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Assessing temporal and spatial variability of hypoxia over the inner Louisiana–upper Texas shelf: Application of an unstructured-grid three-dimensional coupled hydrodynamic-water quality model

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ABSTRACT

Patterns of temporal and spatial variability in hypoxia (<2 mg O_2 l^{-1}) on the inner Louisiana–upper Texas (LaTex) shelf were examined using FVCOM LaTex, an unstructured grid, three-dimensional, hydrodynamic-water quality model. Dynamics of dissolved oxygen were modeled using an expanded and revised version of the Water Analysis Simulation Program (WASP) that was fully coupled to a Finite Volume Coastal Ocean Model (FVCOM). The coupled model was driven by surface wind forcing, tidal forcing, offshore remote forcing, heat fluxes, oxygen exchanges at the air-sea interface, solar radiation, and freshwater and nutrient (nitrogen and phosphorus) fluxes from the Mississippi and Atchafalaya Rivers. The model simulations were carried out over a 9-month period, from January 1 to October 4, 2002, and the model skill was assessed using multiple sets of observational data that included time series of dissolved oxygen concentrations from a station within the core of the Gulf hypoxic zone (C6), dissolved oxygen measurements collected during the mid-summer shelfwide cruise, and vertical dissolved oxygen profiles through the year. The model results indicate that hypoxia originates in bottom waters on the mid-continental shelf, where isolated pockets of hypoxic water develop during early spring and later join into a larger continuous hypoxic zone. The model accurately described the seasonal cycle of hypoxia at station C6, including the episodes of intermittent hypoxia during May and June, persistent hypoxia during July and August, and dissipation of hypoxia during September. The onset of hypoxia coincided with high stability of the water column (i.e., Richardson number values >1) and the initial transition from normoxia (i.e., 6 mg O_2 l^{-1}) to hypoxia lasted about three weeks. The model results point to a significant short-term variability in the extent of hypoxic bottom waters, indicating that the size of the mid-summer hypoxic zone cannot be adequately captured by a single shelfwide cruise. The dynamics of bottom-water hypoxia is clearly influenced by the bathymetric features of the LaTex shelf, namely the presence of three shallow shoals (<5 m) in the Atchafalaya Bay region and several deeper shoals (<10 m) in the northwestern section of the study area. Lastly, the model results support the view that dynamics of hypoxia on the LaTex shelf is strongly modulated by the frequency and intensity of cold fronts and tropical storms. High winds associated with these events disturb stratification, causing partial or complete breakdown of hypoxia. However, cold fronts and tropical storms also cause significant sediment resuspension that fuels respiration in the lower water column, and in this manner promote redevelopment of hypoxia.

1. Introduction

The inner Louisiana–upper Texas (LaTex) shelf in the northern Gulf of Mexico (GoM; Fig. 1) is the site of one of the world's largest hypoxic zones (<2 mg O_2 l^{-1}) in the coastal ocean (Rabalais et al., 2007a). Historical reconstruction based on dated sediment cores (Turner and Rabalais, 2004; Rabalais et al., 2007b; Osterman et al., 2008, 2009) and model hindcasts (Justić et al., 2002) indicate that bottom-water hypoxia started to develop in the early part of the 20th century, and has become more frequent and widespread since the 1960s. Regular mid-summer cruises since 1985 have mapped the extent of hypoxic bottom waters across the LaTex shelf, with summer hypoxic area averaging 13,500 km^2 for 1985–2009 (Rabalais et al., 2010). The extent of the mid-summer hypoxic zone has varied greatly over the years, from near zero in 1988 to 22,000 km^2 in 2002 (Rabalais et al., 2007a). Hypoxia typically develops in waters below the pycnocline and extends from the depths of ~5 m near the shore to as deep as 60 m at the offshore boundary of the hypoxic zone (Rabalais et al., 2007a).

Hypoxia develops as a synergistic product of a suite of physical and biological factors that control the supply of oxygen and its utilization in the water column and sediments (Rabalais and

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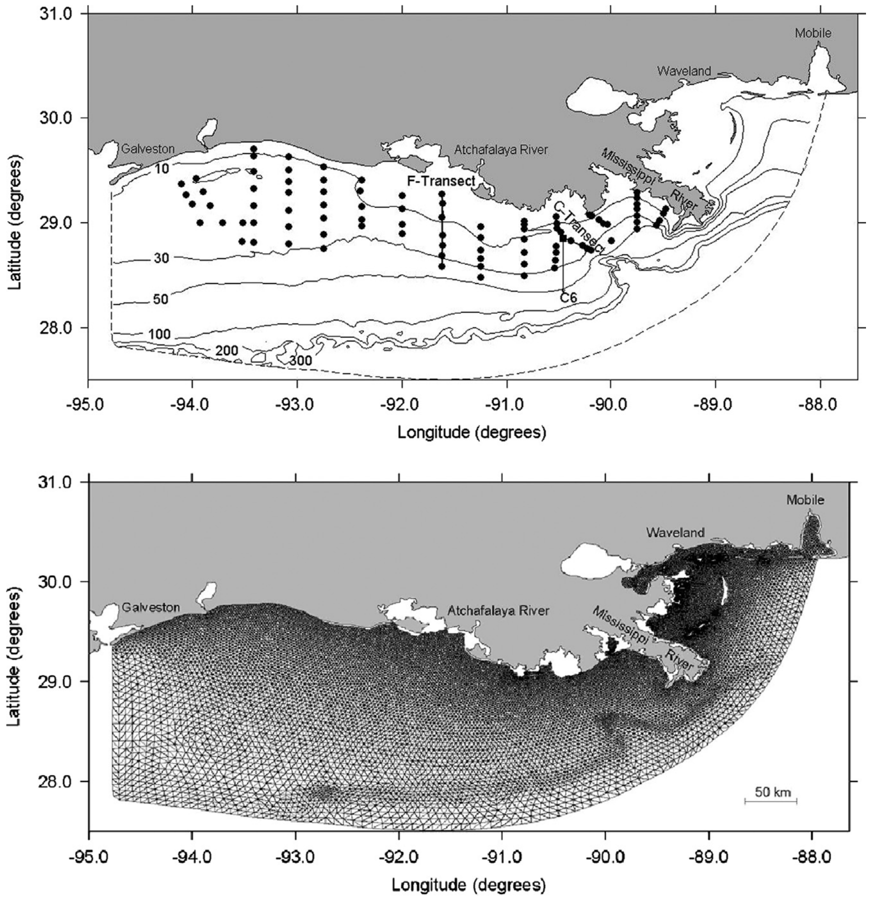

Fig. 1. Map of the northern Gulf of Mexico showing bathymetry and the locations of monitoring stations (upper panel) and model computational grid (lower panel). Transects C and F are indicated by solid lines.
(Adapted from Wang and Justić (2009)).

Turner, 2001). The synergism of physical and biological factors is complex and cannot be inferred solely from the observational studies (Justić et al., 1996; Dale et al., 2010). Because of intricate nutrient transformation pathways, rapidly changing coastal circulation and stratification patterns, and limited spatial observations, simulation modeling has emerged as a major research tool to study the dynamics of hypoxia (Justić et al., 2007). In particular, recent advances in three-dimensional (3-D) coupled hydrodynamic-water quality models for the GoM hypoxic zone (e.g., Hetland and DiMarco, 2008; Wang and Justić, 2009; Fennel et al., 2011) have afforded researchers the opportunity to examine the relative roles of physics and biology as controls of hypoxia in coastal bottom waters.

There are several important research questions where simulation modeling can help advance our understanding of hypoxia. One of the questions relates to the mechanism of hypoxia development on the LaTex shelf. It is generally believed that phytoplankton production, enhanced by nutrient loading from the Mississippi and Atchafalaya Rivers, supplies the labile organic matter that is respired within the LaTex hypoxic zone. This view is supported by retrospective analyses based on sediment records (Eadie and McKee, 1994; Turner and Rabalais, 1994; Sen Gupta et al., 1996) and model simulations pointing to strong coupling between the increased riverine nutrient loads and the extent and severity of hypoxia (Justić et al., 2002; Scavia et al., 2003, 2004; Turner et al., 2007, 2012; Liu et al., 2010). However, at present it is not known whether the majority of labile organic matter is produced in the surface waters overlying the hypoxic zone, or supplied through the cross-shelf transport from the highly productive shallow (0–10 m) coastal waters (Boesch et al., 2009; Murrell et al., 2013). Examining the linkages between circulation and dynamics of dissolved oxygen (DO) may provide important clues regarding the sources of labile organic matter and the mechanism of hypoxia development on the LaTex shelf.

A related question concerns the scales of temporal and spatial variability in hypoxia on the LaTex shelf. Continuous oxygen measurements in the core of the Gulf hypoxic zone (Station C6, Fig. 1) have shown that there is substantial short-term (hours to days) variability in the bottom DO concentrations (Rabalais et al., 2007a). However, the extent of the hypoxic zone is determined based on a single 5–6 day long mid-summer shelfwide cruise, typically carried out during the last week in July (Rabalais et al., 2007a). It is likely that the size of the hypoxic zone changes during the course of the summer, leading to an imprecise areal estimate of hypoxia. Yet, because there have been few sequential hypoxia surveys, the patterns of short-term variability in the areal extent of hypoxia are largely unknown.

Another significant question that modeling can address pertains to the degree to which the seasonal cycle of hypoxia is controlled by the frequency and intensity of cold fronts and tropical storms. Although observational and modeling studies have shown that strong winds associated with frontal or tropical events often lead to partial or complete breakdown of hypoxia (e.g., Rabalais et al., 2007a; Wang and Justić, 2009), it is not known what role the strength of stratification may play in modulating the impacts of these storms.

Knowing the answers to these questions is important both for understanding the underlying causes for hypoxia and for establishing realistic goals reducing its size. The Action Plan developed by the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (Task Force, 2001) set a goal to reduce the 5-yr running average of