growth. Depth-averaged nutrient limitation coefficients (see Eqs. A9–A10) along multiple isobaths exhibited salient spatial and temporal patterns for both PS and PL (Fig. 9 and C3–C6). For example, along the 15 m isobath (Fig. 9), in the mid and west shelf, the PS growth was usually limited by N in mid- and late summer but by P in other late spring and early summer. In the east shelf, P limitation on PS growth was usually dominated from May to August (Fig. 9a). Types of limited nutrients for PL exhibited a distinguishable west-east pattern along the 15 m isobath: the growth of PL was usually limited by P in the east and by Si in the middle. The limited nutrients shifted between N and Si on the shallow mid and west shelf in different summers. In contrast, P limitation on PS growth and Si limitation on PL growth was likely to be more common in the open shelf (Fig. C3–C6). N limitation was negligible along the 30 m isobath and beyond, where the growth of PS was mostly limited by P and the growth of PL by Si in the west and by P in the east, respectively.

N limitation was commonly simulated in the shallow (< 20 m) middle and west shelf for the two phytoplankton groups, while in other parts, primary production was more likely to be limited by P or Si. Bioassays studies by Turner and Rabalais (2013) suggested that phytoplankton biomass was mostly limited by N or by a co-limitation of N and P in high salinity (> 20) waters. In the shallow mid and west part of the shelf, where salinity was usually greater than 20 during summer, model results suggested an N-limited environment, which agreed with the bioassays studies. However, in other parts, regardless of salinity ranges, the system was more limited by P and Si. Previous bioassays studies usually neglected Si effects on production (e.g., Turner and Rabalais, 2013; Zhao and Quigg, 2014). Quigg et al. (2011) pointed out that P limitation was detected particularly at sites directly adjacent to the Mississippi River plume, while Si limitation was found in four out of eight bioassays where production was limited by nutrients. These measurements supported our model results regarding the importance of P and Si limitation on the shelf primary production.

(a) Nutrient limitation on PS (15 m isobath)   **(b) Nutrient limitation on PL (15 m isobath)**
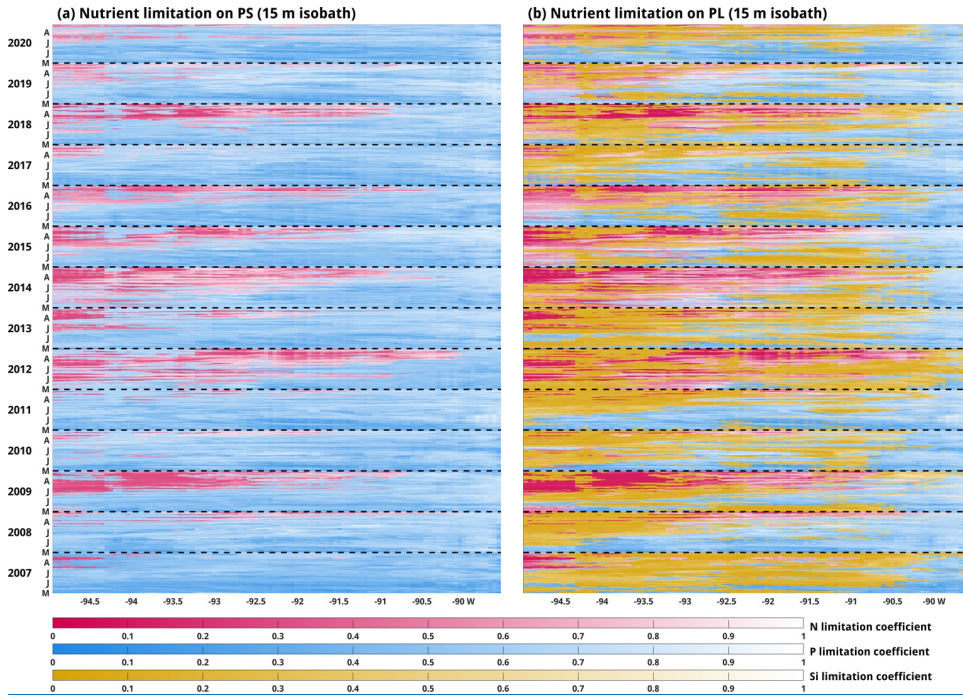
Figure 9. Evolution of depth-averaged nutrient limitation coefficients for (a) PS (and PL) along the 15 m isobath during late spring and summer. The notations of M, J, J, and A in the y-axis represent the first day of May, June, July, and August, respectively. Note that a lower (deeper colored) coefficient represents stronger limitations on phytoplankton growth. The dashed black lines indicate the time record on May 1 of each year.

4.2 Plankton community dynamics

As suggested by previous observations (Schaeffer et al., 2012; Chakraborty and Lohrenz; 2015), the LaTex shelf phytoplankton community is largely supported by the diatom group, which is consistent with our model simulation. Integrated over entire water columns and the LaTex shelf, the modeled total productions (primary + secondary productions, in mmol N) were supported mostly by PL, which contributed ~70 % in early spring and ~50 % in summer (Fig. 10b). Contributions from PS biomass supported ~20 – ~35 % of total biomass from spring to summer (Fig. 10a) when the secondary production (ZS+ZL+ZP) only contributed ~10 % (Fig. 10c). In the meantime, the seasonality of different biomass subsets exhibited different patterns. The PS biomass reached its first peak in late April and then varied till July. The PL biomass climbed to its higher peak in early April, decreased, and rebounded slightly to its lower peak in mid-May. During summer, the PS biomass (3–4 $\times 10^{12}$ mmol N)

21

was at a similar magnitude to the PL biomass (5–6 ×10^{12} mmol N). After summer, both PS and PL biomass decreased gradually to troughs in October. The seasonality of total production, therefore, exhibited a bi-peak (in late spring and early summer) pattern with the two peaks at a similar magnitude. Such a bi-peak pattern could also be found in both satellite-derived chlorophyll *a* concentration and model simulations with a similar plankton community as this study (see comparisons of modeled and satellite chlorophyll *a* concentration in Gomez et al., 2018) but was hardly captured by models using only one plankton group (e.g., Fennel et al., 2011).

Competition of PS and PL on nutrients may provide a clue to the bi-peak production. Nutrient loads from the Mississippi and Atchafalaya Rivers usually maximize in late spring and early summer, after which the loads decrease gradually and reach the minimum in October (Fig. C1). With greater (Table B4) half-saturation coefficients on nutrients, the PL group outcompetes the PS group in a high-nutritious environment in April but would not exhibit such superiority in growth in summer when nutrient supplies decrease. Top-down effects were also detected from the time series of PS and secondary production (Fig. 10a and 10c). The PS biomass experienced a surge during April and reached its first peak around the end of April, while the secondary production did not see a salient increase until mid-April and climbed to the highest at the beginning of May. Both time series then exhibited a pronounced fluctuation after reaching their first peak and declined steadily after August. During this high-production period, the two time series were out-of-phase with the PS led by about 6 days. There was no distinguishable phase lag between the seasonality of PL and the secondary production.
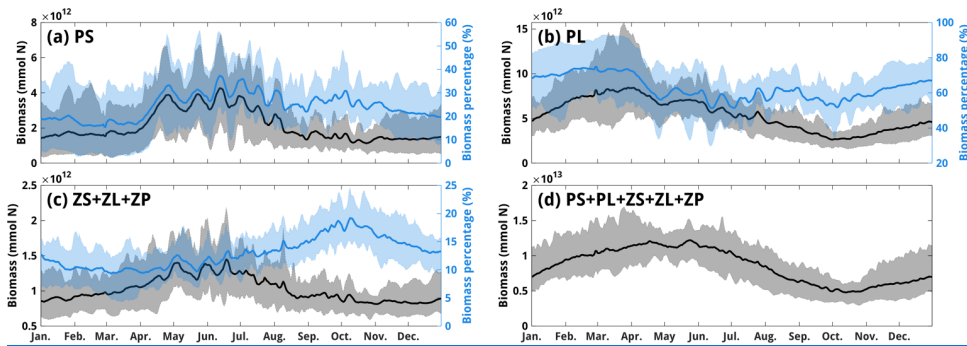
Figure 10. Climatologically daily mean of (a) PS, (b) PL, (c) ZS+ZL+ZP, and (d) total production. The corresponding percentages for different biomass subsets are related to the total production and are shown as blue solid lines. The color patches indicate the range of 10–90 percentiles. Note that the biomass matrices were integrated over the entire water column and the LaTex shelf before temporal averages.

22

984 We further examined the variance of the daily time series of simulated total productions (4987 records from January 2007 to
985 August 2020). As the total production was formulated as the sum of productions by PS, PL, ZS, ZL, and ZP, the variance can
986 be expanded mathematically, as shown in Table 3. The PL explained 63 % of the total variance, while PS explained only 20
987 %. The daily variability of the shelf production was, therefore, mostly controlled by that of the PL. As Si and P limitations
988 were commonly found for the growth of phytoplankton (Fig. 9 and C3–C6), more pronounced changes in total production and
989 the resulting DO concentration would be expected when only adjusting riverine Si or P loads rather than N loads. In the
990 meantime, the responses in different types of plankton biomass may be different to the changing nutrient loads due to the
991 competition between PS and PL (bottom-up effects) and also grazing of zooplankton on phytoplankton (top-down effects).

992

993 **Table 3. The expansion of variance (unit: $\times 10^{22}$ mmol N^2) of total production. Note that the sum of the listed variances and**
994 **covariances is equal to the variances of the total production mathematically. Statistics are derived from the daily time series of**
995 **plankton biomass (in mmol N) integrated over the entire water column and the LaTex shelf (color-shaded area in Fig. 2b).**
996 **Percentages in the brackets represent variance contributions.**

var(PS)	var(PL)	var(ZS)	var(ZL)	var(ZP)
216 (20.32 %)	669 (62.97 %)	3.14 (0.30 %)	4.24 (0.40 %)	0.21 (0.02 %)
2cov(PS,PL)	2cov(PS,ZS)	2cov(PS,ZL)	2cov(PS,ZP)	2cov(PL,ZS)
41.6 (3.92 %)	18.6 (1.75 %)	32.2 (3.03 %)	8.86 (0.83 %)	-18.2 (1.71 %)
2cov(PL,ZL)	2cov(PL,ZP)	2cov(ZS,ZL)	2cov(ZS,ZP)	2cov(ZL,ZP)
36.6 (3.45 %)	12.1 (1.14 %)	-0.03 (0.01 %)	0.26 (0.02 %)	1.35 (0.13 %)
sum				
1030				

997 **4.3 Plankton contribution to PON$_{sed}$ pool**

998 In the model, the PON$_{sed}$ pool is supported by sinking organic matters (represented by PON), which are contributed directly
999 from plankton detritus due to phytoplankton and zooplankton mortality and zooplankton egestion. Although PL biomass
1000 dominated total production, the daily variability of PON$_{sed}$ was more correlated to the PS and secondary production, with
1001 correlation coefficients of 0.64 ($p<0.001$) and 0.70 ($p<0.001$), respectively, than to the PL, with a coefficient of 0.51 ($p<0.001$)
1002 (Fig. 11). Multiple linear regression (MLR) models were built to study the linear relationships between PON$_{sed}$ (as the response
1003 variable) and biomass of different types of plankton groups (i.e., PS, PL, and secondary production as explanatory variables).
1004 All variables were normalized within a range from 0 to 1 before model construction. The highest R^2 was found when PON$_{sed}$
1005 lagged the explanatory variables by 6 days (Table 4). Regression coefficients were found to be significantly positive between
1006 plankton biomass and PON$_{sed}$. The contribution of secondary production (coefficient = 0.5388) to PON$_{sed}$ variability was much

1007 higher than the contribution from PS (0.4796) or PL (0.4758). Moreover, changes in PS and PL (both normalized) would lead

1008 to similar changes in PON_{sed} even though the PL dominated the shelf total production.

1009

1010 The results indicate the effects of plankton community structure on PON_{sed} accumulation on the seafloor. A linear function of

1011 mortality was applied to PS, PL, ZS, and ZL, while a quadratic mortality function was used for ZP. The modeled mortality

1012 rates of PS, PL, ZS, and ZL are thus proportional to the corresponding plankton concentration, the mortality rate at 0 °C, and

1013 a temperature-dependent term in which the temperature coefficients were parameterized as 0.0693 °C^{-1} for all groups. The

1014 mortality rate of ZP is similar to the other groups but is proportional to the square of ZP concentration. The mortality rates of

1015 PS and PL at 0 °C (Mor_{PS0}=0.002 m^3 mmol N^{-1} day^{-1} and Mor_{PL0}=0.001 m^3 mmol N^{-1} day^{-1}, respectively shown in Table B4)

1016 were parameterized 11–22 times lower than those for ZS and ZL (Mor_{ZS0}=0.022 m^3 mmol N^{-1} day^{-1} and Mor_{ZL0}=0.022 m^3

1017 mmol N^{-1} day^{-1}) and 60–120 times lower than the parameter for ZP (Mor_{ZP0}=0.12 m^3 mmol N^{-1} day^{-1}). However, concentration

1018 (or biomass) ratios between phytoplankton and zooplankton barely reached as high as 10 or more (Fig. 10). Therefore, mortality

1019 rates of PS and PL were typically lower than the mortality rates of ZS, ZL, and ZP, given the same ambient water temperature.

1020 Through mortality processes, the contribution of zooplankton biomass to water column PON and eventually PON_{sed} was

1021 considered greater than that of phytoplankton biomass. In addition, a certain part of zooplankton-induced biomass contributed

1022 to the water column PON via egestion processes that were not formulated for the phytoplankton groups. Therefore, the

1023 contribution of the secondary production to PON_{sed} exceeded that of the primary production.

1024

1025 The PS mortality rate was lower than the PL mortality rate as PS concentration was usually less than (non-summer) or nearly

1026 (summer) half of the PL concentration. As a result, the variability of PON_{sed} accumulation should be more sensitive to that of

1027 PL biomass, which was not supported by the regression model. The top-down effects provide another angle in explaining the

1028 regression coefficients. The PS supported the growth of ZS, which was at the bottom trophic level in the zooplankton

1029 community. Changes in PS could be reflected in the changes in all types of zooplankton biomass through grazing and predation

1030 processes in the zooplankton community (top-down effects as indicated by Fig. 10a and 10c) and further in the changes in

1031 PON_{sed}. PL was grazed by ZL and ZP, which were at a higher trophic level than ZS, changes in PL could be mostly reflected

1032 in biomass changes in these two groups only. Thus, despite that only half (~51 % on average; figure not shown) of the biomass

1033 source in the zooplankton community was supported by PS, a considerable amount of PON_{sed} supported by zooplankton was

1034 from PS. This effect offsets the high mortality rate of PL. It may explain the comparable regression coefficients for PS and PL

1035 on the PON_{sed} variability.

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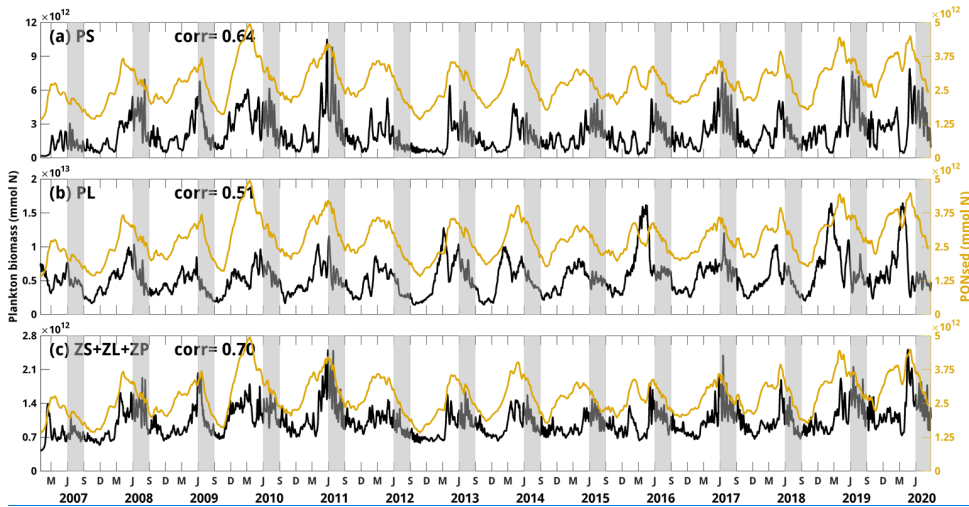
Figure 11. Comparisons between daily PON$_{sed}$ and plankton biomass (i.e., (a) PS, (b) PL, and (c) secondary production). All biomass matrices were integrated over the entire water column and the LaTex shelf.

Table 4. A multiple linear regression model with a response variable of PON$_{sed}$ lagging the explanatory variables by 6 days. Note that the model was built upon normalized daily time series.

Linear regression model:

PON$_{sed}$ (lag by 6 days) ~1 + PS + PL + secondary production

Estimated coefficients:

	Estimate	Std. Error	t-statistic	p-value
Intercept	0.0091	0.0036	2.5496	0.01[*]
PS	0.4796	0.0135	35.5370	<2E-16[***]
PL	0.4758	0.0084	56.5040	<2E-16[***]
Secondary production	0.5388	0.0134	40.0680	<2E-16[***]

Significance codes:	0 ([***]) 0.001 ([**]) 0.01 ([*])

Number of observations: 4980, Error degrees of freedom: 4976

Root Mean Squared Error: 0.0997

R-squared: 0.74, Adjusted R-Squared: 0.74

25

F-statistic vs. constant model: 4.62e+03, p-value = 0

4.4 Water column DO

In this study, we focus on the responses of bottom DO to the changing nutrient, biomass, and the associated biogeochemical processes. Thus, it is necessary to compare the contribution of different plankton groups to water DO. Such contributions were quantified by ratios of total DO generated or consumed by a given plankton group over its biomass. In water above the bottom 2 m, both PS and PL tended to produce more DO than they consumed (Table 5). DO contributed by PS (per mmol N) was at least twice greater than that by PL. As PL biomass was usually greater than PS biomass (Fig. 10), such differences resulted from a higher temperature-dependent respiration rate for PL (K_{ResPL}=0.0693 °C^{-1}; Table B4) than for PS (K_{ResPS}=0.0519 °C^{-1}). DO consumptions by ZS and ZL metabolism were found to be three times greater than those by ZP on average. The rates of zooplankton metabolism were formulated proportionally to total biomass flows from lower trophic levels. ZS and ZL consumed more biomass through grazing than ZP, which could be reflected in the percentages of total zooplankton biomass (ZS accounted for 32 % on average, ZL for 39 %, ZP for 29 %, figure not shown). Taking all plankton functional groups as a whole, the net DO contribution by the community (per unit biomass) was found to be mostly positive (positive maximum, median, mean, first quartile, and third quartile; Table 5).

In the water within the bottom 2 m, the DO consumed by the plankton community had a higher chance to exceed the production than in the layers above (Table 5). Firstly, the DO production by the phytoplankton community within the bottom 2 m was found to be nearly half of that found in the layers above, as nutrients and light were more likely to be limited. Secondly, the first quartile of DO contribution by PL was found to be slightly negative within the bottom 2 m, while in the layers above, the corresponding statistic was positive. Finally, the net DO contribution was found to be generally positive (mean and median) but had a higher chance to be negative (minimum and first quartile) than waters above the bottom 2 m. The above statistics help us to understand how DO changes when nutrient supplies are altered. For example, if riverine nutrient supplies are reduced, photosynthesis rates will decrease. As the respiration rate of phytoplankton was formulated as a function of water temperature and phytoplankton concentration only, nutrient changes will not lead to changes in respiration rate per unit biomass. The net DO production by phytoplankton will decrease.

Table 5. Statistics of plankton contribution per unit biomass in producing or consuming DO over water layers above and within the bottom 2 m. Statistics are calculated based on depth-integrated daily matrices without spatial average or spatial integration. Note that negative signs shown denote DO consumption.

Contributions at layers above the bottom 2 m (unit: $\times 10^{-5}\ mmol\ O_2\ s^{-1}\ mmol\ N^{-1}$)						
	min	max	median	mean	first quartile	third quartile	Std.
PS	-1.19	27.64	7.45	7.02	3.40	10.42	4.09

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	min	max	median	mean	first quartile	third quartile	Std.
PL	-2.10	58.83	2.22	3.03	1.31	3.62	3.40
ZS	0	-23.18	-6.77	-7.25	-3.76	-10.66	4.37
ZL	0	-19.78	-6.42	-6.63	-4.95	-8.10	2.72
ZP	-0.22	-9.60	-2.21	-2.60	-1.64	-3.08	1.42
Entire community	-13.76	35.40	0.99	1.25	0.24	1.94	1.84

Contributions at layers within the bottom 2 m (unit: $\times 10^{-5}$ $mmol\ O_2\ s^{-1}\ mmol\ N^{-1}$)

	min	max	median	mean	first quartile	third quartile	Std.
PS	-1.29	23.69	3.51	3.89	0.21	6.17	4.09
PL	-2.28	46.99	1.38	2.48	-0.40	3.74	4.29
ZS	0	-18.53	-4.17	-4.90	-1.66	-7.11	3.92
ZL	0	-19.00	-5.83	-5.72	-4.50	-7.19	2.50
ZP	0	-9.48	-1.89	-2.01	-1.45	-2.36	1.10
Entire community	-39.77	35.93	0.35	0.33	-1.74	1.75	3.71

5 Discussion

5.1 Si limitation on PL growth

Previous studies suggested that there is potential Si limitation in the LaTex shelf (Quigg et al., 2011; Nelson and Dortch, 1996; Lohrenz et al., 1999) due to the increase in riverine N:Si loads (from 1:3 to 1:1) since the 1950s (Turner et al., 1998). Over the studied period, the ratio of N:Si loads from the Mississippi and Atchafalaya Rivers was slightly greater than 1:1 during late spring and summer, while N:Si over the shelf was usually greater than 2:1 (Fig. 8b). Nelson and Dortch (1996) pointed out that within the plume, > 99 % of silicate supported by rivers was removed by biological uptake during spring and 80–95 % during summer. Cruise observations indicated strong Si limitation over the Mississippi River plume (east of 92°W) during spring and little or no Si limitation during summer (Nelson and Dortch, 1996; Lohrenz et al., 1999). Results of limitation coefficients indicated that Si was more limited than N for the growth of PL during spring and summer (Fig. 9 and C3–C6). It should be noted that the Si limitation was only related to the growth of PL in our model, while the Si limitation found in cruise studies was related to the growth of plankton assemblages. During summer, the biomass of PS and PL reached a similar magnitude showing a shift in phytoplankton composition. As the growth of PS was mostly limited by P during summer, especially over the deep or east shelf, P limitation should be considered equally important as Si limitation on the growth of total phytoplankton. Our model results also suggested that a potential co-limitation of nutrients may be more crucial to shelf productivity than the limitation of a single nutrient type. Indeed, bioassays studies illustrated that co-limitation of N+P or N+P+Si occurred and might have a greater impact on the production than single-nutrient limitation (Zhao and Quigg, 2014; Quigg et al., 2011; Turner and Rabalais, 2013).

A critical factor associated with nutrient limitation is the half-saturation coefficient of phytoplankton nutrient uptake. Uptake kinetic studies for different marine diatom species suggested a wide range of half-saturation coefficients of silicate (K_{SiOH_4} from 0.85 to 17.4 mmol Si m^{-3}; Table 6). The average, median, first quartile, and third quartile of the listed measured coefficients in Table 6 were found to be 5.9, 4.5, 2.3, and 7.0 mmol Si m^{-3}, respectively. In our model, the half-saturation coefficient of silicate uptake by PL was then set as 6.0 mmol Si m^{-3}. We applied the average rather than the median of the published coefficients to our model since the PL group should be considered as a marine diatom assemblage. However, the K_{SiOH_4} for a diatom assemblage may shift given changing ambient silicate concentration. For example, as pointed out by Nelson and Dortch (1996), K_{SiOH_4} for the sampled phytoplankton assemblage (dominated by diatom species) remained low from 0.48 to 1.71 mmol Si m^{-3} when the ambient silicate concentration was low between 0.13 to 0.41 mmol Si m^{-3}, but increased to 5.29 mmol Si m^{-3} as ambient silicate concentration was 4.72 mmol Si m^{-3}. Further investigations and improvements in model parameterization for the dependency of K_{SiOH_4} on silicate concentration are therefore needed.

Table 6. Half-saturation coefficient (unit: mmol Si m^{-3}) for silicate uptake by different diatom species according to multiple uptake kinetic studies.

Diatom species	K_{SiOH_4}	Reference
Cylindrotheca fusiformis	0.85	Del Amo and Brzezinski (1999)
Nitzschia alba	6.8	Azam (1974)
Nitzschia alba	4.5	Azam et al. (1974)
Phaeodactylum tricornutum	4.0, 9.2, 6.3	Del Amo and Brzezinski (1999)
Thalassiosira nordenskioeldii	2.8	Kristiansen and Hoell, (2002)
Thalassiosira pseudonana	7.04	Thamatrakoln and Hildebrand (2008)
Thalassiosira pseudonana	1.4	Del Amo and Brzezinski (1999)
Thalassiosira pseudonana	0.8, 2.3	Nelson et al. (1976)
Thalassiosira weissflogii	15.2, 17.4	Milligan et al. (2004)
Thalassiosira weissflogii	4.5	Del Amo and Brzezinski (1999)
Average	5.9	
Diatom functional group (PL)	6.0	This study

5.2 Riverine nutrient reductions

Since 2001, the Mississippi River/Gulf of Mexico Hypoxia Task Force has set up a goal of controlling the size of the mid-summer hypoxic zone below 5000 km^2 in a 5-year running average (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001; 2008) by reducing riverine nutrient loads. Fennel and Laurent (2018) suggested that a reduction of 63 ±

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1109 18% (referred to as the 2000–2016 average) in total N loads or a dual reduction of 48 ± 21% in total N and P loads could be

1110 necessary to fulfill the hypoxia reduction goal. Statistic models (Scavia et al., 2013; Obenour et al., 2015; Turner et al., 2012;

1111 Laurent and Fennel, 2019) suggested a nutrient reduction of 52%–58% related to the 1980–1996 average should be enough to

1112 fulfill the goal. Nonetheless, inorganic nutrient types considered in these statistical models were either N-based (i.e., ammonia

1113 and nitrite+nitrate) or a combination of N and P-based nutrients. The plankton community embedded in existing models was

1114 simplified with one phytoplankton functional group and one zooplankton functional group (e.g., Fennel et al., 2006, 2011,

1115 2013; Fennel and Laurent, 2018; Justić and Wang, 2014). Here we aimed to explore the sensitivity of bottom DO to the riverine

1116 nutrient discharge with different nutrient (N, P, and Si) reduction combinations, the corresponding changes in plankton

1117 community, and implications for hypoxia reduction. A total of six sensitivity experiments (Table 7) were set up with different

1118 combinations of nutrient reductions. The riverine nutrient concentration was the only variable adjusted among these sensitivity

1119 tests. To remove numerical bias introduced by initial conditions, all sensitivity experiments were initialized on 1 January 2012

1120 based on the output of the long-term simulations and were conducted from 1 January 2012 to 26 August 2020. Thus, any

1121 changes in bottom DO due to nutrient reductions should result from changes in biogeochemical processes, including changes

1122 in SOC, changes in DO at the water within the bottom 2 m, and changes in DO at layers above the bottom 2 m.

1123

1124 **Table 7. Riverine inorganic nutrient reduction percentages for different sensitivity experiments. Note that all the runs listed were**
1125 **initialized on 1 January 2012 and were conducted from 1 January 2012 to 26 August 2020.**

Experiment	Riverine inorganic nutrients reduction percentages (%)		
	N	P	Si
control	0	0	0
N60	60	0	0
P60	0	60	0
Si60	0	0	60
NP60	60	60	0
NSi60	60	0	60
NPSi60	60	60	60

1126

5.2.1 Responses of PON$_{sed}$ and SOC

1128 The total biomass of PON$_{sed}$ was likely to decrease in all nutrient reduction scenarios except for experiments Si60 and NSi60

1129 (Fig. 12a). Responses in SOC (Fig. 12b) followed strictly with those in PON$_{sed}$, as SOC was formulated as a function of PON$_{sed}$

1130 and water temperature and the latter remained unchanged among the six experiments. We found different responses in PON$_{sed}$

1131 (or SOC) in different nutrient reduction strategies. The changes in depth-integrated plankton biomass over the entire column

1132 can help to explain such differences (Fig. C7). As discussed above, the variability of PON$_{sed}$ was mainly from that of secondary

1133 production (Fig. 11 and Table 4). In most of the sensitivity tests (N60, P60, NP60, and NPSi60), the secondary production

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1224 experienced a salient decrease (Fig. C7b) due to fewer food supply (Fig. C7c). PON_{sed} or SOC, therefore, decreased in these

1225 scenarios. However, in scenarios Si60 and NSi60, secondary production did not exhibit pronounced changes (near-zero mean

1226 and median; Fig C7b) but either increased or decreased in nearly half of the simulation. Such a high uncertainty could lead to

1227 either an increase or a decrease in PON_{sed} biomass (Fig. 12a). On average, a slightly positive change in PON_{sed} biomass was

1228 simulated, which should be a result of an enlarging ZS group (Fig. C7d) and can be explained by bottom-up and top-down

1229 effects. As the growth of PL was commonly limited by Si on the shelf (Fig. 9 and C3–C6), PL biomass would generally

1230 decrease (Fig. C7g) as Si loads were reduced. It would further lead to biomass decreases in ZL (Fig. C7f) and ZP (Fig. C7h),

1231 both of which grazed on PL (bottom-up effects). ZS biomass would likely increase (top-down; Fig. C7d) as the predation

1232 pressure from ZL and ZP was weakened. Such responses in scenarios Si60 and NSi60 can also be found for the biomass

1233 integrated over the layers above the bottom 2 m (Fig. C8).

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5.2.2 Responses of DO in water columns

Among the six experiments, responses in biomass regarding reduced river nutrient loads are similar at the layers above the bottom 2 m (Fig. C8) and over the entire column (Fig. C7). Changes in total DO supply rates (Fig. 12c) and total production (Fig. C8a) generally exhibited a negative pattern in all nutrient reduction scenarios. Such responses are expected in the upper water column as the plankton community produced more DO than it consumed (Table 5) even though when nutrient supplies were reduced. Decreases in total production would lead to decreases in DO supplies. The most significant decreases in total biomass and DO supplies occurred when N, P, and Si loads were all reduced by 60 % (NPSi60), while minor decreases occurred in experiment N60. Our simulations suggested that the primary production on the shelf was more limited by P and Si rather than by N only. Therefore, the changes in biomass would be less pronounced in N60 than in other scenarios.

Response in total DO supplies to nutrient reductions became more complicated when reaching down near the bottom, where net DO contribution from the community (i.e., (photosynthesis - total respiration)/total biomass) would be more likely to shift between positive and negative than in the upper water column (Table 5). But detailed responses varied from case to case. In scenario N60, most of the time, the plankton community produced more DO than it consumed in water within the bottom 2 m (same as in the control experiment), as decreases in N may not lead to a dramatic decrease in photosynthesis rate. Decreases in total production (Fig. C9a) would result in lower DO production rates (negative mean and median of changes in total DO supply rates for N60 shown in Fig. 12d). However, net DO contributions from plankton community can switch to negative when N limitation was commonly detected (e.g., 2012, 2014, and 2018, Fig. 9). The photosynthesis rates can be significantly restricted below the total respiration rates, indicating that decreases in total production would lead to less DO consumption or increase in net DO supply rates (positive interval in Fig. 12d for N60).

In scenarios P60, Si60, NSi60, and NPSi60, changes in total biomass (negative; Fig. C9a) and total DO supply rates (positive; Fig. 12d) were in opposite phases, suggesting that net DO contribution by the community was usually negative at layers within the bottom 2 m. The shifts in net DO contribution in these cases mainly result from the reductions in limited nutrients (i.e., P and Si). Photosynthesis rates decrease pronouncedly below the total respiration rates, leading to a negative net DO contribution. A great uncertainty in changes in total DO supply rates (wide range of quartiles; Fig. 12d) was found when P load reduction was not incorporated (i.e., Si60 and NSi60). It can be explained by different responses of biomass in the plankton community due to competition, bottom-up effects, and top-down effects. Reductions in Si supplies would lead to less PL (Fig. C9g) but more PS (Fig. C9e) and introduce more uncertainty in primary production (Fig., C9c). Unlike at the layers above, here, near the bottom, increases in ZS (Fig. C9d) might be more related to bottom-up effects rather than top-down effects as ZL and ZP did not exhibit pronounced changes (Fig. C9f and C9h). Such responses in ZL and ZP were a combined effect of increased food supply from PS but less from PL. Thus, high uncertainty in responses in the secondary productions was also found (Fig. C9b). In scenario NP60, within the bottom 2 m, total plankton biomass experienced a salient decrease (Fig. C9a), while changes

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in total DO supply rates fluctuated around zero with a slightly negative mean and median (Fig. 12d). It indicated that net DO contribution by the plankton community shifted between positive and negative in this experiment. Such complex responses in the biomass and in the plankton community's role in DO contribution highlight the need for a multi-group plankton parameterization in hypoxia simulation.

5.2.3 Responses in bottom DO and hypoxic area

The responses in bottom DO and hypoxic area to nutrient reductions are a combined effect of changes of DO in sediment and water column. The most significant decrease in SOC (Fig. 12b) may not necessarily lead to the most significant increase (decrease) in bottom DO (hypoxic area) (e.g., NP60; Fig. 12e–12f), while the most significant drop in DO supplies in the upper layers (Fig. 12c) may not cause a pronounced decrease in bottom DO (e.g., NPSi60; Fig. 12e–12f). The most significant increase in bottom DO was found when supplies of all three types of nutrients were reduced by 60 % (NPSi60), where the bottom hypoxic area (2012-2000) reached 5275 km^2. The size of the hypoxic area was also saliently reduced in P60, Si60, NP60, and NSi60. For NPSi60 and P60, SOC rates dropped saliently (Fig. 12b), corresponding with an increase in total DO supply rates by water column biogeochemical processes at layers within the bottom 2 m (Fig. 12d). Although DO supplies from the upper layers decreased in these two scenarios, bottom hypoxia would still be significantly relieved. In scenarios of Si60, NP60, and NSi60, a more significant uncertainty was found in the responses of bottom DO and hypoxic area (Fig. 12e–12f), which could be attributed to the different responses of the five plankton groups (Fig. C7 and C9).

Intriguingly, compared to existing models (e.g., Justić et al., 2003, 2007; Laurent and Fennel, 2014; Fennel and Laurent, 2018) or statistical studies (Scavia et al., 2013; Obenour et al., 2015; Turner et al., 2012; Laurent and Fennel, 2019), our model simulated a different response of hypoxia development when only N is reduced by 60% (N60 Fig. 12e–12f). Existing studies generally agree that a 60% reduction in N load will reduce SOC and thus relieve the hypoxic condition. In this study, For N60, as fewer productions are supported, we found the magnitude of DO reduction (less production) in the water column (both upper and bottom layers) exceeded that of SOC reduction (less consumption), resulting in a decrease in bottom DO and worsen the hypoxic condition.

5 Conclusions

We modified a three-dimensional coupled hydrodynamic–biogeochemical model (NEMURO) and adapted it to the Gulf of Mexico to study the bottom DO variability in the LaTex Shelf. In addition to N and Si, a P flow was embedded into the NEMURO model to account for the impacts of P limitation on hypoxia development. Built on the SOC scheme of the instantaneous remineralization developed by Fennel et al. (2006), a pool of sedimentary PON was added to account for temporal delays in SOC to the peak of plankton blooms. The model can well reproduce the vertical profiles of inorganic nutrient concentration (i.e., nitrate, phosphate, and silicate), the ratio of diatom/total phytoplankton, and the magnitude of SOC

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The model's robustness in DO simulation was affirmed via 1) comparison of the DO profiles against cruise observations from two different databases, 2) comparison of spatial distributions of bottom DO, and 3) time series of the hypoxic area against the shelf-wide cruise observations.

Model results suggested that P and Si limitations could be more common than previously reported. N limitation was more commonly found in the shallow (< 20 m) middle and west shelf for both PS and PL, while in the other parts, primary production was more likely to be limited by P or Si. PL was found as a dominant plankton group accounting for about 50 – 70 % of total production during early spring and summer, explaining 63 % of the daily variability of the total production. The contribution of PS supported about 20 – 35 % of total biomass. The seasonality of total production exhibited a bi-peak (in late spring and early summer) pattern, which can be explained by the competition between PS and PL and was hardly captured by previous numerical models. We further explored the plankton contribution to DO budgets in water and sediment layers, respectively. We found 1) the PON_{sed} pool was contributed mainly by zooplankton mortality and egestion, 2) the plankton community, in general, produced more DO than it consumed in the waters above the bottom 2 m, with more uncertainty within the bottom 2 m of waters.

The types of limited nutrients, interactions (competition, grazing, and predation behaviors) among plankton groups, and the shifts in net DO contribution by the plankton community lead to complex responses in biomass, water DO, and bottom hypoxia. A 60 % reduction in all nutrient supplies would achieve the hypoxic area reduction goal set by the Task Force. The complex responses in the plankton biomass and their contribution to DO variation highlighted the importance of the complexity of the plankton community in the hypoxia evolution.

Code/Data availability: Model data is available at the LSU mass storage system and details are on the webpage of the Coupled Ocean Modeling Group at LSU (https://faculty.lsu.edu/zxue/). Data requests can be sent to the corresponding author via this webpage.

Author contribution: Z. George Xue designed the experiments and Yanda Ou carried them out. Yanda Ou developed the model code and performed the simulations. Yanda Ou and Z. George Xue prepared the manuscript.

Competing interests: The authors declare that they have no conflict of interest.

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Deleted: A 15-year coupled physical-biogeochemical hindcast was achieved covering the period of 2006-2020. Three DO transport terms (i.e., horizontal advection, vertical advection, and vertical diffusion) and a biochemical term (i.e., SOC) were found as the most influential factors modulating the bottom DO dynamics in the LaTex shelf. They jointly contributed ~80% of the variability in bottom DO throughout the year. Specifically, the contribution of SOC (34%) outcompetes other factors in summer. In different subregions of the shelf, the contributions of the four terms vary with depth and distance from the Mississippi River mouth. In the nearshore regions, SOC plays a much more important role in modulating the summer bottom DO concentration with a maximum contribution of 33%–51%; while in the offshore regions, its contribution decreases notably to 19%–27% in summer, which is comparable to the contributions of the other three hydrodynamic-induced terms (18%–26% for the horizontal advection, 17%–25% for the vertical advection, and 7%–16% for the vertical diffusion). ¶

¶
If the advection and vertical diffusion are considered jointly as a hydrodynamic term, the impacts of SOC (33%–51%) and hydrodynamics (28%–55%) are almost equally important in modulating the summer bottom DO in the nearshore regions, while in the offshore areas, contributions from hydrodynamics (51%–59%) outcompete the SOC impacts (19%–27%). The strong linear correlations between PEA and the advection terms suggest that increased water stability in summer leads to weaker DO exchanges from advection processes. Nevertheless, the relationship between PEA and vertical diffusion of DO across the bottom layer appears to be non-linear. As PEA starts to increase in early summer, the bottom DO starts to drop, resulting in strong vertical DO gradients at the bottom layer and enhanced vertical diffusion. As the strong water column stratification persists in mid and late summer, vertical diffusion of DO tends to be suppressed due to the weaker DO gradient resulting from the continuous DO consumption and the decreasing DO supply from the upper layers.¶

¶
We further examined the sensitivity of summer bottom DO to riverine nutrient reductions. Our sensitivity experiments highlighted the importance of the complexity of the lower-trophic community in bottom DO's response to the changing nutrient loads. Sole nutrient reductions in total nitrogen do not guarantee a hypoxic area decrease. Reduced nitrogen load can stimulate the competition between PS and PL and uncertainties to secondary productivity. Sole phosphorous reductions can, in general, reduce hypoxic area as PS and associated decreases in secondary productivity are reduced. A silicon reduction is more effective in reducing the hypoxic zone than the other two nutrients exhibited by the reductions in PL, ZS, and ZP concentration. One should also note that changes in the bottom DO are not evenly distributed over the shelf. A triple reduction strategy for all nutrients performs the best in reducing shelf hypoxic areas. When riverine nitrogen, phosphorous, and silicon loads are reduced by ~80% simultaneously, the hypoxia reduction goal of 5000 km² is likely to be achieved. ¶

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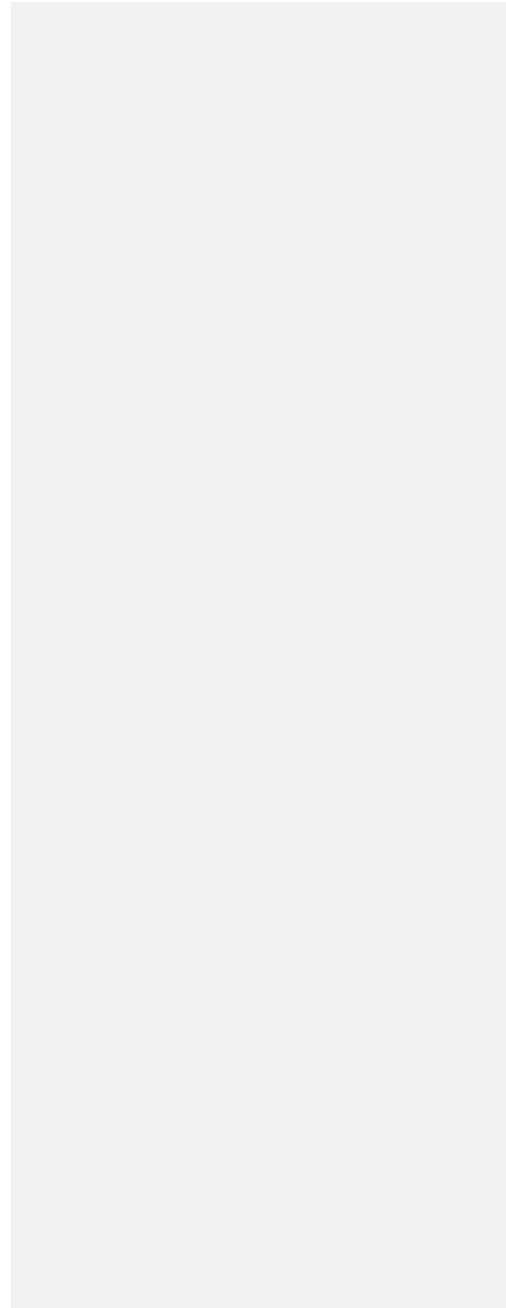
1464 **Appendix A: Expressions of processes terms modified in this study**

1465 Detailed descriptions of related terms and parameters are listed in Appendix B.

1466 **A1 Update gross primary production of PS and PL due to the additional phosphate limitation**

1467 $GppPSn = GppNPS + GppAPS,$ (A1)

1468 $GppPLn = GppNPL + GppAPL,$ (A2)

1469 where,

1470 $GppNPS = PSn\ V_{maxS}\ exp(K_{GppS}\ TMP) \left[1 - exp\left(-\frac{\alpha_{PS}}{V_{maxS}} I_{PS}\right)\right] exp\left(-\frac{\beta_{PS}}{V_{maxS}} I_{PS}\right) NutlimPS\ RnewS,$ (A3)

1471 $GppAPS = PSn\ V_{maxS}\ exp(K_{GppS}\ TMP) \left[1 - exp\left(-\frac{\alpha_{PS}}{V_{maxS}} I_{PS}\right)\right] exp\left(-\frac{\beta_{PS}}{V_{maxS}} I_{PS}\right) NutlimPS\ (1 - RnewS),$ (A4)

1472 $GppNPL = PLn\ V_{maxL}\ exp(K_{GppL}\ TMP) \left[1 - exp\left(-\frac{\alpha_{PL}}{V_{maxL}} I_{PL}\right)\right] exp\left(-\frac{\beta_{PL}}{V_{maxL}} I_{PL}\right) NutlimPL\ RnewL,$ (A5)

1473 $GppAPL = PLn\ V_{maxL}\ exp(K_{GppL}\ TMP) \left[1 - exp\left(-\frac{\alpha_{PL}}{V_{maxL}} I_{PL}\right)\right] exp\left(-\frac{\beta_{PL}}{V_{maxL}} I_{PL}\right) NutlimPL\ (1 - RnewL),$ (A6)

1474

1475 $RnewS = \frac{NO_3}{(NO_3 + K_{NO_3 S})\left(1 + \frac{NH_4}{K_{NH_4 S}}\right)} \frac{1}{\frac{NO_3}{(NO_3 + K_{NO_3 S})\left(1 + \frac{NH_4}{K_{NH_4 S}}\right)} + \frac{NH_4}{NH_4 + K_{NH_4 S}}},$ (A7)

1476 $RnewL = \frac{NO_3}{(NO_3 + K_{NO_3 L})\left(1 + \frac{NH_4}{K_{NH_4 L}}\right)} \frac{1}{\frac{NO_3}{(NO_3 + K_{NO_3 L})\left(1 + \frac{NH_4}{K_{NH_4 L}}\right)} + \frac{NH_4}{NH_4 + K_{NH_4 L}}},$ (A8)

1477 $NutlimPS = min\left(\frac{NO_3}{(NO_3 + K_{NO_3 S})\left(1 + \frac{NH_4}{K_{NH_4 S}}\right)} + \frac{NH_4}{NH_4 + K_{NH_4 S}}, \frac{PO_4}{PO_4 + K_{PO_4 S}}\right),$ (A9)

1478 $NutlimPL = min\left(\frac{NO_3}{(NO_3 + K_{NO_3 L})\left(1 + \frac{NH_4}{K_{NH_4 L}}\right)} + \frac{NH_4}{NH_4 + K_{NH_4 L}}, \frac{PO_4}{PO_4 + K_{PO_4 L}}, \frac{SiOH_4}{SiOH_4 + K_{SiOH_4 L}}\right),$ (A10)

1479 $I_{PS} = PAR\ frac\ exp\left\{z\ AttSW + AttPS \int_z^0 [PSn(\zeta) + PLn(\zeta)] d\zeta\right\},$ (A11)

1480 $I_{PL} = PAR\ frac\ exp\left\{z\ AttSW + AttPL \int_z^0 [PSn(\zeta) + PLn(\zeta)] d\zeta\right\},$ (A12)

1481 **A2 Update aerobic decomposition from PON to NH4 and from DON to NH4 due to the introduction of oxygen**
1482 **dependency**

1483 $DecP2N = PON\ VP2N_0\ exp(K_{P2N}\ TMP)\ r,$ (A13)

1484 $DecD2N = PON\ VD2N_0\ exp(K_{D2N}\ TMP)\ r,$ (A14)

1485 where,

1486 $r = max\left[\frac{max(0, Oxyg - Oxyg_{th})}{K_{Oxyg} + Oxyg - Oxyg_{th}}, 0\right],$ (A15)

A3 Update water column nitrification due to the introduction of oxygen dependency and light limitation

$$Nit = Nit_0 \, exp(K_{Nit} \, TMP) \, LgtlimN \, r,$$ (A16)

where,

$$LgtlimN = 1 - max\left(0, \frac{I_N - I_0}{I_N - I_0 + k_I}\right),$$ (A17)

$$I_N = PAR \, frac \, exp\left\{z \, AttSW + max(AttPS, AttPL) \int_z^0 [PSn(\zeta) + PLn(\zeta)]d\zeta\right\},$$ (A18)

A4 Additional SOC term:

$$SOC = 8.3865 \, PON_{sed} \, VP2N_0 \, exp(K_{P2N} \, TMP),$$ (A19)

Appendix B: Descriptions of terms and parameters

Table B1. Descriptions of state variables

Terms	Description	Unit
NH_4	Ammonium concentration	mmolN m^{-3}
NO_3	Nitrate concentration	mmolN m^{-3}
PO_4	Phosphate concentration	mmolP m^{-3}
DOP	Dissolved organic phosphorus concentration	mmolP m^{-3}
POP	Particulate organic phosphorus concentration	mmolP m^{-3}
$SiOH_4$	Silicate concentration	mmolSi m^{-3}
PSn	Small phytoplankton biomass concentration measured in nitrogen	mmolN m^{-3}
PLn	Large phytoplankton biomass concentration measured in nitrogen	mmolN m^{-3}
$Oxyg$	Dissolved oxygen concentration	mmolO$_2$ m^{-3}

Table B2 Descriptions of related terms involved in the phosphorus cycle and nutrient limitation. Superscripts "*" and "+" denote that the mathematic expressions of corresponding terms are the same as those in Kishi et al. (2007) and Shropshire et al. (2020), respectively. Expressions of terms with no superscript are updated and reported in Appendix A.

Terms	Description	Unit
$DecP2N$	Decomposition rate from PON to NH$_4$	mmolN m^{-3} day^{-1}
$DecD2N$	Decomposition rate from DON to NH$_4$	mmolN m^{-3} day^{-1}
$DecP2D^{*+}$	Decomposition rate from PON to DON	mmolN m^{-3} day^{-1}
$EgeZLn^{+}$	Large zooplankton egestion rate measured in nitrogen	mmolN m^{-3} day^{-1}
$EgeZPn^{*+}$	Predatory zooplankton egestion rate measured in nitrogen	mmolN m^{-3} day^{-1}

37

$EgeZSn^{*+}$	Small zooplankton egestion rate measured in nitrogen	mmolN m^{-3} day^{-1}
$ExcPSn^{*+}$	Small phytoplankton extracellular excretion rate to DON and is measured in nitrogen	mmolN m^{-3} day^{-1}
$ExcPLn^{*+}$	Large phytoplankton extracellular excretion rate to DON and is measured in nitrogen	mmolN m^{-3} day^{-1}
$ExcZSn^{*+}$	Small zooplankton excretion rate to NH$_4$ and is measured in nitrogen	mmolN m^{-3} day^{-1}
$ExcZLn^{+}$	Large zooplankton excretion rate to NH$_4$ and is measured in nitrogen	mmolN m^{-3} day^{-1}
$ExcZPn^{*+}$	Predatory zooplankton excretion rate to NH$_4$ and is measured in nitrogen	mmolN m^{-3} day^{-1}
$GppNPS$	Small phytoplankton nitrate-induced gross primary production rate measured in nitrogen	mmolN m^{-3} day^{-1}
$GppAPS$	Small phytoplankton ammonium-induced gross primary production rate measured in nitrogen	mmolN m^{-3} day^{-1}
$GppPSn$	Small phytoplankton gross primary production rate measured in nitrogen	mmolN m^{-3} day^{-1}
$GppNPL$	Large phytoplankton nitrate-induced gross primary production rate measured in nitrogen	mmolN m^{-3} day^{-1}
$GppAPL$	Large phytoplankton ammonium-induced gross primary production rate measured in nitrogen	mmolN m^{-3} day^{-1}
$GppPLn$	Large phytoplankton gross primary production rate measured in nitrogen	mmolN m^{-3} day^{-1}
$MorPSn^{+}$	Small phytoplankton mortality rate measured in nitrogen	mmolN m^{-3} day^{-1}
$MorPLn^{+}$	Large phytoplankton mortality rate measured in nitrogen	mmolN m^{-3} day^{-1}
$MorZSn^{+}$	Small zooplankton mortality rate measured in nitrogen	mmolN m^{-3} day^{-1}
$MorZLn^{+}$	Large zooplankton mortality rate measured in nitrogen	mmolN m^{-3} day^{-1}
$MorZPn^{*+}$	Predatory zooplankton mortality rate measured in nitrogen	mmolN m^{-3} day^{-1}
Nit	Nitrification rate	mmolN m^{-3} day^{-1}
$ResPSn^{*+}$	Small phytoplankton respiration rate measured in nitrogen	mmolN m^{-3} day^{-1}
$ResPLn^{*+}$	Large phytoplankton respiration rate measured in nitrogen	mmolN m^{-3} day^{-1}
SOC	Sediment oxygen consumption rate	mmolO$_2$ m^{-2} day^{-1}

1502

1503   **Table B3 Descriptions of other variables**

Terms	Description	Unit
I_{PS}	Photosynthetically available radiation for small phytoplankton	W m^{-2}
I_{PL}	Photosynthetically available radiation for large phytoplankton	W m^{-2}
I_N	Maximum photosynthetically available radiation	W m^{-2}
$LgtlimN$	Light inhibition on nitrification rate	no dimension
$NutlimPS$	Nutrient limitation term for small phytoplankton	no dimension
$NutlimPL$	Nutrient limitation term for large phytoplankton	no dimension
PAR	Net short-wave radiation on water surface	W m^{-2}
r	Oxygen inhibition on nitrification and aerobic decomposition rates	no dimension
$RnewS$	The f-ratio of small phytoplankton which is defined by the ratio of nitrate uptake to total uptake of nitrate and ammonium	no dimension
$RnewL$	The f-ratio of large phytoplankton which is defined by the ratio of nitrate uptake to total uptake of nitrate and ammonium	no dimension
$Thickness_{bot}$	Thickness of the bottom water layer	m
TMP	Water temperature	°C
z, ζ	Vertical coordinate which is negative below sea surface	m

1504

1505 **Table B4. Descriptions and values of all model parameters. Superscripts "S", "L", "F06", and "F13" denote that the corresponding**
1506 **parameters follow Shropshire et al. (2020), Laurent et al. (2012), Fennel et al. (2006), and Fennel et al. (2013), respectively.**
1507 **Superscript "*" indicates the corresponding parameters are from this study.**

Parameter	Description	Units	Values
		Small phytoplankton	
V_{maxS}	Small phytoplankton maximum photosynthetic rate at 0 °C	day^{-1}	0.4^S
K_{NO_3S}	Small Phytoplankton half saturation constant for nitrate	mmolN m^{-3}	0.5^S
K_{NH_4S}	Small Phytoplankton half saturation constant for ammonium	mmolN m^{-3}	0.1^S
K_{PO_4S}	Small Phytoplankton half saturation constant for phosphate	mmolP m^{-3}	0.5^L
α_{PS}	Small phytoplankton photochemical reaction coefficient, initial slope of P-I curve	m^2 W^{-1} day^{-1}	0.1^S

β_{PS}	Small phytoplankton photoinhibition coefficient	$m^2 W^{-1} day^{-1}$	0.00045^S
Res_{PS0}	Small phytoplankton respiration rate at 0 °C	day^{-1}	0.03^S
Mor_{PS0}	Small phytoplankton mortality rate at 0 °C	$m^3 mmolN^{-1} day^{-1}$	0.002^S
γ_S	Ratio of extracellular excretion to photosynthesis for small phytoplankton	no dimension	0.135^S
K_{GppS}	Small phytoplankton temperature coefficient for photosynthetic rate	$°C^{-1}$	0.0693^S
K_{ResPS}	Small phytoplankton temperature coefficient for respiration	$°C^{-1}$	0.0519^S
K_{MorPS}	Small phytoplankton temperature coefficient for mortality	$°C^{-1}$	0.0693^S

Large phytoplankton			
V_{maxL}	Large phytoplankton maximum photosynthetic rate at 0 °C	day^{-1}	0.8^S
K_{NO_3L}	Large Phytoplankton half saturation constant for nitrate	$mmolN\ m^{-3}$	3.0^S
K_{NH_4L}	Large Phytoplankton half saturation constant for ammonium	$mmolN\ m^{-3}$	0.3^S
K_{PO_4L}	Large Phytoplankton half saturation constant for phosphate	$mmolP\ m^{-3}$	0.5^L
K_{SiOH_4L}	Large Phytoplankton half saturation constant for silicate	$mmolSi\ m^{-3}$	6.0^S
α_{PL}	Large phytoplankton photochemical reaction coefficient, initial slope of P-I curve	$m^2 W^{-1} day^{-1}$	0.1^S
β_{PL}	Large phytoplankton photoinhibition coefficient	$m^2 W^{-1} day^{-1}$	0.00045^S
Res_{PL0}	Large phytoplankton respiration rate at 0 °C	day^{-1}	0.03^S
Mor_{PL0}	Large phytoplankton mortality rate at 0 °C	$m^3 mmolN^{-1} day^{-1}$	0.001^S

γ_L	Ratio of extracellular excretion to photosynthesis for large phytoplankton	no dimension	0.135[S]
K_{GppL}	Large phytoplankton temperature coefficient for photosynthetic rate	$°C^{-1}$	0.0693[S]
K_{MorPL}	Large phytoplankton temperature coefficient for mortality	$°C^{-1}$	0.0693[S]
K_{ResPL}	Large phytoplankton temperature coefficient for respiration	$°C^{-1}$	0.0693[S]

<div align="center">Small zooplankton</div>

GR_{maxSps}	Small zooplankton maximum grazing rate on small phytoplankton at 0 °C	day^{-1}	0.6[S]
λ_S	Ivlev constant of small zooplankton	m^3 mmolN^{-1}	1.4[S]
$PS2ZS$	Small zooplankton threshold value for grazing on small phytoplankton	mmolN m^{-3}	0.043[S]
α_{ZS}	Assimilation efficiency of small zooplankton	no dimension	0.7[S]
β_{ZS}	Growth efficiency of small zooplankton	no dimension	0.3[S]
Mor_{ZS0}	Small zooplankton mortality rate at 0 °C	m^3 mmolN^{-1} day^{-1}	0.022[S]
K_{GraS}	Small zooplankton temperature coefficient for grazing	$°C^{-1}$	0.0693[S]
K_{MorZS}	Small zooplankton temperature coefficient for mortality	$°C^{-1}$	0.0693[S]

<div align="center">Large zooplankton</div>

GR_{maxLps}	Large zooplankton maximum grazing rate on small phytoplankton at 0 °C	day^{-1}	0[S]
GR_{maxLpl}	Large zooplankton maximum grazing rate on large phytoplankton at 0 °C	day^{-1}	0.3[S]
GR_{maxLzs}	Large zooplankton maximum grazing rate on small zooplankton at 0 °C	day^{-1}	0.3[S]
λ_L	Ivlev constant of large zooplankton	m^3 mmolN^{-1}	1.4[S]
$PL2ZL$	Large zooplankton threshold value for grazing on large phytoplankton	mmolN m^{-3}	0.040[S]

$ZS2ZL$	Large zooplankton threshold value for grazing on small zooplankton	mmolN m^{-3}	0.040[S]
α_{ZL}	Assimilation efficiency of large zooplankton	no dimension	0.7[S]
β_{ZL}	Growth efficiency of large zooplankton	no dimension	0.3[S]
Mor_{ZL0}	Large zooplankton mortality rate at 0 ℃	m^3 mmolN^{-1} day^{-1}	0.022[S]
K_{GraL}	Large zooplankton temperature coefficient for grazing	℃$^{-1}$	0.0693[S]
K_{MorZL}	Large zooplankton temperature coefficient for mortality	℃$^{-1}$	0.0693[S]

<div align="center">Predatory zooplankton</div>

GR_{maxPpl}	Predatory zooplankton maximum grazing rate on large phytoplankton at 0 ℃	day^{-1}	0.1[S]
GR_{maxPzs}	Predatory zooplankton maximum grazing rate on small zooplankton at 0 ℃	day^{-1}	0.1[S]
GR_{maxPzl}	Predatory zooplankton maximum grazing rate on large zooplankton at 0 ℃	day^{-1}	0.3[S]
λ_P	Ivlev constant of predatory zooplankton	m^3 mmolN^{-1}	1.4[S]
$PL2ZP$	Predatory zooplankton threshold value for grazing on large phytoplankton	mmolN m^{-3}	0.040[S]
$ZS2ZP$	Predatory zooplankton threshold value for grazing on small zooplankton	mmolN m^{-3}	0.040[S]
$ZL2ZP$	Predatory zooplankton threshold value for grazing on large zooplankton	mmolN m^{-3}	0.040[S]
α_{ZP}	Assimilation efficiency of predatory zooplankton	no dimension	0.7[S]
β_{ZP}	Growth efficiency of predatory zooplankton	no dimension	0.3[S]
Mor_{ZP0}	Predatory zooplankton mortality rate at 0 ℃	m^3 mmolN^{-1} day^{-1}	0.12[S]
K_{GraP}	Predatory zooplankton temperature coefficient for grazing	℃$^{-1}$	0.0693[S]

K_{MorZP}	Predatory zooplankton temperature coefficient for mortality	$°C^{-1}$	0.0693[S]
ψ_{PL}	Grazing inhibition coefficient of predatory zooplankton grazing on large phytoplankton	$m^3\ mmolN^{-1}$	4.605[S]
ψ_{ZS}	Grazing inhibition coefficient of predatory zooplankton grazing on small zooplankton	$m^3\ mmolN^{-1}$	3.01[S]

<table>
<tr><td colspan="4" align="center">Light</td></tr>
</table>

$AttSW$	Light attenuation due to seawater	m^{-1}	0.03[S]
$AttPS$	Light attenuation due to small phytoplankton, self-shading coefficient	$m^2\ mmolN^{-1}$	0.03[S]
$AttPL$	Light attenuation due to large phytoplankton, self-shading coefficient	$m^2\ mmolN^{-1}$	0.03[S]
$frac$	Fraction of shortwave radiation that is photosynthetically active	no dimension	0.43[S]
I_0	Threshold of light inhibition of nitrification	$W\ m^{-2}$	0.0095[F06]
k_I	Light intensity at which light inhibition of nitrification is half-saturated	$W\ m^{-2}$	0.1[F06]

<table>
<tr><td colspan="4" align="center">Water column nitrification and aerobic decomposition</td></tr>
</table>

Nit_0	Nitrification rate at 0 °C	day^{-1}	0.003[S]
$VP2N_0$	Decomposition rate at 0 °C (PON→NH_4)	day^{-1}	0.01[S]
$VP2D_0$	Decomposition rate at 0 °C (PON→DON)	day^{-1}	0.05[S]
$VD2N_0$	Decomposition rate at 0 °C (DON→NH_4)	day^{-1}	0.02[S]
$VO2S_0$	Decomposition rate at 0 °C (Opal→$Si(OH)_4$)	day^{-1}	0.01[S]
K_{Nit}	Temperature coefficient for nitrification	$°C^{-1}$	0.0693[S]
K_{P2D}	Temperature coefficient for decomposition (PON→DON)	$°C^{-1}$	0.0693[S]
K_{P2N}	Temperature coefficient for decomposition (PON→NH_4)	$°C^{-1}$	0.0693[S]
K_{D2N}	Temperature coefficient for decomposition (DON→NH_4)	$°C^{-1}$	0.0693[S]

K_{O2S}	Temperature coefficient for decomposition (Opal→Si(OH)$_4$)	$°C^{-1}$		0.0693[S]

Other parameters			
K_{Oxyg}	Oxygen concentration at which inhibition of nitrification and aerobic respiration are half-saturated	mmolO$_2$ m^{-3}	3.0[F13]
$Oxyg_{th}$	Oxygen concentration threshold below which no aerobic respiration or nitrification occurs	mmolO$_2$ m^{-3}	6.0[F13]
$RPO4N$	P: N ratio	mmolP mmolN^{-1}	1/16[L]
$RSiN$	Si: N ratio	mmolSi mmolN^{-1}	1[S]
$rOxNO_3$	Stoichiometric ratios corresponding to the oxygen produced per mol of nitrate assimilated during photosynthesis	mmolO$_2$ mmolNO$_3$$^{-1}$	138/16[F13]
$rOxNH_4$	Stoichiometric ratios corresponding to the oxygen produced per mol of ammonium assimilated during photosynthesis	mmolO$_2$ mmolNH$_4$$^{-1}$	106/16[F13]
$setVPON$	Sinking velocity of PON	m day^{-1}	-5[*]
$setVOpal$	Sinking velocity of Opal	m day^{-1}	-5[*]

1508

Appendix C: Supporting figures and tables
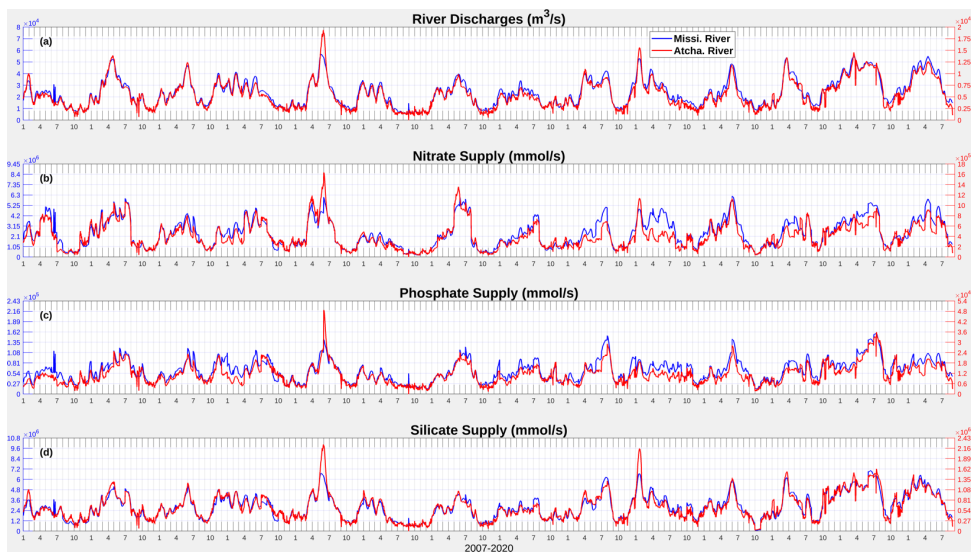
1510

1511 **Figure C1. Daily time series (2007–2020) of river discharges of freshwater, nitrate, phosphate, and silicate from the Mississippi and**
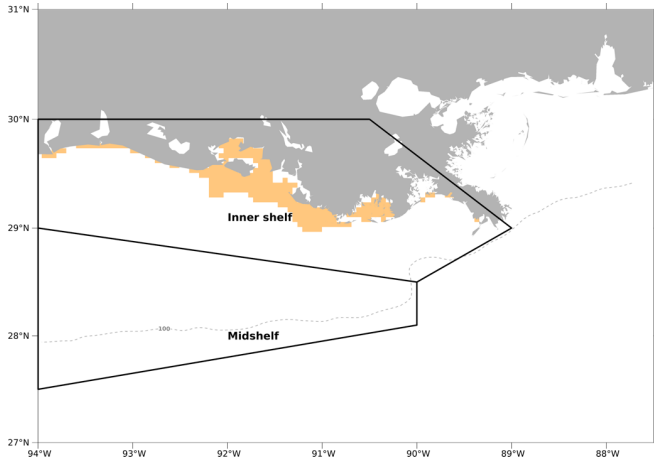1512 **Atchafalaya Rivers.**

1513 **Table C1. A correlation matrix of daily inorganic nutrient loads by the Mississippi River and the Atchafalaya River from 2007 to**
1514 **2020. Correlation coefficients shown are all significant ($p<0.001$).**

	Mississippi nitrate+nitrite	Atchafalaya nitrate+nitrite	Mississippi phosphate	Atchafalaya phosphate	Mississippi silicate	Atchafalaya silicate
Mississippi nitrate+nitrite	1					
Atchafalaya nitrate+nitrite	0.9123	1				
Mississippi phosphate	0.8328	0.7577	1			
Atchafalaya phosphate	0.7517	0.7913	0.9155	1		
Mississippi silicate	0.8583	0.7795	0.8759	0.7942	1	

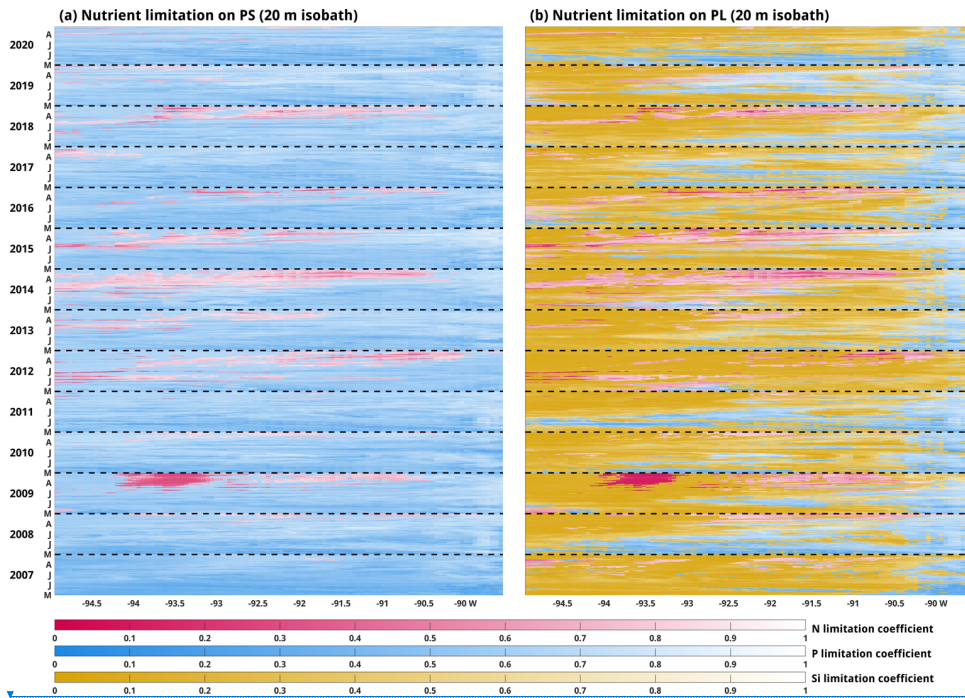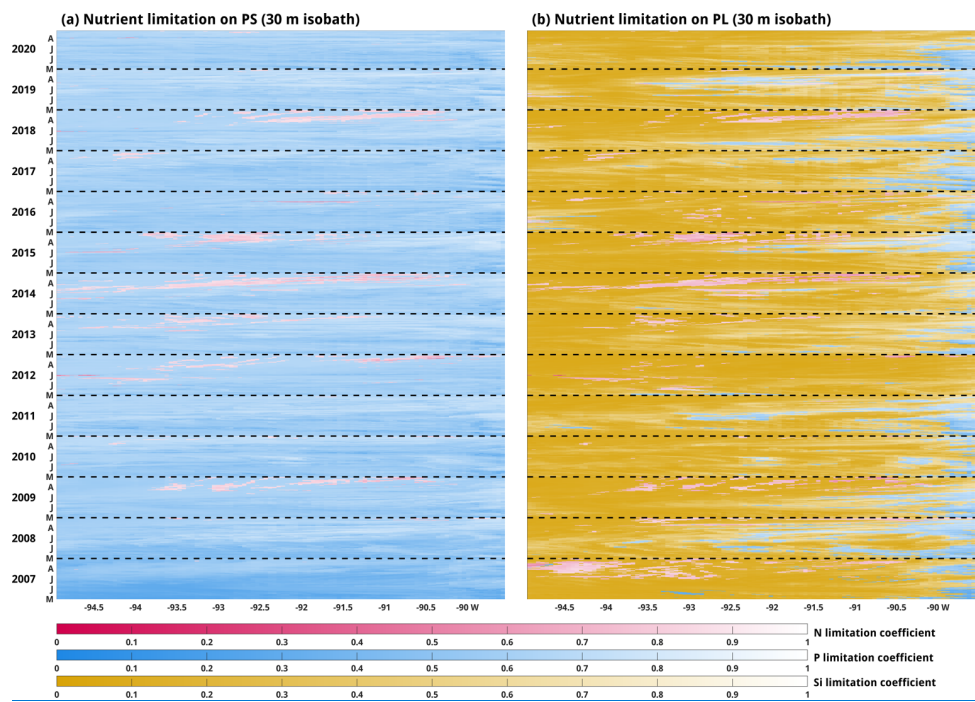|					
Atchafalaya silicate	0.7938	0.7956	0.8131	0.8148	0.9520	1

1516

1517

Figure C2. The model computational meshes over which the regionally averaged diatom ratios were conducted for validation purposes. The orange-patched region covers roughly the study regions in Schaeffer et al. (2012), while the regions restricted by two black polygons are two regions (i.e., inner shelf and mid-shelf) where samples were collected in Chakraborty and Lohrenz's (2015) study.

(a) Nutrient limitation on PS (20 m isobath) (b) Nutrient limitation on PL (20 m isobath)

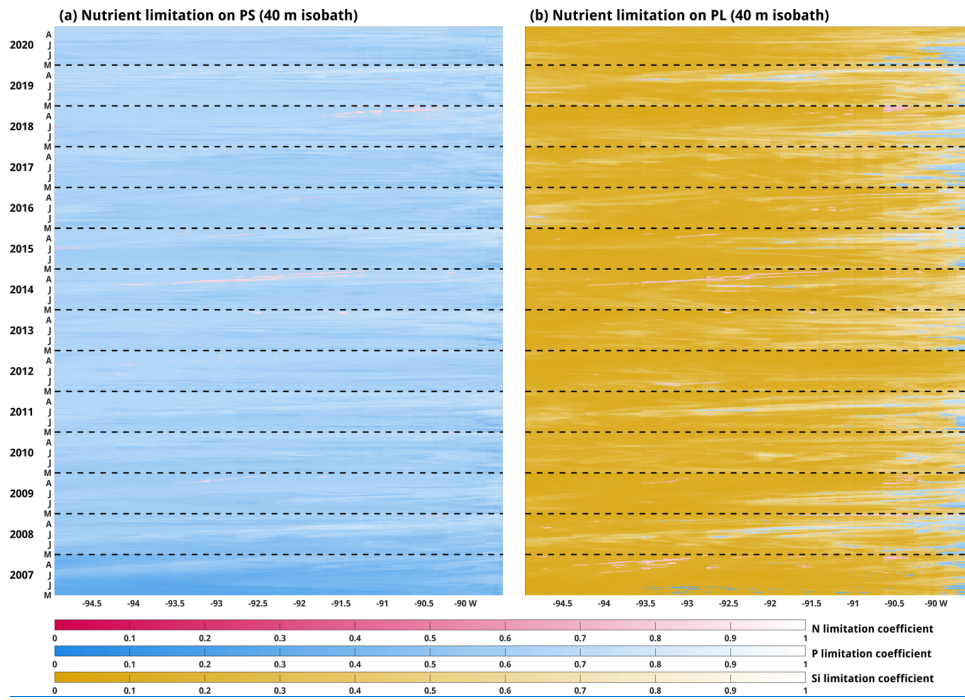N limitation coefficient

P limitation coefficient

Si limitation coefficient

Figure C3. Evolution of depth-averaged nutrient limitation coefficients for (a) PS and (PL) along the 20 m isobath during late spring and summer. The notations of M, J, J, and A in the y-axis represent the first day of May, June, July, and August, respectively. Note that a lower (deeper colored) coefficient represents stronger limitations on phytoplankton growth. The dashed black lines indicate the time record on May 1 of each year.

(a) Nutrient limitation on PS (30 m isobath)   (b) Nutrient limitation on PL (30 m isobath)

N limitation coefficient
0   0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1

P limitation coefficient
0   0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1

Si limitation coefficient
0   0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1

1529

1530   Figure C4. Same as Figure C3, but along the 30 m isobath.

48

(a) Nutrient limitation on PS (40 m isobath)

(b) Nutrient limitation on PL (40 m isobath)

N limitation coefficient

P limitation coefficient

Si limitation coefficient

Figure C5. Same as Figure C3, but along the 40 m isobath.

(a) Nutrient limitation on PS (50 m isobath)

(b) Nutrient limitation on PL (50 m isobath)

N limitation coefficient

P limitation coefficient

Si limitation coefficient
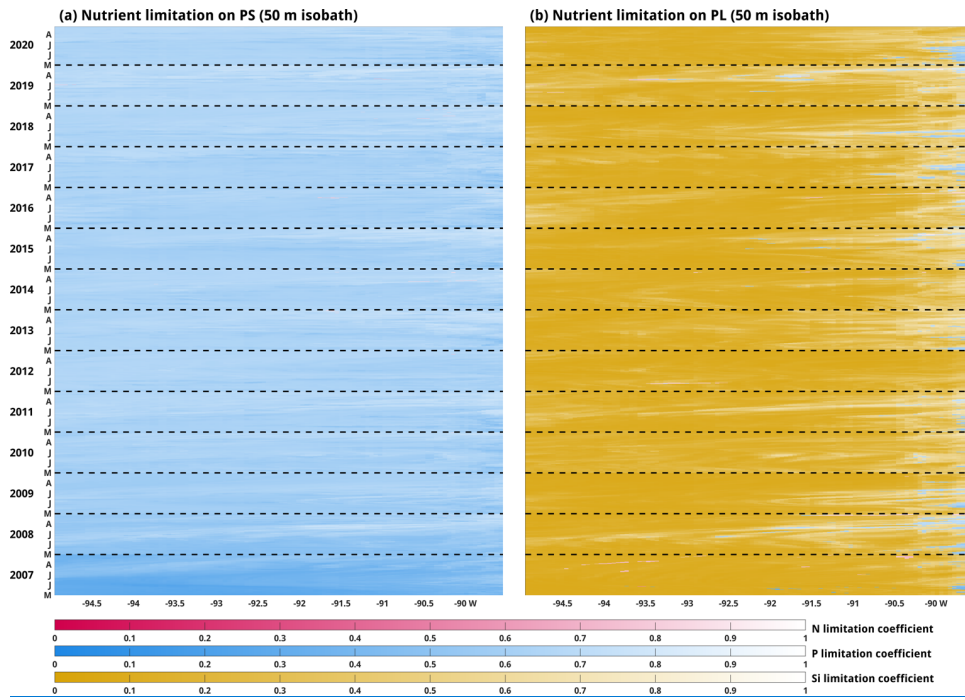
Figure C6. Same as Figure C3, but along the 50 m isobath.

50

1536
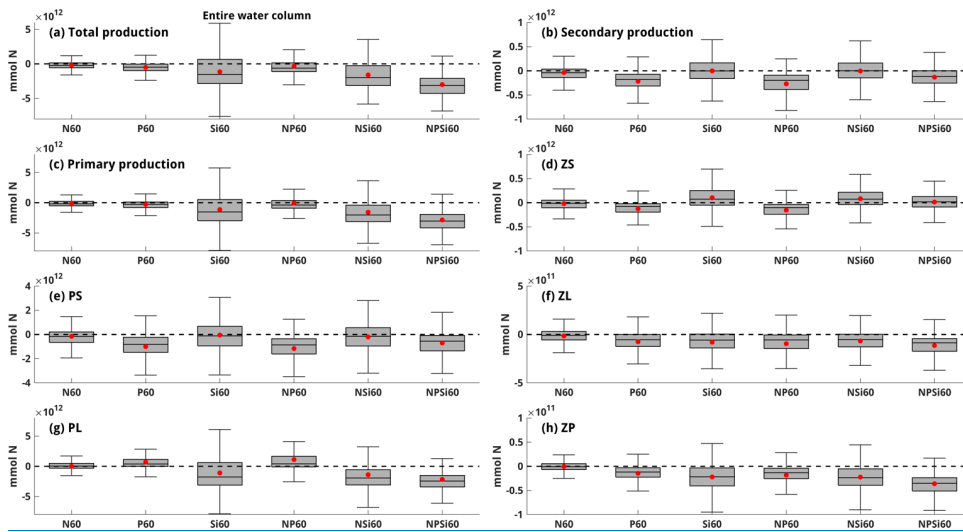
Figure C7. Responses of (a) total production, (b) secondary production, (c) primary production, (d) ZS biomass, (e) PS biomass, (f) ZL biomass, (g) PL biomass, and (h) ZP biomass to the reductions in riverine nutrient loads. All biomass matrices were integrated over the entire water column and the LaTex shelf. Statistics shown are mean (red dots), median, first quartile, third quartile, minimum, and maximum derived from the differences between sensitivity tests and the control run during late spring and summer (May–August).

51
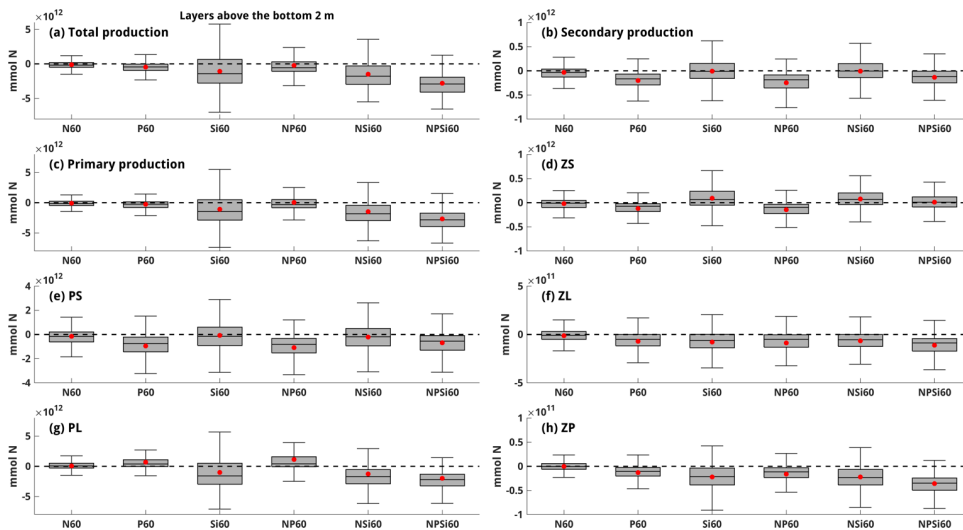
Figure C8. Same as Fig. C7, but for integrated biomass over layers above the bottom 2 m.
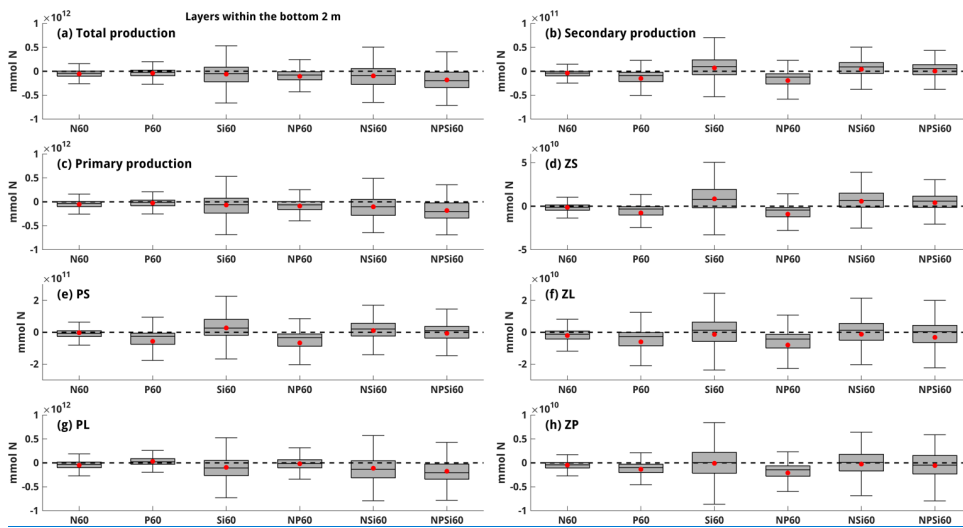
Figure C9. Same as Fig. C7, but for integrated biomass at layers within 2 m above the bottom.

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References

Del Amo, Y. and Brzezinski, M. A.: The chemical form of dissolved Si taken up by marine diatoms, J. Phycol., 35, 1162–1170, https://doi.org/10.1046/j.1529-8817.1999.3561162.x, 1999.

Anglès, S., Jordi, A., Henrichs, D. W., and Campbell, L.: Influence of coastal upwelling and river discharge on the phytoplankton community composition in the northwestern Gulf of Mexico, Prog. Oceanogr., 173, 26–36, https://doi.org/10.1016/j.pocean.2019.02.001, 2019.

Azam, F.: Silicic-acid uptake in diatoms studied with [68Ge]germanic acid as tracer, Planta, 121, 205–212, https://doi.org/10.1007/BF00389321, 1974.

Azam, F., Hemmingsen, B. B., and Volcani, B. E.: Role of silicon in diatom metabolism - V. silicic acid transport and metabolism in the heterotrophic diatom Nitzschia alba, Arch. Microbiol., 97, 103–114, https://doi.org/10.1007/BF00403050, 1974.

Bianchi, T. S., DiMarco, S. F., Cowan, J. H., Hetland, R. D., Chapman, P., Day, J. W., and Allison, M. A.: The science of hypoxia in the northern Gulf of Mexico: A review, Sci. Total Environ., 408, 1471–1484, https://doi.org/10.1016/j.scitotenv.2009.11.047, 2010.

Bleck, R.: An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates, Ocean Model., 4, 55–88, https://doi.org/10.1016/S1463-5003(01)00012-9, 2002.

Bleck, R. and Boudra, D. B.: Initial testing of a numerical ocean circulation model using a hybrid (quasi-isopycnic) vertical coordinate, J. Phys. Oceanogr., 11, 755–770, https://doi.org/https://doi.org/10.1175/1520-0485(1981)011<0755:ITOANO>2.0.CO;2, 1981.

Boyer, T. P., Baranova, O. K., Coleman, C., Garcia, H. E., Grodsky, A., Locarnini, R. A., Mishonov, A. V, Paver, C. R., Reagan, J. R., Seidov, D., Smolyar, I. V, Weathers, K. W., and Zweng, M. M.: World Ocean Database 2018, Technical., edited by: Mishonov, A. V., NOAA Atlas NESDIS 87, 2018.

Chakraborty, S. and Lohrenz, S. E.: Phytoplankton community structure in the river-influenced continental margin of the northern Gulf of Mexico, Mar. Ecol. Prog. Ser., 521, 31–47, https://doi.org/10.3354/meps11107, 2015.

Chakraborty, S., Lohrenz, S. E., and Gundersen, K.: Photophysiological and light absorption properties of phytoplankton communities in the river-dominated margin of the northern Gulf of Mexico, J. Geophys. Res. Ocean., 122, 4922–4938, https://doi.org/10.1002/2016JC012092, 2017.

Chapman, D. C.: Numerical treatment of cross-shelf open boundaries in a barotropic coastal ocean model., https://doi.org/10.1175/1520-0485(1985)015<1060:ntocso>2.0.co;2, 1985.

Cummings, J. A.: Operational multivariate ocean data assimilation, Q. J. R. Meteorol. Soc., 131, 3583–3604, https://doi.org/10.1256/qj.05.105, 2005.

Cummings, J. A. and Smedstad, O. M.: Variational Data Assimilation for the Global Ocean, in: Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications, vol. II, edited by: Park, S. K. and Xu, L., Springer Berlin Heidelberg, 303–343, https://doi.org/10.1007/978-3-642-35088-7_13, 2013.

Dortch, Q. and Whitledge, T. E.: Does nitrogen or silicon limit phytoplankton production in the Mississippi River plume and nearby regions?, Cont. Shelf Res., 12, 1293–1309, https://doi.org/10.1016/0278-4343(92)90065-R, 1992.

Feng, Y., Fennel, K., Jackson, G. A., DiMarco, S. F., and Hetland, R. D.: A model study of the response of hypoxia to upwelling-favorable wind on the northern Gulf of Mexico shelf, J. Mar. Syst., 131, 63–73, https://doi.org/10.1016/j.jmarsys.2013.11.009, 2014.

Fennel, K. and Laurent, A.: N and P as ultimate and proximate limiting nutrients in the northern Gulf of Mexico: Implications for hypoxia reduction strategies, 15, 3121–3131, https://doi.org/10.5194/bg-15-3121-2018, 2018.

Fennel, K. and Testa, J. M.: Biogeochemical Controls on Coastal Hypoxia, Ann. Rev. Mar. Sci., 11, 105–130, https://doi.org/10.1146/annurev-marine-010318-095138, 2019.

Fennel, K., Wilkin, J., Levin, J., Moisan, J., O'Reilly, J., and Haidvogel, D.: Nitrogen cycling in the Middle Atlantic Bight: Results from a three-dimensional model and implications for the North Atlantic nitrogen budget, Global Biogeochem. Cycles, 20, 1–14, https://doi.org/10.1029/2005GB002456, 2006.

Fennel, K., Hetland, R., Feng, Y., and Dimarco, S.: A coupled physical-biological model of the Northern Gulf of Mexico shelf: Model description, validation and analysis of phytoplankton variability, 8, 1881–1899, https://doi.org/10.5194/bg-8-1881-2011, 2011.

Fennel, K., Hu, J., Laurent, A., Marta-Almeida, M., and Hetland, R.: Sensitivity of hypoxia predictions for the northern Gulf of Mexico to sediment oxygen consumption and model nesting, J. Geophys. Res. Ocean., 118, 990–1002, https://doi.org/10.1002/jgrc.20077, 2013.

Fennel, K., Laurent, A., Hetland, R., Justic, D., Ko, D. S., Lehrter, J., Murrell, M., Wang, L., Yu, L., and Zhang, W.: Effects of model physics on hypoxia simulations for the northern Gulf of Mexico: A model intercomparison, J. Geophys. Res. Ocean., 121, 5731–5750, https://doi.org/10.1002/2015JC011516, 2016.

Fiechter, J. and Moore, A. M.: Interannual spring bloom variability and Ekman pumping in the coastal Gulf of Alaska, J. Geophys. Res. Ocean., 114, 1–19, https://doi.org/10.1029/2008JC005140, 2009.

Flather, R. A.: A tidal model of the northwest European continental shelf, Mem. la Soc. R. Sci. Liege, 10, 141–164, 1976.

Fox, D. N., Teague, W. J., Barron, C. N., Carnes, M. R., and Lee, C. M.: The Modular Ocean Data Assimilation System (MODAS), J. Atmos. Ocean. Technol., 19, 240–252, https://doi.org/10.1175/1520-0426(2002)019<0240:TMODAS>2.0.CO;2, 2002.

Garcia, H. E., Weathers, K., Paver, C. R., Smolyar, I., Boyer, T. P., Locarnini, R. A., Zweng, M. M., Mishonov, A. V., Baranova, O. K., Seidov, D., and Reagan, J. R.: World Ocean Atlas 2018, Volume 3: Dissolved Oxygen, Apparent Oxygen Utilization, and Oxygen Saturation, Technical., edited by: Mishonov, A. V., NOAA Atlas NESDIS 83, 38 pp., 2018.

Gomez, F. A., Lee, S. K., Liu, Y., Hernandez, F. J., Muller-Karger, F. E., and Lamkin, J. T.: Seasonal patterns in phytoplankton biomass across the northern and deep Gulf of Mexico: A numerical model study, 15, 3561–3576, https://doi.org/10.5194/bg-15-3561-2018, 2018.

Große, F., Fennel, K., and Laurent, A.: Quantifying the Relative Importance of Riverine and Open-Ocean Nitrogen Sources for Hypoxia Formation in the Northern Gulf of Mexico, J. Geophys. Res. Ocean., 5451–5467, https://doi.org/10.1029/2019jc015230, 2019.

Haidvogel, D. B., Arango, H. G., Hedstrom, K., Beckmann, A., Malanotte-Rizzoli, P., and Shchepetkin, A. F.: Model evaluation experiments in the North Atlantic Basin: Simulations in nonlinear terrain-following coordinates, Dyn. Atmos. Ocean., 32, 239–281, https://doi.org/10.1016/S0377-0265(00)00049-X, 2000.

Helber, R. W., Townsend, T. L., Barron, C. N., Dastugue, J. M., and Carnes, M. R.: Validation Test Report for the Improved Synthetic Ocean Profile (ISOP) System, Part I: Synthetic Profile Methods and Algorithm, 2013.

Hetland, R. D. and DiMarco, S. F.: How does the character of oxygen demand control the structure of hypoxia on the Texas-Louisiana continental shelf?, J. Mar. Syst., 70, 49–62, https://doi.org/10.1016/j.jmarsys.2007.03.002, 2008.

Justić, D. and Wang, L.: Assessing temporal and spatial variability of hypoxia over the inner Louisiana-upper Texas shelf: Application of an unstructured-grid three-dimensional coupled hydrodynamic-water quality model, Cont. Shelf Res., 72, 163–179, https://doi.org/10.1016/j.csr.2013.08.006, 2014.

Justić, D., Rabalais, N. N., and Turner, R. E.: Simulated responses of the Gulf of Mexico hypoxia to variations in climate and anthropogenic nutrient loading, J. Mar. Syst., 42, 115–126, https://doi.org/10.1016/S0924-7963(03)00070-8, 2003.

Justić, D., Bierman, V. J. J., Scavia, D., and Hetland, R. D.: Forecasting Gulf's Hypoxia: The Next 50 Years?, 30, 791–801, 2007.

Kishi, M. J., Kashiwai, M., Ware, D. M., Megrey, B. A., Eslinger, D. L., Werner, F. E., Noguchi-Aita, M., Azumaya, T., Fujii, M., Hashimoto, S., Huang, D., Iizumi, H., Ishida, Y., Kang, S., Kantakov, G. A., Kim, H. cheol, Komatsu, K., Navrotsky, V. V., Smith, S. L., Tadokoro, K., Tsuda, A., Yamamura, O., Yamanaka, Y., Yokouchi, K., Yoshie, N., Zhang, J., Zuenko, Y. I., and Zvalinsky, V. I.: NEMURO-a lower trophic level model for the North Pacific marine ecosystem, Ecol. Modell., 202, 12–25, https://doi.org/10.1016/j.ecolmodel.2006.08.021, 2007.

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Kristiansen, S. and Hoell, E. E.: The importance of silicon for marine production, Hydrobiologia, 484, 21–31, https://doi.org/10.1023/A:1021392618824, 2002.

Laurent, A. and Fennel, K.: Simulated reduction of hypoxia in the northern Gulf of Mexico due to phosphorus limitation, Elem. Sci. Anthr., 2, 1–12, https://doi.org/10.12952/journal.elementa.000022, 2014.

Laurent, A. and Fennel, K.: Time-Evolving, Spatially Explicit Forecasts of the Northern Gulf of Mexico Hypoxic Zone, Environ. Sci. Technol., 53, 14449–14458, https://doi.org/10.1021/acs.est.9b05790, 2019.

Laurent, A., Fennel, K., Hu, J., and Hetland, R.: Simulating the effects of phosphorus limitation in the Mississippi and Atchafalaya river plumes, 9, 4707–4723, https://doi.org/10.5194/bg-9-4707-2012, 2012.

Laurent, A., Fennel, K., Wilson, R., Lehrter, J., and Devereux, R.: Parameterization of biogeochemical sediment-water fluxes using in situ measurements and a diagenetic model, 13, 77–94, https://doi.org/10.5194/bg-13-77-2016, 2016.

Laurent, A., Fennel, K., Ko, D. S., and Lehrter, J.: Climate change projected to exacerbate impacts of coastal Eutrophication in the Northern Gulf of Mexico, J. Geophys. Res. Ocean., 123, 3408–3426, https://doi.org/10.1002/2017JC013583, 2018.

Li, Q. P., Franks, P. J. S., Landry, M. R., Goericke, R., and Taylor, A. G.: Modeling phytoplankton growth rates and chlorophyll to carbon ratios in California coastal and pelagic ecosystems, J. Geophys. Res. Biogeosciences, 115, 1–12, https://doi.org/10.1029/2009JG001111, 2010.

Lohrenz, S. E., Fahnenstiel, G. L., Redalje, D. G., Lang, G. A., Dagg, M. J., Whitledge, T. E., and Dortch, Q.: Nutrients, irradiance, and mixing as factors regulating primary production in coastal waters impacted by the Mississippi River plume, Cont. Shelf Res., 19, 1113–1141, https://doi.org/10.1016/S0278-4343(99)00012-6, 1999.

Marchesiello, P., McWilliams, J. C., and Shchepetkin, A.: Open boundary conditions for long-term integration of regional oceanic models, Ocean Model., 3, 1–20, https://doi.org/10.1016/S1463-5003(00)00013-5, 2001.

Mattern, J. P., Fennel, K., and Dowd, M.: Sensitivity and uncertainty analysis of model hypoxia estimates for the Texas-Louisiana shelf, J. Geophys. Res. Ocean., 118, 1316–1332, https://doi.org/10.1002/jgrc.20130, 2013.

McCarthy, M. J., Carini, S. A., Liu, Z., Ostrom, N. E., and Gardner, W. S.: Oxygen consumption in the water column and sediments of the northern Gulf of Mexico hypoxic zone, Estuar. Coast. Shelf Sci., 123, 46–53, https://doi.org/10.1016/j.ecss.2013.02.019, 2013.

Milligan, A. J., Varela, D. E., Brzezinski, M. A., and Morel, F. M. M.: Dynamics of silicon metabolism and silicon isotopic discrimination in a marine diatom as a function of pCO2, Limnol. Oceanogr., 49, 322–329, https://doi.org/10.4319/lo.2004.49.2.0322, 2004.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force: Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico, Washington,DC., 2001.

Mississippi River/Gulf of Mexico Watershed Nutrient Task Force: Gulf Hypoxia Action Plan 2008 for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin, Washington,DC., 2008.

Moriarty, J. M., Harris, C. K., Friedrichs, M. A. M., Fennel, K., and Xu, K.: Impact of Seabed Resuspension on Oxygen and Nitrogen Dynamics in the Northern Gulf of Mexico: A Numerical Modeling Study, J. Geophys. Res. Ocean., 123, 7237–7263, https://doi.org/10.1029/2018JC013950, 2018.

Murrell, M. C. and Lehrter, J. C.: Sediment and Lower Water Column Oxygen Consumption in the Seasonally Hypoxic Region of the Louisiana Continental Shelf, 34, 912–924, https://doi.org/10.1007/s12237-010-9351-9, 2011.

Nelson, D. M. and Dortch, Q.: Silicic acid depletion and silicon limitation in the plume of the Mississippi River: Evidence from kinetic studies in spring and summer, Mar. Ecol. Prog. Ser., 136, 163–178, https://doi.org/10.3354/meps136163, 1996.

Nelson, D. M., Goering. John J., Kilham, S. S., and Guillard., R. R. L.: Kinetics of silicic acid uptake and rates of silica dissolution in the marine diatom Thalassiosira pseudonana, J. Phycol, 12, 246–252, https://doi.org/https://doi.org/10.1111/j.1529-8817.1976.tb00510.x, 1976.

Obenour, D. R., Michalak, A. M., and Scavia, D.: Assessing biophysical controls on Gulf of Mexico hypoxia through probabilistic modeling, Ecol. Appl., 25, 492–505, https://doi.org/10.1890/13-2257.1, 2015.

Olson, R. J.: Differential photoinhibition of marine nitrifying bacteria: a possible mechanism for the formation of the primary nitrite maximum, J. Mar. Res., 39, 227–238, 1981.

Parker, R. A.: Dynamic models for ammonium inhibition of nitrate uptake by phytoplankton, Ecol. Modell., 66, 113–120, https://doi.org/10.1016/0304-3800(93)90042-Q, 1993.

Platt, T., Gallegos, C. L., and Harrison, W. G.: Photoinhibition of photosynthesis in natural assemblages of marine phytoplankton, J. Mar. Res., 38, 687–701, 1980.

Quigg, A., Sylvan, J. B., Gustafson, A. B., Fisher, T. R., Oliver, R. L., Tozzi, S., and Ammerman, J. W.: Going West: Nutrient Limitation of Primary Production in the Northern Gulf of Mexico and the Importance of the Atchafalaya River, Aquat. Geochemistry, 17, 519–544, https://doi.org/10.1007/s10498-011-9134-3, 2011.

Rabalais, N. N. and Baustian, M. M.: Historical Shifts in Benthic Infaunal Diversity in the Northern Gulf of Mexico since the Appearance of Seasonally Severe Hypoxia, 12, https://doi.org/10.3390/d12020049, 2020.

Rabalais, N. N. and Turner, R. E.: Gulf of Mexico Hypoxia: Past, Present, and Future, Limnol. Oceanogr. Bull., 28, 117–124, https://doi.org/10.1002/lob.10351, 2019.

Rabalais, N. N., Turner, R. E., and Wiseman, W. J.: Gulf of Mexico hypoxia, a.k.a. "The dead zone," Annu. Rev. Ecol. Syst., 33, 235–263, https://doi.org/10.1146/annurev.ecolsys.33.010802.150513, 2002.

Rabalais, N. N., Turner, R. E., Sen Gupta, B. K., Boesch, D. F., Chapman, P., and Murrell, M. C.: Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate, and control hypoxia?, 30, 753–772, https://doi.org/10.1007/BF02841332, 2007a.

Rabalais, N. N., Turner, R. E., Gupta, B. K. S., Platon, E., and Parsons, M. L.: Sediments tell the history of eutrophication and hypoxia in the northern Gulf of Mexico, Ecol. Appl., 17, 129–143, https://doi.org/10.1890/06-0644.1, 2007b.

Robertson, R. and Hartlipp, P.: Surface wind mixing in the Regional Ocean Modeling System (ROMS), Geosci. Lett., 4, https://doi.org/10.1186/s40562-017-0090-7, 2017.

Rowe, G. T., Cruz Kaegi, M. E., Morse, J. W., Boland, G. S., and Escobar Briones, E. G.: Sediment community metabolism associated with continental shelf hypoxia, northern Gulf of Mexico, 25, 1097–1106, https://doi.org/10.1007/BF02692207, 2002.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y.-T., Chuang, H.-Y., Juang, H.-M. H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Van Delst, P., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., van den Dool, H., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C.-Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G., and Goldberg, M.: NCEP Climate Forecast System Reanalysis (CFSR) 6-hourly Products, January 1979 to December 2010, https://doi.org/10.5065/D69K487J, 2010.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E.: NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products, https://doi.org/10.5065/D61C1TXF, 2011.

Scavia, D., Evans, M. A., and Obenour, D. R.: A scenario and forecast model for gulf of mexico hypoxic area and volume, Environ. Sci. Technol., 47, 10423–10428, https://doi.org/10.1021/es4025035, 2013.

Schaeffer, B. A., Kurtz, J. C., and Hein, M. K.: Phytoplankton community composition in nearshore coastal waters of Louisiana, Mar. Pollut. Bull., 64, 1705–1712, https://doi.org/10.1016/j.marpolbul.2012.03.017, 2012.

Seitzinger, S. P. and Giblin, A. E.: Estimating denitrification in North Atlantic continental shelf sediments, in: Nitrogen Cycling in the North Atlantic Ocean and its Watersheds, edited by: Howarth, R. W., Springer Dordrecht, 235–260, https://doi.org/10.1007/978-94-009-1776-7_7, 1996.

Shchepetkin, A. F. and McWilliams, J. C.: The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model, Ocean Model., 9, 347–404, https://doi.org/10.1016/j.ocemod.2004.08.002, 2005.

Shchepetkin, A. F. and McWilliams, J. C.: Correction and commentary for "Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the regional ocean modeling system" by Haidvogel et al., J. Comp. Phys. 227, pp. 3595-3624, J. Comput. Phys., 228, 8985–9000, https://doi.org/10.1016/j.jcp.2009.09.002, 2009.

Shropshire, T., Morey, S., Chassignet, E., Bozec, A., Coles, V., Landry, M., Swalethorp, R., Zapfe, G., and Stukel, M.: Quantifying spatiotemporal variability in zooplankton dynamics in the Gulf of Mexico with a physical-biogeochemical model, 17, 3385–3407, https://doi.org/10.5194/bg-17-3385-2020, 2020.

Sylvan, J. B., Quigg, A., Tozzi, S., and Ammerman, J. W.: Eutrophication-induced phosphorus limitation in the Mississippi River plume: Evidence from fast repetition rate fluorometry, Limnol. Oceanogr., 52, 2679–2685, https://doi.org/10.4319/lo.2007.52.6.2679, 2007.

Testa, J. M. and Michael Kemp, W.: Hypoxia-induced shifts in nitrogen and phosphorus cycling in Chesapeake Bay, Limnol. Oceanogr., 57, 835–850, https://doi.org/10.4319/lo.2012.57.3.0835, 2012.

Thamatrakoln, K. and Hildebrand, M.: Silicon uptake in diatoms revisited: A model for saturable and nonsaturable uptake kinetics and the role of silicon transporters, Plant Physiol., 146, 1397–1407, https://doi.org/10.1104/pp.107.107094, 2008.

Turner, R. and Rabalais, N.: Nitrogen and phosphorus phytoplankton growth limitation in the northern Gulf of Mexico, Aquat. Microb. Ecol., 68, 159–169, https://doi.org/10.3354/ame01607, 2013.

Turner, R. E., Qureshi, N., Rabalais, N. N., Dortch, Q., Justić, D., Shaw, R. F., and Cope, J.: Fluctuating silicate:nitrate ratios and coastal plankton food webs, Proc. Natl. Acad. Sci. U. S. A., 95, 13048–13051, https://doi.org/10.1073/pnas.95.22.13048, 1998.

Turner, R. E., Rabalais, N. N., and Justić, D.: Predicting summer hypoxia in the northern Gulf of Mexico: Redux, Mar. Pollut. Bull., 64, 319–324, https://doi.org/10.1016/j.marpolbul.2011.11.008, 2012.

Wang, L. and Justić, D.: A modeling study of the physical processes affecting the development of seasonal hypoxia over the inner Louisiana-Texas shelf: Circulation and stratification, Cont. Shelf Res., 29, 1464–1476, https://doi.org/10.1016/j.csr.2009.03.014, 2009.

Wanninkhof, R.: Relationship Between Wind Speed and Gas Exchange Over the Ocean, J. Geophys. Res., 97, 7373–7382, https://doi.org/10.1029/92JC00188, 1992.

Warner, J. C., Geyer, W. R., and Lerczak, J. A.: Numerical modeling of an estuary: A comprehensive skill assessment, J. Geophys. Res. C Ocean., 110, 1–13, https://doi.org/10.1029/2004JC002691, 2005.

Warner, J. C., Armstrong, B., He, R., and Zambon, J. B.: Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System, Ocean Model., 35, 230–244, https://doi.org/10.1016/j.ocemod.2010.07.010, 2010.

Warner, J. C., Defne, Z., Haas, K., and Arango, H. G.: A wetting and drying scheme for ROMS, Comput. Geosci., 58, 54–61, https://doi.org/10.1016/j.cageo.2013.05.004, 2013.

Wawrik, B. and Paul, J. H.: Phytoplankton community structure and productivity along the axis of the Mississippi River plume in oligotrophic Gulf of Mexico waters, Aquat. Microb. Ecol., 35, 185–196, https://doi.org/10.3354/ame035185, 2004.

Yu, L., Fennel, K., and Laurent, A.: A modeling study of physical controls on hypoxia generation in the northern Gulf of Mexico, J. Geophys. Res. Ocean., 120, 5019–5039, https://doi.org/10.1002/ 2014JC010634, 2015.

Zang, Z., Xue, Z. G., Bao, S., Chen, Q., Walker, N. D., Haag, A. S., Ge, Q., and Yao, Z.: Numerical study of sediment dynamics during hurricane Gustav, Ocean Model., 126, 29–42, https://doi.org/10.1016/j.ocemod.2018.04.002, 2018.

Zang, Z., Xue, Z. G., Xu, K., Bentley, S. J., Chen, Q., D'Sa, E. J., and Ge, Q.: A Two Decadal (1993–2012) Numerical Assessment of Sediment Dynamics in the Northern Gulf of Mexico, 11, 938, https://doi.org/10.3390/w11050938, 2019.

Zang, Z., Xue, Z. G., Xu, K., Ozdemir, C. E., Chen, Q., Bentley, S. J., and Sahin, C.: A Numerical Investigation of Wave-Supported Gravity

1764   Flow During Cold Fronts Over the Atchafalaya Shelf, J. Geophys. Res. Ocean., 125, 1–24, https://doi.org/10.1029/2019JC015269, 2020.

1765   Zhao, Y. and Quigg, A.: Nutrient limitation in Northern Gulf of Mexico (NGOM): Phytoplankton communities and photosynthesis respond
1766   to nutrient pulse, PLoS One, 9, https://doi.org/10.1371/journal.pone.0088732, 2014.

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