

Forecasting Gulf's Hypoxia: The Next 50 Years?

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ABSTRACT: This review discusses the use of hypoxia models in synthesizing the knowledge about the causes of Gulf of Mexico hypoxia, predicting the probable consequences of management actions, and building a consensus about the management of hypoxia. It also offers suggestions for future efforts related to simulating and forecasting Gulf hypoxia. The existing hypoxia models for the northern Gulf of Mexico range from simple regression models to complex three-dimensional simulation models, and they capture very different aspects of the physics, chemistry, and biology of this region. Several of these models were successfully calibrated to observations relevant for their process formulations and spatial-temporal scales. Available model results are compared to reach the consensus that large-scale hypoxia probably did not begin in the Gulf of Mexico until the mid 1970s, and that the 30% nitrogen load reduction that is called for by the Action Plan may not be sufficient to achieve its goal. The present models results suggest that a 40–45% reduction in riverine nitrogen load may be necessary to achieve the desired reduction in the areal extent of hypoxia. These model results underscore the importance of setting this goal as a running average because of significant interannual variability. Caution is raised for setting resource management goals without considering the long-term consequences of climate variability and change.

Introduction

Large-scale hypoxia ($< 2 \text{ mg O}_2 \text{ l}^{-1}$) in the northern Gulf of Mexico, up to 22,000 km², overlaps with habitat and fishing grounds of commercially important fish and shrimp. Hypoxia typically occurs from March through October in waters below the pycnocline, and extends between 5 and 60 m depth offshore (Rabalais and Turner 2001; Rabalais et al. 2007). Retrospective analyses (Eadie et al. 1994; Turner and Rabalais 1994; Sen Gupta et al. 1996) and model simulations (Justić et al. 2002; Scavia et al. 2003, 2004) suggest that Gulf hypoxia has intensified during the last five decades, as a probable consequence of increased riverine nitrogen inputs and more balanced nutrient ratios in discharged freshwaters (Turner and Rabalais 1991; Justić et al. 1995a,b; Goolsby et al. 1999; Turner et al. 2006). The concentration of nitrate, the predominant form of nitrogen in the Mississippi River, has increased 2.5-fold since the 1950s, coincidentally with the increased use of fertilizers in the watershed (Turner and Rabalais 1991; Howarth et al. 1996; Goolsby et al. 1999). Nitrogen is often considered to be the limiting nutrient for estuarine and coastal phytoplankton (e.g., D'Elia et al. 1986; Limno-Tech, Inc. 1995; Rabalais 2004), and there is strong evidence that it controls the extent of primary

production in the northern Gulf of Mexico (Lohrenz et al. 1990, 1997, 1999; Rabalais et al. 2002).

Hypoxia develops from a suite of biological and physical factors, two of which are most important: nutrient-enhanced surface primary productivity, which is also manifested in a high carbon flux to sediments (Justić et al. 1996; Lohrenz et al. 1997; Rabalais and Turner 2001), and high stability of the water column, which controls vertical diffusive oxygen flux (Wiseman et al. 1997, 2004). Changes in the areal extent of hypoxia between flood years and drought years provide perhaps the best example of the synergistic nature of these influences. During the drought of 1988 (a 52-yr low discharge record of the Mississippi River), bottom oxygen concentrations were significantly higher than normal, and formation of a continuous hypoxic zone along the coast did not occur that summer. The opposite was the case during the flood of 1993 (a 62-yr maximum discharge for June–September), when the areal extent of summertime hypoxia showed a twofold increase with respect to the average hydrologic year (Rabalais et al. 1998). The 1993 event was associated with both increased stability of the water column and nutrient-enhanced primary productivity, as indicated by the greatly increased nutrient concentrations and phytoplankton biomass in the coastal waters (Rabalais et al. 1998).

Because of potential ecological and economic effects, Gulf hypoxia has received considerable scientific and public attention. In 2001, the Mis-

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Mississippi River/Gulf of Mexico Watershed Nutrient Task Force set a goal to reduce the 5-yr running average of the Gulf's hypoxic zone to less than 5,000 km² by the year 2015 (Task Force 2001; Rabalais et al. 2002; Rabalais et al. 2007). Two critical questions surfaced during development of the Action Plan to reduce, mitigate, and control Gulf hypoxia (Task Force 2001; Rabalais et al. 2002). The first question was: When did large-scale hypoxia start in the Gulf of Mexico? The second question was: What nitrogen load reduction would be needed to reach the societal goal set for hypoxia? The Action Plan included a goal to reduce the 5-yr running average size of the hypoxic zone to below 5,000 km² by 2015. Knowing the answers to these questions is important both for understanding the underlying causes for Gulf hypoxia and for identifying reasonable and practical goals for reducing its size. If large-scale hypoxia were common before the significant increase in riverine nitrogen loads, it would not be reasonable to consider those loads as a primary cause. Also, if hypoxia is strongly affected by the variability in climatic factors, then different nutrient control end points may be required to reach the same goal for hypoxia. The Action Plan suggested that a 30% decrease in nitrogen load was needed to reach this goal, and that the Plan's implementation should be based on voluntary, incentive-based strategies applied to the watershed.

While the linkage between the anthropogenic nutrient inputs and hypoxia was addressed in the Action Plan (Task Force 2001), the importance of climatic factors has not received full consideration. There are several lines of evidence suggesting that climatic factors profoundly influence the decadal and interannual variability of hypoxia in the northern Gulf of Mexico. The average Mississippi River discharge increased 30% since the 1950s, which contributed to the overall increase in nitrate flux (Goolsby et al. 1999; Justić et al. 2003b). Development of hypoxia in the northern Gulf of Mexico is highly sensitive to interannual variability in the Mississippi River discharge, as evidenced by changes in the areal extent and severity of hypoxia between flood and drought years (Rabalais et al. 1998). Although the size of the hypoxic zone has varied greatly over the past 23 yr, it has been significantly larger in wet years, compared to dry years (Rabalais et al. 1996, 1999; Rabalais and Turner 2001). Both the drought of 1988 and the flood of 1993 were caused by anomalous precipitation patterns associated in part with the El Niño-Southern Oscillation (ENSO) cycle (Trenberth and Guillemot 1996). During 1988, a particularly strong, cool ENSO phase (La Niña) in the tropical Pacific triggered a series of anomalous circulation events that are believed to be responsible for the drought.

TABLE 1. Gulf of Mexico hypoxia models.

Reference	Model Class
Bierman et al. (1994)	Simulation
Chen et al. (1997)	Simulation
Wiseman et al. (1997)	Statistical
Justić et al. (1996, 1997, 2002)	Simulation
Rowe (2001)	Simulation
Scavia et al. (2003, 2004)	Simulation
Stow et al. (2005)	Statistical
Turner et al. (2005, 2006)	Statistical
Hetland and DiMarco (2007)	Simulation

The 1993 flood was partly the outcome of an extended warm ENSO phase (El Niño).

This review discusses the use of hypoxia models in synthesizing the knowledge about the causes of Gulf hypoxia, predicting the probable consequences of management actions, and building a consensus about the management of hypoxia. It also offers suggestions for future efforts related to simulating and forecasting Gulf hypoxia.

BUILDING A CONSENSUS THROUGH MODELING

A number of different simulation and statistical models have been used to nowcast, hindcast, and forecast the severity and areal extent of hypoxia in the northern Gulf of Mexico (Tables 1 and 2). Bierman et al. (1994) developed a variation of the U.S. Environmental Protection Agency Water Analysis Simulation Program and applied it to a 21-segment, three-dimensional (3-D) spatial grid on the Louisiana inner shelf. Chen et al. (1997) applied a coupled physical-biological model to study the influence of river discharge on the Louisiana-Texas shelf. Justić et al. (1996, 2002, 2003a) developed a time-dependent, coupled physical-biological, two-box model, in order to study the oxygen cycling in the core region of the Gulf's hypoxic zone. Scavia et al. (2003, 2004) developed a variation of river dissolved oxygen model (= Streeter-Phelps model) that predicts hypoxic zone length using advection velocities for the bottom layer. Hetland and DiMarco (2007) developed a hydrodynamic model of the Texas-Louisiana shelf that included various simple respiration models. They used this coupled model to isolate the effects of stratification and circulation on the formation and maintenance of hypoxia. A number of simple and multiple regression models were developed that predict the areal extent of hypoxia based on riverine freshwater and nutrient fluxes (e.g., Goolsby et al. 2003; Turner et al. 2005, 2006).

Hindcasts of the areal extent of hypoxia in the Gulf of Mexico (Fig. 1) suggest that large hypoxic regions were not likely to have been present prior to the mid 1970s and that the size of those regions grew steadily until the mid 1980s (Scavia et al.

TABLE 2. Principal attributes of simulation models that have been used to estimate the potential effects of changes in riverine nitrogen loads on Gulf of Mexico hypoxia (adapted from Limno-Tech, Inc. 2004).

Attribute	Model		
	Bierman et al. (1994)	Justić et al. (1996, 2002)	Scavia et al. (2003, 2004)
General description	Moderately complex mechanistic eutrophication model	Simple two-layer dissolved oxygen model	Simple dissolved oxygen model for bottom waters
State variables	Dissolved oxygen, biochemical oxygen demand, salinity, algal carbon, nutrients (nitrogen, phosphorus, and silicon)	Dissolved oxygen, organic carbon in sediments	Dissolved oxygen, biochemical oxygen demand
Spatial scale	3-D with 21 spatial segments in hypoxic zone	1-D vertical at station C6 in core of hypoxic zone	1-D horizontal in subpycnocline downstream of river inputs
Temporal scale	Summer, steady-state	Monthly, time-variable	Summer, steady-state
Nutrients	Nitrogen, phosphorus, and silicon	Nitrogen	Nitrogen
Hypoxia characterization	3-D structure of summer-average dissolved oxygen concentrations in hypoxic zone	Seasonal dynamics of dissolved oxygen concentrations in core of hypoxic zone	Interannual variability in hypoxic zone length and area
Calibration time periods	1985, 1988, and 1990	1985–1993	1985–2002

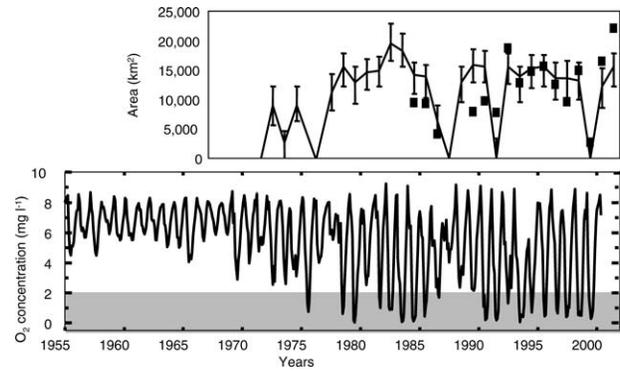


Fig. 1. Upper panel: Scavia et al. (2003) model hindcasts. Probabilistic hindcast of the areal extent of hypoxia during 1968–2002. Solid curve and error bars represent the 1st, 2nd, and 3rd quartiles from 1,000 Monte Carlo simulations. Boxes represent observed hypoxic zone area. Lower panel: Justić et al. (2002) model hindcasts. Simulated changes in the average bottom (10–20 m) oxygen concentration at a station within the core of the Gulf's hypoxic zone during 1955–2000. Shaded area denotes hypoxia (from Scavia et al. 2004, reprinted with permission of Estuarine Research Federation).

2003). Hindcasts of subpycnocline oxygen concentrations (Justić et al. 2002) suggest that summertime oxygen minima in the central section of the Gulf's hypoxic zone between 1955 and 1969 were fairly constant, always $> 2 \text{ mg l}^{-1}$ and most often $> 4 \text{ mg l}^{-1}$ (Fig. 1). The oxygen concentrations decreased during the 1970s, and have remained consistently lower than 2 mg l^{-1} in most years since. Similar hindcasts by Turner et al. (2006) corroborate the findings in Fig. 1. Results of model hindcasts are consistent with the limited historical oxygen concentration data collected between 1970 and 1985, before the shelfwide surveys began (Turner and Allen 1982; Rabalais et al. 1999, 2002). They are also supported by retrospective analyses of sedimentary records, including organic carbon accumulation rates (Eadie et al. 1994), biogenic silica content (Turner and Rabalais 1994), and stratigraphic records of benthic foraminifera (Sen Gupta et al. 1996; Platon and Sen Gupta 2001; Platon et al. 2005). Translating these findings into shelfwide conditions is difficult because of the relatively few sampling locations and the significant horizontal spatial heterogeneity in the sediment record. The significant changes since the middle of the last century from locations where sediment cores have been taken are consistent with changes in riverine nitrate fluxes (Turner and Rabalais 1994).

Forecasts of the areal extent of hypoxia under various load reduction scenarios conducted by Scavia et al. (2003) suggested that 40–45% reductions in the total nitrogen flux during May and June, relative to the 1980–1996 average, will be required to reduce the extent of hypoxia below

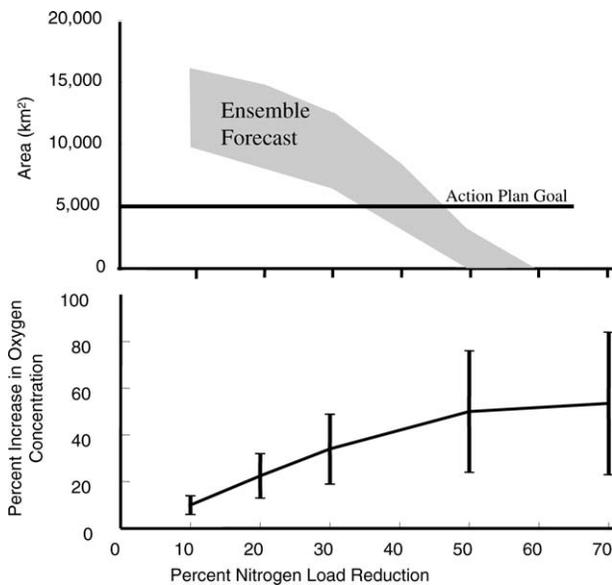


Fig. 2. Upper panel: Scavia et al. (2003) model forecasts. Ensemble forecasts of the responses of hypoxia to changes in riverine nitrogen load. Percent reduction is based on the 1980–1996 mean May–June total nitrogen loads. The shaded area contains values between the first and third quartiles from 1,000 simulations. The horizontal bar at 5,000 km² represents the Action Plan goal (Task Force 2001). Lower panel: Bierman et al. (1994) model forecasts (Limno-Tech, Inc. 1995). Simulated increases in subpycnoclinal oxygen concentrations in response to riverine nitrogen load reduction. Vertical bars denote the range of model results for different spatial segments (from Scavia et al. 2004, reprinted with permission of Estuarine Research Federation).

5,000 km² (Fig. 2). The 3-D model developed by Bierman et al. (1994) did not have the spatial resolution required to forecast changes in the areal extent of hypoxia. The forecasting of subpycnoclinal oxygen concentrations indicated that decreases in riverine nitrogen flux of 30–50% would result in a 35–50% increase in oxygen concentrations (Fig. 2; Limno-Tech, Inc. 1995; Bierman et al. 2003). Similar decreases in phosphorus flux were less effective in increasing subpycnoclinal oxygen levels (Limno-Tech, Inc. 1995). This is consistent with experimental observations (Ammerman 1992; Lohrenz et al. 1997, 1999; Rabalais et al. 2002) and model results (Fig. 3; Limno-Tech, Inc. 1995), indicating that phytoplankton production over much of the area affected by hypoxia is limited by nitrogen.

IMPROVING HYPOXIA MODELS

The existing Gulf's hypoxia models support the view that large-scale reductions in the nitrogen flux of the Mississippi River would eventually lead to a decrease in areal extent and severity of hypoxia. Because most current forecasting models have inadequate spatial resolution, they are not able to

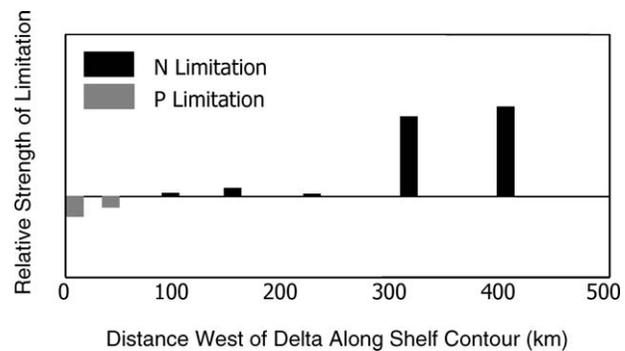


Fig. 3. Simulated changes in the nitrogen and phosphorus limitations along shelf contour between the Mississippi River Delta and the Texas Coast during July 1990 (from Limno-Tech, Inc. 1995).

predict how the location and the volume of hypoxic waters will change in response to nutrient reduction. The exception to this is the relatively simple, one-dimensional biophysical model of Scavia et al. (2003, 2004) that does predict areal extent and general location of the hypoxic region. There is an apparent need for model development along two fronts: refinement of relatively simple models that can provide forecast rigor at the expense of detailed mechanistic insight, and enhancement of more complex 3-D models that can help describe and dissect controls and consequences at the expense of forecast rigor.

Potential areas of refinement for the simple biophysical models (e.g., Scavia et al. 2003, 2004) include extending areal forecasts to volume forecast through regression, considerations of higher spatial resolution, modeling of the horizontal distribution of primary production along the river plume that generates distributed sources of organic material to subpycnocline regions, and moving from steady-state to time-dependent solutions. Regression models (e.g., Goolsby et al. 2003; Turner et al. 2005, 2006) can also be expanded by considering other potential forms of nutrient limitation, different spatial and temporal frameworks, and by including additional years of observations.

The more complex 3-D models can be used to drive research questions such as hypothesis testing and identify missing data that need to be collected, so that the effects of uncertain future conditions (e.g., climate change) can be assessed before they happen. These models can be refined by incorporating data acquisition, remote sensing, multi-layered databases, graphical user interface, visualization, and internet tools to help refine our understanding of the ecological and physical factors affecting hypoxia (Fig. 4). Recent developments in adjoint methods provide numerous opportunities to use numerical models for data assimilation, array

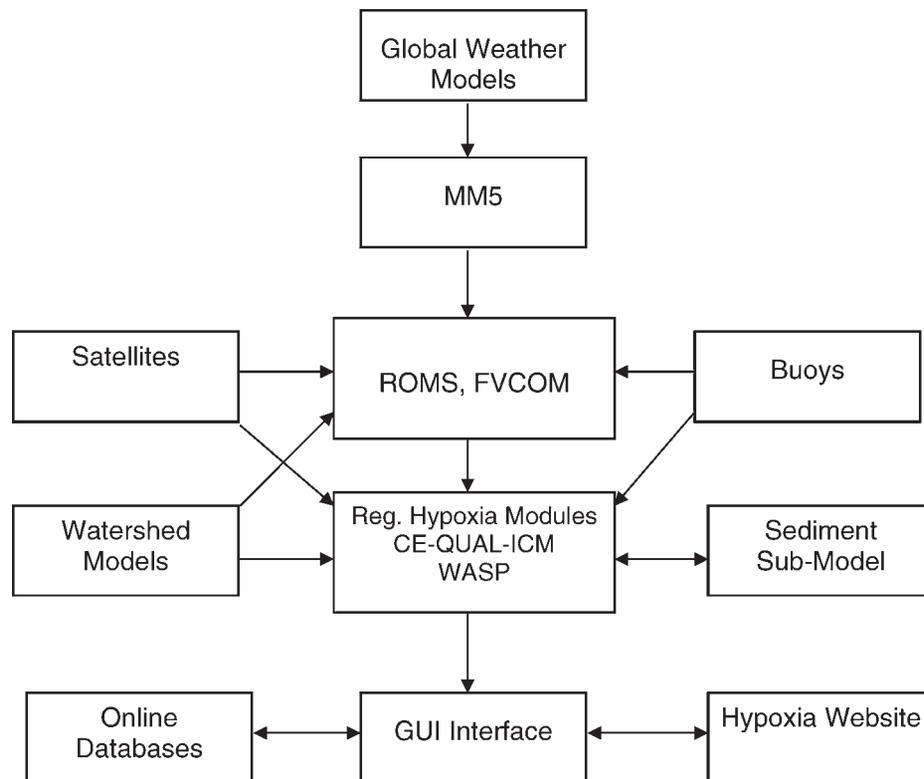


Fig. 4. Elements of the Gulf of Mexico Hypoxia Forecasting System. ROMS = Regional Ocean Modeling System (Shchepetkin and McWilliams 2005), FVCOM = Finite Volume Coastal Ocean Model (Chen et al. 2003), WASP = Water Analysis Simulation Program (Ambrose et al. 1988, 1993), CE-QUAL-ICM (Cercio and Cole 1993, 1995), MM5 = Pennsylvania State University, National Center for Atmospheric Research mesoscale model, GUI = Graphical User Interface.

design, and sensitivity studies (Moore et al. 2004), and to couple these models with ocean observing systems. Because of the critical roles of local wind and buoyancy forcing in the development of hypoxia, even the most complex models will not be able to forecast the spatial extent of hypoxia beyond a few days to a week into the future. Our ability to predict weather patterns is limited and longer-term predictions of hypoxia must be based on statistical wind patterns and flow conditions. Hydrodynamic models can be used to examine the relative importance of various factors controlling stratification, and extend the existing statistical models of hypoxia to include more realistic representations of stratification.

There are a number of hydrodynamic models that simulate circulation in the Gulf of Mexico and the Caribbean Seas. Operational models are run by the Naval Research Laboratory (<http://www7320.nrlssc.navy.mil/ATLhycom1-12/gom1.html>) and Texas A&M University (<http://seawater.tamu.edu/tglo/>). These models focus predominantly on Gulf-wide circulation and the Loop Current and Loop Current Eddy system (Oey et al. 2005). Although the Loop Current system affects the circulation over

the Texas-Louisiana shelf, deep ocean circulation is typically secondary to local wind and buoyancy forcing on the inner shelf, inside of the 50-m isobath where hypoxia usually occurs (Rabalais et al. 1999). Upwelling wind stress can cause freshwater to pool over the Texas-Louisiana shelf (Morey et al. 2005). Buoyant plumes are difficult to simulate because of both strong advection and active mixing throughout the plume. There have been many recent advances in simulation of buoyancy driven flows that are relevant to the Mississippi-Atchafalaya River plume system (Yankovsky and Chapman 1997; Fong and Geyer 2001; Garvine 2001; Garcia Berdeal et al. 2002; Hetland and Signell 2005). Hetland (2005) provided a framework for setting up and analyzing numerical simulations of buoyant plumes, and this approach was used in a development of a hydrodynamic model of the Texas-Louisiana shelf (Hetland and DiMarco 2007). This model was tested using a variety of simple respiration models in an effort to describe the importance of stratification and circulation for the formation and maintenance of hypoxia. The results indicate that water column respiration reproduces observed temporal and spatial structures of hypoxia in the vicinity of the

Mississippi River Delta, while the benthic respiration seems to be a predominant oxygen sink in the rest of the area experiencing hypoxia. The formation and breakdown of hypoxia are primarily vertical processes and it appears that hypoxic waters formed in one region of the shelf are not advected to the other.

In addition to developing complex 3-D hypoxia models, it is equally important to refine model algorithms by including the latest findings from observational studies in the region. None of the existing hypoxia models describes a succession from lightly-silicified diatoms to heavily-silicified diatoms, which may be an important controlling mechanism for Gulf hypoxia development (Turner et al. 1998; Dortch et al. 2001; Turner 2001). Another area of concern that needs to be addressed in model algorithm development relates to the benthic oxygen cycling. Benthic photosynthesis has been repeatedly measured on the Louisiana shelf (Dortch et al. 1994; Rowe et al. 1995), yet this oxygen source is not explicitly included in models that have been used to forecast Gulf's hypoxia (e.g., Bierman et al. 1994; Justić et al. 2002; Scavia et al. 2003, 2004). The model developed by Bierman et al. (1994) did include subpynocline primary production, and model simulations revealed that this oxygen source had a significant effect on bottom oxygen concentrations west of the Atchafalaya River.

Estimating the relative forcings of biology and physics as controls of hypoxia in relatively stagnant bottom waters remains one of the biggest challenges in hypoxia modeling. Conventional oxygen budgets based on oxygen concentration measurements are not particularly helpful in this regard because effects of biological factors are masked by physical factors, and vice versa. A decrease in bottom oxygen content may be a result of benthic or water-column respiration. An increase in the oxygen content may be an effect of in situ photosynthesis or a consequence of oxygen influx due to advection or diffusion. As a result, conventional hypoxia models often suffer from errors in model parameterization and excessive use of default parameters. In more recent years, a second approach to measuring oxygen dynamics has been developed that uses oxygen isotopes in addition to the more conventional oxygen concentration measurements. Most work with oxygen isotope budgets has focused on open ocean systems (e.g., Bender and Grande 1987; Quay et al. 1993), with important contributions also made in studies of the Amazon River system (Quay et al. 1995). Quiñones-Rivera et al. (2007) proposed a novel dual-budget approach aimed at quantifying oxygen sources and sinks in the Gulf's hypoxic zone. The approach is based on the partitioning of oxygen dynamics among the key biological and

physical processes using oxygen isotopes, in addition to budget studies based on oxygen concentration measurements.

SIMPLE VERSUS COMPLEX MODELS

It is impossible to predict the future, especially in detail, and this applies to both simple and complex models. Yet it is possible to design scenarios that involve specified values and ranges for external forcing functions and to conduct forecast simulations with both simple and complex models. Model results should be expected to be reasonable and useful for management decisions only to the extent that actual future external forcing functions match those in the forecast scenarios.

Simple and complex models each have their own unique sets of advantages and drawbacks. An advantage of simple models is that their data requirements for inputs and calibration-validation are much less extensive than for complex models. One consequence of this advantage is that simple models (e.g., Justić et al. 2002; Scavia et al. 2003) can often be applied and tested using data from much longer periods of record than complex models (e.g., Bierman et al. 1994). The ability to test simple models for long periods of record confers them with a degree of robustness that strengthens their ability to forecast future conditions, subject to the above caveats. The offset for this advantage is that simple models provide information on only a limited number of parameters, e.g., average oxygen concentrations at a single station (Justić et al. 2002) or summer average hypoxic area (Scavia et al. 2003). Simple hypoxia models can indeed be valuable as forecasting tools, but they do so at the expense of providing understanding of the complex cause-effect mechanisms governing the development of hypoxia.

An advantage of complex models, if they are well formulated and tested, is that they can provide understanding of cause-effect mechanisms that are impossible to derive solely from observational data (e.g., mass balance components for carbon, oxygen, and nutrients; relative importance of light, temperature, and nutrients in limiting primary production; transport and fate of organic carbon). A disadvantage of complex models is their extensive data requirements for inputs, calibration, and validation. It is much more difficult to apply complex models for long periods of record and confirm their robustness over the full dynamic ranges of their external forcing functions (e.g., Bierman et al. 1994 model calibration periods - three summer snapshots: 1985, 1988 and 1990). Complex models can also be valuable as forecasting tools, but it is much more difficult and expensive to develop, calibrate, and validate such models and demonstrate their

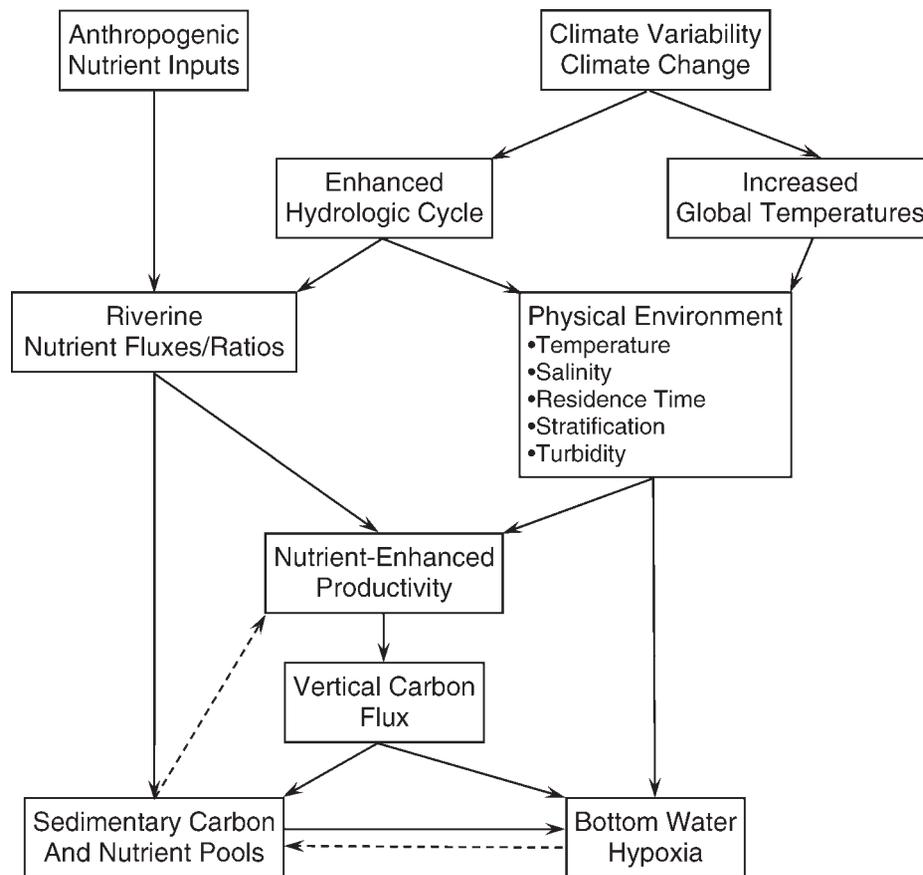


Fig. 5. Coupling between climate variability, coastal eutrophication, and hypoxia (from Justić et al. 2005, reprinted with permission from Elsevier).

robustness over the full range of conditions for which they were designed.

THE NEXT 50 YEARS?

A scientific consensus now exists that the buildup of greenhouse gases in the atmosphere is warming the earth. General circulation models have projected further temperature increases of 1–6°C over the next 100 yr (IPCC 2001). An increase in global temperatures of such a magnitude is expected to produce a general intensification of the hydrologic cycle that would be manifested in increased global precipitation, evapotranspiration and runoff (Miller and Russell 1992). Hydrologic extremes such as floods and droughts would likely become more common and more intense (Easterling et al. 2000). A modeling study that examined the effects of global warming on the annual discharge of the 33 largest rivers of the world (Miller and Russell 1992) suggested that the average annual discharge of the Mississippi River would increase 20% if the concentration of atmospheric CO₂ doubled. Other studies have shown that runoff estimates for the Mississippi

River differed greatly between the Canadian model and the Hadley model (Wolock and McCabe 1999). The annual runoff of the Mississippi River was projected to decrease 30% by the Canadian model and increase 40% by the Hadley model by the year 2099.

Climate change, if manifested by increased global temperatures and altered hydrologic cycle, may influence the Gulf's coastal region in two major ways (Fig. 5). The magnitude and seasonal patterns of freshwater and nutrient inputs would be affected, which could have an immediate effect on nutrient-enhanced coastal productivity. The fundamental characteristics of the physical environment would likely change, affecting the susceptibility of this ecosystem to eutrophication. In this respect, climate variability would interfere with nutrient management efforts in the Mississippi River Basin. It is difficult at this time to reliably predict future trends in the Mississippi River nutrient fluxes. While it is likely that global riverine nitrogen flux will continue to increase in response to increased human population with its concomitant increased

TABLE 3. Simulated changes in the average oxygen concentration of the lower water column (10–20 m) in the core of the Gulf of Mexico's hypoxic zone for a number of climatic and nitrogen loading scenarios (adapted from Justić et al. 2003a). The nominal model was forced using time series of observed monthly values of the Mississippi River discharge (Q) and nitrate concentration (N-NO₃) over a 45-yr period from 1955 to 2000. The investigated model scenarios are based on the available projections of general circulation models for the continental U.S., the Mississippi River, and the northern Gulf of Mexico, as well as the proposed nutrient management goals.

Model Scenario	# of Years with Hypoxia ($< 2 \text{ mg O}_2 \text{ l}^{-1}$)	% Change Relative to the Nominal Model
Nominal model	19	—
Scenario 1 (–30% Q)	8	–58
Scenario 2 (1955–1967 N-NO ₃)	0	–100
Scenario 3 (+20% Q)	26	+37
Scenario 4 (+4°C)	25	+32
Scenario 5 (+20% Q, +4°C)	31	+63
Scenario 6 (–30% N-NO ₃)	12	–37

use of agricultural fertilizers (Tilman et al. 2001; Howarth et al. 2002), future estimates for the Mississippi River Basin are not available. Nitrate concentrations in the Mississippi River may increase in response to an increase in precipitation and freshwater discharge (Goolsby et al. 1999; Justić et al. 2003b) or decrease as a result of nutrient control efforts in the Mississippi River Basin (McIsaac et al. 2001; Task Force 2001). Nitrate accumulates in soils and underground waters during dry years and is flushed into streams and the main river channel during wet years (Goolsby et al. 1999). A higher discharge also decreases the water residence times in canals, lakes, and small streams in the upper parts of the watershed. This reduces nitrogen losses due to denitrification (Howarth et al. 1996; Alexander et al. 2000) and leads to higher nitrate concentration in the mainstem of the river. The data clearly show that dry years followed by subsequent wet years tend to produce the largest increases in nitrate flux (Goolsby et al. 1999; Justić et al. 2003b). Unless anthropogenic nitrogen inputs to watersheds are reduced, higher and more variable precipitation, projected by many climate models (Wolock and McCabe 1999; Easterling et al. 2000), would enhance nitrate delivery to the Gulf. Riverine phosphorus concentrations have generally paralleled the increasing nitrogen concentrations in watersheds with significant anthropogenic influence (Marchetti et al. 1989; Turner and Rabalais 1991; Howarth et al. 1996). Silicate concentrations have remained constant or decreased in some rivers (Justić et al. 1995a,b).

In a series of modeling studies Justić et al. (2003a) examined the potential effects of future climate variability on nutrient-enhanced productivity and hypoxia in the northern Gulf of Mexico (Table 3). Model scenarios were based on projected

changes in the Mississippi River discharge, Mississippi River nitrate flux, and ambient water temperatures. The results were compared to the nominal model simulation, in which the model was forced by the observed time series of temperature, riverine freshwater discharge, and nitrate flux over a 45-yr period (1955–2000). Simulations of the nominal model identified the mid 1970s as a start of the recurring hypoxia in the lower water column, and predicted a total of 19 yr with hypoxia between 1955 and 2000. These results are in good agreement with the timing of first reports documenting hypoxia in the northern Gulf of Mexico (Rabalais and Turner 2001) and are additionally supported by the retrospective analyses of sedimentary records (Turner and Rabalais 1994). For a scenario with 30% decrease in the average Mississippi River discharge (Scenario 1), the model predicted 8 yr with hypoxia, which is a 58% decrease in frequency relative to the nominal model dynamics. For a scenario with 20% increase in the average Mississippi River discharge (Scenario 3), the model predicted a 37% increase in frequency of hypoxia. For a scenario with 4°C increase in the average temperatures of the northern Gulf of Mexico (Scenario 4), the model predicted an increase in the frequency of hypoxia of 32%. For a scenario with 4°C increase in the average temperatures of the northern Gulf of Mexico and a 20% increase in the average Mississippi River discharge (Scenario 5), the model predicted 31 yr with hypoxia, which is an increase of 63%. A 30% decrease in the Mississippi River nitrate concentrations (Scenario 6) would result in a 37% decrease in the frequency of hypoxia. A 20% increase in the Mississippi River discharge would offset a decrease in the frequency of hypoxia resulting from a 30% decrease in the anthropogenic nitrogen flux. Depending on the assumptions about directions and magnitude of future changes in freshwater inflow, both major increases and decreases in the frequency of hypoxia are possible.

Results from the simpler model (Scavia et al. 2003) indicate that a 20% increase in nitrate load over the 1980–1996 mean would increase the size of the hypoxic zone by 26%, from the 1980–1996 simulation mean of 12,900 km² to 16,200 km². Donner and Scavia (2007) show that year-to-year variability in central U.S. climate must be considered in developing nutrient management policy because precipitation in the previous November–December and precipitation in March–April–May is a strong predictor of spring nitrate flux to the Gulf of Mexico. They forecast that during a wet year, a nitrogen reduction of 50–60% – close to twice the Action Plan recommended target – is required to meet the goal of reducing the hypoxia zone to less

than 5,000 km² in size. While there is significant uncertainty in these climate scenarios, it is important to note that this potentially warmer-wetter scenario is capable of compensating for management-based nitrogen load reductions.

Conclusions

Forecasts of the areal extent of Gulf's hypoxia under various load reduction scenarios suggested that 40–45% reductions in the total nitrogen flux during May and June, relative to the 1980–1996 average, will be required to reduce the extent of hypoxia below 5,000 km². Similar decreases in phosphorus flux were less effective in increasing subpycnoclinical oxygen levels. Forecasts considering interannual and long-term changes in precipitation suggest larger reductions in nutrient loads may be required to compensate for increased water (and nutrient) flux to the Gulf.

Because most current forecasting models have inadequate spatial resolution, they are not able to predict how the location and volume of hypoxic waters will change in response to nutrient reduction. There is an apparent need for model development along two fronts: refinement of relatively simple models that can provide forecast rigor at the expense of detailed mechanistic insight, and enhancement of more complex 3-D models that can help describe and dissect controls and consequences at the expense of forecast rigor. Simple models will be most useful for providing long-range forecasts of responses to policy changes within the Mississippi basin because their relatively simple framework enables statistical treatment of changes in weather and climate patterns. More complex 3-D models are needed to simulate detailed changes in severity-areal extent-volume of hypoxic waters under different potential anthropogenic and climate scenarios. In both cases, it is important to refine model algorithms by including the latest findings from observational studies in the region. A particular area of concern that needs to be addressed in model algorithm development relates to the benthic oxygen cycling. Benthic photosynthesis has been repeatedly measured on the Louisiana shelf, yet this oxygen source is not explicitly included in models that have been used to forecast Gulf's hypoxia.

Because of the high degree of sensitivity of hypoxia to climate-driven variations in the Mississippi River freshwater and nutrient fluxes, models should be developed within the framework of a larger hypoxia forecasting system. Such a system of simple and complex models would allow models to be refined by incorporating data acquisition, remote sensing, multilayered databases, graphical user interface, visualization, and internet tools. It would help communities that need long-term and near-real time forecasts, e.g., managers who need

models to develop realistic nutrient management scenarios and fishermen who want to know where the hypoxic zone is located. Forecasts also should increase Gulf's hypoxia visibility for the public at large, and so increase public support to resolve this national environmental problem.

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