Available online at www.sciencedirect.com
ScienceDirect
Journal of Marine Systems 70 (2008) 49–62
JOURNAL OF MARINE SYSTEMS
www.elsevier.com/locate/jmarsys

How does the character of oxygen demand control the structure of hypoxia on the Texas–Louisiana continental shelf?

Robert D. Hetland *, Steven F. DiMarco

Department of Oceanography, Texas A&M University, College Station, TX, United States

Received 12 January 2006; received in revised form 28 February 2007; accepted 13 March 2007
Available online 21 April 2007

Abstract

A realistic hydrodynamic model of the Texas–Louisiana shelf is configured with various simple oxygen respiration models to isolate the effects of stratification and circulation on the formation and maintenance of hypoxia. Biological activity is parameterized through various forms of respiration rather than using a complex biogeochemical model. The model domain covers the region that has historically been observed to be affected by seasonal hypoxia, and is forced with observed fresh water fluxes from the Mississippi and Atchafalaya Rivers and winds. Three simple parameterizations of biological respiration are compared. Results of the numerical simulations indicate that water column respiration (dependent on the position of the two regional fresh water plumes) reproduces observed temporal and spatial structures of seasonal hypoxia in Louisiana Bight, whereas benthic respiration (dependent on local temperature and oxygen concentrations) reproduces the temporal and spatial structure of hypoxia west of Terrebonne Bay. The differences in the structure of hypoxia are related to the differences in vertical stratification east and west of Terrebonne Bay, which are controlled by the outflow characteristics from the two major river plumes. The model shows two dynamically distinct plumes. The Mississippi River plume enters the shelf near the shelf edge, forms a recirculating gyre in Louisiana Bight, and typically does not interact directly with topography. Conversely, the Atchafalaya River plume enters a broad shelf at the coast, is more diffuse, and interacts more with the shallow coastal topography. Both plumes are strongly affected by winds, and tend offshore during the mean summer conditions of upwelling winds. The principle conclusion of this study is that the biological processes responsible for producing hypoxia change from east to west, with the shelf region south of Terrebone Bay being the approximate dividing line between water column respiration (predominantly causing hypoxia to the east) and benthic respiration (causing hypoxia to the west). Also, the formation and destruction of hypoxia is a primarily vertical process; hypoxia formed in one region is not advected laterally to different shelf regions.

Keywords: Hypoxia; Texas/Louisiana shelf; Numerical model

1. Introduction

The Mississippi and Atchafalaya Rivers introduce large amounts of fresh water and nutrients to the Texas–Louisiana continental shelf. During summer when winds are generally upwelling favorable (i.e., from the west) and weak, the fresh water introduced by the rivers causes the shelf to be stratified (Cochrane and Kelly, 1986; Cho et al., 1998; Nowlin et al., 2005). At the same time, the large nutrient flux may cause locally elevated biological production in surface waters, which increases the supply of organic material to waters below the pycnocline relative to other shelf regions in the Gulf of Mexico (e.g., Lohrenz et al., 1990; Turner and Rabalais, 1994; Lohrenz et al., 1997, 1999). These two effects combine to create a

---

* Corresponding author.
E-mail address: hetland@tamu.edu (R.D. Hetland).

0924-7963/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmarsys.2007.03.002

subsurface layer where respiration is high, due to the high biological production, and replenishment of oxygen through contact with the atmosphere is low, due to the strong stable stratification. Respiration may be high enough to create hypoxic conditions — conditions where the oxygen levels are low enough to adversely affect marine life — typically defined as approximately 40% of local oxygen saturation, or about 60 μM (e.g., Rabalais et al., 1999). Oxygen concentrations on the Texas–Louisiana continental shelf during summer show some regions with only slightly depressed oxygen concentrations, other locations may be anoxic or nearly so. Previous studies have suggested that enhanced nitrogen loading from the Mississippi/Atchafalaya River system may be responsible for summertime hypoxia (e.g., Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2004, and works cited within).

Previous hindcasts and predictions of the magnitude of hypoxia or hypoxic extent rely on statistical relationships between fresh water flux to the shelf, nutrient loading, and enhanced primary productivity (Justić et al., 2002; Scavia et al., 2003; Turner et al., 2005). Indeed, there is a strong correlation between the areal extent of hypoxia and Mississippi River discharge($R^2 \sim 0.6$ Wiseman et al., 1997).[1] However, stratification of shelf waters and the supply of organic material to the bottom waters are both enhanced by increased fresh water flux from regional rivers. Thus, it is difficult to separate the physical effect of stratification from the biological effect of eutrophication in controlling the timing and extent of hypoxia.

Despite strong similarities in the methods used to link biological productivity to riverine flux, previous models of the magnitude of hypoxia or hypoxic extent invoke a wide variety of simple, conceptual models to represent the physical processes. Justić et al. (2002) use a (vertical) two-layer model, and ignore horizontal differences in water column structure. Scavia et al. (2003) require a westward 'advection' in the lower water column (which incorporates all physical processes) to transport organic material and low oxygen water from the point sources of organic material supply near the two river sources. Turner et al. (2005) do not explicitly address the physical field, but rely on purely statistical relationships between near-shore nitrogen concentrations (in turn correlated to lagged fresh water discharge) and the areal extent of hypoxia. None of these models have predictive abilities greater than the direct correlation between Mississippi River discharge and areal hypoxia extent based on R^2 calculations given in Scavia et al. (2003) and Turner et al. (2005). (Justić et al. (2002) do not give an R^2 for their model, since the data were used to train the model.)

We believe the inability of previous models to outpredict a straightforward correlation between river discharge and hypoxic area is because none of these models separate biological causes of hypoxia through eutrophication, the *hypoxic potential*, from physical limitations on hypoxic area, the *stratification envelope*. The hypoxic potential represents the amount of organic material that is available to be respired — the fuel for the formation of hypoxia. The stratification envelope represents the area of the shelf that is sufficiently stratified to prevent the ventilation of the lower layer — the region over which water mass and circulation patterns allow persistent and widespread hypoxia to develop. Since both stratification and organic material are required for hypoxia to form on the shelf, it will be the lesser of these two factors that limits the areal extent of hypoxia. Without understanding which factors are limiting hypoxic extent and duration, it is impossible to improve our predictive ability of summertime hypoxia on the Texas–Louisiana shelf.

The primary goal of this paper is to isolate the physical effects that control hypoxic extent by applying simple, idealized models of biological respiration to a three-dimensional hydrodynamic model of coastal circulation. Previous models of hypoxia make many simplifying assumptions about the physical field in favor of a more complicated treatment of biological processes; this paper takes the opposite approach: simple parameterizations of biological processes are embedded within a relatively complex physical model. Spatial patterns of hypoxia caused by stratification are isolated by decoupling the biological models from the fresh water flux; that is, the parameterization of biological processes is independent of the fresh water flux from the river. Thus, this paper studies only the limits of the stratification envelope. Since there are no limits on the net amount of respiration that can occur (although there are still reasonable limits set on the *rates* of respiration) the hypoxic potential is infinite. Our primary result is that different parameterizations of respiration result in different spatial patterns in the areal extent of hypoxia. This suggests that different biological processes are responsible for hypoxia in different physical regimes as postulated by Rowe and Chapman (2002).

2. Numerical model configuration

2.1. Physical model

The Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams, 2005) was configured for

---

[1] There is a typo in this paper regarding this correlation coefficient, given as 0.934. Visual inspection suggests this value is too large. Recalculation yields an R^2 of approximately 0.6.

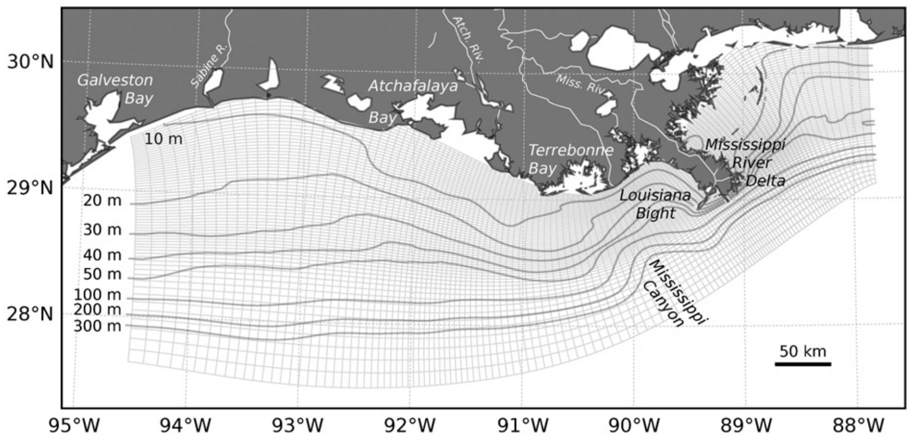


Fig. 1. The numerical simulations of the Mississippi/Atchafalaya fresh water outflow use a domain that covers much of the Texas–Louisiana continental shelf. The grid is shown over contours of the smoothed model shelf topography. Bathymetric contours are unlabeled in other figures, but are identical to those shown here.

the Mississippi/Atchafalaya outflow region. The domain and topography are shown in Fig. 1. The model is configured to use fourth-order horizontal advection of tracers, third-order upwind advection of momentum, conservative splines to calculate vertical gradients, and Mellor and Yamada (1974) turbulence closure with the Galperin et al. (1988) stability functions. The model is initialized on January 1, 1993 with an averaged climatological profile of temperature and salinity, horizontally uniform, based on historical hydrographic surveys. The tracer boundary conditions use an adaptive nudging technique (Marchesiello et al., 2003); tracers are relaxed to the horizontally uniform monthly climatology throughout the integration with a timescale of 10 days for outgoing information, 1 day for incoming information. Radiation conditions are used for the three-dimensional velocities, and a Flather (1976) condition with no mean barotropic background flow is used for the two-dimensional velocities and free surface.

The model is forced with spatially uniform but temporally varying winds, measured every 3 h at the BURL 1 C-MAN weather station (28°54′18″N 89°25′42″ W, near the mouth of Southwest Pass, the major pass of the Mississippi Delta). This is appropriate given the spacial and temporal scales of the local wind field (Wang et al., 1998). Fresh water inputs from the Mississippi and Atchafalaya rivers are specified using daily measurements of the Mississippi River Transport at Tarbert Landing by the U.S. Army Corps of Engineers. Surface heat and fresh water fluxes are specified using climatological measurements (da Silva et al., 1994a,b). Tides were not included, but are known to be small in the region (DiMarco and Reid, 1998).

Circulation over the Texas–Louisiana shelf has two distinct modes during summer (June, July, and August) and non-summer periods (Cochrane and Kelly, 1986; Cho et al., 1998). During the non-summer months, mean winds are typically downwelling favorable, and the circulation is westward (downcoast). During summer, the mean winds switch direction to upwelling favorable, and the circulation is generally offshore over the Texas/Louisiana shelf. The physical model reproduces the mean observed circulation patterns during these two periods. Model/data comparisons (not shown) also indicate that the model reproduces the magnitude of weather band variability (periods of 2–15 days) in the simulated currents. Finally, comparisons between simulated surface salinity fields and salinity measured from the ship's water intake during a recent cruise (unpublished data, not shown) demonstrate that the model does a reasonable job at reproducing the surface salinity fields over the inner shelf. For the purposes of this study, we are interested only in the general effects of stratification on hypoxia formation and maintenance, not in reproducing the flow field for any given year. Thus, the physical portion of the model is an adequate tool to examine how physical processes affect hypoxia.

There is significant weather band variability in the circulation patterns and stratification, particularly with regard to the positions of the two river plumes. Winds cause the two river plumes to both mix (Lentz, 2004; Hetland, 2005) and translate (Fong and Geyer, 2001; García Berdeal et al., 2002). For example, Fig. 2 shows the simulated surface salinity at two times, just over a week apart, at the beginning of the late summer season. The surface salinity on Aug 5, 1993 shows the response of the two river plumes to an upwelling favorable wind stress. This kind of upwelling circulation is responsible for the mean summertime anticyclonic circulation pattern on the Texas–Louisiana continental shelf (Cochrane and Kelly,

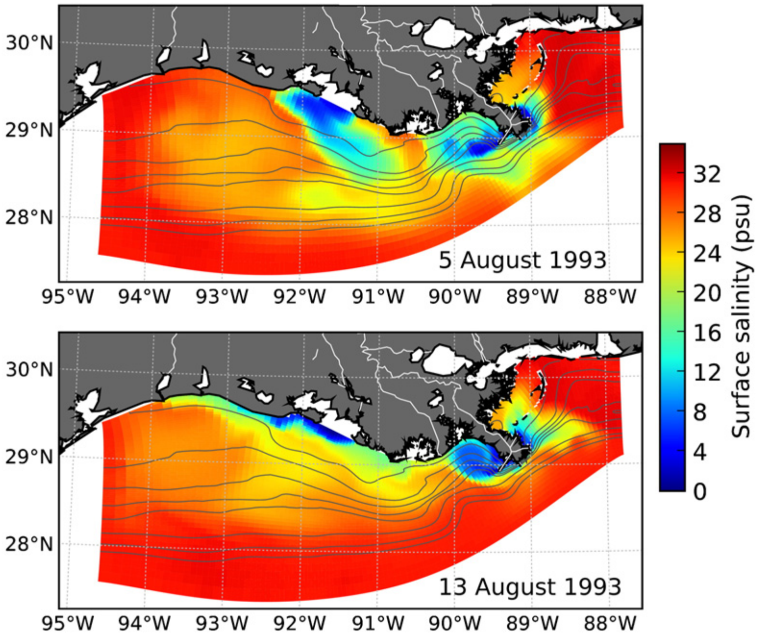


Fig. 2. Surface salinity is shown for two days in the model simulation. The two river plumes from the Mississippi and Atchafalaya Rivers are clearly seen as two distinct, fresh (blue) pools leaving the respective source regions.

1986; Cho et al., 1998). In this case, there is a net offshore flux of fresh water, most notably in the Atchafalaya plume. The upwelling circulation tends to press the Mississippi plume up against the Delta, with a portion of the fresh water flowing seaward, but with a significant portion of the fresh water remaining in Louisiana Bight. Just over one week later, a shift to downwelling favorable winds causes the Atchafalaya plume to be pressed against the coast, with a net westward transport of fresh water within the plume. The Mississippi River plume has formed a recirculating bulge within Louisiana Bight, as observed by Wiseman et al. (1997) and Ichiye (1960).

2.2. Respiration formulations

Oxygen consumption in the model is parameterized using three formulations for the respiration of organic matter. This allows us to ask the question: What is the temporal and spatial structure of dissolved oxygen concentrations, given a particular spatial structure of respiration? Ideally, we would like to include a biogeochemical model that would allow us to estimate the structure based on nutrient inputs, productivity, and benthic chemistry. However, this sort of model has not yet been developed for the Northern Gulf region. However, by specifying the structure of respiration directly, we can still gain much insight into the physical controls over the structure of hypoxia for different types of respiration that we know occur in the region.

We divide respiration into two broad categories: water column respiration and benthic respiration. Both kinds of respiration are well known to occur in all coastal regions, and each has been studied by other investigators in the Texas–Louisiana shelf region (discussed in more detail below). Water column respiration is also divided into two classes: respiration beneath the fresh plumes from the Mississippi and Atchafalaya, and water column respiration near the fresh water sources. Respiration is assumed to be elevated beneath the plumes because of the high primary productivity in the two river plumes (Lohrenz et al., 1999; Dagg and Breed, 2003). The final case, high respiration near the two fresh water sources, is included to investigate how much locally formed hypoxia may bleed out over the rest of the shelf.

These simple biological models are not intended to predict hypoxic conditions over the shelf, rather they are used to illustrate the role of stratification in forming hypoxia for different spatial structures of respiration. In the cases discussed in this paper, respiration does not depend on the supply of organic material, and thus does not depend indirectly on environmental factors that would reduce or enhance the supply of organic material. For example the effects of variability in local primary production is not included. There is no global stochiometric balance that either enhances or limits respiration. However, different respiration parameterizations are based on observations, so although the respiration parameterizations do not depend on the supply of organic material, respiration rates are still realistic in magnitude. Thus, these biological models are designed to test the limits of the stratification envelope, since the hypoxic potential is determined solely by the respiration timescales and the size of the region of stratified water. The hypoxic potential has no biologically determined bound; that is, respiration is never limited by a lack of organic material.

In order to include each of these respiration parameterizations in the model, an additional passive tracer representing oxygen was introduced. Oxygen in the model is initialized at saturated values everywhere, based on temperature and salinity (Weiss, 1970). Water from the rivers is also saturated with respect to oxygen, the oxygen at the open boundaries is relaxed to saturation in exactly the same way as the dynamical tracers, and surface values of oxygen are set identically equal to saturated values to represent exchange with the atmosphere. The possible effects of photosynthesis increasing water column oxygen above saturated values are not considered. The mathematical structure used for each of the three respiration parameterizations is described below.

2.2.1. Benthic respiration

The benthic respiration biological model specifies benthic respiration based on bottom temperature and oxygen concentrations. The functional form is based on data collected by (Rowe et al., 2002), and is given by

$$\text{Bottom } O_2 \text{ flux} = 6.0\,[O_2 \mathrm{m}^{-2} \mathrm{days}^{-1}] \times 2^{T/10.0^\circ\mathrm{C}} \times \left[1 - \exp\left(\frac{O_2}{30.0\mu\mathrm{M}\ O_2}\right)\right]. \quad (1)$$

This function is shown in Fig. 3, along with the data from Rowe et al. (2002) normalized to T=5 °C that were used to estimate the two fitted constants (6.0 and 30.0). The benthic oxygen flux is applied at the sea floor, as a bottom boundary condition in the model.

Benthic respiration is also modified by local temperature, with the respiration slowing by a factor of two every 10° colder. Within the hydrodynamic simulations, temperature below 50 m depth does not vary by more than about 5°, although seasonal variations shallower than 50 m may vary by more than 15°. Thus, temperature is not a first order control on respiration in summer, but may influences seasonal changes in respiration.

2.2.2. Plume-dependent respiration

The plume-dependent respiration model is used to place high respiration where the plume salinity is lowest. The basis of the plume-dependent respiration (and the near-source respiration, below) is a simple exponential decay of oxygen based on a timescale, τ,

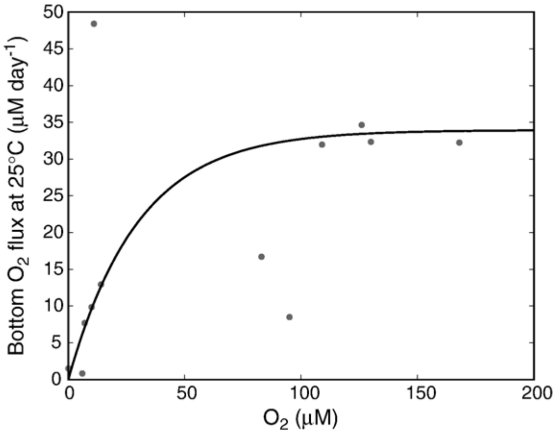


Fig. 3. The benthic oxygen flux used in the model (solid line) is shown in comparison to measurements (gray points) of benthic oxygen flux made by Rowe et al. (2002). Both the data and measurements are normalized to benthic oxygen flux at 25.0 °C using a Q_{10} normalization (i.e., measurements are multiplied by $2^{(25.0\ ^\circ\mathrm{C}-T)/10.0\ ^\circ\mathrm{C}}$, where T is the local temperature).

$$\frac{\mathrm{DO_2}}{\mathrm{Dt}} = \tau^{-1} O_2. \quad (2)$$

The decay timescale is a function of surface salinity, and local temperature and oxygen concentrations. The formulation for the dependence of biological production on surface salinity is based conceptually on the results of Dagg and Breed (2003). The assumption here is that high biological production occurring in the plume will tend to follow the spatial patterns of the plume itself, and thus respiration below the plume will be correlated with surface salinity (see Hetland, 2005). The approximate timescales of respiration used are

$$\tau = \begin{cases} 10 \text{ days} & : \quad s < 20 \text{ psu} \\ 150 \text{ days} & : \quad s > 20 \text{ psu}. \end{cases} \quad (3)$$

The actual equation used in the model is a continuous function that varies smoothly between these two limits:

$$\tau_{\text{plume}} = \frac{1.0}{10.0 \text{ days}} 2^{(T-25^\circ\mathrm{C})/10.0^\circ\mathrm{C}} \left[\left(1 - \frac{1}{15}\right) \times \left(0.5 - 0.5 \tanh\left(\frac{S - 20.0 \text{ psu}}{2.0 \text{ psu}}\right)\right) + \frac{1}{15}\right] \quad (4)$$

Thus, at surface salinities fresher than the critical salinity, S_{crit}=20 psu, the shorter timescale is used, representing higher respiration due to organic material supplied by the river plumes; the longer background respiration

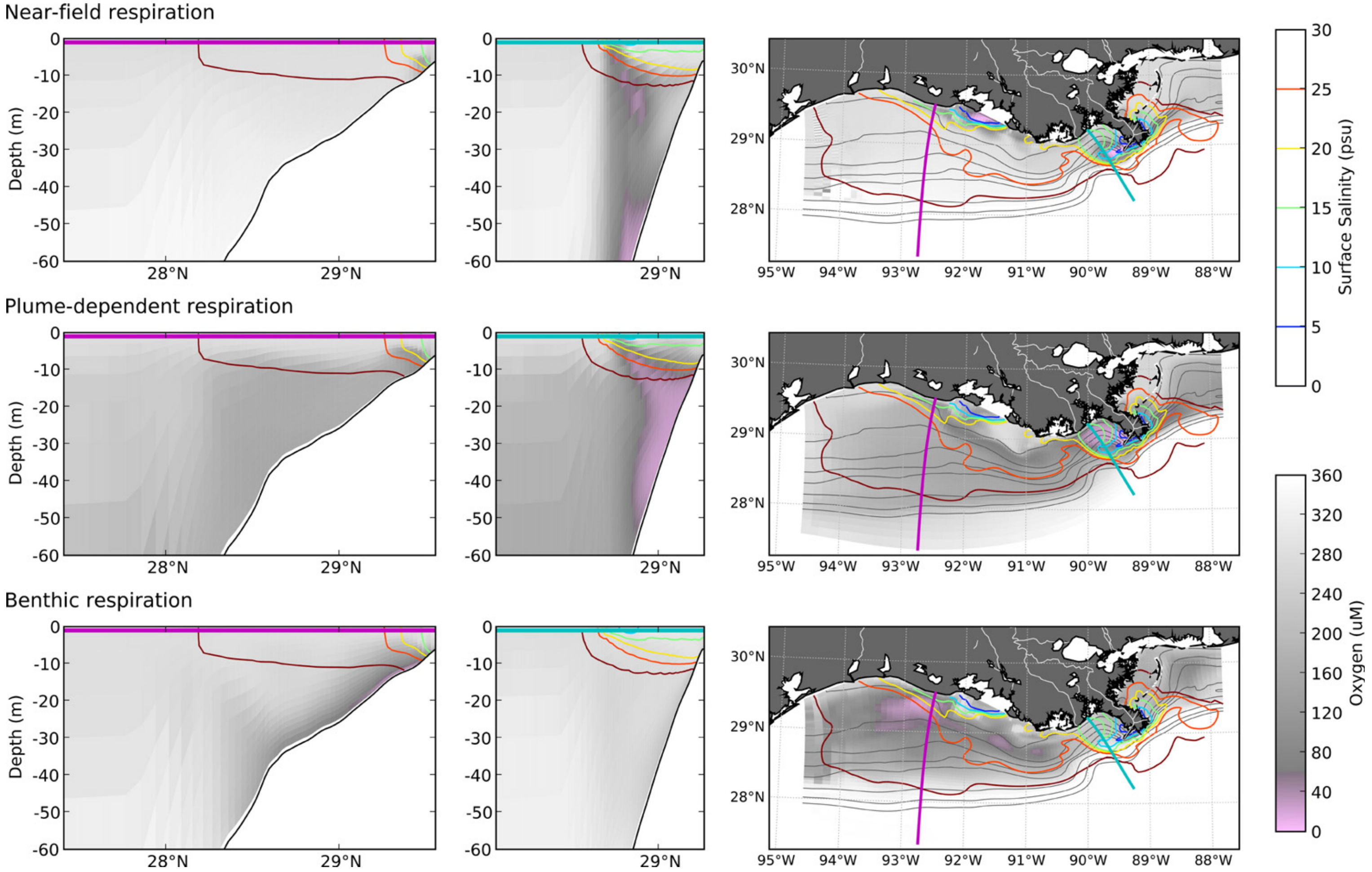


Fig. 4. These panels show plan views of bottom oxygen and cross-sections for all three parameterizations of respiration on 13 August 1993, the same time as the lower panel in Fig. 2. The break in the oxygen colormap is at 60 μM, representing near-hypoxic waters.

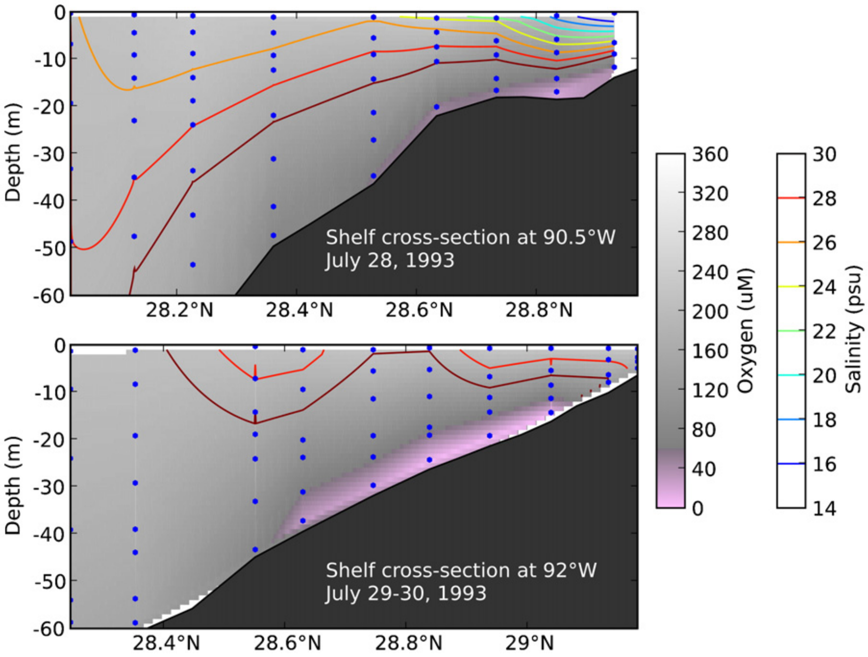


Fig. 5. Cross-sections of observed oxygen and salinity are shown for two transects across the shelf, taken during the LATEX program (Nowlin et al., 1998).

timescale is used for saltier surface waters. Temperature dependence on plume-dependent respiration is identical to that used in the parameterization of benthic respiration.

The timescales of water column respiration are within observed values (Dortch et al., 1994). However, this respiration model is sensitive to the exact values specified, and can produce a very large hypoxic area if a smaller timescale is used for the background value for respiration. The additional part of the shelf that becomes hypoxic when larger values of background respiration are used stretches from Mississippi Canyon westward along the shelf edge, seaward of the region that goes hypoxic in the benthic respiration case. This additional region of hypoxia is deeper than hypoxia is typically observed, and is therefore not a realistic feature of the solution.

2.2.3. Near-source respiration

The near-source respiration biological model specifies uniform respiration throughout the water column with a respiration timescale that increases with distance from the mouths of the two fresh water sources. Thus, respiration is higher near the locations where the rivers enter the ocean,

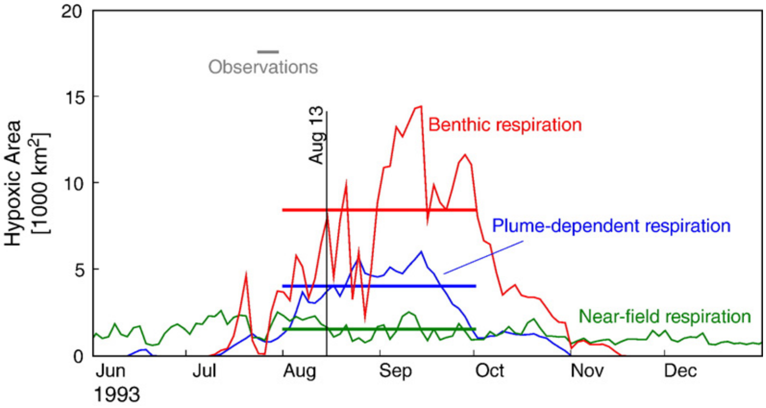
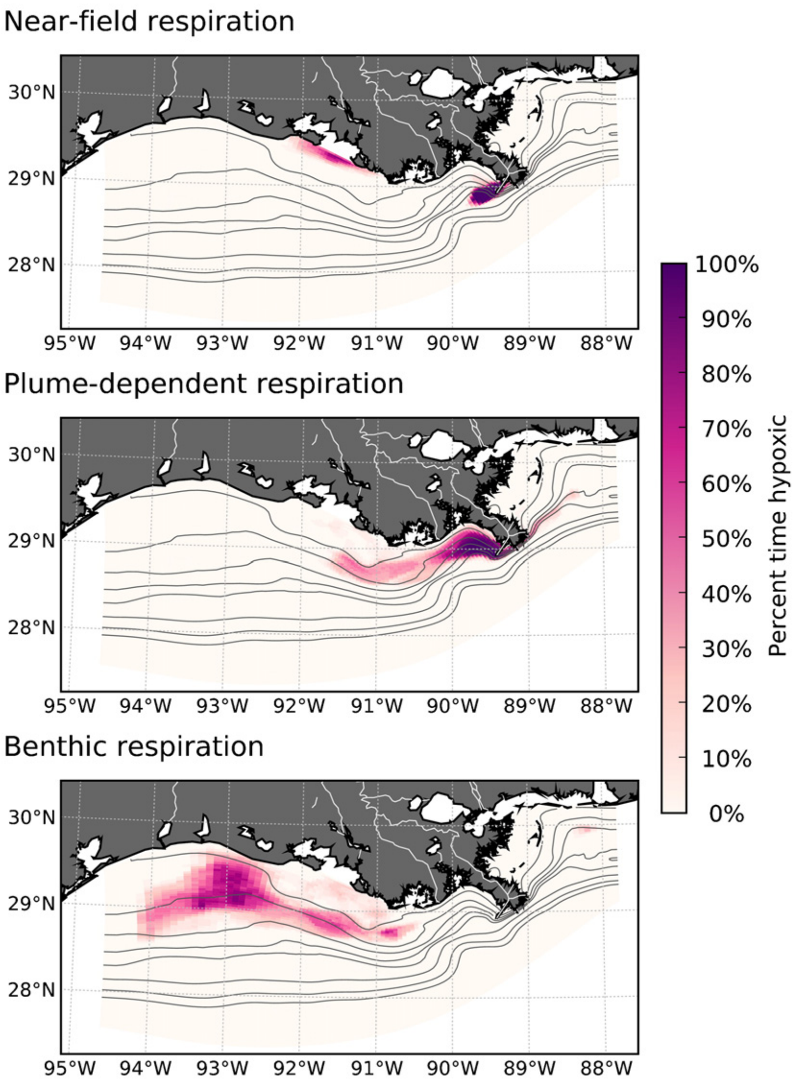


Fig. 6. These three timeseries show the area within the model domain with hypoxic conditions at the bottom of the water column, defined as oxygen concentrations less than 60 μM O_2, for the three parameterizations of respiration. The solid lines show the mean area in August and September of the 1993 simulation year. The solid gray line represents the estimated areal extent of hypoxia, 17,600 km^2, measured 24–30 July 1993. (Rabalais et al., 1999).


Near-field respiration

Plume-dependent respiration

Benthic respiration

Fig. 7. The three panels show the percentage of time different areas of the shelf are affected by hypoxic conditions (less than 60 µM O_2 at the bottom) during August and September.

where organic materials derived from eutrophication near the river mouths are abundant. This model is motivated by the results of Scavia et al. (2003), who model the extent of hypoxia through loading of organic material near the two fresh water sources in the presence of a mean westward flow. In the near-source respiration model, oxygen respiration is specified as an exponential decay with a timescale of τ, as in Eq. (2). Here, τ is determined by the distance away from a fixed point in space,

$$\tau_{\text{near}} = \tau_0 e^{-|x-x_0|^2/R^2}, \qquad (5)$$

where x represents a horizontal position on the shelf, and x_0 is the location of either the Mississippi or Atchafalaya River discharge (so that $|x-x_0|$ is the distance from the point to the source). The Mississippi River x_0 is located at the tip of southwest pass, the Atchafalaya River x_0 is located at the center of the Atchafalaya Bay mouth. The characteristic radius of these regions of high respiration, R, is chosen to be 50 km for the Mississippi Delta and 75 km for the Atchafalaya. Peak respiration is specified with a decay scale of $\tau_0 = 1$ day, exponentially reducing to an infinitely large timescale (i.e., no respiration) away from the fresh water sources.

Because of the short respiration time-scale used, the water column near the two sources is perpetually hypoxic. The purpose of this parameterization is to examine the extent to which hypoxia formed near the two sources is advected into other regions of the shelf.

3. Results

Although the model was integrated for three years, this section focuses on the results from 1993, the first year of simulation. The structure of hypoxia was very similar in the other two years, and the general results discussed below are true for the entire simulated record. A snapshot of the model results on 13 August 1993 is shown in Fig. 4. The simulated transects can be compared with actual cross-sections of oxygen and salinity across the shelf, shown in Fig. 5.

The extent and timing of hypoxia on the Louisiana shelf is examined by calculating the area of low oxygen on the shelf, defined as the region where bottom oxygen concentrations are lower than 60 μM, similar to the classic definition of hypoxia (approximately 2 mg L^{-1}). Time-series of the shelf area affected by hypoxic conditions are shown in Fig. 6. All three parameterizations differ in the timing and extent of hypoxia. The near-source respiration parameterization does not produce a summertime peak in hypoxic area. However, both the plume-dependent and benthic respiration parameterizations create an increased region affected hypoxia in late summer. The areas of the shelf affected by hypoxic conditions are shown in Fig. 7.

Near-source respiration produces only a slightly elevated hypoxic area, remaining below 2000 km^2. In this case, low oxygen waters formed in the vicinity of the two fresh water sources do not bleed out into the rest of the shelf. Currents do indeed carry low oxygen water westward, as in the conceptual model of Scavia et al. (2003). However, this water is quickly mixed with ambient, higher oxygen shelf water as it enters the mid-shelf and does not remain hypoxic more than about 50 km away from the source.

Hypoxia caused by plume-dependent respiration is most persistent near the Mississippi Delta, with very persistent hypoxia forming to the west of the Delta in the Louisiana Bight. The vertical structure of hypoxia is not consistent with observations, in that hypoxic waters form over a significant percentage of the water column beneath the pycnocline (see Figs. 4 and 8).

The benthic respiration model does not produce significant hypoxic conditions near the Mississippi Delta, but does do so west of Terrebonne Bay past the Louisiana/Texas border. Hypoxic conditions caused by benthic respiration are only found inshore of the 50 m isobath. Hypoxia is also only found near the bottom within the bottom boundary layer, in agreement with observations (see Fig. 5). Near-shore, hypoxic conditions are ephemeral, with the most persistent hypoxia centered along the 20 m isobath.

Both plume-dependent and benthic respiration show a marked increase in the area affected by hypoxia, beginning in late July and extending through the late summer, similar to observations. The region of low oxygen caused by benthic respiration is generally confined to the mid-

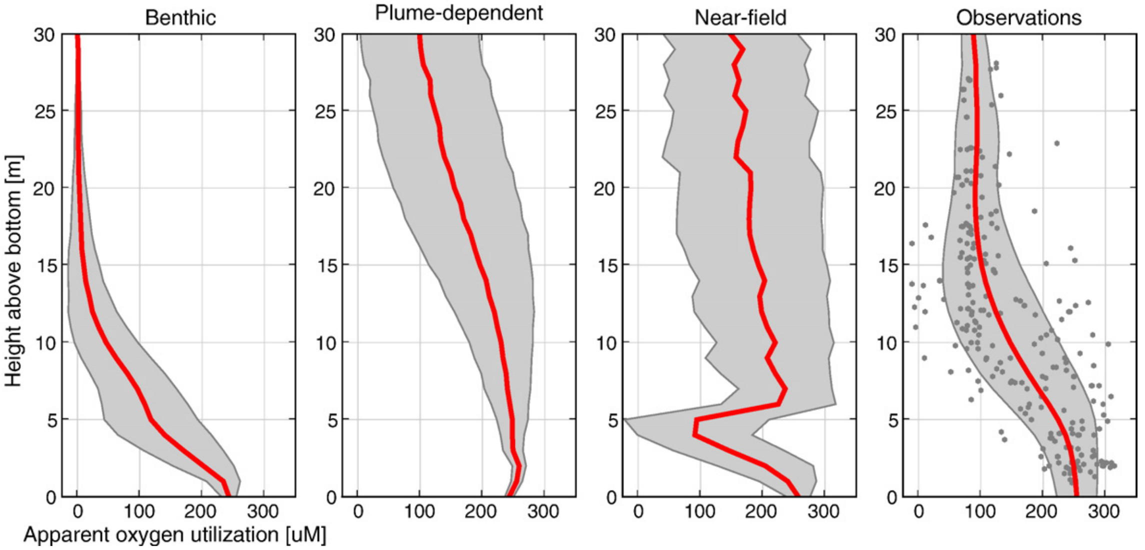


Fig. 8. Each panel shows the apparent oxygen utilization (AOU), the difference between the simulated or observed oxygen subtracted from the saturation value defined as a function of local temperature and salinity. The red line in each case represents an mean AOU profile, the shaded region is the AOU standard deviation. Profiles are referenced to the sea-floor, and shown in terms of height above bottom. The observations shown in the rightmost panel are taken in 1993–1995 during the LATEX program (Nowlin et al., 1998). Individual observations are shown as grey dots.

shelf (between 10 and 70 m, see Fig. 4). The extent of this low oxygen region is largest in late summer; it is greatly diminished by mid-October and is destroyed completely by winter because increased wind mixing homogenizes the water over the shelf. Different respiration parameterizations create regions of hypoxia that are half to a quarter of the area of the shelf observed to be affected by hypoxia in 1993. Given the uncertainties in the plume-dependent respiration, the sum of the plume-dependent and benthic respiration parameterizations create a region of hypoxia similar in magnitude to that observed. Also, the combination of plume-dependent and benthic respiration hypoxia covers approximately the same region as observed hypoxia — from the Mississippi Delta to 93°W, and between 10 and 50 m depth.

The vertical structure of apparent oxygen utilization was calculated for each of the respiration parameterizations and hydrographic profiles by calculating the mean profile of apparent oxygen utilization above the sea floor. The apparent oxygen utilization is defined as the simulated or observed oxygen concentration subtracted from the saturated oxygen concentration based on the local temperature and salinity. Only profiles where the bottom oxygen was hypoxic (bottom oxygen concentrations less than 60 μM O_2) were included in the average profiles, thus these profiles represent the mean oxygen structure only within the region affected by hypoxia. The results of this calculation are shown in Fig. 8. Simulated near-source and plume-dependent respiration both show a gradually decaying oxygen profile with depth. Simulated benthic respiration and observed oxygen deficit profiles both show a break in the oxygen profile at approximately 15 m above bottom, with uniform oxygen above this point, and a linear decrease in oxygen below this point. The observations were primarily taken west of Terrebonne Bay, in the region where the model suggests that hypoxia formation is dominated by benthic respiration. Other studies (e.g., Dortch et al., 1994) have shown that water column respiration may be locally strong, so it is probable that water column respiration is more important near the Mississippi Delta, as the model suggests.

4. Discussion

One of the primary results of this study is that hypoxia formation is primarily a vertical, rather than horizontal, process. Low oxygen conditions do not advect laterally, but are rather formed by local respiration processes and destroyed by vertical mixing. In particular, the results of the near-source respiration model suggest that hypoxic waters do not spread from locations of high respiration near the river mouths to other parts of the shelf. The simple model described by Scavia et al. (2003) uses a weak westward current to advect both organic material and low oxygen waters westward. Their model requires westward currents of about 0.005 m s^{-1}. A simple scaling analysis demonstrates that coherent water parcels are considerably diffused by even modest horizontal mixing given this modest westward advection. For example, assume there is a patch of low oxygen water with an initial diameter of 20 km, advected by a westward flow of 0.005 m s^{-1}, and a horizontal turbulent diffusion rate of 20.0 m^2 s^{-1} typical for coastal flows. This parcel will be diluted by a factor of approximately four after it has been advected 50 km, essentially destroying the hypoxic patch through diffusion just as smoke from a smokestack disperses away from the source.

Because hypoxia formation and destruction is a primarily vertical process, it might appear possible to model hypoxia using a one-dimensional (vertical) model similar to that used by Justić et al. (2002). However, alongshore differences in the dominant type of respiration causing hypoxia would make it difficult to use a single parameterization for respiration — a series of model runs for different shelf regions would be required.

However, even though the formation and destruction of hypoxia due to respiration and mixing may be predominately vertical processes, the supply of organic material to fuel biological respiration (which this study does not explicitly address) must be a horizontal process. Organic material is most likely carried laterally across the shelf by wind-driven motions of the two surface river plumes.

Model results also show two separate regions, divided at approximately 90.5°W, where the shelf bends at Terrebonne Bay. The eastern regime is influenced primarily by discharge from the Mississippi River Delta, the flow from Southwest Pass supplying the majority of the fresh water. Water column respiration is the primary cause of hypoxia in the eastern regime. The western regime is influenced by both the discharge from the Atchafalaya and shelf-wide wind-driven currents, with bottom respiration being the primary cause of hypoxia. Although these two regimes have very similar forcing, the geometry of the shelf and the locations of the fresh water sources create two very distinct physical regimes. The fresh water flux is similar in magnitude since half of the Mississippi River Delta discharge is advected eastward (Dinnel and Wiseman, 1986; Etter et al., 2004), and atmospheric scales are large enough that the wind stress and heat fluxes over the shelf are quite similar (Wang et al., 1998).

The westward-flowing portion of the Mississippi River Delta discharge empties out near the shelf break, and travels over the relatively deep water at the head of Mississippi Canyon. The exact location of the plume depends on the orientation of the outflow jet and the local wind stress, which shifts the plume water approximately as a surface Ekman layer (see, e.g., Hetland, 2005). The plume from Southwest Pass, the most distinct individual plume from any of the many Mississippi Delta passes, may often be identified in true color satellite images. This jet often flows over the head of Mississippi Canyon (>50 m deep) and contributes to a recirculating anticyclonic gyre in the Louisiana Bight described by Ichiye (1960) and Wiseman et al. (1997) (also seen in Fig. 2). The recirculating gyre is most prominent during downwelling conditions. This recirculating gyre is similar to the surface trapped plume described by Yankovsky and Chapman (1997); it is influenced strongly by both advection and the earth's rotation, and does not interact directly with the bottom. The Mississippi River plume maintains some stratification within Louisiana Bight even under upwelling conditions, as evident in Fig. 2. The geographical configuration of the extended delta mid-shelf also presents a physical barrier for shelf waters east of the delta to be advected west onto the Texas–Louisiana shelf.

The Atchafalaya empties out into the very shallow coastal region of a broad, gently-sloping shelf. Thus, although the fresh water contributions are similar, the fresh water from the Atchafalaya will tend to have a longer residence time on the shelf since it must traverse the entire shelf before crossing the shelf break and entering the deep Gulf. Relatively fresh water is forced out onto the shelf such that the bottom waters shoreward of the point where the river plume front intersects the bottom, near the mouth of Atchafalaya Bay, are ventilated. This process creates a near-shore region around the mouth of the Bay that is unaffected by seasonal hypoxia, as seen in the seaward extent of hypoxia under bottom respiration (Fig. 7, third panel).

Both rivers contribute to the general salinity stratification observed over the entire shelf. This salinity stratification is caused by the upwelled plumes mixing into the background waters, thereby creating a freshened upper mixed layer not as distinct as the river plumes themselves, but still strongly stratified by the presence of fresh, warm water at the surface.

The physical environment favors the formation of hypoxia due to different types of respiration in different regions. The model results indicate that water column respiration is most likely the dominant cause of hypoxia in the region affected by the Mississippi River plume, east of Terrebonne Bay, whereas west of Terrebonne Bay hypoxia is linked to bottom respiration. If the effects of plume-dependent and bottom respiration are combined, results shown in Fig. 7 suggest the structure of observed hypoxia may be caused by the sum of plume-dependent respiration and bottom respiration. Bottom respiration best reproduces the observed vertical structure of oxygen in the water column west of Terrebonne Bay. However, observations show that although the mean oxygen profile above 15 m above bottom is approximately uniform, it is not saturated, indicating that water column respiration (and the mitigating effect of oxygen production due to photosynthesis) might be significant even if it is not what ultimately creates hypoxia.

Biological processes are affected by the physical environment in which they occur; timescales of plume motion, stratification, and water column mixing will all influence in situ biological processes. As discussed above, the oxygen structure caused by bottom respiration will be affected by the magnitude of local stratification, which is in turn influenced by buoyancy inputs, wind stress, internal and shelf waves. Wind stress changes on seasonal timescales, but there is also considerable variability in the weather band, with timescales of a few days to weeks. Fig. 2 gives an example of how quickly the two river plumes may change position, and alter the stratification on the shelf. It appears that the seasonal timescale of the creation of stratification by weak, upwelling-favorable winds is important when hypoxia is forming, but weather-band variability due to frontal passages is important in the fall when hypoxia is destroyed. Model results show that hypoxia is destroyed by strong wind events in the late fall, in agreement with our understanding of the temporal changes in hypoxic structure. The wind events mix near-shore water first, and progressively erodes stratification from shallow to deep waters in bursts as atmospheric fronts pass over the region. Thus, although the timescales that create the stratification envelope and allow hypoxia to form are relatively long, being associated with the seasonal shift in the mean winds, the timescales of the destruction of hypoxia are relatively short. Of course, summertime hurricanes can fundamentally disrupt the seasonal progression described here; the effects of hurricanes will be investigated in future studies.

Correlations between satellite derived ocean color and either wind stress or river discharge show two distinct regions of correlation (Salisbury et al., 2004). Ocean color over the shelf region south of the Atchafalaya River is strongly correlated with the wind, where ocean color is strongly correlated with Mississippi River discharge in the region around the Mississippi River Delta. Wind forcing is important in resuspending sediments over the broad, shallow shelf west of Terrebonne Bay, while advective plume processes are important in the Mississippi River Delta region east of

Terrebonne Bay. The physical mechanisms that are responsible for the different optical properties are most likely different than those that differentiate the two regions of hypoxia in the present study, however, the underlying differences in the physical regimes of each region are responsible for creating two distinct regions both in terms of ocean color and dominant mode of respiration.

An obvious weakness of the modeling approach presented here is that the supply of organic material is not considered. Since benthic respiration is thought to be relatively constant along the Texas–Louisiana shelf (Rowe et al., 2002), the primary differences will be in water column respiration. Here, we consider organic material derived from river-borne nutrients through the plume-dependent respiration parameterization. However, it is likely that other sources of nutrients from bays (Krug, 2007), or coastal upwelling will be important in supplying organic material to different regions away from Louisiana Bight. This paper focused only on river-borne nutrients, as that has been the only source of nutrients considered by previous predictive modeling studies (Justić et al., 2002; Scavia et al., 2003). The modeling results presented here suggest that river-borne nutrients may be directly important in creating hypoxia within Louisiana Bight, but not west of Terrebonne Bay. If we are to better understand and predict seasonal hypoxia, particularly in the region south and west of Atchafalaya Bay, we need to better understand all of the nutrient pathways that influence production on the shelf.

5. Conclusions

The extent and timing of hypoxia along the shelf is controlled by the interactions between both physical processes and the character of respiration. Ultimately, either physical processes or biological processes must be the limiting factor in the creation and maintenance of hypoxia. The supply of organic material creates a *hypoxic potential*: a biological bound on the extent and magnitude of hypoxia due to the amount of material available to be respired. For this potential to be realized, the physical environment must be favorable; the water column must be stratified. The extent of physical stratification creates a *stratification envelope*: a physical bound on the region where hypoxia may occur.

The formation and destruction of hypoxia is a vertical process, a balance between respiration and vertical mixing. Patches of hypoxia are not formed in one region and advected to other regions, but rather are created and destroyed in a single location on the shelf. This result is true for all numerical experiments shown, and is therefore not an artifact of the details of the respiration parameterizations. However, lateral advection is most likely very important in bringing organic material to different locations on the shelf.

This study isolates the physical influences that help to create hypoxia by examining very simple parameterizations of respiration. We do not believe that these simple parameterizations are appropriate for realistic simulations of hypoxia. Regions near the shelf edge that are often hypoxic in this study are most likely limited by the supply of organic material. To investigate the combined limits of the stratification envelope and the hypoxic potential, a biological model that at least contains a nitrogen budget must be used. However, we believe the simulations shown in this paper do reproduce the essence of the different types of biological processes acting to draw down oxygen in the water column, and highlight the differences between the eastern and western portions of the shelf. These differences are caused by the geometry of the shelf: region east of Terrebonne Bay is characterized by a steep, narrow shelf, while the region west of Terrebonne Bay is characterized by a broad, gently-sloping shelf.

Different physical environments may enhance or repress the effects of different types of respiration. Thus, the physical environment may not only select for the regions of the shelf where respiration may create hypoxia, but may also select the dominant type of respiration that forms hypoxia. The Mississippi River plume most strongly affects the region between the Mississippi River Delta and Terrebonne Bay. This region of hypoxia is controlled by water column respiration. West of Terrebonne Bay, stratification is controlled by fresh water leaving the Louisiana Bight as well as local runoff from the Atchafalaya River. In this region, the pycnocline is not as sharp, and the buoyancy driven flow interacts directly with the bottom topography. Hypoxia west of Terrebonne Bay is controlled by bottom respiration. Because of these differences in the structure of respiration causing hypoxia, extrapolating measurements of stratification, respiration, and mixing at a single point will not adequately describe the processes influencing hypoxia over the entire shelf.

Although the biological respiration is not limited by a finite source of organic material, these simple forms of respiration result in an areal extent of hypoxia over the shelf similar to observations. Thus, it is possible that the areal extent of hypoxia over the Texas–Louisiana shelf is determined by the stratification envelope rather than nutrient supply from the river systems. This may be particularly true for the along-shelf extent of hypoxia. Scavia et al. (2003) note that the areal extent of hypoxia is highly correlated with the along-shore extent of the hypoxic area, thus variations in the stratification envelope are almost certainly important in determining the inter-annual variations in the size of the hypoxic region.

Acknowledgments

This work was funded by the NOAA Center for Sponsored Coastal Ocean Research under grant NA03NOS4780039. We would like to thank Leila Belabbassi, Piers Chapman, and Gilbert Rowe for their data analysis and many helpful comments.

References

Cho, K., Reid, R.O., Nowlin, W.D., 1998. Objectively mapped stream function fields on the Texas–Louisiana shelf based on 32 months of moored current meter data. J. Geophys. Res. 103 (C5), 10,377–10,390.

Cochrane, J.D., Kelly, F.J., 1986. Low-frequency circulation on the Texas-Louisiana continental shelf. J. Geophys. Res. 91 (C9), 10,645–10,659.

da Silva, A.M., Young-Molling, C.C., Levitus, S., 1994a. Atlas of Surface Marine Data 1994 Vol. 3: Anomalies of Fluxes of Heat and Momentum. NOAA Atlas NESDIS 8. Technical Report. U.S. Gov. Printing Office, Wash., D.C.

da Silva, A.M., Young-Molling, C.C., Levitus, S., 1994b. Atlas of Surface Marine Data 1994 Vol. 4: Anomalies of Fresh Water Fluxes. NOAA Atlas NESDIS 9. Technical Report. U.S. Gov. Printing Office, Wash., D.C.

Dagg, M.J., Breed, G.A., 2003. Biological effects of Mississippi River nitrogen on the northern Gulf of Mexico — a review and synthesis. J. Mar. Syst. 43, 133–152.

DiMarco, S.F., Reid, R.O., 1998. Characterization of the principal tidal current constituents on the Texas–Louisiana Shelf. J. Geophys. Res. 103 (2), 3093–3110.

Dinnel, S.P., Wiseman Jr., W.J., 1986. Freshwater on the Louisiana and Texas shelf. Cont. Shelf Res. 6, 765–784.

Dortch, Q., Rabalais, N.N., Turner, R.E., Rowe, G.T., 1994. Respiration rates and hypoxia on the Louisiana shelf. Estuaries 17, 862–872.

Etter, P.C., Howard, M.K., Cochrane, J.D., 2004. Heat and freshwater budgets of the Texas–Louisiana shelf. J. Geophys. Res. 109 (C2), C02024. doi:10.1029/2003JC001820.

Flather, R.A., 1976. A tidal model of the northwest European continental shelf. Mem. Soc. R. Sci. Liege 10 (6), 141–164.

Fong, D.A., Geyer, W.R., 2001. Response of a river plume during an upwelling favorable wind event. J. Geophys. Res. 106 (C1), 1067–1084.

Galperin, B., Kantha, L.H., Rosati, A., 1988. A quasi-equilibrium turbulent energy model for geophysical flows. J. Atmos. Sci. 45, 55–62.

García Berdeal, I., Hickey, B.M., Kawase, M., 2002. Influence of wind stress and ambient flow on a high discharge river plume. J. Geophys. Res. 107 (C9), 13–1–13–24.

Hetland, R.D., 2005. Relating river plume structure to vertical mixing. J. Phys. Oceanogr. 35 (9), 1667–1688.

Ichiye, T., 1960. On the hydrography near Mississippi Delta. Oceanogr. Mag. 11 (2), 65–78.

Justić, D., Rabalais, N.N., Turner, R.E., 2002. Modeling the impacts of decadal changes in riverine nutrient fluxes on coastal eutrophication near the Mississippi River Delta. Ecol. Model. 152, 33–46.

Krug, E.C., 2007. Coastal change and hypoxia in the northern Gulf of Mexico: Part I. Hydrol. Earth Syst. Sci. 11, 180–190.

Lentz, S., 2004. The response of buoyant coastal plumes to upwelling-favorable winds. J. Phys. Oceanogr. 34 (11), 2458–2467.

Lohrenz, S.E., Dagg, M.J., Whitledge, T.E., 1990. Enhanced primary production at the plume/oceanic interface of the Mississippi River. Cont. Shelf Res. 10, 639–664.

Lohrenz, S.E., Fahenstiel, G.L., Redalje, D.G., Lang, G.A., Chen, X., Dagg, M.J., 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. Mar. Ecol. Prog. Ser. 155, 45–54.

Lohrenz, S.E., Fahnenstiel, G.L., Redalje, D.G., Land, G.A., Dagg, M.J., Whitledge, T.E., Dortch, Q., 1999. Nutrients, irradiance, and mixing as factors regulating primary production in coastal waters impacted by the Mississippi River plume. Cont. Shelf Res. 19, 1113–1141.

Marchesiello, P., McWilliams, J.C., Shchepetkin, A., 2003. Equilibrium structure and dynamics of the California Current System. J. Phys. Oceanogr. 33, 753–783.

Mellor, G.L., Yamada, T., 1974. A hierarchy of turbulent closure models for planetary boundary layers. J. Atmos. Sci. 31, 1791–1806.

Mississippi River/Gulf of Mexico watershed nutrient task force, 2004. A Science Strategy to Support Management Decisions Related to Hypoxia in the Northern Gulf of Mexico and Excess Nutrients in the Mississippi River Basin. U.S. Geological Survey Circular, vol. 1270.

Nowlin, W.D., Jochens, A.E., Reid, R.O., DiMarco, S.F., 1998. Texas–Louisiana shelf circulation and transport process study: synthesis report LATEX A, Vols. 1. and 2. OCS Study MMS 98-0035 and MMS 98-0036, Technical Report, U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans.

Nowlin, W.D., Jochens, A.E., DiMarco, S.F., Reid, R.O., Howard, M. K., 2005. Low-frequency circulation over the Texas–Louisiana continental shelf. In: Wilton, Lugo-Fernandez, A. (Eds.), Circulation in the Gulf of Mexico. American Geophysical Union, pp. 219–240.

Rabalais, N.N., Turner, R.E., Justic, D., Dortch, Q., Wiseman, W.J., 1999. Characterization of Hypoxia: Topic 1 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. Technical Report, NOAA Coastal Ocean Program, Silver Spring, MD.

Rowe, G.T., Chapman, P., 2002. Continental shelf hypoxia: some nagging questions. Gulf Mex. Sci. 20 (2), 153–160.

Rowe, G.T., Kaeki, M.E.C., Morse, J.W., Boland, G.S., Briones, E.G.E., 2002. Sediment community metabolism associated with continental shelf hypoxia, northern Gulf of Mexico. Estuaries 25 (6), 1097–1106.

Salisbury, J.E., Campbell, J.W., Linder, E., Meeker, L.D., Müller-Karger, F.E., Vörösmarty, C.J., 2004. On the seasonal correlation of surface particle fields with wind stress and Mississippi discharge in the northern Gulf of Mexico. Deep-Sea Res., Part II, Top. Stud. Oceanogr. 51, 1187–1203.

Scavia, D., Rabalais, N.N., Turner, R.E., Justić, D., Wiseman Jr., W.J., 2003. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. Limnol. Oceanogr. 48 (3), 951–956.

Shchepetkin, A.F., McWilliams, J.C., 2005. The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topographically-following-coordinate oceanic model. Ocean Model 9, 347–404.

Turner, R.E., Rabalais, N.N., 1994. Coastal eutrophication near the Mississippi river delta. Nature 368 (14), 619–621.

Turner, R.E., Rabalais, N.N., Swenson, E.M., Kasprzak, M., Romaire, T., 2005. Summer hypoxia in the northern Gulf of Mexico and its prediction from 1978 to 1995. Mar. Environ. Res. 59, 65–77.

Wang, W., Nowlin, W.D., Reid, R.O., 1998. Analyzed surface meteorological fields over the northwestern Gulf of Mexico for 1992–94: mean, seasonal, and monthly patterns. Mon. Weather Rev. 126 (11), 2864–2883.

Weiss, R.F., 1970. The solubility of nitrogen, oxygen, and argon in water and seawater. Deep-Sea Res. 17, 721–735.

Wiseman Jr., W.J., Rabalais, N.N., Turner, R.E., Dinnel, S.P., MacNaughton, A., 1997. Seasonal and interannual variability within the Louisiana coastal current: stratification and hypoxia. J. Mar. Syst. 12, 237–248.

Yankovsky, A.E., Chapman, D.C., 1997. A simple theory for the fate of buoyant coastal discharges. J. Phys. Oceanogr. 27, 1386–1401.