Chapter 2
Characterization of Hypoxia

The hypoxic region along the northern Gulf of Mexico (NGOM) extends up to 125 km offshore and to 60 m water depth, has substantial variability with an average midsummer areal extent of 16,500 km^2 (2001–2007), and extends in some years from the Mississippi River mouth westward to Texas coastal waters (Rabalais et al., 2007a, 2007b). This hypoxic region (Fig. 1.1) occurs along a relatively shallow, open coastline with complex circulation and water column structure typical of many coastal regions and includes massive inputs of freshwater, weak tidal energies, seasonally varying stratification strength, generally high water temperature, wind effects from both frontal weather systems and hurricanes, and mixing of river plumes from the Atchafalaya and Mississippi Rivers and other smaller sources (DiMarco et al., 2006; Hetland and DiMarco, 2007). The plumes of the Mississippi and Atchafalya Rivers can be observed as areas of highly turbid low-salinity surface water. The limits of these plumes have been defined in different ways, but in satellite imagery their boundaries can be clearly observed as sharp color discontinuities. Since the release of the *Integrated Assessment* and the *Action Plan* in 2001, the measured areal extent of the hypoxic region has averaged 16,500 km^2, with a range of 8,500–22,000 km^2. Many reports from both the *Integrated Assessment* and the post-*Integrated Assessment* periods concluded that physical and morphological characteristics such as these make the NGOM prone to hypoxic conditions.

2.1 Historical Patterns and Evidence for Hypoxia on the Shelf

An important question regarding hypoxia on the Mississippi River shelf is how far back in time has hypoxia been observed? Is it a recent phenomenon or has hypoxia been a regular natural feature of a productive shelf region? Unfortunately the monitoring data are not entirely sufficient to address this question, for only a limited number of measurements are available prior to the time when widespread hypoxia was first observed on the Louisiana shelf in the mid-1980s (Rabalais et al., 1999a). However, a limited number of additional paleoecological studies have been carried out on the Mississippi River shelf since the *Integrated Assessment* (e.g., Swarzenski et al., 2008). All studies from dated sediment cores show recent increases in low

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oxygen concentrations with time, although the precise timing and response varies depending upon the proxy studied and the dating of cores. The accumulated body of evidence shows that the pattern of change is concomitant with recent (since the 1960s) increases in nutrient loading from the Mississippi River causing increasingly severe hypoxia on the shelf. The spatial distribution of reliably dated sediment cores, with most cores taken on the southeastern Louisiana shelf just west of the Mississippi River delta, is not sufficient to determine the increases in the spatial extent of hypoxia with time.

A limiting factor in all paleoecological studies is the availability of undisturbed sediment cores to provide an accurate picture of changes through time. This is a particular challenge in a hydrologically dynamic, relatively shallow environment as found on the Mississippi River shelf with resuspension processes, movement of fluid muds, mixing by benthic organisms, and more recently sediment disturbance of upper sediment layers through bottom trawling. Despite these challenges, a number of reasonably dated sediment cores, primarily within the Louisiana bight, have provided a coherent picture of changes in hypoxia with time.

Bacterial pigments measured in sediments at one location on the Louisiana shelf were characteristic of anoxygenic phototrophic sulfur bacteria and have their highest concentrations between 1960 and the present (Chen et al., 2001). These bacterial pigments were not present prior to 1900. Further evidence of increased hypoxia is provided by Chen et al. (2001) using algal pigments, which show increases in the 1960s. The increase in these pigments reflects enhanced preservation with hypoxia as well as nutrient-driven increases in production. Rabalais et al. (2004, 2007a) also report increases in algal pigment concentrations over time from a number of sediment cores, with gradual changes from 1955 to 1970, followed by a steady increase to the late 1990s. However, the patterns observed by Rabalais et al. (2004, 2007a) are confounded by the rapid degradation of carbon and algal pigments in upper surface sediments with most studies of sediment pigments correcting for diagenesis by normalizing pigments with organic carbon (Leavitt and Hodson, 2001). In addition, there is some evidence for spatial increases in hypoxic extent through time: increases in pigment concentrations from one sediment core from west of the Atchafalaya River outflow suggests that nutrient-driven increases in production occurred later at this location than in the Mississippi River Bight (Rabalais et al., 2004). There has been an increased accumulation of total organic carbon and biogenic silica in recent sediments near the mouth of the Mississippi River (Turner et al., 2004; Turner and Rabalais, 1994), although the spatial and temporal variations observed between dated sediment cores are large.

Several studies have examined changes in the benthic foraminiferal community in dated sediment cores (Osterman et al., 2005; Platon et al., 2005; Platon and Sen Gupta, 2001). Different species of bottom-living benthic foraminifera are particularly sensitive to changes in bottom water oxygen concentrations, and the abundance of these species is a widely used indicator of hypoxia. Significant changes in the composition of the benthic foraminiferal community have occurred in the past century. Several indicators, e.g., the PEB index (the relative abundance of three low-oxygen tolerant species of benthic foraminifers: *Pseudononin*

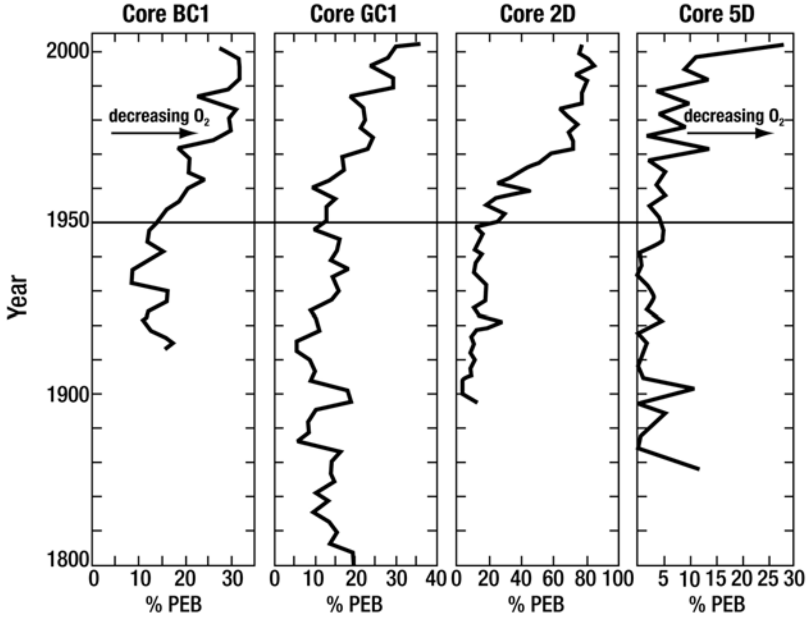

Fig. 2.1 Plots of the PEB index (%PEB) in sediment cores from the Louisiana shelf. Higher values of the PEB index indicate lower dissolved oxygen contents in bottom waters. Taken from Osterman et al. (2005)

altlanticum, Epistominella vitrea, and *Buliminella morgani*) (Osterman et al., 2005) and the A/P ratio (agglutinated to porcelaneous orders) (Platon et al., 2005) indicate that increases in the occurrence of low oxygen events have occurred over the past 50 years (Fig. 2.1). In addition, the porcelaneous genus *Quinqueloculina*, an organism that occurs where dissolved oxygen concentrations are higher than 2 mg/l, was present but has disappeared from the foraminiferal community since 1900, indicating that prior to this time there was sufficient oxygen at the sediment–water interface to enable survival of such species (Rabalais et al., 2007a). Osterman et al. (2005) have shown that several probable low oxygen events that occurred in the past 180 years are associated with high Mississippi River discharge rates, although the recent changes in foraminiferal communities are more extreme than any that occurred in the past. The data support the interpretation that hypoxia is a recent phenomenon and has been amplified from an otherwise naturally occurring process.

Key Findings and Recommendations

The Study Group finds that the paleoecological data are consistent with increased prevalence of hypoxic conditions in recent decades. However, the spatial distribution of sediment cores is not sufficient to determine the increases in the spatial extent of hypoxia with time. Although given the complex nature of disturbance, there may be limited opportunities to determine temporal changes in the extent of hypoxia. To advance the understanding of spatial and temporal trends in hypoxia in the NGOM, the Study Group offers the following recommendations.

- In future research on the Mississippi River shelf, more attention should be focused on establishing reliable chronologies in additional sediment cores.
- In order to establish spatial changes in hypoxia over time, where possible, additional sediment cores should be collected over a broader area of the Mississippi River shelf.

2.2 The Physical Context

2.2.1 Oxygen Budget: General Considerations

The oxygen budget on the NGOM shelf is influenced by several sink and source terms. Oxygen (O_2) concentration in the bottom layer will decrease and possibly become hypoxic or even anoxic when the export and consumption of oxygen by respiration exceed the import or production of "new" oxygenated water by photosynthesis. Mathematically, this relationship can be expressed in its simplest form by the following oxygen balance equation:

$$\begin{aligned} \underset{\text{Change}}{\frac{\partial O_2}{\partial t}} &= \underset{(1)}{-u\frac{\partial O_2}{\partial x}} \underset{(2)}{- v\frac{\partial O_2}{\partial y}} \underset{(3)}{- w\frac{\partial O_2}{\partial z}} \underset{(4)}{+ K_{\mathrm{Z}}\frac{\partial^2 O_2}{\partial z^2}} \underset{(5)}{+ K_{\mathrm{H}}\left(\frac{\partial^2 O_2}{\partial x^2}+\frac{\partial^2 O_2}{\partial y^2}\right)} \\ &\quad \underset{(6)}{+\vec{F}_{\mathrm{as}}} \underset{(7)}{- \text{resp.}} \underset{(8)}{+ \text{photosynthesis}} \end{aligned} \tag{2.1}$$

in which the left-hand term represents the change of oxygen concentration with time; term (1) on the right represents the horizontal advection by across-shelf currents, u; term (2) represents the horizontal advection by along-shelf currents, v; term (3) represents vertical transport by upwelling or downwelling; term (4) represents vertical mixing, and $K_{\mathrm{Z}}\,(x,y,z)$ is the vertical eddy diffusivity; term (5) represents horizontal diffusion, and $K_{\mathrm{H}}\,(x,y,z)$ is the horizontal eddy diffusivity; term (6) is oxygen flux across the air–sea interface; term (7) is the nonconservative sink (i.e., oxygen consumption); and term (8) refers to in situ production of oxygen by photosynthesis. The horizontal advection terms may reflect contributions from tides, wind stress, buoyancy, and momentum input from rivers, large-scale and mesoscale eddies, or topographically trapped shelf waves. Three-dimensional hydrodynamic models are required to adequately account for these contributions (Hetland and DiMarco, 2007; Morey et al., 2003a, 2003b). The respiration term (7) relates directly to organic matter mineralization and must be understood in the context of water column and sediment biogeochemical processes described in later sections. As depicted in Eq. 2.1, the change in oxygen concentration with time at any point in the water column is affected by sources and sinks of oxygen at and below the surface. Term (6) (oxygen flux across the air-sea interface) represents a surface source and sink, while term (8) (photosynthesis) is a source of oxygen in waters beneath the air–sea interface. Although Eq. 2.1 above suggests that alongshore and cross-shore dispersion coefficients are of equal magnitude, the Study Group notes that this has not been demonstrated. The effects of cross-shore dispersion processes must be parameterized and additional research on lateral mixing processes must be completed before such parameterization can be performed with confidence.

2.2.2 *Vertical Mixing as a Function of Stratification and Vertical Shear*

Over the Louisiana–Texas shelf, the vertical mixing term (4) plays a key role in the local oxygen balance. Its magnitude depends on the value of vertical eddy diffusivity K_z, which is highly variable in both space and time and depends on the gradient Richardson number *Ri* (MacKinnon and Gregg, 2005), defined by

$$Ri = \frac{N^2}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} = \frac{\left(\frac{-g}{\rho}\frac{\partial \rho}{\partial z}\right)}{\left(\frac{\partial V}{\partial z}\right)^2} \tag{2.2}$$

where N is an index of stratification strength known as the buoyancy frequency, ρ is the water density, g is the gravitational acceleration (9.8 m/s^2), and $\partial V/\partial z$ is the vertical shear of horizontal current. The gradient Richardson number, Ri, expresses the ratio of turbulence suppression by stratification (numerator) relative to vertical shear production of turbulence (denominator). When Ri > ¼, turbulence is suppressed, and vertical transport of oxygen from surface to bottom layers by turbulent mixing is unlikely to occur. Thus, strong vertical density gradients (for example, when freshwater sits on top of salty water) and/or weak current shears can suppress vertical mixing and be favorable to hypoxia. Key physical factors that produce stronger vertical density gradients ($\partial\rho/\partial z$) and thus reduce vertical mixing include freshwater inputs from rivers or precipitation, warmer surface temperatures from absorption of solar radiation or sensible heat input, and near-bed suspended sediment (which causes benthic stratification). Factors responsible for producing enhanced vertical shear ($\partial V/\partial z$) and enhanced vertical mixing include tidal and wind-driven currents, inertial waves, internal tides, surface waves, and Langmuir cells (Kantha and Clayson, 2000). Although no field studies of vertical mixing by microstructure measurements of the turbulent dissipation rates of velocity, salinity, and temperature fluctuations have been reported for the NGOM, many of the physical mechanisms described on the New England shelf (MacKinnon and Gregg, 2005) and in Monterrey Bay (Carter et al., 2005) are at play on the NGOM as well.

While the *tributaries* within the Mississippi River basin are the sources of nutrient loading to the river trunk, the *distributaries* within the Mississippi Delta are critical to the final dispersal of nutrients, buoyancy, and sediment into the Gulf of Mexico. The multiple distributary mouths of the Mississippi and Atchafalaya Rivers are, for the most part, highly stratified "salt wedge" estuaries, and their combined effluent debouches onto the shelf as a discrete layer of fresh water that is spread into the surface layer. Exceptions occur where smaller distributaries enter shallow bays where salinity is nearly uniform from top to bottom. Total buoyancy fluxes are, of course, proportional to river discharge and cause the turbulence suppressing stratification of the upper water column that is strongly implicated in hypoxia. In most inner shelf environments, tidal currents are the major source of mixing, and the position of temperature fronts (sharp horizontal temperature gradients) can often be accurately predicted from the h/U_t^3 criterion of Simpson and Hunter (1974), where h is the local depth and U_t represents the depth-averaged tidal velocity. Unfortunately, the Simpson–Hunter criterion of tidal mixing has not yet been mapped for the northern Gulf of Mexico. Nevertheless, it is generally agreed that tidal mixing over the Louisiana–Texas shelf is very weak because the tidal range is only about 40 cm and tidal currents typically do not exceed 10 cm/s (Kantha, 2005). So the contribution of tidal mixing to the vertical exchange of oxygen is minimal over the shelf, particularly off the mouths of the larger distributaries, such as Southwest and South Passes, which debouch into deep water. Wind-driven currents are stronger than tidal currents but occur episodically (Ohlmann and Niiler, 2005). Winds also cause breaking and white capping waves as well as vertical circulation (Langmuir) cells (Thorpe, 2004) that contribute to mixing in the upper water column.

The hydrologic regime of the Mississippi River and the spatial distribution and timing of freshwater inputs to the shelf relative to the occurrence of energetic currents and waves are critical to vertical mixing intensity, stratification, and hypoxia. These influences were recognized in the CENR report (Rabalais et al., 1999a). Using oxygen measurements within 2 m of the bottom and vertical profiles of temperature and salinity collected during the 1992–1994 LaTex experiment on the Louisiana–Texas shelf and during the 1996–1998 NECOP (Northeastern Gulf of Mexico Chemical Oceanography Program) in the region east of the Mississippi delta and north of Tampa Bay, Belabbassi (2006) performed an evaluation of the empirical relationships between the maximum value of the buoyancy frequency $N_{\max}$ in the water column, bottom silicate concentration as a proxy of phytoplankton remineralization, and the occurrence of hypoxic waters (< 2 mg/L) or low-oxygen waters (< 3.4 mg/L). She found that low-oxygen and hypoxic bottom waters only occurred when $N_{\max}$ evaluated at a vertical resolution of 0.5 m was greater than 40 cycles per hour (cph), which corresponds to a buoyancy period shorter than 1.5 min. This result confirms that strong density stratification is a prerequisite for hypoxia occurrence on the northern Gulf of Mexico shelf. She also found that low-salinity water from the Mississippi and Atchalafaya rivers was generally the main contributor to stratification in spring and summer, although temperature was more important than salinity in determining stratification during summer at all depths west of Galveston Bay and at depths greater than 20 m between Galveston Bay and Terrebonne Bay. Interestingly, stations with strong stratification ($N_{\max}$ greater than 40 cph) but low bottom silicate concentrations (less than 18 mmol m^{-3}) did not have low-oxygen or hypoxic bottom waters. The analyses of Belabbassi (2006) thus indicate that strong stratification ($N_{\max}$ greater than 40 cph) is a necessary but not sufficient condition for bottom layer hypoxia; a second necessary condition for hypoxia occurrence is high bottom water remineralization as indicated by the proxy of high concentrations of bottom water silicates (greater than 18 mmol m^{-3}). Simply put, there cannot be hypoxia without both density stratification and degradation of labile organic matter.

Stow et al. (2005) attempted to disentangle the relative contributions of eutrophication and stratification as drivers of hypoxia in the NGOM. Their analysis indicates that the probability of observing bottom hypoxia increases rapidly when the top to bottom salinity difference reaches a threshold of 4.1. Stow et al. (2005) also showed that this salinity threshold decreased from 1982 to 2002. Concurrently, they highlighted that surface temperature had increased, while surface dissolved oxygen decreased, suggesting that changes in surface mixed layer properties may be partly responsible for oxygen decrease in the bottom layer.

2.2.3 *Changes in Mississippi River Hydrology and Their Effects on Vertical Mixing*

By far the most important change in local hydrology has been the increased flow of the Atchafalaya River during the 20th century. Available data show that in the early 1900s the discharge from the Atchafalaya River accounted for less than 15% of the combined Atchafalaya–Mississippi River discharge (Fig. 2.2). This proportion progressively increased to reach about 30% in 1960, peaked at 35% in 1975, and since then was reduced to 30% by means of regulatory measures (Bratkovich et al., 1994). To understand the significance of this change on circulation patterns and on the strength of stratification on the Louisiana–Texas shelf, it must be kept in mind that the Mississippi River plume enters the shelf near the shelf edge and typically

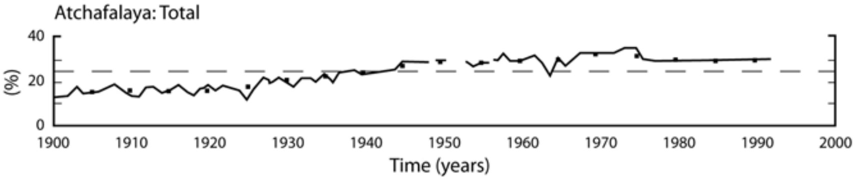

Fig. 2.2 Change in the relative importance of the Atchafalaya flow to the combined flows from the Mississippi and Atchafalaya Rivers over the 20th century. Reprinted from Bratkovich et al. (1994)

does not extend to the bottom, even near the river mouth. On the other hand, the Atchafalaya River plume enters a broader shelf, is more diffuse, and extends to the bottom over a larger distance from the river mouth.

The short distances (10–30 km) separating Mississippi River delta passes from the shelf break facilitate the export of plume waters offshore and to the east by sporadic wind events or by eddies present on the upper continental slope, some of which may have been spun off by the Loop Current (Oey et al., 2005a, 2005b; Ohlmann and Niiler, 2005). The modeling study of Morey et al. (2003a) shows that a prime export pathway for river freshwater during the summer months is to the east and offshore of the Mississippi River delta. During nonsummer months, the main freshwater export pathway consists of a coastal jet flowing westward to Texas and then southward. Etter et al. (2004) estimate that 43 ± 10% of the Mississippi River discharge is carried westward to the Louisiana–Texas continental shelf, the remainder being carried offshore and/or eastward. While this proportion is slightly lower than the earlier estimate of 53 ± 10% from Dinnel and Wiseman (1986), both studies indicate that roughly half of the freshwater from the Mississippi River goes westward, toward the Louisiana–Texas continental shelf.

In contrast, 100% of the Atchafalaya River discharge of freshwater, nutrients, and sediments is delivered to the Louisiana–Texas continental shelf. Moreover, the very broad shelf near Atchafalaya Bay implies longer residence times of this freshwater source on the shelf compared with freshwater from the Mississippi River delta. A “back-of-the-envelope” calculation helps capture the full significance of the increased Atchafalaya River flow. In the early 1900s, for every 100 m^3 of water discharged, 85 m^3 took the Mississippi River delta route. Of these, roughly 42.5 m^3 went westward and 42.5 m^3 went offshore or eastward. The 42.5 m^3 that went westward were added to the 15 m^3 that took the Atchafalaya River route to give a grand total of 57.5 m^3 of freshwater on the Louisiana–Texas continental shelf. By contrast, in the post-1970s, for every 100 m^3 of combined Atchafalaya and Mississippi River outflows, 70 m^3 took the Mississippi River route. Of these, roughly 35 m^3 went westward and 35 m^3 went offshore or eastward. The 35 m^3 that went westward were added to the 30 m^3 that took the Atchafalaya River route to give a grand total of 65 m^3 of freshwater on the Louisiana–Texas continental shelf. This simple calculation reveals two things. First, it suggests that even in the absence of a temporal trend in combined Atchafalaya–Mississippi River freshwater discharge, the amount of freshwater delivered to the Louisiana–Texas continental shelf would have increased by 13% (65/57.5 = 1.13). Second and more importantly, it reveals that in the 1920s, the Atchafalaya River contributed about one-quarter (15/57.5 = 0.26) of the freshwater discharge to the Louisiana–Texas continental shelf. Between 1920 and about 1960, the Atchafalaya River’s contribution markedly increased to about one-half (30/65 = 0.46) of the freshwater discharge to the Louisiana–Texas continental shelf. While this probably made the Louisiana–Texas continental shelf more prone to hypoxia, the timing of this change occurred 15–20 years earlier than the onset of regular summer hypoxia (Section 2.1.1).

Future physical modeling studies are needed to investigate the effects of past and proposed future changes in the distribution of freshwater flows, including inputs to

Atchafalaya Bay some 200 km to the west of the Mississippi River delta, on changes in the spatial distribution of surface salinity, temperature, and stratification on the Louisiana–Texas continental shelf and on the Mississippi Sound to the east of the “bird’s foot” delta. Physical oceanographic models that can adequately answer such questions about the impacts of flow diversions already exist but have only been run using the post-1970s flow conditions (30% Atchalafaya River, 70% Mississippi River). One such modeling study by Hetland and DiMarco (2007) suggests that the freshwater plumes from the Atchafalaya and Mississippi Rivers are often distinct from one another (Fig. 2.3) and that both contribute significantly to the development of hypoxia (Fig. 1.1) on the shelf through their influence on stratification and nutrient delivery (Rabalais et al., 2002). In addition, maps of observed surface salinity and satellite images of chlorophyll (e.g., Fig. 2.7) show the same result. It thus appears likely that increases in freshwater discharge from the Atchafalaya River and resulting increased stratification from the early 1900s to the mid-1970s have increased the area of the Louisiana–Texas continental shelf that is prone to bottom layer hypoxia.

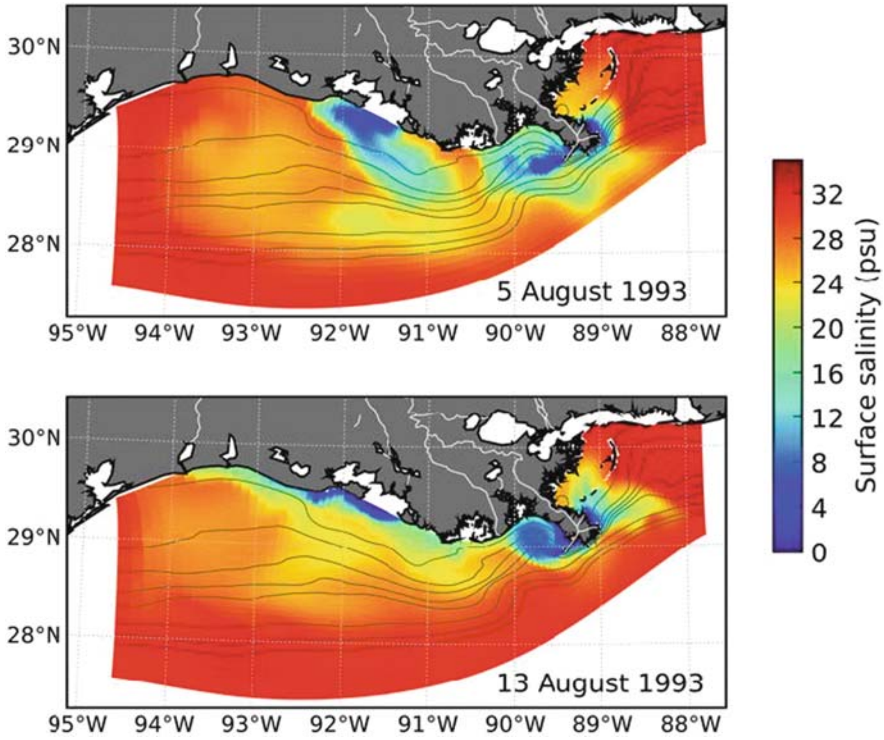

Fig. 2.3 Modeled surface salinity showing the freshwater plumes from the Atchafalaya and Mississippi Rivers during upwelling-favorable winds (top panel) and during downwelling favorable winds 8 days later (bottom panel). Adapted from Hetland and DiMarco (2007)

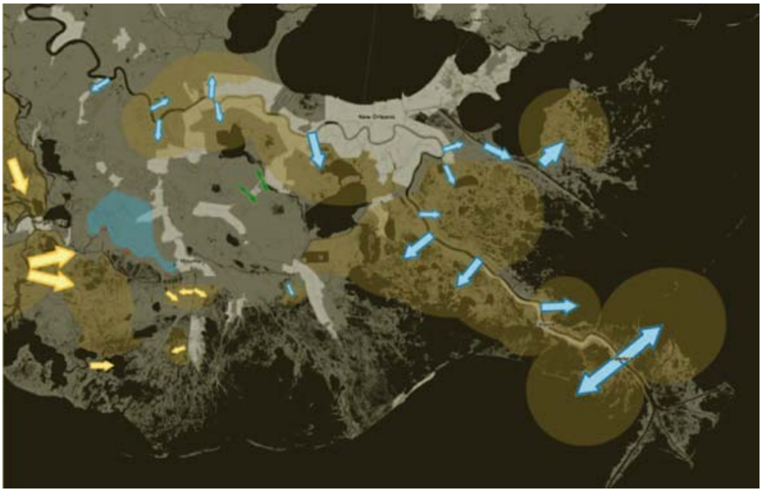

Fig. 2.4 Proposed diversions of Mississippi effluents for coastal protection. From Coastal Protection and Restoration Authority (CPRA) of Louisiana, 2007 Integrated Ecosystem Restoration and Hurricane Protection: Louisiana's Comprehensive Master Plan for a Sustainable Coast. CPRA, Office of the Governor (LA) 117 pp

Recently evolved plans for protecting coastal Louisiana (CPRA, 2007) propose significant diversions of the water, nutrients, and sediment outflow from the Mississippi River into the Gulf. Figure 2.4 illustrates a diversion scenario that involves redirecting a large part of the outflow into shallow bays upstream of the present day "bird's foot" delta. This scenario could alter the shelf hydrodynamics, particularly if more of the buoyancy is directed into shallow water instead of the deep water off the active river mouths, which are near the shelf edge. It is important that three-dimensional numerical circulation models be applied to these scenarios. Future management strategies may be able to utilize engineered modulations of the timing of freshwater releases to coincide more closely with more energetic waves and current conditions, thereby reducing the strength of stratification (i.e., Ri). This approach will, of course, rely on engineering innovations and effective diversion management. The opportunity exists for USEPA and other federal and management agencies to urge flow diversion strategies that also consider the goal of reducing the volume and bottom area of hypoxic waters on the NGOM shelf without endangering other estuarine and coastal waters. The CPRA/US Army Corp of Engineers proposals also highlight the need for interagency coordination and for an integrated approach to management strategies for jointly addressing multiple issues including hypoxia, coastal protection, and coastal inundation.

2.2.4 Zones of Hypoxia Controls

The resulting stratified region influenced by the Mississippi and Atchafalaya River plumes exerts strong control on the extent and spatial distribution of hypoxia and is an important factor in determining where hypoxia may occur (Rabalais and Turner, 2006). The buoyancy fluxes from the rivers also contribute to regional circulation in the form of baroclinic flows (Morey et al., 2003a, 2003b). Following a similar line of reasoning used in earlier work by Rhoads et al. (1985) off the mouth of the Changjiang (Yangtze) River, Rowe and Chapman (2002) defined three zones of hypoxia control in the NGOM. The boundaries between these three zones are admittedly fuzzy and change through time; however, Fig. 2.5 illustrates the Study Group's view of these concepts as represented by four zones. In zone 1, which is most proximal to river mouth sources, strongly stratified and light as well as nutrient limited, respiration of organic carbon coming both directly from the river efflux and from nutrient-dominated eutrophication dominates. The relative importance of these organic carbon sources as the cause of hypoxia remains somewhat uncertain, although the model of Green et al. (2006b) indicates a major dominance by in situ phytoplankton production even in the immediate plume of the Mississippi River. In the intermediate zone 2, stratification is also strong; light limitation is less than in zone 1; very high rates of phytoplankton production occur; and water column respiration fuels bottom layer hypoxia. Farther along the coast from the river mouths but within the low-salinity coastal plume (zone 3), local phytoplankton production is less, but labile organic matter may have been imported from zone 2 and deposited on the bottom. In zone 3, stratification remains strong, and oxygen consumption in the

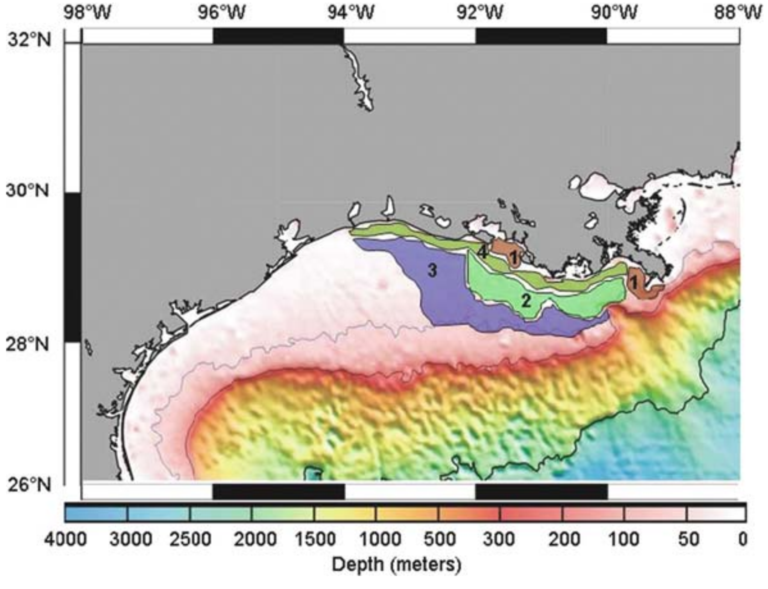

Fig. 2.5 An illustration depicting different zones (Zones 1–4, numbered above) in the NGOM during the period when hypoxia can occur. These zones are controlled by differing physical, chemical, and biological processes, are variable in size, and move temporally and spatially. Diagram created by D. Gilbert

sediment is more important than water column respiration in driving hypoxia. Zone 4 depicts the highly productive, coastal current, as suggested by Boesch (2003).

Boesch (2003) strongly criticized the physical, biological, and chemical reasoning behind the delineation of the Louisiana–Texas continental shelf into these three distinct zones of hypoxia control. He also argued that these zones did not capture well the physics and biology of the Louisiana coastal current, which is characterized by low salinities and high nutrient and chlorophyll levels (Wiseman et al., 2004). Nevertheless, Rowe and Chapman (2002) stimulated new research into the role that stratification plays in the reduction of vertical mixing rates and the flux of oxygen through the pycnocline in the regions of the Louisiana–Texas continental shelf under the influence of the Mississippi and Atchafalaya River plumes. Using realistic three-dimensional physics (Eq. 2.1) with simple representations of water column and benthic respiration for the zones A, B, and C of Rowe and Chapman (2002), Hetland and DiMarco (2007) were able to represent the bottom area, thickness, and volume of hypoxic waters over the NGOM fairly well.

So far as we are aware, time series measurements of physical oceanographic parameters are inadequate to support or refute hypotheses regarding changes in shelf circulation, stratification, and vertical mixing during the 20th century. Initial planning for a Gulf of Mexico Coastal Ocean Observing System (GCOOS) has begun (for additional information see http://www.gcoos.org). As these GCOOS plans continue to evolve and implementation begins over the next few years, it is important that physical parameters relevant to oxygen dynamics be included among the measurements. Empirical parameterizations of vertical eddy diffusivity K_Z as a function of vertical shear and density stratification are available for shallow continental shelf environments (MacKinnon and Gregg, 2005). These parameterizations enable quantification of vertical mixing [term (4) in Eq. 2.1] with vertical shear measurements from moored Acoustic Doppler Current Profilers (ADCPs) and vertically profiling conductivity, temperature, and depth instrumentation (CTDs) tethered on a cable. Ship-based microstructure measurements of the turbulent rates of dissipation of velocity, salinity, and temperature fluctuations (Gregg, 1999) should also be conducted occasionally to complement the moored ADCP and profiling CTD measurements. Physics-based models of ocean mixing and turbulence exist today and are part of three-dimensional circulation models (Mellor and Yamada, 1982). These models need to be rigorously tested using ADCP, CTD, and microstructure data because vertical mixing is the most important physical process to model correctly when hypoxia is under consideration.

2.2.5 Shelf Circulation: Local Versus Regional

Circulation in the NGOM can be considered on two scales: Gulf-wide deep-sea circulation and shelf circulation near the coast. Among the most prominent features of the large-scale Gulf-wide circulation are the Loop Current and the Loop Current Eddy System (Oey et al., 2005a, 2005b). Although these features impinge on and affect the outer shelf, Rabalais et al. (1999a) conclude that local wind forcing and buoyancy are more important to shelf circulation inshore of the 50 m isobath. Direct shipboard observations by Jarosz and Murray (2005) during five separate cruises led those authors to conclude that the momentum balance on the inner and mid-shelf to the west of the active “bird’s foot” delta is indeed dominated by wind stress. During summer, alongshore sea-surface slope caused by buoyancy forcing was also important in forcing currents. On the 20 m isobath off Terrebonne Bay, ADCP measurements (Wiseman et al., 2004) show periods of several days with negligible vertical shear followed by other periods of a few days with much more elevated vertical shear and reduced density gradients, suggestive of more intense vertical mixing.

Several physical oceanographic models taking into account the crucial baroclinic effects that typify the Louisiana–Texas continental shelf are now available (e.g., Morey et al., 2003a, 2003b; Zavala-Hidalgo et al., 2003). The model results of Hetland and DiMarco (2007) show that the plume from the Mississippi River, which enters the shelf near the shelf edge, forms a recirculating gyre in Louisiana Bight and does not interact with the seabed, whereas the Atchafalaya River plume interacts with the shallow coastal topography (Hetland and DiMarco, 2007). Both plumes respond directly to local winds and are advected seaward during upwelling-favorable winds (Fig. 2.3). The distinct plumes from the Mississippi and Atchafalaya Rivers influence the spatial pattern of bottom hypoxia on the Louisiana–Texas continental shelf. This influence is clearly seen on the 1985–2005 map of hypoxia frequency of occurrence (Fig. 1.1) and is even more obvious in certain years (e.g., 1986, Rabalais and Turner, 2006). Given this interaction, planned diversions of Mississippi River and Atchafalaya River flow may alter shelf circulation and the spatial pattern of bottom hypoxia. Applications of three-dimensional baroclinic models to future scenarios such as that portrayed in Fig. 2.4 are thus important to planning for future strategies for coastal restoration (CPRA, 2007).

In their analysis of low-frequency (occurring over a timescale greater than 24 h) currents over the shelf, Nowlin et al. (2005) distinguished between currents that respond within the “weather band” of 2–10 days and those within the mesoscale band of 10–100 days corresponding to large-scale eddies off the shelf. Inshore of the 50 m isobath, the local winds within the weather band dominated and drove currents from east to west during nonsummer months influenced by the passage of frontal systems. Current fluctuations seaward of the 50 m isobath were primarily within the mesoscale band and predominantly oriented from west to east but with high variability. Along-shelf and across-shelf currents in the upper layer over the inner shelf, as reported by Nowlin et al. (2005), averaged about 10 and 1 cm/s, respectively. Over the outer shelf and near the seabed, flows were weaker.

Key Findings and Recommendations

The Study Group finds that 20th century changes in the hydrologic regime of the Mississippi and Atchalafaya Rivers and the timing of freshwater inputs to the Louisiana–Texas continental shelf have likely increased the shelf area with potential for hypoxia, although these changes occurred mostly from the 1920s to the 1960s, before the measured onset of hypoxia in the mid-1970s. Additional work is needed to advance the understanding of the relative importance of physical factors in the formation of hypoxia in the NGOM. The Study Group therefore provides the following recommendations.

- The development of a new suite of models that integrate physics and biogeochemistry should be encouraged and supported. This suite should include multiple types of models [i.e., relatively simple models such as those developed by Scavia et al. (2003) as well as more complex three-dimensional types, such as Hetland and DiMarco (2007)].
- A comparative impact study of past, present, and future river flow diversions and scenarios of altered nutrient supply to the river mouths should be encouraged and supported. Three-dimensional hydrodynamic modeling studies are needed to compare the spatial distribution of salinity and stratification with 15% (early 1900s) and 30% (post-1970s) Atchafalaya River contributions to the combined Atchafalaya–Mississippi River outflow. Coupling of this three-dimensional hydrodynamic model with a biogeochemical model would allow quantification of the impacts of past river flow diversions on the spatiotemporal extent of hypoxia. In addition, to anticipate the possible effects of proposed future effluent diversion plans via rerouted deltaic distributaries (CPRA, 2007), these three-dimensional biogeochemical and baroclinic shelf circulation models need to be applied to scenarios such as that shown in Fig. 2.4 while also considering the effects of nutrient-rich Mississippi River waters discharged into local bays and estuaries.
- Emerging coastal ocean observing and predicting systems in the Gulf of Mexico (http://www.gcoos.org) should be encouraged to measure and disseminate information needed by hypoxia modelers and those charged with adaptive management. Direct measurements of physical and biogeochemical parameters as well as direct time series measurement of dissolved oxygen in the bottom boundary layer should be routinely provided by the next generation of shelf moorings.
- Studies of turbulent mixing processes involving the effects of stratification over the Louisiana–Texas shelf with instruments and techniques capable of quantifying turbulent dissipation rates of velocity, salinity, and temperature fluctuations should also be encouraged. Studies of the importance of lateral mixing processes should be encouraged.

2.3 Role of N and P in Controlling Primary Production

2.3.1 Nitrogen and Phosphorus Fluxes to the NGOM Background

Excessive nutrient loading, dominated by discharge from the MARB, enhances planktonic primary production in the shallow near-shore receiving waters of the NGOM (Lohrenz et al., 1990, 1992; Rabalais et al., 1999a; Turner and Rabalais, 1994). The nutrients of concern are nitrogen (N), phosphorus (P), and silicon (Si) in the form of silicate. Both primary productivity and phytoplankton biomass are stimulated by these nutrient sources (Ammerman and Sylvan, 2004; Lohrenz et al., 1990, 1992; Sylvan et al., 2006). The spatial and temporal extent and magnitudes of this stimulation vary significantly, and their patterns and size appear to be related to (1) amounts of freshwater discharge and their nutrient loads; (2) the nature and frequencies of discharge (i.e., acute, storm- and flood-based versus more gradual, chronic, seasonal discharge); and (3) the direction and spatial patterns of discharge plumes as they enter and disperse in the NGOM (Justić et al., 1993; Lohrenz et al., 1994; Rabalais et al., 1999b). The *Integrated Assessment* concluded that N loading from the MARB was the primary driver for hypoxia in the NGOM. Since the *Integrated Assessment*, however, considerable knowledge has been gained concerning the processes that influence primary production and the relative importance of elements other than N as is discussed below.

A proportion of the freshwater discharge transits via freshwater and coastal wetlands and coastal groundwater aquifers, which modify the concentrations and total loads of nutrients entering the NGOM (Day et al., 2003; Turner, 2005). The extent to which wetlands alter nutrient loads and the effects wetland losses have had on changes in nutrient processing and loading are subjects of considerable debate (Day et al., 2003; Mitsch et al., 2001; Turner, 2005). Nutrients can also enter this region from deeper offshore sources, by advective transport over the shelf, a modified form of "upwelling" (Cai and Lohrenz, 2005; Chen et al., 2000), although this input is estimated to be only 7% of the nitrogen coming down the Mississippi River (Howarth, 1998). Lastly, nutrients can be derived from atmospheric deposition directly onto nutrient-sensitive NGOM waters (deposition onto the MARB and subsequent downstream export to the Gulf is considered in later sections). For nitrogen, this direct deposition is estimated to be 13% of the amount of nitrogen that flows down the river (Howarth, 1998).

Historic analyses indicate a great deal of variability in seasonal, interannual, and decadal-scale patterns and amounts of freshwater and nutrient discharge to the NGOM (Rabalais et al., 2002; Turner and Rabalais, 1991). As a result, primary productivity and phytoplankton biomass response can vary dramatically on similar timescales, which poses a significant challenge to interpreting trends in nutrient-driven eutrophication in the NGOM as in other systems (Boynton and Kemp, 2000; Harding, 1994; Paerl et al., 2006b). Furthermore, in the turbid and highly colored waters (containing colored dissolved organic matter or CDOM) of the river plumes entering the NGOM, nutrient and light availability strongly interact as controls of primary production and biomass. These interactive controls modulate the relationships between nutrient inputs and phytoplankton growth responses in this region (Justić et al., 2003a, 2003b; Lohrenz et al., 1994). Ultimately these interactions affect the formation and fate of autochthonously produced organic carbon that provides an important source of the "fuel" for bottom water hypoxia in this region.

2.3.2 N and P Limitation in Different Shelf Zones and Linkages Between High Primary Production Inshore and the Hypoxic Regions Farther Offshore

Physically, chemically, and biologically, the NGOM region is highly complex, and nutrient limitation reflects this complexity. Along the freshwater to full-salinity hydrologic continuum representing the coastal NGOM influenced by river discharge, ratios of nutrient concentrations vary significantly, both in time and in space. For example, depending on the season, specific hydrologic events, and conditions (storms, floods, droughts), molar ratios of total N to P (N:P) supplied to these waters can vary from over 300 to less than 5 (Ammerman and Sylvan, 2004; Sylvan et al., 2006; Turner et al., 1999; Turner et al., 2007a). Furthermore, additional environmental factors, such as flushing rate (residence time), turbidity and water color (light limitation), internal nutrient recycling, and vertical mixing, strongly interact to determine which nutrient(s) may be controlling primary production (Lohrenz et al., 1999b). Compounding this complexity is the frequent spatial separation among high nutrient loads, the zones of maximum productivity, and hypoxia (e.g., Fig. 2.5). Conceivably, primary production and algal biomass accumulation limited by a specific nutrient in the river plume region near-shore may constitute the "fuel" for hypoxia further offshore in the next zone, where productivity in the overlying water column may be limited by another nutrient. Limitation by different nutrients in different areas appears to be the case during the spring to summer transitional period, when primary production in the river plume region near-shore is P limited (Ammerman and Sylvan, 2004; Lohrenz et al., 1992, 1997; Sylvan et al., 2006), but offshore productivity is largely N limited (Dortch and Whitledge, 1992; Lohrenz 1992, 1997). The relevant questions concerning causes of hypoxia are what are the relative amounts of inshore river plume (largely P-limited) versus offshore (largely N-limited) productivity and what roles do these different sources of productivity play in "fueling" hypoxia?

Early work on NGOM nutrient limitation tended to focus on the waters overlying the hypoxic zone; typically, these waters are over the shelf but farther offshore than the river plume waters. Stoichiometric N:P ratios indicated that, during summer months when hypoxia was most pronounced, N should be the most limiting nutrient (Justić et al., 1995; Rabalais et al., 2002). This work has been the basis for the general conclusion that N is most limiting and that reductions in N loading would be most effective in reducing "new" carbon (C) fixation and resultant phytoplankton biomass supporting hypoxia (Rabalais et al., 2002,2004). This conclusion, coupled with the nutrient loading trend data over the past 40–50 years, which showed N loading increasing more rapidly than P loading, has formed the basis for arguing that N input reductions would be most effective in reducing the eutrophication potential and hence formation of "new" C supporting hypoxic conditions. The 2000 report from the National Academy of Sciences' Committee on Causes and Management of Coastal Eutrophication (National Research Council, 2000) concluded that nitrogen is the primary cause of eutrophication in most coastal marine systems in the United States at salinities greater than 5–10 parts per thousand (ppt), including the NGOM.

While it is likely that N limitation characterizes coastal shelf and offshore waters, more recent nutrient addition bioassays (Ammerman and Sylvan, 2004; Sylvan et al., 2006) and examinations of nutrient stoichiometric ratios have shown that river plume-influenced inshore productivity appears to be more P limited, especially during periods of highest productivity and phytoplankton biomass formation (February–May) (Fig. 2.6) when freshwater discharge and total nutrient loading are also highest (Lohrenz et al., 1999a, 1999b; Sylvan et al., 2006).

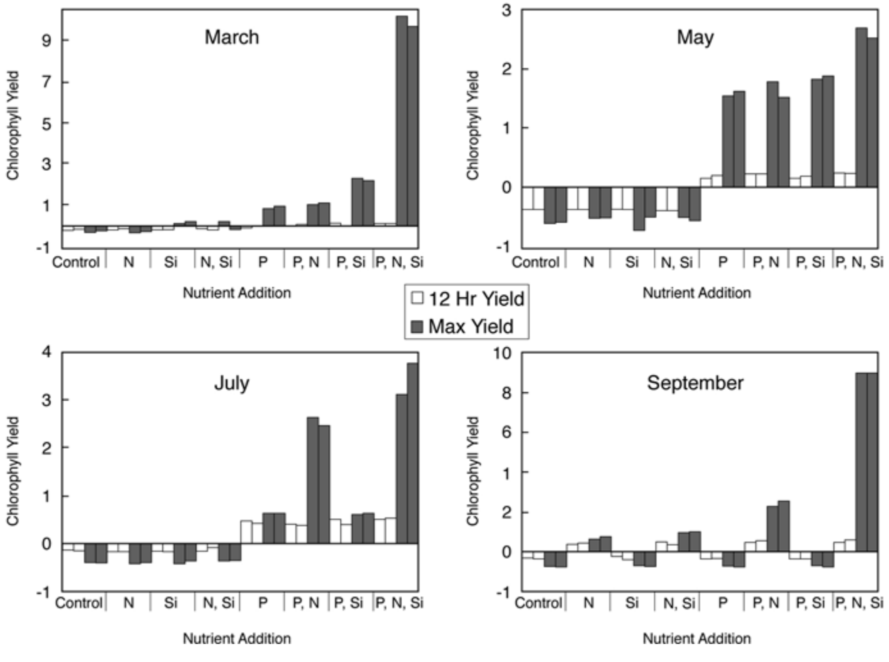

Fig. 2.6 Response of natural phytoplankton assemblages from coastal NGOM stations to nutrient additions, March through September. All experiments, except those done in September, indicate a strong response to P additions. Taken from Sylvan et al., 2006

The strong P limitation during this period appears to be a result of the very high rates of N loading that have increased more rapidly than P loading over recent history (the past 50 years) (Turner et al., 1999; Turner and Rabalais, 1991). This situation is exacerbated during periods of high freshwater runoff, which typically contain very high N:P ratios. Primary productivity in the river plume region nearshore tends to shift into a more N-limited mode once freshwater discharge decreases during the drier summer–fall period (June–October). However, total primary production and phytoplankton biomass accumulation are far lower during this more N-limited period than during the earlier P-limited period. Overall, maximum "new" organic C formation in recent years tends to coincide with periods of highest N:P, which are P limited (Ammerman and Sylvan, 2004; Lohrenz et al., 1992, 1997, 1999a; Sylvan et al., 2006).

Field data and remote-sensing imagery indicate that in situ phytoplankton biomass (as chlorophyll *a*) concentrations can be quite high in river plume-influenced inshore waters that have been shown to be P limited. This pattern is evident in Fig. 2.7, an image provided by the National Oceanic and Atmospheric Administration Sea-viewing Wide Field-of-view Sensor Project (NASA-SeaWiFS, 2007). Therefore, the following question emerges. What is the spatiotemporal linkage of this P-limited high primary production and phytoplankton biomass accumulation to hypoxic bottom waters located further offshore? Furthermore, what are the relationships between N-limited production later in the summer and hypoxic conditions, which typically are most extensive during this period? These potential "relationships" are complicated by the fact that there are strong, co-occurring physical drivers of hypoxia, including vertical density stratification and respiration rates, which tend to be maximal during periods of maximum development of hypoxia (c.f. Hetland and DiMarco, 2008; Rowe and Chapman, 2002; Wiseman et al., 2004).

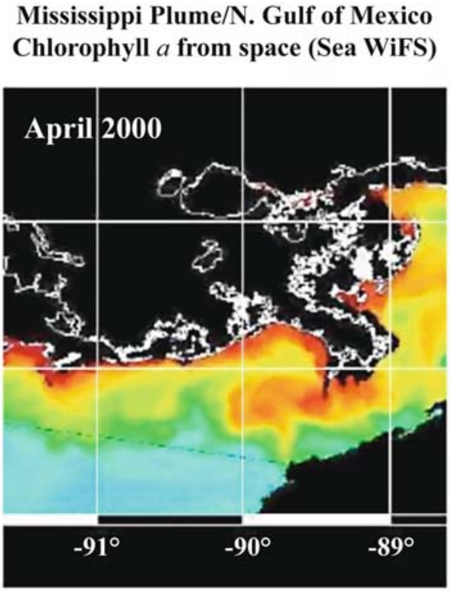

Fig. 2.7 NASA-SeaWiFS image of the Northern Gulf of Mexico recorded in April, 2000. This image shows the distributions and relative concentrations of chlorophyll *a*, an indicator of phytoplankton biomass in this region. Note the very high concentrations (orange to red) present in the inshore regions of the mouths of the Mississippi and Atchafalaya Rivers

There are likely to be periods when both P and N are supplied at very low levels and co-limit phytoplankton production. These periods occur during the transition from spring to summer. A similar condition is observed in large estuarine systems with a history of eutrophication, such as Chesapeake Bay (Fisher et al., 1992). Spatially, the upstream, freshwater segments of Chesapeake Bay tend to be most P limited, especially during spring runoff conditions, while the more saline down-estuarine waters tend to be most N limited. In Chesapeake Bay, the more turbid upstream freshwater component tends to exhibit interactive light and P limitation or N+P co-limitation (Fisher et al., 1992; Harding et al., 2002). Farther downstream, light limitation plays a less important role. This scenario could prove similar to the riverine-coastal continuum in the NGOM, where the most turbid upstream river plume waters are likely to exhibit the highest probability for light-nutrient interactive limitation of primary production (Lohrenz et al., 1999a, b).

While bioassay data tend to indicate P limitation during springtime in the lower salinity portions of this continuum and N and P co-limitation and N limitation in the more saline offshore waters during summer months, the bioassays do not account for sediment–water column exchange because sediments are excluded during the course of incubation. It is possible, although unlikely because of short incubation times, that sediment–water column P cycling in the shallow NGOM water column may minimize P limitation in situ. In order for this scenario to be operative, parallel N recycling would have to be far less efficient than P cycling, which numerous studies suggest is the case (Bode and Dortch, 1996; Cai and Lohrenz, 2005; Gardner et al., 1994; Jochem et al., 2004; Pakulski et al., 2000; Wawrik et al., 2004). Bioassay-based N limitation results might also be influenced by the elimination of "internal" sediment–water column N recycling, although this situation seems unlikely as well, especially if denitrification is operative (Childs et al., 2002). Sediment-based denitrification would lead to N "losses" from the system, thereby exacerbating N limitation. This influence would not be captured in bioassays, which isolate the sediments from the water column during incubation. The relatively short incubation times of bioassays probably preclude these potential artifacts. They offer a "snapshot" of nutrient limitation to complement longer-term, ecosystem-scale assessments.

The degree of N and P limitation can be calculated from bioassays, and the data can be used to create ratios of N and P limitation (Dodds et al., 2004). Interestingly, N and P limitation inferred from stoichiometric ratios of soluble (and hence biologically available) inorganic or total N or P concentrations and inputs (loads) tends to confirm bioassay-based conclusions concerning specific nutrient limitations. For example, inshore, river-influenced waters exhibit quite high molar N:P ratios, often exceeding 50 [Nutrient Enhanced Coastal Ocean Productivity (NECOP) Reports, NOAA, 2007]. Nutrient addition bioassays initially conducted in these waters by Lohrenz et al. (1999a) and more recently by Sylvan et al. (2006), consistently revealed P limitation, especially during spring periods of maximum primary production and phytoplankton biomass accumulation. These same studies also indicated a tendency toward N and P co-limitation and exclusive N limitation during later summer months, when soluble and total N:P values dipped below 15. It should also be noted, however, that rates of primary production and phytoplankton biomass during this more N-limited period are at least 5-fold lower than spring values, according the Gulf of Mexico NECOP data (Lohrenz et al., 1999a, b). Sylvan et al. (2006) point out that P-limited spring production of “new” C may play a proportionately greater role than N-limited summer production as a source of “fuel” supporting hypoxia in the NGOM. The degree and extent to which C from this nutrient-enhanced elevated spring production is transported and accounts for summer hypoxia need to be quantified. Developing an understanding of processes that link zones and periods of high primary production and phytoplankton biomass to zones exhibiting bottom water hypoxia is a fundamentally important and challenging area of research. Such research is necessary to improve understanding of the linkage between nutrient-enhanced production and bottom water hypoxia in the NGOM. Extrapolation of C production to hypoxia data along the entire riverine-coastal shelf continuum, where zones and periods of maximum productivity and bottom water hypoxia do not necessarily coincide or overlap, depends on knowing C transport and storage (including burial), internal nutrient, and C cycling and C consumption (heterotrophic metabolism and respiration) processes along this continuum (Cai and Lohrenz, 2005; Redalje et al., 1992). Quantifying the links between locations and periods of specific nutrient limitation (or stimulation) of production and the fate of this production relative to hypoxia will contribute to long-term, effective nutrient management strategies for this region.

Key Findings and Recommendations

The Study Group finds that there is compelling evidence that the near-shore Mississippi/Atchafalaya River plume-influenced waters are P limited and P–N co-limited during the spring periods of highest primary production. Nitrogen limitation of primary production prevails during summer periods. Recent research results indicate that the spring period of maximum primary production is P limited in at least the plumes of the rivers, largely due to excessive N input. As a result of this man-made imbalance in nutrient loading during this crucial period, P availability plays an important role in contributing to the production of “new” organic carbon in the spring time and quite likely contributing in a major way to the “fueling” of summer hypoxia in the NGOM. However, as stressed elsewhere in this book, there is great uncertainty over the coupling in space or time of phytoplankton production and its decomposition leading to hypoxia. Therefore, a better understanding of the spatial extent and temporal patterns of these nutrient limitations is needed. The Study Group recommends that the following work be undertaken to advance knowledge of the importance of nutrient limitation and co-limitation as factors in the formation of Gulf hypoxia.

- Research should be conducted to develop a more complete understanding of the spatial and temporal linkages between river plume-influenced inshore P (in spring) and/or N-limited (in summer) primary production, and offshore coastal shelf, more N-limited production, as well the fate of C produced in each zone throughout the year.
- Research should be conducted to link in time and space near-shore river-plume-influenced production to O_2 depletion farther offshore. Green et al. (2006b) suggest that the small region that the central Mississippi River plume could supply is responsible for about 25% of the C necessary to fuel hypoxia. The role of the Atchafalaya plume and other riverine influenced inshore high productivity regions in offshore hypoxia needs to be clarified.
- Research should be conducted to address the following questions. How closely linked are the periods of high productivity and hypoxic events throughout the regions in which they occur? What is the lag between C production and its ultimate degradation?

2.4 Other Limiting Factors and the Role of Si

While excessive N and P loading are implicated in eutrophication of the NGOM, these nutrients also play a role in the balance, availability, and ecological manifestations of other potentially limiting nutrients, most notably Si. In the Mississippi River plume region, N is supplied in excess of the stoichiometric nutrient ratios needed to support phytoplankton and higher plant growth (i.e., Redfield ratio, Redfield, 1958). If N over-enrichment persists for days to weeks, other nutrient limitations may, at times, result and seasonally dominate; the most obvious and important is P limitation, which has recently been demonstrated in bioassays (Ammerman and Sylvan, 2004; Sylvan et al., 2006). In addition to P limitation, N and P co-limitation and Si limitation (of diatom growth) have been observed in the fresh and brackish water components of riverine plumes that can extend more than 100 km into the receiving waters (Dortch et al., 2001; Dortch and Whitledge, 1992; Lohrenz et al., 1999a). A similar scenario is evident in the Chesapeake Bay, where elevated N loading accompanying the spring maximal freshwater runoff period increases the potential for P limitation (Fisher and Gustafson, 2004). The biogeochemical and trophic ramifications of such shifts are discussed below.

With regard to nutrient primary production interactions, it is important to know who the dominant primary producers are, where they reside, what their contributions to new production are, and what their fate is. In NGOM waters downstream of the rivers, wetlands, and intertidal regions, microalgae are by far the dominant primary producers (Lohrenz et al., 1992, 1997; Rabalais et al., 1999a; Redalje et al., 1992). The microalgal communities are dominated by phytoplankton (Chen et al., 2000; Redalje et al., 1994a, 1994b), although benthic microalgal communities can also be important sites of primary production and nutrient cycling, especially in near-shore regions (Jochem et al., 2004). As nutrient loads and limitations change over time and space, the proportions of planktonic versus benthic microalgae may also change; i.e., as nutrient inputs are reduced and planktonic primary production is reduced, the microalgal community may shift to a more benthic-dominated one. This process could yield significant implications for biogeochemical (nutrients, carbon, and oxygen) cycling and trophodynamics (Darrow et al., 2003; Rizzo et al., 1992).

Historic and contemporary evidence supports the contention that anthropogenically and climatically induced changes in N and P loading have increased NGOM primary productivity and phytoplankton biomass and altered phytoplankton community composition. There are several reasons why phytoplankton community composition may have been altered by changes in nutrient loading: (1) competitive interactions among phytoplankton taxa based on varying nutrient supply rates and differing affinities for nutrient uptake and assimilation (i.e., varying nutrient uptake affinities and kinetics); (2) competitive interactions based on the relationships between nutrient supply rates and photosynthetically available light (i.e., low versus high light adapted taxa); (3) competitive interactions based on changes in N versus P supply rates (e.g., differential N versus P uptake capabilities and selection for nitrogen fixing cyanobacteria); (4) competition based on the ratios of N and P versus Si (silicious versus nonsilicious taxa and heavily versus lightly silicified diatoms); (5) differential grazing on phytoplankton taxa (top-down controls); and (6) nutrient-salinity controls (interactive effects of changes in freshwater discharge on NGOM salinity and nutrient regimes due to climatic and watershed hydrologic control changes). Each set of controls can influence the amounts and composition of primary producers. These controls can also interact in time and space, greatly compounding and confounding the interpretation of their combined effects.

One important aspect of differential nutrient loading is the well-documented increase in N and P relative to Si loading. While N and P loads tend to reflect human activities in and alterations of the watershed, Si loads tend to reflect the mineral (bedrock and soil) composition of the watershed; a geochemical aspect that is less influenced by human watershed perturbations. Agricultural, urban, and industrial development and hydrologic alterations in the MARB have led to dramatic increases in N and P relative to Si loading. In addition, the construction of reservoirs on tributaries of these river systems has further exacerbated this situation by trapping Si relative to N and P. This anthropogenic biogeochemical change has been shown to alter phytoplankton community structure (i.e., away from diatom dominance), with subsequent impacts on nutrient and carbon cycling and food web dynamics (Humborg et al., 2000; Ragueneau et al., 2006a, 2006b). The overall result has been an increase in N:Si and P:Si ratios that can influence both the amounts and the composition of phytoplankton; including potential shifts from diatoms to flagellates and dinoflagellates (Justić et al., 1995; Rabalais and Turner, 2001; Turner et al., 1998). Diatoms are a highly desired food item for a variety of planktonic and benthic grazers, including key zooplankton species serving an intermediate role in the NGOM food web (Dagg, 1995). The dinoflagellates, cyanobacteria, and even a few diatom species, while serving important roles in the food web, also contain species that may be toxic and/or inedible (Anderson and Garrison, 1997; Paerl and Fulton, 2006). Some of these species can rapidly proliferate or "bloom" under nutrient sufficient and enriched conditions, and thus constitute harmful algal bloom (HAB) species. Toxicity may directly and negatively impact consumers of phytoplankton as well as higher-ranked consumers, including finfish, shellfish, and mammals (including humans). If nontoxic but inedible (due to size, shape, coloniality) phytoplankton taxa increase in dominance, trophic transfer may be impaired. Planktonic invertebrates, shellfish, and finfish consumers (whose diets are highly dependent on the composition and abundance of specific phytoplankton food species and groups) may then be affected (Turner et al., 1998). This could have consequences for C flux, with a relatively higher fraction of C being processed through microbial pathways (i.e., the "microbial loop") or sedimented to the bottom. In either case, a greater fraction of the primary production would remain in the system, as opposed to being exported out of the system by transfer to higher trophic level and fisheries. The net result would be more C metabolized within the system, leading to enhanced oxygen consumption and increased hypoxia potentials.

Key Findings and Recommendations

Research has shown the potential importance of silicate in structuring phytoplankton communities. Based on this finding, the Study Group offers the following recommendation.

- The potential for silicate limitation and its effects on phytoplankton production and composition on the Louisiana–Texas continental shelf should be explored when carrying out experiments on the importance of N and P as limiting factors and when considering nutrient management scenarios.

2.5 Sources of Organic Matter to the Hypoxic Zone

As noted earlier, the physical and geomorphological conditions found along the Louisiana coast make the NGOM prone to hypoxic conditions if there is an organic matter supply sufficient to consume deep water dissolved oxygen (DO) at rates exceeding DO replenishment rates. Ecosystems such as the NGOM shelf have available to them an array of organic matter sources, including those transported from the basin by rivers and those produced in situ. These include particulate and dissolved organic carbon/colored dissolved organic matter (POC and DOC/CDOM) from terrestrial sources in the basin, POC, and DOC from coastal wetland losses, and in situ production by phytoplankton, macrophytes, and benthic microalgae.

The *Integrated Assessment* largely supported the argument that hypoxia in the NGOM was driven by increased N loading to the Gulf of Mexico, which, in turn, stimulated increased in situ phytoplanktonic production of labile (i.e., readily decomposed) organic matter. A portion of this organic matter sinks to deeper, sub-pycnoclinal waters and is used by the heterotrophic community at rates sufficient to deplete DO concentrations to hypoxic levels. Emphasis at that time focused on N, but more recent work has indicated that P also plays a role in regulating organic matter (OM) supply from phytoplankton (see Section 2.1.3). In addition, a number of investigators have noted that changes in the relative supply rates of N, P, and Si lead to changes in species composition of phytoplankton communities, and this would likely modify some aspects of deposition of OM to deep waters. Substantial rates of primary production have been measured along the NGOM shelf, and these rates are comparable to those observed in other eutrophic coastal systems (e.g., Lohrenz et al., 1990, 1997; Nixon, 1992).

In Rabalais et al. (1999a) and the *Integrated Assessment*, organic matter from the major rivers was discounted as a major source because (1) there have not been changes in river OM loads since the beginning of the hypoxic period that account for the current hypoxic zone size and expansion; (2) dissolved organic matter (DOM) sources from rivers, while large, would need to be converted into particulate forms, with attendant losses from this microbial transformation, and hence would be much reduced; (3) much, but not all, of this terrestrially derived material is far less labile than phytoplanktonic debris and hence is not readily respired at timescales associated with shelf hypoxia (weeks to months). Using an estimated annual load of river OM ($\sim 2.6 \times 10^{12}$ g C/year) delivered to an average hypoxic area (15,000 km^2), and assuming that even as much as 30% of this material were labile, suggests a small impact on DO conditions (~ 0.3 g O_2/m^2/day). Additionally, while there is substantial POC and DOC coming down the Mississippi River, there was undoubtedly far more 100–130 years ago when the Mississippi River basin was first cleared for agriculture and before the dams in the basin were built. While this process apparently has not been modeled in the Mississippi River basin, modeling in other basins strongly suggests a huge increase in organic carbon fluxes at the time of land-use conversion to agriculture, followed by decreasing fluxes as agricultural practices improve (Swaney et al., 1996), and globally the flux of carbon in rivers is tied to agricultural land use (Schlesinger and Melack, 1981). This historical land-use change may well have contributed to the paucity of low oxygen conditions seen in the paleoecological record in the late 1800s (Osterman et al., 2005). Given this historical pattern, Mississippi River derived OM is unlikely to be the trigger for the level of hypoxia that developed in the NGOM during the past 35 years. This period does coincide well with the time N loads increased, due mainly to the use of synthetic N fertilizer in the Mississippi River basin. Given experience in many other coastal and estuarine regions (e.g., National Research Council, 2000), there are strong reasons to believe that in situ NGOM primary productivity exploded in response to increased N inputs over this timescale.

The influence of organic matter losses from coastal wetlands on coastal hypoxia is still debated but seems unlikely to be a primary factor. Whether or not wetlands lose more organic C as they degrade is not well known, but at present this also seems unlikely. While the timing of wetland loss does not coincide with the onset of hypoxia in the 1970s (marsh loss has been occurring since the 1940s), stable isotope and lignin analyses of OM over much of the shelf indicates that terrestrially derived OM is dispersed along and across the shelf (Goni et al., 1998; Gordon et al., 2001). However, marsh particulate organic material is refractory (i.e., resistant to decay) and does not contribute much to hypoxia creation on timescales of weeks to months. Thus, while the conclusion that the main OM source fueling hypoxia is in situ production of marine phytoplankton and that this production increased in response to enhanced nutrient loads from the MARB remains sound, a better understanding of the possible role of other sources would further refine understanding of hypoxia.

2.5.1 Sources of Organic Matter to NGOM: Post 2000 Integrated Assessment

Since the *Integrated Assessment*, there has been substantial research activity in the NGOM regarding organic matter sources, characterization of organic matter, and related issues. Some of this new work has utilized advanced analytical methods and improved field techniques. However, as with the advent of sophisticated imaging devices in medicine, where small and interesting structures in the human body can now be readily observed but not necessarily interpreted in terms of health threats, in marine waters we now have an emerging and more detailed description of the complex mix of organic compounds, which has in the past simply been called organic matter. But it is not yet clear how important some of this material is with respect to hypoxia issues. This elaboration of understanding of OM adds interesting and useful dimensions to this story but does not change the basic theme, which is that enhanced phytoplanktonic production, based on much increased nutrient loading, is the main biological trigger of NGOM hypoxia.

In addition, there have been at least two varieties of what can be called synthesis studies. Studies of the first variety tend to be "review like" wherein the growing time series of observations and new data have been revisited and/or reanalyzed. Several other efforts of this type have also developed revised conceptual models of the role of OM in hypoxia, and these will prove especially useful in time. Studies of the second variety, and these are rarer, involve development of quantitative budgets or models of various sorts. These efforts indicate that the information base regarding many aspects of OM and hypoxia is rich enough to begin these more rigorous examinations. But, in virtually all these efforts, authors conclude that results are preliminary and that more process-based information is critically needed.

2.5.2 Advances in Organic Matter Understanding: Characterization and Processes

A detailed review of these diverse studies is beyond the scope of this effort. However, Table 2.1 summarizes a selection of those works to provide an indication of the diversity of information that is becoming available. Some findings of particular relevance to OM sources are provided below:

Table 2.1 A partial summary of papers published following the *Integrated Assessment* related to sources of organic matter to the Gulf of Mexico

General topics and issues	Comments regarding OM/hypoxia	References
Landside sources		
POC in river sands	Similar in magnitude to suspended POC load in river	Bianchi et al., 2002
Sedimentation of river POC	High deposition of terrestrial POC in plume region	Corbett et al., 2004
Relict peats	Source of old organic matter to plume area	Galler et al., 2003
Seasonal transport of POC	Fluid muds are transported seasonally to GOM	McKee et al., 2004
Sediment storage and transport	Seasonal transport of mobile muds from delta to shelf	Corbett et al., 2006
River OM loads	DOC and DON loads to GOM	Bianchi et al., 2004; Duan et al., 2007
River inputs	Transport of river diatoms to plume area	Duan and Bianchi, 2006; Wysocki et al., 2006
Terrestrial OM	Fate of lignin	Hernes and Benner, 2003
Riverine DON	Photoammonification of DON to DIN	Pakulski et al., 2000
Riverine OM and nutrients	Effects of flow through coastal wetlands	Xu, 2006
Riverine DOM	CDOM analysis	Chen and Gardner, 2004
Marsh/estuary DOC	High DOC concentrations in these systems	Engelhaupt and Bianchi, 2001
OM distribution	Sources and fate of OM from rivers to shelf	Gordon et al., 2001
Water column/sediment processes		
Flocculation and sedimentation	Enhanced process in plume area; high rates	Dagg et al., 2004
Light field	Light absorption/scattering limiting production	D'Sa and Miller, 2003
Plankton characteristics	Satellite-based relations between N loads and chlorophyll	Walker and Rabalais, 2006
Plume budget	CO_2 budget in plume	Cai, 2003
OM source	High rates of plankton production west of plume	Dagg et al., 2007
Deposition	Influence of larvaceans on deposition	Dagg and Brown, 2005

Table 2.1 (continued)

General topics and issues	Comments regarding OM/hypoxia	References
DOM characteristics	Lability of DOM in region II	Benner and Opsahl, 2001
Sediment DOC	Release of DOC from shelf sediments	Sutula et al., 2004
Fate of benthic diatoms	Benthic diatom shunted to MR canyon; cleansing effect	Bianchi et al., 2006
Hurricane effects	Storm transport of deposited materials – decadal scale	Corbett et al., 2006
Sediment processes	Ammonium flux from sediments important for plankton	Eldridge and Morse, 2008
Plankton composition	Diatom occurrence in western regions of hypoxic zone	Wawrik et al., 2004
Plankton composition	Microbial processes in shelf waters	Liu et al., 2004
Synthesis/overviews		
OM budget	Carbon budget for plume area	Green et al., 2006b
Conceptual model/synthesis	Planktonic dynamics of region outside plume	Dagg and Breed, 2003
Model analysis	Differences between water and sediment respiration	Hetland and DiMarco, 2007
Statistical model	Relates N load to hypoxia; phytoplankton OM implied	Scavia et al., 2003
Water column synthesis	Plume contributions to hypoxia; gaps in understanding	Dagg et al., 2007
Review/synthesis	New monitoring data strengthens nutrient/hypoxia model	Rabalais et al., 2007a
Nutrient/Organic loads	Confirms *Integrated Assessment*, wetland loss small OM source	Turner et al., 2007
Forecasting hypoxia	Examines models and suggests nutrients major driver	Justić et al., 2007
Primary production-nitrate model	Model indicates buffered response to N-load reductions	Green et al., 2008
Concepts of hypoxic zones	Suggests spatial dimensions/processes in hypoxic zones	Rowe and Chapman, 2002

*Entries are shown for a variety of topics and comments are focused on issues related to organic matter in the GOM. This table is not a complete summary of all papers published on this subject; rather it provides an indication of the great diversity of studies conducted since the *Integrated Assessment.*

- POC associated with sand transport in bottom waters in the lower Mississippi River is similar in magnitude to loading of suspended POC (Bianchi et al., 2007).
- The vertical flux of terrestrially derived particles in the Mississippi River plume is typically very high and mainly deposits locally (Corbett et al., 2004).
- Recent analyses suggested that woody angiosperm material (^{13}C-depleted) preferentially settled within the lower Mississippi River and in the river plume

(Bianchi et al., 2002). Other work has demonstrated that erosion of relict peat in transgressional facies of the lower Mississippi River provide a source of "old" vascular plant detritus to the river plume (Galler et al., 2003).

- High sedimentation rates in the river plume result in the formation of mobile mud, commonly observed in other large river–ocean interfaces (McKee et al., 2004). It is estimated that about 50% of the sediments (and associated OM) delivered to this region are temporarily stored near the delta – with a large fraction transported along/across the shelf in the benthic boundary layer (Corbett et al., 2004, 2006).
- Diatom signals in surface sediments suggested possible inputs of riverine diatom phytodetritus to the inner shelf (Wysocki et al., 2006). Previous work showed higher phytoplankton biomass, mostly as diatoms, than expected in the lower river (Dagg et al., 2007; Duan and Bianchi, 2006) with conversion, via lysis, to DOC. Hence, river nutrients were converted to river phytoplankton biomass and then ultimately to DOC, providing a labile food resource for bacterioplankton.
- An analysis of OM production to the west of the plume found phytoplankton at the outer edge of this region declined due to nutrient limitation, microzooplankton followed trends in phytoplankton, most particle sinking was associated with mesoplankton fecal pellets, phytoplankton-derived DOM reached a peak and was correlated with bacterioplankton, and water column recycling was most intense in this region (Dagg and Breed, 2003).
- Estimates suggested 10–52% of the DOM in the region west of the plume is quite labile (Benner and Opsahl, 2001). More recent data indicated that most riverine DOC was photochemically converted to dissolved inorganic carbon (DIC) over a period of weeks in this region (Dagg et al., 2007). More terrestrially derived components such as lignin had similar fates (Hernes and Benner, 2003).
- Some labile sedimentary organic matter, from in situ diatom production, was rapidly (day to weeks) shunted to the Mississippi River Canyon (Bianchi et al., 2006), essentially bypassing the hypoxic zone to the west. The supply rate of this phytodetritus was sufficient to support macrobenthic polychaete populations that do not exist in near-shore waters off the Louisiana coast. The removal of labile OM by winter season and hurricane events may act as a cleansing mechanism, reducing the potential for hypoxia (Bianchi et al., 2006).
- There are plumes from rivers and local estuaries along the coast containing colored dissolved organic matter (Chen and Gardner, 2004). DOC concentrations are also generally high (Engelhaupt and Bianchi, 2001) but higher still in the Atchafalaya River than the Mississippi River (Bianchi et al., 2004; Chen and Gardner, 2004; Pakulski et al., 2000).

These brief comments hardly do justice to the vast amount of work completed since the *Integrated Assessment*. However, they do provide evidence of improved understanding and elaboration of the role of different forms of OM in the NGOM ecosystem.

2.5.3 Synthesis Efforts Regarding Organic Matter Sources

In most environmental analyses, synthesis of diverse data sets is essential for clarifying cause–effect couplings and sorting out primary from secondary effects. Hypoxia and the role of various OM sources in NGOM hypoxia are no exception. Fortunately, a variety of descriptive and more quantitative syntheses/reviews have been developed since the *Integrated Assessment*.

Several studies, including those of Rabalais et al. (2002), Turner et al. (2007), Justić et al. (2007), and Rabalais et al. (2007a) largely reaffirm the primacy of river nutrients in supporting high rates of in situ primary production as the dominant source of OM supporting intense ecosystem respiration and development of hypoxic conditions. Walker and Rabalais (2006) analyzed SeaWiFS algal biomass data in relationship to river flow, nitrate loads from rivers, and hypoxia. Results confirmed strong relationships between nutrient loading and algal biomass distributions; direct relationships to hypoxic waters remained elusive for a variety of reasons. The importance of this work lies in the fact that the whole hypoxic-prone zone was assessed in a synoptic fashion and data were available for both low and high nutrient load periods. Dagg et al. (2007) also reviewed data to determine Mississippi River plume contributions to hypoxia. Results were largely consistent with those noted above, but Dagg et al. (2007) focused on the important role of the plume in both producing and consuming organic matter and dissolved oxygen and in building a case for the importance of coastal wetlands as an important organic matter source. However, there are problems with the magnitude of wetland OM contributions suggested by these calculations, including conversion of wetland sediment losses to OM mass, no consideration for on-marsh respiration of this material, and no consideration of the refractory nature of the particulate material, a major portion of this OM. Based on present understanding of the issue, it seems unlikely that wetland loss could be a prime source of OM to the hypoxic zone.

Finally, there have been several quantitative assessments of OM for portions of the hypoxic zone, and these are emphasized here because it seems that these types of syntheses are especially useful in understanding hypoxia and could serve as templates for designing future data acquisition programs. Several other studies, including those of Rowe and Chapman (2002) and Dagg and Breed (2003), have proposed broader conceptual models for the plume and the full hypoxic zone, respectively, and these might also be useful in study design and improving our vocabulary when discussing the hypoxic zone and the role of various OM sources. Gordon et al. (2001) used a variety of measurements to evaluate the distribution and accumulation of organic matter on the shelf west of the Atchafalaya River. They reported inputs from rivers and in situ production (in situ production dominated), estimated OM losses due to water column and sediment respiration (OM substrates being marine and riverine, respectively) and long-term burial (<5% of total inputs). Green et al. (2006b) used careful delineation of the Mississippi River turbidity plume coupled to a biological model to investigate OM budgets for this zone. They reported that labile OM was mainly from autochthonous phytoplankton production and that riverine OM inputs to the plume were three times as large but quite refractory. Losses of OM were mainly from microbial respiration, and, importantly, the plume as a whole was net autotrophic, again suggesting the primacy of in situ production. Finally, while the plume is a small fraction of the full hypoxic zone, Green et al. (2006b) estimated that plume-derived OM was equivalent to about 23% of the OM needed to create observed hypoxia on the full shelf.

Key Findings and Recommendations

The Study Group concludes this section with several findings. First, there is general and strong support for the conclusion that riverine nutrients support levels of plankton production capable of creating observed hypoxic conditions. However, some aspects of the relationship between in situ phytoplankton production and hypoxia remain uncertain. There is need for additional study of the hypoxia issue that emphasizes process studies and better coupling of physics to the chemical and biological features of the hypoxic zone. The Study Group therefore provides the following recommendations.

- Continued research should be conducted to further elucidate the role of N and P from the MARB in stimulating phytoplankton production, the primary drivers creating excess OM and thus hypoxia in the Gulf.
- A series of consistent, well-placed, and well-timed process studies should be conducted in the NGOM. Virtually all the OM review/synthesis papers referenced above state that their analyses suffer from a lack of pertinent process data.
- DOM and POM delivered to the NGOM by rivers and from coastal wetland losses represent potential OM sources. The weight of evidence currently available suggests that it is unlikely these were triggers for hypoxia development or primary OM sources for hypoxia maintenance. However, the magnitude of river OM sources is large, and hence further characterization of this material is warranted.

2.6 Denitrification, P Burial, and Nutrient Recycling

The availability of N and P in an ecosystem is controlled both by external loadings and internal biogeochemical processes. Ideally information is needed on the load of biologically available nutrients, which is not necessarily well reflected by either the load of dissolved inorganic nutrients or the load of total nutrients. Internal biogeochemical processes are poorly known for the NGOM. Some, but not all, of the dissolved organic nutrients and particle-bound nutrients delivered to coastal waters become biologically available on ecologically meaningful timescales (days to months). In the Mississippi River, the fate of the particle-bound P is of particular interest since it is the most common form of P in the river (Sutula et al., 2004). The bioavailability of this form of P is low within the freshwater portions of the Mississippi River, but, as the particles encounter the increasingly more saline waters of the Gulf of Mexico, the high ion abundances of seawater cause much of the adsorbed inorganic P to desorb, converting it into highly bioavailable dissolved inorganic P (Fox et al., 1985; Froelich, 1988; Howarth et al., 1995; Sutula et al., 2004). In addition, sediment diagenetic processes further increase the biological availability of particle-bound P delivered to the Gulf (Sutula et al., 2004).

For many coastal marine systems, the tendency is for benthic processes to make N limitation more prevalent since the N sink through denitrification is relatively larger than is the loss of P through permanent sediment burial (Blomqvist et al., 2004; Howarth and Marino, 2006; National Research Council, 2000). Phosphorus release from sediments is frequently less than the rate of P remineralization, due to P adsorption and storage in surface sediments (Howarth and Marino, 2006; National Research Council, 2000). Variations in P release are probably due to differences in the amount and forms of iron in the sediments, the extent of sulfate reduction, and mixing by the benthic fauna, particularly as this affects microscale variation in pH (Howarth et al., 1995). The dynamics of P-sediment exchanges in the Louisiana shelf region are sufficiently complex that in a recently published model of sediment diagenesis (Morse and Eldridge, 2007), P processes were deliberately not considered (John Morse, personal communication, 10/27/06). Given the recent evidence of the role of P in controlling phytoplankton production in the plume and near-plume regions, this process needs further examination.

Sulfate reduction is particularly important in affecting the P cycle of coastal marine sediments because it can transform highly adsorptive forms of iron (III) oxides and hydroxides into nonsorptive iron (II) sulfides (Blomqvist et al., 2004; Caraco et al., 1989, 1990; Krom and Berner, 1980). Sulfate reduction may also release P from covalently bound minerals as diagenesis proceeds (Sutula et al., 2004). Sulfate reduction dominates the metabolism of the sediments to the west of the Mississippi River on the Louisiana shelf away from the immediate plume of the river (Rowe et al., 2002), as is true for many coastal marine sediments (Howarth, 1984). Sutula et al. (2004) have demonstrated that the P content of these sediments is only half that of the riverine sediments in the Mississippi from which they are derived due to losses during diagenesis. Sulfate reduction and the concomitant changes in sediment iron chemistry may not be the only factor involved. Sutula et al. (2004) noted that significant sediment P is lost in the immediate plume area of the Mississippi River, a high-energy environment subject to physical mixing and sediment reworking, which may make sulfate reduction unlikely [the "sub-oxic fluidized bed reactor" processes that Aller (1998) described for other riverine plumes].

Studies in the Gulf of Mexico have shown that aerobic respiration in the sediments is low during hypoxic events (Rowe et al., 2002). This result suggests that anaerobic respiration, the accumulation of reduced compounds, and subsequent oxidation of these reduced species in the benthic boundary layer (BBL) and sediments may account for a large percentage of the oxygen draw down in this area (Morse and Rowe, 1999). Other work has found that the balance between the frequency of seabed disturbance, rate of geochemical reactions, and reactant concentrations work together to promote efficient remineralization through redox cycling in highly mobile muds near large rivers (Aller et al., 2004; Chen et al., 2005; Chen and Gardner, 2004; McKee et al., 2004). This frequent cycling of reduced and oxidized compounds is likely to have a profound effect on short-term oxygen consumption in the BBL, which could influence development of bottom hypoxia.

Hypoxia and bottom water oxygen deficiency influence not only the habitat of living resources but also the biogeochemical processes that control nutrient concentrations in the water column. Internal feedbacks on biogeochemical processes occur with oxygen depletion. Increased P flux from sediments into overlying waters with hypoxia is a classic response in freshwater systems (Mortimer, 1941) and has been well-documented in coastal marine ecosystems (Conley et al., 2002a, 2002b; Nixon et al., 1980). However, relatively little work has been done on the Mississippi River shelf on estimating the magnitude of enhanced P release with hypoxia and the impact on the overall P biogeochemical cycle. Higher P levels do accumulate in the bottom waters of the NGOM during hypoxia, but there is no evidence that this mixes into the overlying photic zone where it could be available to phytoplankton. This is critical information as P can be an important limiting nutrient in the plume (Sylvan et al., 2006).

Hypoxia also may influence rates of denitrification. Denitrification is one of the major losses of fixed nitrogen in the oceans (Seitzinger and Giblin, 1996), however, its measurement is difficult (Groffman et al., 2006). Denitrification is the reductive respiration of nitrate or nitrite to N_2 or N_2O and includes the recently discovered anaerobic ammonia oxidation (ANNAMOX) process (Dalsgaard et al., 2003). The rates of denitrification are dependent on a variety of factors, but a major control is the availability of starting products [e.g., nitrate (Kemp et al., 1990) and carbon (Sloth et al., 1995; Smith and Hollibaugh, 1989)]. Note that denitrification is favored by the absence of oxygen, but most coastal marine sediments are anoxic below the top few mm. Given that large-scale increases in nitrate concentrations and in productivity that have occurred on the Mississippi River shelf, it is likely that the rates of denitrification have also increased through time. Very few measurements on this important process are available, however.

An open question is how much hypoxia affects the annual rates of denitrification. Few direct measurements of denitrification exist for the Mississippi River shelf, with most previous estimates using potential denitrification rates. Lower rates of potential denitrification were observed in the Gulf of Mexico zone of hypoxia when low oxygen concentrations were encountered (Childs et al., 2002, 2003), although the observed rates were at the low end of rates reported for other systems (Herbert, 1999). Denitrification can be limited by the availability of nitrate, and hypoxia may reduce the supply rate of nitrate by slowing rates of nitrification (the oxidation of ammonium to nitrate); however, nitrate concentrations in the hypoxic area were high enough in the Childs et al.'s (2002) study not to be limiting. In addition, sulfide, which is commonly found in anoxic environments, acts to inhibit nitrification (the oxidation of ammonium to nitrate) (Joye and Hollibaugh, 1995), thus reducing the availability of nitrate. In Danish coastal waters, rates of denitrification are highest during winter when nitrate concentrations are at their annual maximum (Nielsen et al., 1995), and low rates are observed during the summer. There are no seasonal measurements of denitrification available for the NGOM to estimate the overall effect of hypoxia. In general, the overall rates of denitrification are believed to be lower with hypoxia (Graco et al., 2001; Sørensen et al., 1987) and eutrophication (Smith and Hollibaugh, 1989), although Vahtera et al. (2007) suggest that denitrification has potentially increased with hypoxia. Water column rates of denitrification in the oceans are high in mid-water hypoxia areas (Deutsch et al., 2007). Further investigations of the effects of hypoxia on the rates of denitrification are sorely needed on the Mississippi River shelf, as this is the major pathway of nitrogen loss.

Measurement of the fluxes of N and P from sediments provides a direct means to assess the role of sediment processes on the relative balance of N and P in the overlying water column. There are relatively few NGOM studies where both N and P fluxes from sediments have been determined simultaneously. A compilation of these studies shows a dissolved inorganic nitrogen/dissolved inorganic phosphorus (DIN:DIP) flux ratio that varies from approximately 1:1 to 25:1, with a mean of $\sim$10:1 (Twilley et al., 1999).

Key Findings and Recommendations

The Study Group finds that additional information is needed on internal biogeochemical processes controlling the availability of nutrients to support primary production in the NGOM. The Study Group recommends that research be conducted in the following areas.

- The dynamics of sediment–water exchanges of P on the Louisiana shelf and their relative role in P cycling. Information on both aerobic and anaerobic processes is needed.
- The effects of hypoxia on the rates of denitrification and on long-term burial and regeneration of C, N, and P on the Louisiana shelf.
- N and P biogeochemical processes in sediments that include analysis of oxygen dynamics and the rates of supply of oxygen to the sediment surface.

2.7 Possible Regime Shift in the Gulf of Mexico

Hypoxia can act as a positive feedback to enhance the effects of eutrophication (Vahtera et al., 2007). It has long been known in lakes (Mortimer, 1941) that the internal P loading from sediments during anoxia can sustain eutrophication. In the Baltic Sea, which is one of the largest coastal areas in the world to suffer from eutrophication-induced hypoxia, large internal P loading occurs with hypoxia. The amount of DIP released from sediments in the Baltic is an order of magnitude larger than external inputs from rivers (Conley et al., 2002a). Large sediment–water fluxes of DIP with hypoxia must also occur in the Gulf of Mexico, returning DIP to a partially P-limited water column (Sylvan et al., 2006), stimulating phytoplankton growth and acting as a positive feedback to increase hypoxia severity. As discussed earlier (Section 2.1.6), hypoxia has the potential to reduce rates of denitrification, which would cause less N to be lost from the system, and also act as a positive feedback to increase hypoxia severity.

Recent studies in other coastal marine ecosystems, including Chesapeake Bay (Hagy et al., 2004) and Danish coastal waters (Conley et al., 2007), suggest that repeated hypoxic events can help to sustain hypoxic conditions. Large-scale changes in benthic communities occur with hypoxia, reducing the abundance of large, slow-growing, deeper dwelling animals and facilitating smaller, fast-growing species that can colonize surface sediments rapidly following hypoxia (Diaz and Rosenberg, 1995). Reductions in the abundance and size structure of benthic organisms have been observed in the NGOM with hypoxia (Rabalais and Turner, 2001). These smaller, surface-dwelling species have less capability to irrigate and bring oxygen downward into the sediments, helping to keep the sediments anoxic. The loss of benthic communities and the inability of the communities to recover with repeated hypoxic events (Karlson et al., 2002) may make ecosystems more vulnerable to the development and persistence of hypoxia. In addition, with the loss of sediment buffering capacity through the loss of electron acceptors (NO_3, O_2, Fe^{2+}, Mn^{2+}), there is a change in sediment metabolism from aerobic to anaerobic pathways, changing the production rates and processing of organic matter.

Wiseman et al. (1997) showed that the area of hypoxia along the Louisiana–Texas shelf was correlated to Mississippi River flow. These relationships were similar to those found for Chesapeake Bay (Boicourt, 1992) demonstrating the important role of river inputs in providing both freshwater-induced stratification and adding nutrients stimulating phytoplankton production. However, this apparent relationship has broken down since 1993 (data provided by DiMarco, personal communication). It appears that the Gulf of Mexico hypoxia has worsened following the record breaking 1993 spring floods, e.g., smaller river flows now induce a larger response in hypoxia (see Section 2.1.2). The first large ($>15,000\,km^2$) hypoxic event occurred after the 1993 flood, with large hypoxic areas over $15,000\,km^2$ observed in most following years. This pattern of a more sensitive system is also evident with May–June nitrate loading causing a larger hypoxic area in the NGOM than prior to 1993 (data not shown). A similar pattern of an increasingly sensitive system following the initial occurrence of hypoxia has been observed in Danish coastal waters with worsened hypoxia following the first appearance of large-scale hypoxic events (Conley et al., 2007).

Changes such as those described above suggest that a regime shift has occurred in coastal marine ecosystems that have been affected by large-scale hypoxia (Conley et al., 2007; Turner et al., 2008). Regime shifts are rapid transitions that change the structure and functioning of the ecosystem from one state to another as a consequence of a change in an independent variable. Once a threshold is passed, the ecosystem changes to a new alternative state, with changes in biological variables that can propagate through several trophic levels (Collie et al., 2004; Scheffer et al., 2001). For example, an increase in certain pelagic species (e.g., gelatinous carnivores) can disrupt top-down control of the food web structure causing a regime shift to an alternative stable state. The new stable system may not respond to changes in nutrient levels, a bottom up control, until nutrient input is reduced to a point below which the regime shift occurred. A regime shift due to hypoxia implies that, due to hysteresis in the system, nutrients will need to be reduced below the level at which the threshold occurred in order to reduce hypoxia. The management implications are that nutrients should be reduced as soon as possible before the even larger nutrient reductions are required to reduce the area of hypoxia.

Regime shifts can have large consequences for fisheries (Collie et al., 2004; Oguz and Gilbert, 2007). The Gulf of Mexico ecosystem is a tremendously valuable resource from economic, ecological, and social perspectives. In 2004, the value of commercial fish harvest in the Gulf of Mexico was $670 million (NOAA, 2007). The Gulf of Mexico shrimp fishery is among the most valuable fisheries in the nation, with a total value in 2004 of about $370 million, and about $140 million in Louisiana alone. Additionally, an estimated 24.6 million recreational fishing days occurred in the Gulf of Mexico in 2004, with about 4.8 million of those occurring in Louisiana waters (NOAA, 2007). The Gulf of Mexico also serves as habitat for a host of other species, including endangered sea turtles and marine mammals. Thus, the Gulf of Mexico is a valuable resource that is potentially being threatened by hypoxia.

Earlier studies found it difficult to identify impacts of hypoxia in fisheries landings statistics (Diaz and Solow, 1999; Rabalais and Turner, 2001), although there has been a shift in relative population abundance from benthic to pelagic species (Chesney and Baltz, 2001). A summary of published studies and works in progress on the effects of hypoxia on living resources in the NGOM are mentioned in Appendix A. There is strong scientific evidence that ecosystems in the northern Gulf of Mexico are stressed by hypoxia (Diaz et al., 2003; Diaz and Rosenberg, 2009; Breitburg et al., 2009a). Studies have found impacts ranging from the molecular/genetic level (Brouwer, 2006; Hendon et al., 2006; Perez et al., 2006; Wells et al., 2006), the organismal level (Brouwer, 2006; Zou, 2006; Thronson and Quigg, 2008), and the ecosystem level (Craig et al., 2001; Rabalais, 2006; Rabalais and Turner, 2001; Altieri, 2008; Green et al., 2008; Vaquer-Sunyer and Duarte, 2008). Population effects are indicated as well (Rose et al., 2009). Potential impacts due to displacement from preferred habitat have been identified (Craig et al., 2005; Craig and Crowder, 2005; Switzer et al., 2006). There is also recent evidence that hypoxia has affected the valuable brown shrimp fishery (Zimmerman and Nance, 2001).

There are some indications that the Gulf of Mexico has undergone a regime shift. In the hypoxic/anoxic zone of the Louisiana inner shelf many taxa are lost during the peak of hypoxia. Certain typical marine invertebrates are absent from the fauna, for example, pericaridean crustaceans, bivalves, gastropods, and ophiuroids (Rabalais and Turner, 2001). As noted above, a shift has been observed in the relative abundance of fish species. Changes in benthic and fish communities with the change in frequency of hypoxia are cause for concern (Baustien and Rabalais, 2009; Hazen et al., 2009; Levin et al., 2009). If actions to control hypoxia are not taken, further ecosystem impacts could occur within the NGOM, as has been observed in other ecosystems. The recovery of hypoxic ecosystems may occur only after long time periods (Diaz, 2001) or with further reductions in nutrient inputs. Experience has shown recovery to be greatly delayed, taking years to decades for ecosystems to recover after nutrient inputs are reduced, and with probably less than complete recovery possible (e.g., Diaz, 2001; Diaz et al., 2003; Mee, 2006; Raloff, 2004). Some smaller organisms may respond more rapidly and on annual cycles. For example, in low load years there is less hypoxia, lower phytoplankton biomass and presumably less organic deposition, and lower rates of sediment processes. On the other hand, larger benthic organisms respond more slowly, and resident fish and shellfish populations will require more time to return to previous conditions. One potential concern with regime shifts is that the condition is not always reversible. The system can follow a different path to pre-impact conditions and not return to its former state. This is called a hysteresis effect. However, given that the Gulf of Mexico is an open shelf system, recovery should be more rapid than in enclosed ecosystems. Thus, there are potentially large benefits that justify taking action to control hypoxia and thereby avoiding large-scale changes in the Gulf of Mexico ecosystem.

Key Findings and Recommendations

Hypoxia probably increases sediment–water fluxes of P and may reduce the potential for denitrification and change the degradation of organic matter in sediment from aerobic to anaerobic metabolism. Biological changes have occurred in the benthic communities of the NGOM, and there is evidence that the living resources are impacted by hypoxia. The Gulf of Mexico ecosystem appears to have gone through a regime shift with hypoxia such that today the system is more sensitive to inputs of nutrients than in the past, with nutrient inputs inducing a larger response in hypoxia as shown for other coastal marine ecosystems (Chesapeake Bay, Danish coastal waters). The Study Group therefore provides the following recommendation.

- Nutrients should be reduced as soon as possible before the system reaches a point where even larger reductions are required to reduce the area of hypoxia.

2.8 Single Versus Dual Nutrient Removal Strategies

The *Action Plan* seeks to significantly reduce the size of the Gulf of Mexico hypoxic zone by the year 2015, primarily through reductions in nitrogen (N) loadings from the MARB to the NGOM. Increases in N loads have clearly been occurring throughout the past decades, and there is ample evidence to conclude that N from the

MARB is a driving force in determining, at least in part, the timing, severity, and extent of the hypoxic zone. Since the mid-1990s, N loadings from the MARB have decreased, although they are still much elevated over historic levels. Total phosphorus loadings, however, have not changed greatly during this period (Battaglin, 2006; Turner et al., 2007; Section 2.1.9 of this book). This trend in nutrient loadings has led to reduced (albeit still very high by "Redfield" standards) N:P ratios. This evidence suggests that P is an additional nutrient of concern, in terms of input reductions. As conveyed in previous sections of this book, a number of investigators (Dagg et al., 2007; Sylvan et al., 2006) have concluded that P is limiting primary production during key periods of high productivity and in zones of high biomass accumulation in the NGOM adjacent to hypoxic waters. Therefore, the role of P in the onset, extent, and duration of the hypoxic zone is worthy of additional consideration.

Many factors influence the cycling and ultimate fate of both N and P. As both play a significant role in driving primary production within the NGOM (and perhaps, in conjunction with Si, in the composition of the primary producers and the likely fate of produced organic carbon), it is logical to consider the potential for removal of either or both elements as a means to reducing hypoxia. The 2001 *Action Plan* focuses on N reductions but does not preclude either P reduction or dual removal strategies. For example, the most recent report of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force's (MR/GMWNTF's) Management Action Review Team (MART, 2006a) concludes that most load reduction projects developed under the Clean Water Act Section 319 program have targeted both N and P for reduction. Indeed, Howarth et al. (2005) noted that some N control practices utilized in the United States effectively remove P as well, although the reverse is not always the case. However, not all control practices will be effective as a dual nutrient removal strategy; see specific discussion on this topic in Section 4.5.10.

Restoration plans that focus on N alone may not rapidly improve the situation in the MARB where many streams and river segments are degraded by excess P concentrations (MR/GMWNTF, 2001). Given recent discoveries concerning the importance of P in production of organic carbon within significant portions of the NGOM, focusing on N reduction alone may be insufficient to provide the desired reduction in the hypoxic zone. However, some plans being undertaken to reduce nonpoint sources of N (forested buffers, 319 programs, and others [see Section 4.4.2, for example]) will also lead to P reductions, as well. Reductions in P alone will alleviate some of the water quality issues facing freshwater regions of the MARB but are not likely, given our current state of understanding, to significantly address the over-enrichment of the NGOM. Therefore, greater emphasis on a dual nutrient removal strategy is warranted, a conclusion that has been reached in other instances (e.g., Boesch, 2002; Howarth and Marino, 2006; National Research Council, 2000).

Further work is necessary to examine how effectively current reduction strategies target both elements. There may be areas where shifts in removal techniques could improve P reduction. In addition, there is still much to be learned about the response of autotrophic and microbial communities to shifts in nutrient loading and ratios. A better understanding of how these communities have responded to the current loadings and predictions of how they will continue to adapt to nutrient reductions will greatly improve predictions of the likely response in the extent and duration of hypoxia to nutrient reductions in the future.

Key Findings and Recommendations

Recent information clearly indicates that P controls productivity in some portions of the NGOM. The Study Group finds that restoration plans focusing on N alone may not rapidly improve the situation in the MARB and may be insufficient to provide the desired reduction in the hypoxic zone. Reductions in P alone will alleviate some of the water quality issues facing freshwater regions of the basin but are not likely to significantly address the over-enrichment of the NGOM. Therefore the Study Group recommends the following :

- In addition to the N reduction strategy currently in place, reduction strategies for P should be implemented. Section 4.2 provides greater detail on the Study Group's recommended targets for reducing both N and P.

2.9 Current State of Forecasting

There are several types of modeling efforts working toward a better understanding of factors influencing the extent and duration of the Gulf of Mexico hypoxic zone. These vary from the simple to the complex and are based on empirically observed relationships, on mechanistic understanding, or some combination of both.

Empirical models are widely used in the aquatic sciences to establish relationships between variables, with the most well known being the correlation between spring P loading in lakes and summer chlorophyll concentrations (Vollenweider, 1976). This work has been widely used in a management context to justify reductions in anthropogenic phosphorus loading to lakes and to set goals for reductions for particular lakes. Nixon et al. (1996) developed a similar correlation between annual loading of DIN and rates of primary productivity for marine ecosystems. While establishment of empirical models has greatly enhanced understanding of the structure and functioning of aquatic ecosystems (Peters, 1986), the standard criticism of this approach is that correlation does not imply causation. Although correlations between variables exist, they do not explain why variables are correlated or the mechanisms of the relationship. They do, however, provide some very useful predictive capability. In addition, when ecosystem production is greatly different from that predicted, controls on productivity other than nutrients may be dominating, such as light limitation or limitation from rapid flushing (Howarth et al., 2006a).

Some new forecast modeling work has been completed since the *Integrated Assessment*. Turner et al. (2006) developed simple linear and multiple regression models to examine hypoxia in the NGOM. Empirical models require important decisions regarding the choice of variables and of the timescales of model operation. Turner et al. (2006) tested many different nutrient loading lag times and concluded that the best relationship was obtained 2 months (May) prior to the maximum observed extent of hypoxia (July), with significant correlations for nitrate+nitrite, total nitrogen (TN), ortho-P, and total phosphorus (TP) (r^2 values of 0.50, 0.27, 0.54, and 0.60, respectively). A multiple regression analysis was also developed incorporating nutrient load and a new variable "Year" to account for the increase in carbon in surface sediments after the 1970s causing significantly more sediment oxygen demand. A lag of 2 months of nutrient loading was, again, the most significant variable to describe hypoxic area with r^2 values of 0.82, 0.80, 0.69, and 0.64 obtained with nitrate+nitrite, TN, ortho-P, and TP, respectively. Turner et al. (2006) then used the nitrate+nitrite model to extrapolate beyond the data range used to construct their models to predict hypoxic area prior to available measurements. When the hindcasted values became negative, they were plotted as zero values. In general, it is considered incorrect to extrapolate model results in this manner beyond the range of the data supporting the model, as other mechanisms and relationships may exist that may not be included in the regression analysis. Further, the Study Group believes that the addition of the variable "Year" in the multiple regression analysis is inappropriate as the addition of one more year will cause prediction of a positive increase in hypoxia with time.

Among models that address Gulf of Mexico hypoxia and include some consideration of processes and mechanisms, that of Scavia et al. (2003) is one of the simplest. Their model uses a relationship between the nitrogen loading from the MARB and the decay of oxygen "downstream" (i.e., in the NGOM – within the plume and the near-shore reaches to the west of the Mississippi and Atchafalaya River outflows). When used in a forecast mode, this model is able to explain only approximately 45–55% of the variability in hypoxic length and area. This model explicitly addressed uncertainty in prediction. The Study Group found this approach to be very useful. Recently, in combination with a watershed model, the model of Scavia et al. (2003) has been used to address how climatic variability and change may affect Gulf hypoxia (Donner and Scavia, 2007). A similar model has also been applied very successfully to understand hypoxia and anoxia in Chesapeake Bay (Scavia et al., 2006). The Scavia et al. (2003) model focused on N loading and did not consider P. Consideration of P would seem to be a timely addition to the model, as was recently discussed by Scavia and Donnelly (2007). This model approach, and the modeling efforts of Bierman and colleagues and Justić and colleagues (see below) all provide reasonably consistent guidance and suggest similar levels of N reduction that might be required to reduce the extent of the hypoxic zone.

Other process-based models are more complex and attempt to model both physical and biological controls occurring in the hypoxic region. Examples include those of Bierman et al. (1994), Justić et al. (1996, 2002), and Green et al. (2006b). The Bierman et al. (1994) model is the most complex of these approaches and simulates the steady-state summertime conditions for the hypoxic area using three-dimensional modeling of the physics as well as interactions between food web processes, nutrients, and oxygen. The model of Justić et al. (1996, 2002) simulates oxygen dynamics at one location within the hypoxic zone using a simple model that has two vertical layers and meteorological conditions and nitrogen loads as drivers. The Green et al. (2006b) surface mixed layer model is based on food web dynamics and relatively simple two-dimensional physics (no vertical dimensionality) of the Mississippi River plume. This model predicts, among other things, the relationship between carbon sources and bottom water oxygen depletion; the model does not include changes to either N or P inputs or dynamics. None of these more complex models explicitly presented analysis of uncertainty or sensitivity analysis of potential biasing terms. As with the Scavia et al. (2003) model, Bierman et al. (1994) and Justić et al. (1996, 2002) do not consider P loads or dynamics.

It should be pointed out that complex water quality models that could be very useful in the NGOM have been developed and used in other environmentally stressed regions like the Chesapeake Bay system (Cerco and Cole, 1993), the New York/New Jersey Harbor/New York Bight complex (Landeck-Miller and St. John, 2006), and the Massachusetts/Cape Cod Bays system (Besiktepe et al., 2003). These models include a coupling to three-dimensional and time-dependent hydrodynamics, a water column eutrophication submodel and a sediment diagenesis/nutrient flux submodel. [The water-column eutrophication submodel includes state variables for three functional phytoplankton groups; dissolved inorganic nutrients (ammonium, nitrate+nitrite, ortho-phosphate, and silica); labile and refractory forms of dissolved and particulate organic nitrogen and phosphorus; biogenic silica; labile and refractory forms of particulate and dissolved organic carbon; and dissolved oxygen.] The sediment nutrient flux submodel includes state variables for labile, refractory, and inert organic carbon, nitrogen, and phosphorus as well as biogenic silica. Inorganic substances tracked include ammonium, nitrate+nitrite, ortho-phosphate, silica, sulfide, and methane. Processes tracked in the sediment flux model include organic matter deposition; sediment diagenesis; burial; the flux of inorganic nutrients between the water column and the sediment bed; and the generation of sediment oxygen demand (SOD).

There is an inherent tradeoff between model simplicity (where many potentially important factors are not considered) and complexity (where many coefficients and a great amount of data are required). More complex models may have value to help devise effective management strategies, especially if N reductions alone will not be sufficient to control hypoxia and if the more complex models can reasonably capture the importance of P. However, with complexity comes greater numbers of estimated parameters and the uncertainty associated with them. Hence this type of model may not improve forecasting capabilities dramatically. The development of more complex models is likely to prove extremely valuable for understanding the physical factors controlling water and carbon (C) transport, the dynamics of nutrient interactions with primary producers, and the recycling and loss of C and nutrients from the system. There is also great value in refining and further developing simple models, which may, in the end, prove most valuable for making management decisions. Scavia et al. (2004) explicitly compared the models of Scavia et al. (2003), Biermann et al. (1994), and Justić et al. (1996, 2002) for use in managing Gulf of Mexico hypoxia and showed that all three models gave broadly consistent guidance.

The physics of the NGOM region is complex, and there is clear value in developing more complex models of physical processes for this region. Improved three-dimensional models with finer grid structure than present models would have many uses. These uses include assisting the interpretation of monitoring data and serving as platforms upon which improved models of biogeochemistry and ecological response could be built. However, the level of complexity in the biogeochemistry and ecology need not match the complexity of the physical models (Hetland and DiMarco, 2007). Complex physical models could be very valuable in constructing simple box mass balance accounting models for C, N, P, Si, and O, for example. The importance of developing such budget-based models is discussed further below.

In addition to statistical and simulation models, another modeling format that should be considered involves construction and evaluation of material budgets or mass balance models. These are basically quantitative input–output budgets with additional complexity added by consideration of internal processes of production, recycling, and loss. These relatively simple budgets provide a quantitative mass balance framework to test the understanding of how the systems work. These budgets should be developed on a seasonal basis (e.g., summer hypoxic season) and evaluated for distinctive areas (e.g., Mississippi River Plume). These budgets are largely based on empirical observations and are not simulated through time, although data used in a budget analysis are needed in simulation models for both calibration and verification. As an example, an oxygen budget (Eq. 2.1) would involve DO inputs/outputs from air–sea diffusion, horizontal advective/dispersive transport, and vertical transport between euphotic and sub-pycnocline zones. In addition, DO is added through daytime photosynthesis and lost through water column and sediment respiration. Evaluation of these pathways indicates especially important processes, and imbalances in the budget point to areas where understanding or measurements are inadequate. We suggest that conceptual mass balance models also be used to provide a checklist of needed measurements for future NGOM hypoxia research/monitoring.

Other general points regarding modeling efforts are summarized in Section 3.4 of this chapter. An important conclusion for both models of the response of the NGOM to nutrient inputs and watershed models generating estimates of nutrient loads is that a diverse ensemble of models is needed, including both relatively simple and more complex ones. No one best approach to modeling can be identified, and management of Gulf hypoxia is best served by having multiple models with multiple outputs. The Study Group suggests that modeling efforts, ranging from the simple to complex, be conducted in parallel wherein there is the opportunity for cross-testing of results among model formats. When predictions tend to agree, managers can have more confidence in deciding upon courses of action. When models do not agree, dissecting the reasons for divergence can lead to better understanding and, ultimately, better management.

Key Findings and Recommendations

Since the *Integrated Assessment*, a number of modeling approaches have been employed to characterize the onset, volume, extent, and duration of the hypoxic zone. Models have been able to explain approximately 45–55% of the variability in hypoxic length and area. However, the Study Group finds that model development, calibration, and verification are hampered by the relative paucity of data on the duration and extent of hypoxia and on rates of important biogeochemical and physical processes that regulate hypoxia. In addition, the Study Group finds that a diverse ensemble of models is needed, including both relatively simple and more complex ones. No one best approach to modeling can be identified, and management of Gulf hypoxia is best served by having multiple models with multiple outputs. The Study Group provides the following recommendations to advance the science for characterizing the onset, volume, extent, and duration of the hypoxic zone.

- To the extent reasonable, future models (particularly more complex models that rely on accurate representation of ecological and biogeochemical processes) of hypoxia in the Gulf should consider nitrogen, phosphorus, and their interactions. However, this is a significant challenge since these interactions are so poorly studied in the NGOM at present.
- The development of more comprehensive monitoring should be coordinated with model development. For example, the more complex physical models of the NGOM should be used to aid in interpretation of monitoring data on extent and duration of hypoxia. These models can also feed into both simple and complex biogeochemical and ecological models.
- Because there is great value in developing simple mass balance models in the NGOM for organic C, dissolved oxygen, and nutrients, mass balance models should be used to provide a checklist of needed measurements for future NGOM hypoxia research/monitoring.
- Gulf hypoxia models should be designed so that they can be compatible with watershed models. That is, there must be compatibility in (1) the time step between a Gulf hypoxia model and a watershed model, and (2) the form of key variables that serve as outputs from a watershed model and inputs for a Gulf hypoxia model (e.g., a watershed model that predicts total nitrogen is not compatible with a Gulf hypoxia model that requires specific forms of nitrogen).