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Modeling the Relative Importance of Nutrient and Carbon Loads, Boundary Fluxes, and Sediment Fluxes on Gulf of Mexico Hypoxia

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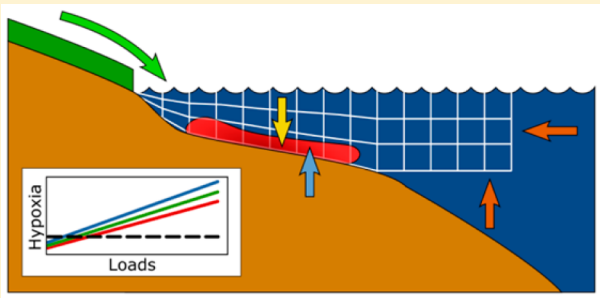
Supporting Information

ABSTRACT: The Louisiana continental shelf in the northern Gulf of Mexico experiences bottom water hypoxia in the summer. In this study, we applied a biogeochemical model that simulates dissolved oxygen concentrations on the shelf in response to varying riverine nutrient and organic carbon loads, boundary fluxes, and sediment fluxes. Five-year model simulations demonstrated that midsummer hypoxic areas were most sensitive to riverine nutrient loads and sediment oxygen demand from settled organic carbon. Hypoxic area predictions were also sensitive to nutrient and organic carbon fluxes from lateral boundaries. The predicted hypoxic area decreased with decreases in nutrient loads, but the extent of change was influenced by the method used to estimate model boundary concentrations. We demonstrated that modeling efforts to predict changes in hypoxic area on the continental shelf in relationship to changes in nutrients should include representative boundary nutrient and organic carbon concentrations and functions for estimating sediment oxygen demand that are linked to settled organic carbon derived from water-column primary production. On the basis of our model analyses using the most representative boundary concentrations, nutrient loads would need to be reduced by 69% to achieve the Gulf of Mexico Nutrient Task Force Action Plan target hypoxic area of 5000 km^2.



INTRODUCTION

Seasonal hypoxia (dissolved oxygen concentrations <2 mg L^{-1}) in the bottom waters of the Louisiana continental shelf (LCS) of the northern Gulf of Mexico has been an ecological concern for several decades.[1−3] The Gulf of Mexico Hypoxia Action Plan[4] proposed a goal of reducing nitrogen and phosphorus loads to reduce the hypoxic area in the northern Gulf of Mexico to a five-year running average of less than 5000 km^2. The Plan also recommended reducing uncertainty associated with predictive hypoxia models to support management efforts toward the target goal. Various models have been developed and applied to the Gulf of Mexico to provide insight into hypoxia on the shelf, but most have only examined the impact of riverine nutrients on hypoxia. There has been little examination of the effects of nutrient and organic carbon boundary fluxes and sediment fluxes on hypoxia, and the interrelationships of these fluxes with riverine loads. In this study, we used a biogeochemical model to investigate these effects and interrelationships and their impact on the hypoxic zone.

Statistical and mechanistic models have been used to evaluate the impacts of riverine loads on hypoxia. These models have included empirical[5−7] or semiempirical formulations,[8,9] with most employing statistical correlations of spring nutrient loads with summer hypoxia. Mechanistic models have also been used to investigate further fluxes and basic processes. Lehrter et al.[10] evaluated nutrient transport and mass budgets on the shelf using simple box models with the same hydrodynamic flows used in this study. These models have also included biogeochemical models with simple model grids.[11,12] Some of

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these models were used to evaluate nutrient reductions needed to meet hypoxic area reduction goals.

Complex, high-resolution mechanistic water quality models have recently been developed[13−15] to gain detailed insight into hypoxia dynamics on the LCS. Although there have been some studies on the effects of inorganic nutrient loads, boundary fluxes, or sediment fluxes on hypoxia, to date there have not been evaluations of the influence of boundary organic carbon or total nutrients nor how these factors interact to affect the hypoxic area. Laurent and Fennel[16] and Obenour et al.[12] have used model studies to evaluate the sensitivity of hypoxia to river nutrient loads. Fennel et al.[17] examined the effects of different hydrodynamic boundaries and vertical layering on simulating hypoxia and evaluated different methods of simulating sediment oxygen consumption. Mattern et al.[18] evaluated the model uncertainty in physical and biological properties, finding that changes in physical properties provided the largest model response. Yu et al.[19] found that physical processes and sediment oxygen consumption were the primary determinants in the spatial extent and dynamics of hypoxia on the LCS.

We previously developed a one-dimensional biogeochemical model, GoMDOM-1D, to explore the sources and fate of organic carbon on the LCS[20] and a three-dimensional biogeochemical model, the Gulf of Mexico Dissolved Oxygen Model (GoMDOM), to evaluate the impact of nutrient boundary concentrations on primary production on the LCS.[15] Results from these modeling studies demonstrated the importance of cross-boundary nutrient fluxes on primary production on the LCS, which suggested the importance of boundary concentrations when modeling hypoxia.

The objective of this modeling study was to evaluate the relative impact of nutrient and organic carbon loads, boundary fluxes, and sediment fluxes on predictions of the size of the LCS midsummer hypoxic area. In addition, we evaluated the relationship between nutrient load reductions and the simulated size of the hypoxic area and how the method of estimation of boundary concentrations affected that relationship.

■ MATERIALS AND METHODS

For the present study, GoMDOM was updated with an expanded model grid and revised organic carbon and sediment equations. The model was calibrated and corroborated, and five-year model runs were conducted to evaluate changes in the predicted hypoxic area caused by changes in fluxes and loads.

Model Changes. We applied GoMDOM to the study area (Figure 1), making several changes compared to the Pauer et al.[15] model: (1) the model grid was enlarged, (2) an updated version of the hydrodynamic model was used, and (3) model kinetics were revised including adding a new sediment organic matter remineralization formulation.

The model grid was extended outward on the southeast corner as suggested by Pauer et al.[15] to represent better the offshore boundary concentrations and to lessen the boundary's effect on the model area directly west of the Mississippi Delta.

The GoMDOM grid uses the same horizontal grid resolution as the previous application but uses a newer version of hydrodynamic output with 20 vertical sigma layers with equal percent thicknesses throughout the water column. The hydrodynamic and water temperature output were from the Navy Coastal Ocean Model−Louisiana Continental Shelf (NCOM-LCS)[10] for the years 2003 through 2007. Hydrodynamic data were aggregated from the NCOM-LCS 1.9 km

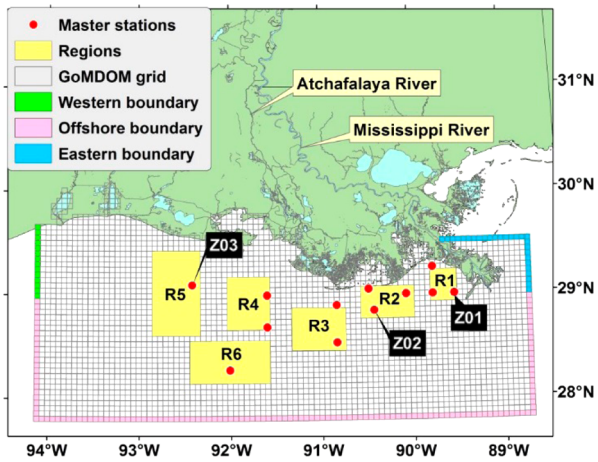

Figure 1. Map showing the model grid, boundary regions, and locations used for comparison to data.

resolution to approximately 6 km resolution and horizontal mixing coefficients were calculated following the same methods as Pauer et al.[15] Vertical mixing coefficients for GoMDOM were calibrated based upon comparisons with salinity and dissolved oxygen data profiles. NCOM-LCS is a hybrid model, with sigma layers for depths from the surface to 100 m and z-layers for depths below 100 m. GoMDOM only used output for the sigma layers. Where the water depth exceeded 100 m and the bottom of the GoMDOM sigma-layer grid was above the continental slope, vertical hydrodynamic model inflows and outflows from NCOM-LCS were tracked through the bottom boundary of the GoMDOM grid in addition to the lateral flows through the sides of the grid. Salinity from NCOM-LCS was compared to simulated salinity from GoMDOM as a model validation.

GoMDOM has 20 state variables: two phytoplankton classes (diatoms and non-diatoms); one zooplankton class; labile and refractory particulate organic classes of carbon, nitrogen and phosphorus; dissolved organic classes of carbon (DOC), nitrogen (DON), and phosphorus (DOP); ammonium; nitrate + nitrite; soluble reactive phosphorus (SRP); biogenic and dissolved available (dSi) silicon; dissolved oxygen (DO); salinity; and a conservative tracer.

Several changes were made to the GoMDOM kinetics to improve hypoxia simulation compared to the model used by Pauer et al.[15] The changes are summarized here and detailed equations are included in Appendix A in the Supporting Information (SI).

An algal dependence term was included to allow enhanced mineralization of DOC in areas of high algal biomass. Bianchi et al.[21] found increased breakdown rates of terrestrially derived organic matter in coastal deltaic regions with high primary productivity and steep gradients of nutrients and light. Bianchi et al.[22] also found that terrestrially derived DOC mineralized substantially faster in the presence of algal-derived dissolved organic matter. We activated a model option to simulate this effect by calculating the DOC mineralization rate as a function of total phytoplankton concentration and a phytoplankton dependence term.

DON and DOP mineralization also included an implicit phytoplankton dependence. In a literature survey, Lønborg et al.[23] described labile and refractory DON and DOP pools in coastal oceans. GoMDOM only has a single state variable for each, so to simulate the labile pool with a fast mineralization

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rate, a fraction of each dissolved organic pool was made directly available for phytoplankton uptake in addition to the dissolved inorganic nutrient forms. The available fractions were determined during the model calibration and set to 5%.

The new formulation for simulated sediment oxygen demand (SOD), ammonium, and nitrate−nitrite sediment fluxes was based on the "instant remineralization" approach,[24,13] but with sediment flux rates capped based upon field studies.[25] Total SOD was calculated as the sum of carbon SOD and sediment nitrification, converted to oxygen equivalents. Carbon SOD was calculated by summing the settled masses of the particulate organic forms of carbon and the carbon fractions of phytoplankton. Because instantly converting settled organic carbon to SOD may result in an unrealistically high SOD rate, especially during periods of large organic carbon settling such as spring and early summer phytoplankton blooms, the rate was capped to ensure it did not exceed observed measurements. Any sediment carbon not completely oxidized during the carbon SOD and denitrification calculations was available for the calculation during the next time step. Sediment nitrification was calculated by summing the settled masses of the particulate organic forms of nitrogen and the nitrogen fractions of phytoplankton. Both carbon SOD and nitrification were reduced if the overlying water DO concentration was too low. Any remaining settled organic nitrogen after nitrification occurred was released as a sediment ammonium flux to the overlying water.

Sediment denitrification was calculated assuming the process was limited by the carbon remaining in the sediments (not oxidized by carbon SOD) and was a function of the overlying water DO concentration. If the amount of nitrate consumed was smaller than the nitrate produced in the sediments by nitrification, the remaining nitrate was released into the bottom layer of the water column. If the nitrate consumed was larger than the nitrate produced by nitrification, nitrate was transported from the bottom water layer into the sediments. The nitrate flux into the sediments was reduced based on the available nitrate concentration in the overlying water. To prevent unrealistically high fluxes of nitrate into the sediment and corresponding depletion of water column nitrate, the nitrate flux into the sediment was limited to a maximum rate based on field data.

Forcing Functions. Sediment fluxes of SRP and dSi were estimated based on site-specific measurements for 2005−2007[25] and additional phosphorus measurements for 2010 (Lehrter unpublished data). SRP fluxes varied by region and ranged from −0.40 to 2.6 mg P m^{-2} d^{-1}. Dissolved silicon fluxes were not found to vary by region and had a uniform value of 49 mg Si m^{-2} d^{-1}.

Riverine nutrient loads entered the GoMDOM grid at 59 locations (SI Figure S1). Loads were calculated as in Pauer et al.[15] and were based upon U.S. Geological Survey loading estimates[26,27] where available or upon river sampling data and flows. Ninety-eight percent of the total nitrogen riverine loads entering the GoMDOM model grid were from the Mississippi and Atchafalaya River Basin. Atmospheric loads for nitrate and ammonium were obtained from the Community Multiscale Air Quality (CMAQ) model output[28] (R. Dennis, personal communication). Wind and solar radiation forcings used the same data sources and methods as Pauer et al.[15]

Observations used for boundary conditions, initial conditions, and for calibration and corroboration of GoMDOM were collected during 13 cruises spanning 2002 to 2010. These observations included physical data, nutrient data, and primary production and respiration rates.[10,25,29−32]

Model runs started on January 1 of the year of interest and initial conditions were calculated from field data from the previous autumn or early winter cruises. Field data were averaged by station and a mean interpolated value (using kriging) was assigned to each model grid cell. The 2003 corroboration and all five-year sensitivity model runs used initial conditions based on data from the December 2002 survey cruise. The 2006 calibration model run used the October 2005 cruise data. This cruise occurred about one month after Hurricane Katrina and particulate matter appeared elevated compared to other autumn cruises. To represent better the concentrations on January 1, 2006, the model was initially run for 1 month and particulate organic carbon, nitrogen, and phosphorus concentrations from day 31 were used as initial concentrations in the calibration model run. Using autumn cruise data for initial conditions had little impact on hypoxia simulations. Regression modeling studies[5−7] found that May loads and flows are the most significant predictor of hypoxic area for the following summer. We also conducted model sensitivity runs using a conservative tracer and greater than ninety-percent of the initial mass was flushed out of the hypoxic area within the first four months of the model run.

Boundary fluxes for each state variable in GoMDOM were calculated by multiplying the hydrodynamic flow across an open boundary by a boundary concentration specified by time and location. The GoMDOM open boundary was divided, based upon similarities in nutrient concentrations, into three boundary regions: western, offshore, and eastern (Figure 1). For the western boundary region, cruise boundary concentrations were calculated by averaging field data from all depths from all stations near the boundary for each respective cruise. For the offshore and eastern boundary regions, where significant vertical gradients were observed, field data for each cruise were averaged separately above and below the pycnocline calculated by Lehrter et al.[30] If data were not available for a region for a specific time period, cruise boundary concentrations were based on values from other years or averages across all data. Initial and boundary concentrations for phytoplankton and zooplankton were generated following the same methods as Pauer et al.[15]

Boundary concentrations were calculated differently for the one-year model runs than for the five-year model runs. For the one-year calibration and corroboration model runs, cruise boundary concentrations for each layer in each region were input as a constant value until replaced by the next cruise boundary concentration at the time of the next cruise. Cruise boundary concentrations for the calibration and corroboration years were calculated from autumn or early winter survey cruises of the preceding year and three cruises during the year of interest. For the five-year model runs, field data were not sufficient to calculate time-varying boundary concentrations for 2004, 2005, and 2007 because of the limited number of cruises. For each layer in each region the median of all cruise boundary concentrations was assumed to be the most representative and was used for the entire five-year run. The median was considered most representative because high concentrations during some cruises could bias other statistical measures. However, for comparison purposes, alternative five-year boundary concentrations were also estimated based on averages and seasons. The "average" boundary concentrations were calculated as the mean of all of the individual cruise boundary

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concentrations for each layer in each region. "Seasonal" boundary concentrations consisted of using cruise boundary concentrations from the three 2006 cruises as representative for all years. SI Tables S1−S3 contain the boundary concentrations for nitrogen, phosphorus, and organic carbon used for the model runs. SI Tables S4−S6 contain summary statistics for nitrogen, phosphorus, and organic carbon individual cruise boundary concentrations.

Where the GoMDOM grid extended over the continental slope and the water depth exceeded 100 m, bottom boundary concentrations were estimated to account for nutrients that were transported from below the grid. Conditions were relatively uniform for the samples at approximately the 100 m depth so spatial and temporal averages of the 2006 field data, the most complete boundary data set, were used to represent bottom boundary conditions for all model runs.

Model Calibration and Corroboration. During GoMDOM calibration we focused on matching dissolved oxygen concentrations and hypoxic extent while keeping primary production, respiration, and sediment fluxes within measured ranges. We also calibrated to nitrogen, organic carbon, phosphorus, and silicon field data concentrations.

Model output was compared to field data for the entire model grid, by regions, and at specific stations. Data and model output were aggregated into six regions (Figure 1) for comparisons representing different areas of the shelf. Data were also compared at 12 "master stations" that were consistently sampled during most cruises for both the calibration and corroboration years (Figure 1). Three of the master stations, Z01, Z02, and Z03 included extensive sediment flux measurements and were sampled repeatedly during 36−42 h station occupations.[25]

The R statistical software package was used to generate plots comparing model output to data and to calculate skill assessment statistics that included: root-mean-square error, $\mathrm{RMSE} = \sqrt{\sum(\mathrm{model} - \mathrm{observed})^2/n}$, where n is the number of observations; percent relative absolute error, $\mathrm{RAE\%} = \sum|(\mathrm{model} - \mathrm{observed})|/\sum(\mathrm{observed})$; and the Spearman correlation coefficient. The modeled hypoxic area was calculated by summing the areas of all model cells with bottom DO less than 2.0 mg/L for the output day of interest. Because the typical metric used for discussing the LCS hypoxic area was based on the results of the annual Louisiana Universities Marine Consortium (LUMCON) survey cruises and these cruises typically occur during the last week of July, we used the average of the predicted hypoxic areas from July 21−28 for each year for comparison among sensitivity model runs.

Initial values for the model coefficients were determined based on field measurements in the Gulf of Mexico, calibration of the one-dimensional version of the model,[20] a previous nutrient calibration of GoMDOM,[15] literature values from process studies, and models from other estuarine and marine systems.[33] The model was calibrated by conducting one-year simulations for the 2006 input data set and manually varying selected model coefficients. For each model run, we compared model output to field data for the entire model grid, the regions, and the master stations and evaluated changes in mass balances for carbon, nitrogen, phosphorus, and dissolved oxygen. Almost two hundred runs were conducted to obtain the best model fit to field data. The final model calibration coefficients were the set that best matched field observations, and these are included in SI Table S7.

Without making any changes to the model code or coefficients, the model was corroborated against data from three cruises in 2003. The same plots and statistics were used to evaluate the corroboration model output as for the calibration.

Sensitivity to External Factors. After calibration and corroboration, GoMDOM was run for a five-year period, 2003−2007, to evaluate the sensitivity of model hypoxic area predictions to changes in boundary concentrations, sediment fluxes, and tributary loads. The modeling time period was representative of recent flows and loads. Mean tributary flows and nitrogen loads for the 2003−2007 modeling period were approximately 90% of the means of the USGS estimates for 1996−2013. Total Mississippi River and Atchafalaya River flows followed the long-term seasonal trends, although there were larger than average flows from autumn 2004 through early spring 2005 and substantially lower than average flows during spring 2006 (Figure S2). Total nitrogen loads generally followed the long-term seasonal trends and magnitudes, although the peak 2005 load was three months early and October 2005 through September 2006 loads were approximately 35% lower than the long-term average (Figure S2).

The five-year base model run used the same model coefficients as the calibration and corroboration runs and loads, initial conditions, and boundary concentrations as previously described. All sensitivity runs used the base model run but with the specified changes. For the boundary concentrations sensitivity runs all forms of nitrogen and phosphorus were increased by 25% for one run and decreased by 25% for the second run. Similar model runs were conducted varying the percentages of all forms of organic carbon. We conducted runs testing the model sensitivity to changing all boundary fluxes and separately for lateral boundaries (the vertical cell faces along all sides of the model grid) and bottom boundaries. For sediment flux sensitivity runs, the amounts of settled nutrients or organic carbon available for remineralization were reduced by 25% compared to the 100% of settled material available for remineralization under the base run. For riverine loads we varied total nutrients or total organic carbon from all inflows. Sediment soluble reactive phosphorus fluxes were changed during the sensitivity analyses, but sediment available silicon fluxes and atmospheric nitrogen loads were not changed.

We also conducted model sensitivity runs to evaluate the effects on the predicted hypoxic area while simultaneously changing boundary concentrations and tributary nutrient loads. Nitrogen and phosphorus tributary loads were equally varied from 0% to 125% of the base loads in combination with the median, average, and seasonal boundary concentrations.

■ RESULTS

Model Calibration and Corroboration. GoMDOM was able to match successfully measurements of hypoxic area, water column primary production and respiration, oxygen and nutrient sediment fluxes, and DO concentrations. GoMDOM also reasonably reproduced carbon and nutrient concentrations.

For the calibration model run, the model matched field DO concentrations (Table 1, Figure 2, and SI Figure S3). During the period of the LUMCON hypoxic area measurements (July 21−28, 2006), GoMDOM simulated a maximum hypoxic area of 17 300 km^2 (Figure 3) and an average daily hypoxic area of 15 600 km^2 compared to the LUMCON-estimated hypoxic area of 16 560 km^2 (http://www.gulfhypoxia.net, February 11, 2016). Model-simulated hypoxia was similar in extent to that

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Table 1. Model Fit to Cruise Data from Surface and Bottom Samples from Six Regions for Calibration, Corroboration, and Five-Year Base Model Runs[a]

calibration	DO	TN	DIN	NO3	TOC	DOC	POC	TP	SRP
RMSE	1.2	64.1	51.6	48.7	525	638	366	7.3	7.2
RAE%	18.9	23.9	76.2	88.9	20.0	27.3	103.5	34.5	82.3
Spearman R	0.85	0.58	0.55	0.59	0.64	0.40	0.61	0.46	0.52
n	36	36	36	36	36	36	36	36	36
corroboration	DO	TN	DIN	NO3	TOC	DOC	POC	TP	SRP
RMSE	1.0	148.2	52.9	53.4			543	9.8	9.1
RAE%	15.1	39.5	72.4	97.2			138.0	38.8	104.5
Spearman R	0.86	−0.28	0.55	0.59			0.30	0.07	0.20
n	36	29	34	34	0	0	35	31	34
5-yr base run	DO	TN	DIN	NO3	TOC	DOC	POC	TP	SRP
RMSE	1.1	99.1	67.3	64.7	594	582	407	7.3	5.5
RAE%	15.9	30.7	69.1	86.1	26.1	27.8	110.5	32.7	57.3
Spearman R	0.84	0.42	0.60	0.57	0.47	0.35	0.44	0.46	0.53
n	110	93	106	106	62	62	109	105	106

[a]RMSE = root-mean-square error, RAE% = percent relative absolute error, and Spearman R = Spearman's rank correlation coefficient.

shown by the LUMCON bottom water DO concentration data[34] (SI Figure S4). Simulated bottom water DO concentrations were also similar to those measured during the cruises for April and September 2006 but slightly underpredicted the June cruise measurements (SI Figures S5−S7).

Simulated phytoplankton primary production rates were also similar to observed rates (SI Figures S8−S10). Simulated water column respiration was also within the measured range but on the lower end of survey measurements. Modeled sediment oxygen demand fluxes were similar to a data set of measured fluxes pooled over several years.

The model was able to match measured total organic carbon concentrations (Table 1), although simulated dissolved organic carbon tended to be slightly underpredicted and particulate organic carbon overpredicted. The model also successfully reproduced total nutrient concentrations although, like the organic carbon, simulated dissolved concentrations tended to be lower and particulate concentrations higher than field data.

The model also reproduced the patterns in the 2003 corroboration data. Dissolved oxygen concentrations matched field data as well as in the 2006 calibration model runs (Table 1, Figure 2, SI Figure S11). There were two severe storms during the summer period that temporarily reduced the hypoxic area.[5] This was reflected in strongly varying model-simulated hypoxic areas (Figure 3) that reached a summer maximum of 23 900 km^2 on June 25, decreased to 3500 km^2 on July 15, and then re-established to 17 100 km^2 on August 8. The LUMCON survey cruise (July 23−28, 2003), with a reported hypoxic area of 8320 km^2 (http://www.gulfhypoxia.net), occurred during this period when the hypoxic area was re-establishing. The model-simulated hypoxic area during the cruise dates ranged from 7800 to 12 100 km^2 with an average of 9900 km^2, showing the challenge of comparing output from a dynamic model to a single shelf-wide cruise during periods of unstable stratification. Model-simulated hypoxia corresponding to the midpoint of the LUMCON cruise compared to the LUMCON bottom water DO concentration data[34] (SI Figure S12) did not match as well as with the calibration year, probably because of the rapid changes in the hypoxic area during this period. Comparison of bottom water DO to measurements showed good matches for the March, June, and November cruises (SI Figures S13−S15).

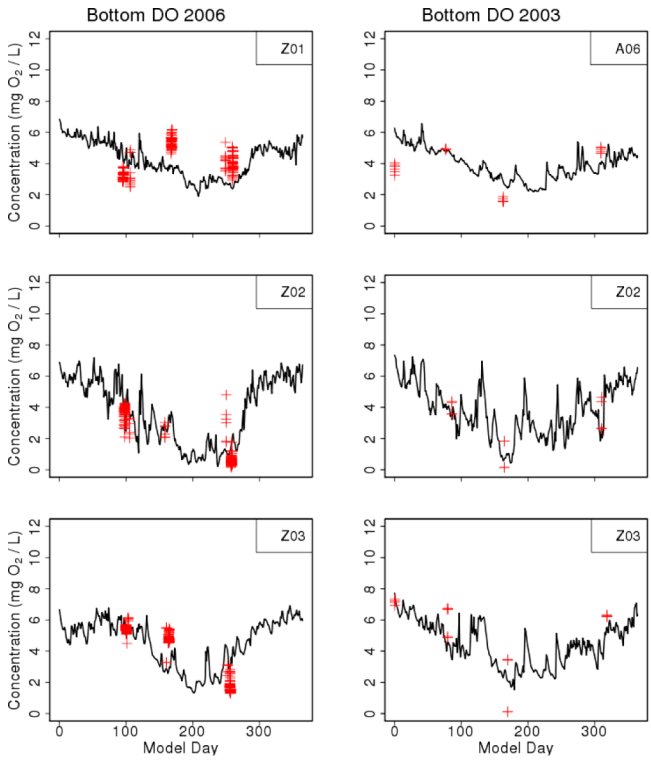

Figure 2. Simulated bottom dissolved oxygen (lines) versus field data (crosses) for the "Z" stations for the 2006 calibration and 2003 corroboration years. Station A06, directly west of Z01, was substituted in 2003 because Z01 was not sampled.

There were no DOC, production, respiration, or sediment flux field data from 2003 for comparison to the model. Most simulated nutrient data concentrations were a reasonable fit to data, although a slightly poorer fit than for the calibration year (Table 1). Dissolved inorganic nitrogen reasonably matched the data, but total nitrogen concentrations did not match overall. Simulated total nitrogen matched data west of the Delta, but the model underpredicted organic nitrogen concentrations for the spring and summer in regions R4, R5, and R6.

Sensitivity Runs. The five-year base model run had smaller midsummer hypoxic areas when compared to plots from the

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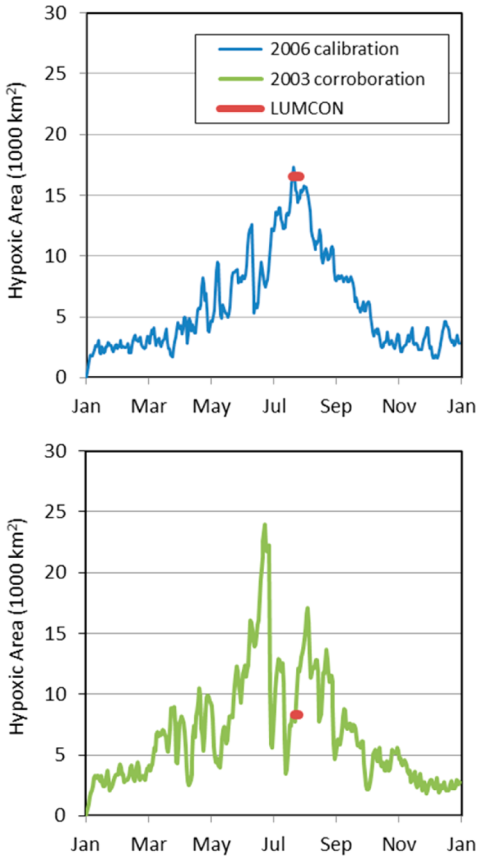

Figure 3. Time series of daily simulated hypoxic areas for the 2006 calibration and the 2003 corroboration compared to LUMCON-estimated hypoxic areas.

calibration and corroboration model runs (SI Figure S16). The base run's average daily hypoxic areas for July of 2003 and 2006 were 28% lower than the calibration and corroboration model runs. For 2006 the peak simulated hypoxic area during the time of LUMCON cruises was substantially smaller than the LUMCON-reported area; however, modeled hypoxic areas were good matches for 2004 and 2007. Modeled hypoxic areas for 2003 and 2005 were in the range of the LUMCON areas, but unstable hypoxic areas caused by storm events around the time of the single annual shelf-wide cruise make comparisons difficult. Plots and summary statistics (Table 1) of individual constituents from the five-year base model run compared to data from all cruises during the period were comparable to those of the calibration and corroboration model runs. Inputs for the five-year base run were the same as inputs for the calibration and corroboration year runs except for the use of temporally uniform median boundary concentrations rather than individual cruise boundary concentrations.

The five-year base model run was used for comparison to the sensitivity model runs. The sensitivity model runs demonstrated that varying tributary nutrient loads and varying the amount of settled organic carbon available for SOD had the largest impacts on model predictions of hypoxic area (Figure 4), closely followed by varying the nutrient boundary concentrations.

Sensitivity of Hypoxia to Nutrient Loads. Changing tributary nutrient loads by ±25% resulted in almost proportional changes (+20%/−22%) (SI Table S8) to the size of the midsummer hypoxic area. Changing tributary organic carbon loads by ±25% had a much smaller effect on the hypoxic area (+5%/−4%), in agreement with previous studies that have indicated hypoxia is mainly driven by primary production of organic matter.[2,35]

The effect of changing tributary nutrient loads on the extent of the hypoxic area varied significantly depending upon how boundary concentrations were estimated (median, average, or seasonal) (Figure 5). The sensitivity runs with average boundary concentrations had the highest hypoxic areas for a given load, with sensitivity runs using seasonal boundary concentrations in the middle and runs with median boundary concentrations the lowest. This resulted in large differences in nutrient reductions needed to achieve a desired hypoxic area.

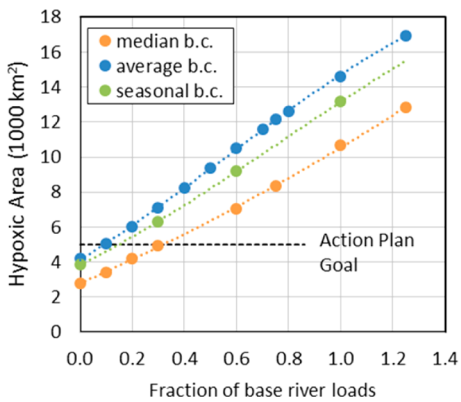

Figure 5. Predicted average five-year late-July hypoxic areas from nutrient load changes and alternate boundary concentration estimates.

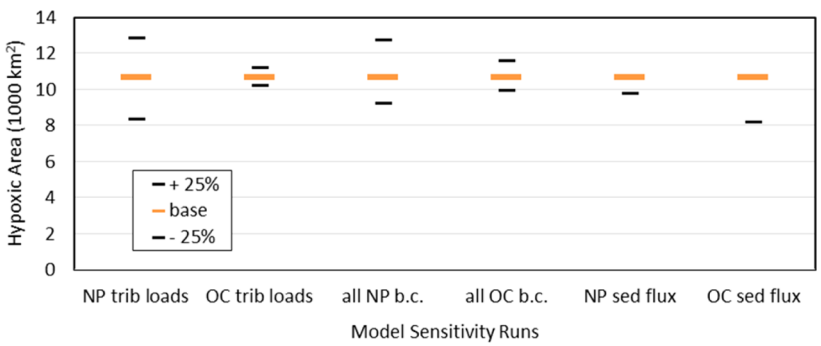

Figure 4. Results of main sensitivity runs and corresponding average five-year late-July hypoxic areas. NP = TN and TP, OC = total organic carbon, trib loads = changes to all river loads, b.c. = boundary concentrations, sed flux = changes to settled mass available for sediment flux calculations.

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Sensitivity of Hypoxia to Sediment Fluxes. Model predictions of hypoxic area were as sensitive to 25% reductions in the amount of settled organic carbon available for SOD (−24%) as they were to reductions in tributary nutrient loads (Figure 4). Reducing the nutrient sediment fluxes had little effect on hypoxia (−8%).

Sensitivity of Hypoxia to Boundary Fluxes. Model predictions of hypoxic areas were also sensitive to changes in boundary concentrations. Changing nutrient boundary concentrations ±25% changed the hypoxic area +19%/−14% (Figure 4). We conducted additional model runs to determine whether DON or dissolved inorganic nitrogen (DIN, the sum of ammonium and nitrate) concentrations were the largest influencing factor of the boundary nutrient fluxes and found that the primary driver was DON fluxes. Changing only DON boundary concentrations by ±25% resulted in hypoxic area changes of +10%/−9% (SI Table S8). Changing only DIN boundary concentrations resulted in small changes in hypoxic area of +3%/−3%. Boundary nutrient fluxes through the bottom of the grid at depths over 100 m contributed only +2%/−2% compared to the base model run. Varying organic carbon boundary concentrations resulted in hypoxic area changes of +8%/−7% (Figure 4), almost all from organic carbon entering the grid through the lateral boundaries with little contribution from bottom boundary fluxes.

■ DISCUSSION

GoMDOM was used to estimate load reductions necessary to meet management goals, to evaluate factors that affect that estimation, and to evaluate which factors are important for modeling hypoxia and may need additional study. Model predictions of hypoxic area were most sensitive to changes in riverine nutrient loads and settled organic carbon available for SOD, but were also influenced by fluxes of nutrients across the lateral model boundaries.

The calibration of GoMDOM and corroboration to an independent data set provided confidence that the model could be used to evaluate how changing model inputs can affect the predictions of hypoxic areas in the LCS. The sensitivity model runs demonstrated the importance of boundary concentrations when modeling hypoxia on the LCS and that the method used for estimating boundary concentrations can have an effect on the predicted relationship between nutrient loads and hypoxic area. Using three different methods for estimating boundary concentrations resulted in a range of 69%−90% in nutrient reductions needed to reduce the average 2003−2007 late-July hypoxic area to the 5000 km^2 Action Plan goal.

Because of the limited number of cruises and limited seasonal representation of cruise data available for estimating boundary concentrations, the runs using the median of cruise boundary concentrations were likely the most representative for the long-term model run. Based upon the median boundary condition model runs, tributary nutrient reductions of 69% would be required to achieve the target hypoxic area goal for this five-year period. The estimated reduction is similar to a 62% reduction suggested by Scavia et al.[9] and is in agreement with Laurent and Fennel[16] who found the reduction would need to be greater than 50%. The accuracy of model predictions is impacted by uncertainties such as the statistical estimation of multiple-year boundary concentrations and whether sediments will continue to respond to nutrient loadings as observed during the period of this study. These uncertainties are discussed below.

The five-year base model run, using the median of cruise boundary concentrations, simulated smaller midsummer daily hypoxic areas for 2006 and 2003 compared to the calibration and corroboration model runs and underpredicted the hypoxic area for 2006 compared to the LUMCON estimates. However, it is not clear if the base model run is underpredicting other years, which would mean that additional nutrient loading reductions might be required to meet the target. The base model run matched the LUMCON hypoxic area estimates for the two other years for which comparisons could be made and summary statistics of model versus data for other constituents were similar to the calibration and corroboration model runs. Using statistically aggregated boundary concentrations may have larger effects on 2006, a year with low river discharge, than on other modeled years.

The model results presented here are the first to use observed boundary concentration data from the period being modeled. Most recent LCS hypoxia models have used a combination of climatological estimates, from historical cruises or the NOAA World Ocean Atlas, for estimates of dissolved inorganic nutrient constituents and small positive values for other constituents[13,16] or used numerical methods.[14] These methods may not completely account for nutrients that impact primary production and formation of the hypoxic area. Using only the climatology constituents for modeling also likely underestimates the constituents that contribute to hypoxia formation. NOAA climatology provides concentrations for nitrate, phosphate, silicate, salinity, and DO but not for ammonium, organic nutrients, or organic carbon. Ammonium is typically directly available for algal growth and during survey cruises was found offshore in concentrations similar in magnitude to nitrate.[29] Mattern et al.[18] found that hypoxic area was not sensitive to boundary concentrations in their model; however, they only evaluated the model sensitivity to boundary concentrations for nitrate and ammonium. Lehrter et al.[10] found that average DIN on the shelf was less than a third of total nitrogen (TN). For our boundary concentrations, offshore DIN is a small fraction of TN (SI Table S1) and model sensitivity runs demonstrated the importance of DON compared to DIN. The sensitivity runs also demonstrated the importance of boundary fluxes of organic carbon to the size of the hypoxic area.

Improving both the quantity and frequency of boundary sampling will help reduce uncertainty associated with model-predicted hypoxia estimates. Although model results were sensitive to the boundary concentrations, there has been little data collected in offshore regions (>100 m) of the northern Gulf shelf with the observations summarized here being the most comprehensive to date.[29] The annual LUMCON hypoxia cruises primarily focused on areas where hypoxia existed and there were few stations deeper than the 50 m contour (http://www.gulfhypoxia.net/research/Shelfwide%20Cruises/).

Changes in boundary concentrations over time could affect hypoxic area response to changes in tributary nutrient loads. We are not aware of any studies that evaluated trends in offshore nutrient concentrations and whether boundary concentrations have increased as nutrient loadings into the Gulf have increased.

GoMDOM hypoxic area predictions were sensitive to the amount of settled organic carbon available for remineralization and the resulting SOD. This highlights the importance of modeling hypoxia with mechanisms that account for the effects of changing nutrient loads and primary production on SOD.[17]

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Fennel et al.,[17] Mattern et al.,[18] and unpublished results from our earlier version of GoMDOM[15] found that SOD formulations in the respective models based upon regression equations with overlying dissolved oxygen concentrations were not responsive to changes in nutrient loads. By using the capped instant remineralization formulation, we could investigate the relationship between SOD and hypoxic area and our sensitivity runs demonstrated that the predicted hypoxic area was as sensitive to percentage changes in settled organic carbon available for SOD as it was to percentage changes in tributary loads. This sensitivity in model response is important because it is unlikely that SOD will remain constant if nutrient loads are reduced, reducing primary production and the resulting amount of settled organic carbon. In our 25% nutrient load reduction model run, primary production was reduced approximately 10% across the entire model grid and carbon settling and SOD were reduced proportionately.

Regression modeling studies[36,6,7] have shown that there is a time component where a given nutrient load creates a larger hypoxic area in recent decades compared to previous decades. Turner et al.[36] hypothesized that this was caused by the accumulation of settled organic carbon in sediments. Our capped instant remineralization model is a very simplistic model of the SOD process, and although the formulation may result in storage of organic carbon in the sediments, an evaluation of model process results found that the storage was temporary and little or no sediment carbon was carried over from one year to the next. GoMDOM was calibrated and able to match the measured hypoxic areas for the time period of our study, but the model may need to be recalibrated if applied to time periods with a different relationship between nutrient loading and hypoxic area. In addition, the nutrient reductions to reach a specified target hypoxic area may also be less if the relationship between nutrient loads and hypoxia formation reverts toward the earlier relationship as nutrient loads decrease. Thus, the capped instant remineralization approach should be used cautiously if used to evaluate multidecadal changes in the response of hypoxic area extent from a specified nutrient load because of possible changes in sediment accumulation of organic carbon. A more complex sediment diagenesis and transport model would be required to evaluate the effects of accumulated sediment carbon on the response of the hypoxic extent to changes in nutrient loadings and could help reduce uncertainty in long-term hypoxic area predictions.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01684.

Contains Appendix A describing model formulation changes, a more detailed study site map, additional plots of model and data comparisons, and tables of boundary concentrations, summary statistics of cruise boundary concentrations, model input parameters, and sensitivity results (PDF).

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Notes

The authors declare no competing financial interest.

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