

Characterization and Long-Term Trends of Hypoxia in the Northern Gulf of Mexico: Does the Science Support the Action Plan?

N. N. Rabalais^{1, †}, R. E. Turner², B. K. Sen Gupta², D. F. Boesch³, P. Chapman², M. C. Murrell⁴

Left running head: N. N. Rabalais et al.

Right running head: Gulf of Mexico Hypoxia

¹Louisiana Universities Marine Consortium, Chauvin, Louisiana 70344 USA

²Louisiana State University, Baton Rouge, Louisiana 70803 USA

³University of Maryland Center for Environmental Science, Cambridge, Maryland

⁴U. S. Environmental Protection Agency, Gulf Ecology Division, Gulf Breeze, Florida 32561 USA

[†]Corresponding author: tele: 985-851-2801; fax: 985-851-2874; e-mail: nrabalais@lumcon.edu

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Abstract

We update and reevaluate the scientific information on the distribution, history and causes of continental shelf hypoxia that supports the 2001 “Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico,” incorporating data, publications, and research results produced since the 1999 integrated assessment. The metric of mid-summer hypoxic area on the Louisiana/Texas shelf is an adequate and suitable measure for continued efforts to reduce nutrients loads from the Mississippi River and hypoxia in the northern Gulf of Mexico as outlined in the Action Plan. Similar, simple metrics, such as hypoxic water volume or combinations of space and time, would also be suitable for a straightforward public discourse of condition and causes. More frequent measurements of simple metrics (e.g., area and volume) from late spring through late summer, however, would ensure that the metric is representative of the system in any given year.

The long-term data on hypoxia, sources of nutrients, associated biological parameters, and paleoindicators continue to strengthen the relationship between the nitrate-N load of the Mississippi River, the extent of hypoxia, and changes in the coastal ecosystem (eutrophication and worsening hypoxia). Multiple lines of evidence, some of them representing independent data sources, are consistent with the ‘big picture’ pattern of increased eutrophication as a result of long-term nutrient increases that result in excess production, carbon accumulation and ultimately

bottom water hypoxia. The additional findings expand our understanding of hypoxia and strengthen the science supporting the Action Plan that focuses on reducing nutrient loads, primarily nitrogen, through multiple actions as for the means to reduce hypoxia in the Gulf of Mexico.

Introduction

The development, extent and persistence of hypoxia in bottom waters of the continental shelf of the northern Gulf of Mexico were unknown until the first systematic mapping and monitoring of hypoxia began in 1985 (Rabalais et al. 1991). At that time, shelf hypoxia was perceived as localized and ephemeral (Turner and Allen 1982). Since that time, a large volume of data has been collected and numerous papers and reports have been published that increased our understanding of the seasonal and interannual distribution of hypoxia and its variability, history, and dynamical causes.

An Integrated Assessment (CENR 2000) of the causes, consequences and actions needed to reduce hypoxia was completed and an Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) was endorsed by federal agencies, states and tribal governments. The Action Plan calls for a long-term adaptive management strategy coupling management actions with enhanced monitoring, modeling and research, and re-assessment of accomplishments and environmental indicators at five-year intervals. This paper is a component of the first re-assessment, updating the earlier reports (Rabalais et al. 1999; Rabalais et al. 2002a,b), which considered publications and observations made through 1998.

The paper reviews newer information on the spatial and temporal (seasonal, annual and long-term) characteristics of hypoxia on the northern Gulf of Mexico shelf developed since the Integrated Assessment. It summarizes our current understanding of the onset, extent and duration of the hypoxic zone and assesses the inadequacies of the available data and uncertainties in the current understanding. We address the relationships between long-term trends in the extent, duration and severity of hypoxia and both increased nutrient loading and other environmental factors that may influence hypoxia, evaluating the degree to which these relationships are understood and quantified. We then answer the questions:

- Do new research contributions and understanding of the science supporting the Action Plan, justify the prior conclusions of the Integrated Assessment concerning increased nitrogen loads, eutrophication, and worsening hypoxia and thus management scenarios to reduce nitrogen loads to the northern Gulf of Mexico?
- Or, do new research findings give us cause to alter the concepts that support nitrogen reductions from the Mississippi River?

Background

The Mississippi River forms the largest watershed on the North American continent with an annual average discharge of 580 km^3 into the northern Gulf of Mexico through two main distributaries—the birdfoot delta southeast of the city of New Orleans, Louisiana and the Atchafalaya River delta 200 km to the west (Meade 1995). The Mississippi and Atchafalaya rivers are the primary sources of fresh water, nitrogen and phosphorus to the northern Gulf of Mexico, delivering 80 percent of the freshwater inflow, 91 percent of the estimated annual nitrogen load, and 88 percent of the phosphorus load (Dunn 1996). If only streams between and inclusive of the Trinity River (Galveston, Texas) and the Mississippi River delta are considered—those most likely to influence the zone of hypoxia—the Mississippi and Atchafalaya rivers account for 96% of the annual freshwater discharge, 98.5% of the annual nitrogen load and 98% of the total annual phosphorus load.

The fresh water, sediments, and dissolved and particulate materials are carried predominantly westward along the Louisiana/Texas inner to mid-continental shelf, especially during peak spring discharge (Rabalais et al. 1996, Smith and Jacobs 2005). Although the area of the discharge's influence is an open continental shelf, the magnitude of flow, annual current regime and average 75-day residence time for fresh water all suggest that the shallow shelf of the northern Gulf of Mexico behaves as an 'unbounded' estuary stratified for much of the year. This stratification is primarily due to salinity differences, and the stratification intensifies in summer with thermal warming of surface waters (Wiseman et al. 1997).

The Integrated Assessment (CENR 2000) concluded that seasonal hypoxia of bottom waters in this region is the result of the strong and persistent stratification coupled with the high organic production in overlying surface waters that is fueled by river-derived nutrients. The nutrients delivered from the Mississippi River Basin support the primary productivity within the immediate vicinity of the river discharges as well as across the broader Louisiana and upper Texas continental shelf. Flux of fixed carbon in the form of senescent phytoplankton, zooplankton fecal pellets or aggregates to the lower water column and seabed provides a large carbon source for decomposition by aerobic bacteria. Decomposition consumes dissolved oxygen in the water column at a higher rate than resupply from the upper water column in a stratified water column, leading to hypoxia, defined as dissolved oxygen levels at or below 2 mg l^{-1} in vast areas of the water column, for months at a time from the spring to the fall (Rabalais and Turner 2001, Rabalais et al. 2002a,b, Stow et al. 2005).

Few marine animals survive in oxygen concentrations below $< 2 \text{ mg l}^{-1}$, unless they are capable of migrating out of the area. The area affected by hypoxic conditions is thus popularly known as the 'Dead Zone.' Hypoxia, as a symptom of eutrophication due to nutrient enrichment, is a growing problem around the world (Diaz and Rosenberg 1995, Boesch 2002, Diaz et al. 2004). The extent and persistence of hypoxia on the Louisiana/Texas shelf makes the Gulf of Mexico Dead Zone one of the most extensive manifestations of coastal eutrophication.

Dimensions and Variability of Hypoxia

MID-SUMMER EXTENT

Rabalais et al. (1999) reported that the mid-summer areal extent of bottom-water hypoxia ($< 2 \text{ mg l}^{-1}$) averaged $8,200 \text{ km}^2$ from 1985-1992 and increased to an average $16,400 \text{ km}^2$ over the next eight years. The maximal extent of bottom-water hypoxia measured since then was $22,000 \text{ km}^2$ in 2002 (Rabalais and Turner 2006) and the five-year average size of bottom-water hypoxia in the Gulf of Mexico for 2002-2006 was $14,900 \text{ km}^2$ (Fig. 1) (N. N. Rabalais et al. unpubl. data). The five-year running average that serves as the environmental goal for the Action Plan is $5,000 \text{ km}^2$, a value well below the current status.

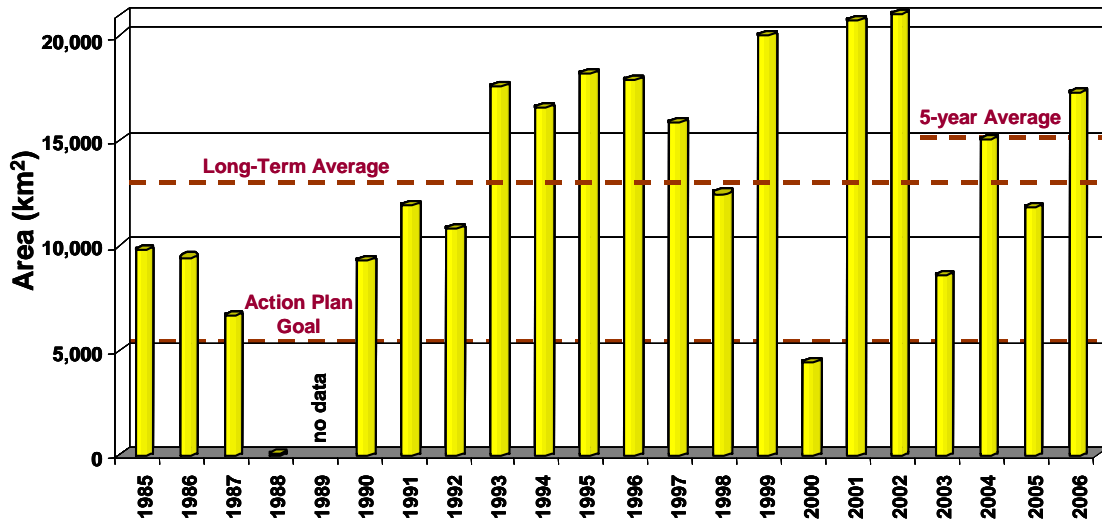


Figure 1. Estimated bottom-water extent of hypoxia (dissolved oxygen $< 2 \text{ mg l}^{-1}$) for mid-summer cruises, superimposed with long-term average, five-year average and 2015 goal of $5,000 \text{ km}^2$ (modified from Rabalais et al. 2002a).

The mid-summer hypoxic water mass is distributed across the Louisiana shelf west of the Mississippi River and onto the upper Texas coast, as mapped during annual quasi-synoptic cruises in mid- to late-July (examples in Fig. 2) (Rabalais and Turner 2001, Rabalais et al. 2002a). Hypoxia extends from near shore to as much as 125 km offshore and in water depths extending from the shore up to 60 m. The size averaged $12,700 \text{ km}^2$ over the period 1985-2005, with a range from negligible in 1988 (a summer drought year for the Mississippi River basin) to $22,000 \text{ km}^2$ in 2002. By mid-summer hypoxia usually extends along a single continuous zone on the inner to mid continental shelf, but may occur in distinct areas west of the Mississippi and Atchafalaya river deltas. The bottom water between these two areas, however, is typically depleted in oxygen (less than 3 mg l^{-1}).

A frequency distribution map compiled from 20 mid-summer shelfwide surveys (1985-2005, Fig. 3) shows that the hypoxia most frequently occurs west of the freshwater discharge zones the Mississippi and Atchafalaya rivers. The mid-summer extent of hypoxia is strongly related to the discharge of freshwater and nutrients from the Mississippi and Atchafalaya rivers, as evaluated in greater depth later. However, variations in hypoxic area may also be caused by the prevailing oceanographic conditions (e.g., 1998 when persistent currents from the west constrained the hypoxic region to a more easterly location, see Fig. 2) or disruption of stratification by tropical storms and hurricanes (e.g. 2003, 2005) within two weeks prior to the mapping.

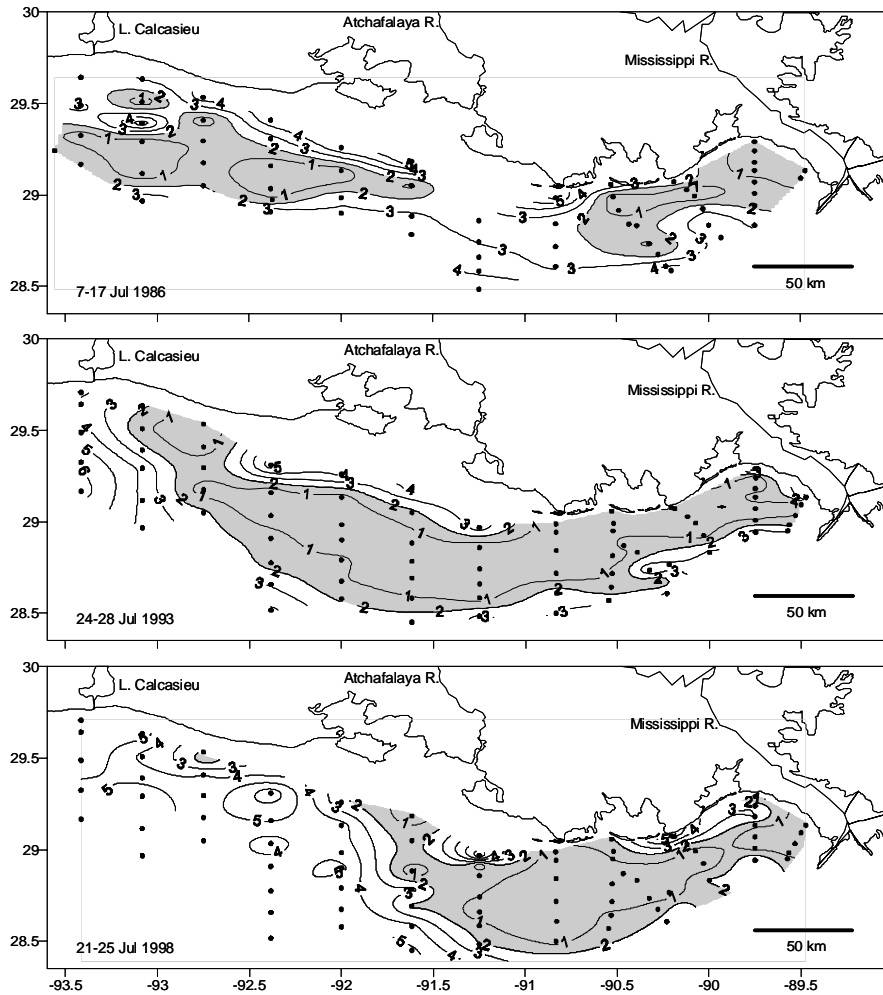


Figure 2. Bottom-water oxygen distributions for mid-summer cruises in 1986, 1993 and 1998. The area of dissolved oxygen less than 2 mg l^{-1} is indicated by shading. (From Rabalais et al. 2002c.)

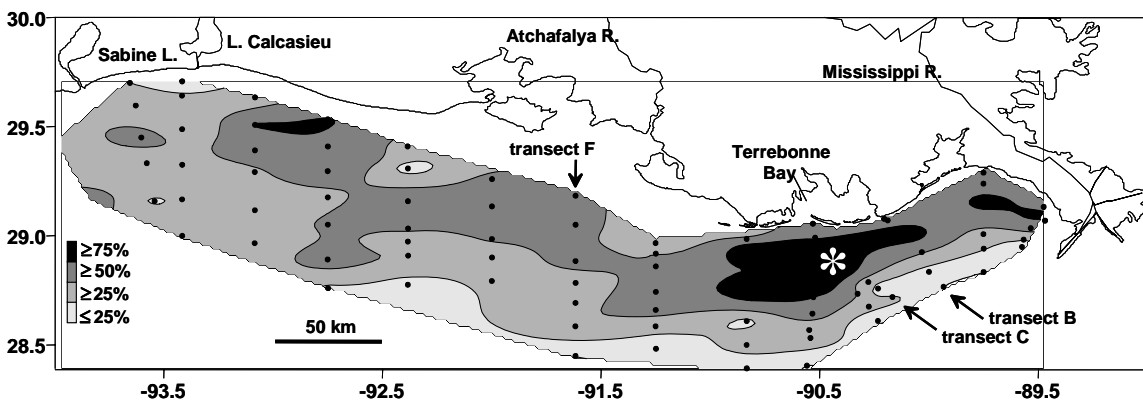


Figure 3. Distribution of frequency of occurrence of mid-summer bottom-water hypoxia over the 60- to 80-station grid from 1985-2005 (updated from Rabalais et al. 2002a). Star indicates general location of observing system station; transects B, C and F identified.

The incidents of hypoxia elsewhere in the northern Gulf of Mexico along the shelf farther to the west or east of the Mississippi River delta are infrequent, short-lived, and limited in extent (summarized in Rabalais et al. 2002a). Hypoxic water masses observed on the upper Texas coast are usually contiguous with the hypoxic zone off Louisiana, and can extend westward to Freeport, Texas southwest of Galveston. Hypoxia east of the Mississippi River occurs more frequently during flood stages of the Mississippi River when summer currents move the river plume to the east of the birdfoot delta (Rabalais 1992). From limited data where both sides of the delta were surveyed (Turner and Allen 1982, National Marine Fisheries Service unpubl. data), there is no evidence that the area of low oxygen forms a continuous band around the delta.

MID-SUMMER VARIABILITY

Multiple mid-summer surveys of hypoxia were reported in the CENR Topic #1 report (Rabalais et al. 1999) and continue to present. Additional data in the hypoxic area during summer have been acquired since 2002. Most of these studies were conducted in support of modeling, benthic and pelagic biological processes, and distribution of demersal organisms, but also provided mid-summer distribution of hypoxia. These data provided evidence of the persistence of hypoxia on a broad scale with some changes in intensity or distribution related to changing hydrographic conditions. For example:

- Two July 2002 bottom-oxygen maps indicated a similar distribution of severe hypoxia offshore of the area between Terrebonne and Atchafalaya Bays.
- A large area of hypoxia was predicted for summer 2003, and the mid-June 2003 data indicated a large area of hypoxia from the Mississippi River delta to Atchafalaya Bay. Tropical Storm Bill and Hurricane Claudette disrupted the stratification resulting in a smaller area of hypoxia mapped during July 23-28. A subsequent cruise in early August 2003 showed that the area of hypoxia had re-established in the area offshore between Terrebonne and Atchafalaya Bays.
- A series of cruises in June, July and August 2004 indicated that the June and late August distributions of hypoxia over comparable areas were smaller than the late July to early August distribution.

The summer distribution of hypoxia in 2005 was well documented (Fig. 4), but was also affected by a series of storms. In early July 2005 there was a large area of hypoxia off the southwestern Louisiana coast. Before the late July mapping of hypoxia, Hurricanes Cindy and Dennis affected the Louisiana shelf. The late July distribution was less than predicted, but the hypoxia was still fairly well formed on the southwestern shelf. Mid-August 2005 hypoxia was patchier than the July distribution. Hurricane Katrina made landfall at the end of August and disrupted hypoxia in depths less than 25 m on transect C, but it reformed in the shallow waters of the Louisiana Bight a few weeks later. A series of frontal passages and Hurricane Rita in September dissipated the hypoxia for the remainder of the year.

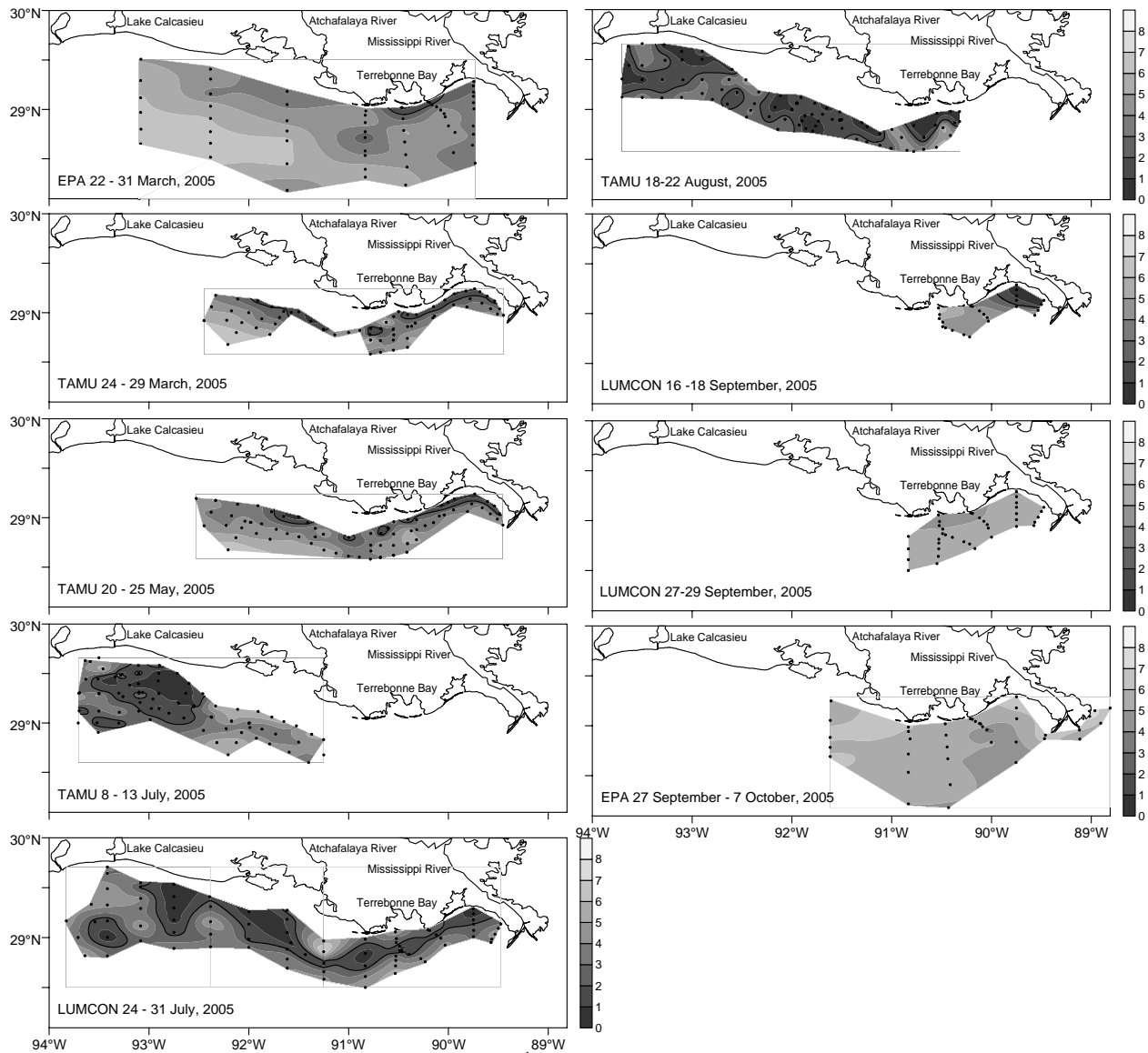


Figure 4. Dissolved oxygen contours (mg l^{-1}) for cruises in 2005. Unpublished data provided by N. N. Rabalais (Louisiana Universities Marine Consortium (LUMCON), M. C. Murrell, U.S. Environmental Protection Agency, Gulf Breeze, Florida (EPA), and S. Dimarco, Texas A&M University (TAMU) and their colleagues in hypoxia research. Data sources and periods are identified in each panel.

DOES ANOXIA OCCUR?

The occurrences of anoxia in the Louisiana hypoxic area are relatively rare even though the oxygen concentrations at the seabed are often below 0.5 mg l^{-1} . Oxygen measurements near the seabed are seldom 0.0 mg l^{-1} ($\pm 0.2 \text{ mg l}^{-1}$). Very often, however, measurements of 0.05 mg l^{-1} or less are made, either with instruments or Winkler titrations. While instrumentation may limit accurate detection of anoxia, the presence of moderate ($20 \mu\text{M}$) H_2S concentrations in bottom water may indicate that the dissolved oxygen concentration is less than 0.2 mg l^{-1} and probably zero or close to it (Wong and Brewer 1977). H_2S concentrations up to $50 \mu\text{M}$ have been measured in bottom water samples that emitted a strong odor of H_2S (N.N. Rabalais et al.

unpubl. data). H_2S concentrations of 2-5 μM have been chemically detected, when there was still a faint H_2S odor. The odor of H_2S as an indicator of very low, near anoxic or anoxic waters can be prevalent within June through September hypoxia surveys at approximately 10 percent of the stations (N.N. Rabalais et al. unpubl. data). H_2S poisoning of oxygen probes and tarnished silver worn by divers are also evident at times (pers. observ.). Sulfur-oxidizing bacteria at the sediment-water interface have been repeatedly observed by divers and by video surveillance from remotely operated vehicles (Rabalais et al. 2001a). Presence of these bacteria indicates extremely low oxygen concentrations, though not necessarily anoxia.

Oxygen consumption rates in near-bottom waters were measured during several spring and summer cruises of multiple years (Turner and Allen 1992, Turner et al. 1998, Rabalais et al. 2002b). Rates varied between 0.0008 to 0.29 $\text{mg O}_2 \text{ l}^{-1} \text{ hr}^{-1}$, and were sufficient to reduce the *in situ* oxygen concentration to zero in less than four weeks. The rates were inversely related to depth and decreased westward of the Mississippi River delta, consistent with the decrease in nutrients and chlorophyll *a* concentrations in surface waters. Oxygen depletion rates calculated from continuous oxygen measurements (see below) are consistent with the findings of Turner and colleagues. If there is no mixing of the stratified layers, the period for reduction of the bottom-water oxygen concentration from about 6 mg l^{-1} to less than 2 mg l^{-1} is 18, 11 or 9 days, in April, May and July, respectively (N. N. Rabalais unpubl. data, derived from oxygen time series at 20-m on transect C, Fig. 3). Given these rates, it is surprising that anoxia was not more prevalent than described earlier.

Light conditions partially influence where hypoxic water masses are located and their severity, as well as explain why anoxia may not be more prevalent. Light reaching the bottom is often sufficient to support benthic oxygen production (R. E. Turner et al. unpubl. data). With sufficient light, photosynthesis at or near the sediment-water interface will occur in some areas and offset oxygen uptake processes to the point that anoxia does not frequently occur (Dortch et al. 1994). A mass balance eutrophication model (Bierman et al. 1994) indicated that deeper light penetration might be more important with regard to hypoxia distribution in the western portion of the Louisiana shelf compared to the eastern area where the water clarity is lower (either due to suspended sediments or shading from high algal biomass). As an indicator of the importance of light, the bottom-water oxygen declined in April 2005 at 29°N 92°W off the Atchafalaya River at a similar rate to the April values on transect C (S. DiMarco et al. unpubl. data), but hypoxia did not develop off the Atchafalaya River.

SHELFWIDE DISTRIBUTION IN SPRING AND FALL

In addition to summertime shelfwide surveys, observations in spring and fall provide information on hypoxia over a large geographic region during the periods when hypoxia is likely to be developing or dissipating. A combination of March, April, May and September cruise data (S. DiMarco et al. unpubl. data; M. Murrell unpubl. data; N. Rabalais et al. unpubl. data, depicted for 2005 in Fig. 4), indicate either a narrow band of hypoxia nearshore or the occurrence of hypoxia at shallow stations in the Louisiana Bight and off Atchafalaya Bay in those months. This is consistent with the longer-term data for transect C off Terrebonne Bay (Rabalais et al. 2002c). Other shelfwide cruises in October, November and December indicate no hypoxia then (no cruises for these months in 2005, Fig. 4).

CROSS-SHELF SPATIAL AND TEMPORAL VARIABILITY, SOUTHEASTERN LOUISIANA

Frequent sampling on transect C (Fig. 2) on the southeastern Louisiana coast off Terrebonne Bay indicates that hypoxia occurs from as early as late February through early October and nearly continuously from mid-May through mid-September (Rabalais et al. 2002a). Data from trawl surveys in the Louisiana Bight indicate that hypoxia occurs in that area in 6- to 10-m water depth as late as November (T. Romaine pers. comm.). Hypoxia is rare in late fall and winter.

Data from transect C and transect F off Atchafalaya Bay (Fig. 2) allow for the generation of monthly-averaged conditions that depict long-term conditions in the two areas (Figs. 5 and 6). The data span 20 years for transect C, but there are fewer data for transect F, for which bimonthly hypoxia and related parameter surveys began in 2001 ($n = 2$ or 3 data points per station month vs. $n \approx 150$ for transect C). The expression of river discharge in surface water salinity is more pronounced on transect C than on transect F, but each shows a spring-summer lowering of salinity across the shelf. For transect F there is an additional signal of lower winter surface salinity nearshore, but this may be an artifact of the limited data. Surface to bottom density differences along each transect reflect the seasonal freshwater inputs and more stable conditions in spring-summer.

The surface dissolved inorganic nitrogen is composed primarily of nitrate-N for both transects with high nearshore concentrations on transect F, which is in close proximity to the Atchafalaya River discharge, while nitrate-N is lower but more evenly distributed along transect C, which is 100 km from the discharge of the Mississippi River at Southwest Pass. Ammonium-N concentrations can be high nearshore on transect F. Higher concentrations of chlorophyll *a* in surface waters on transect C occur after the winter-early spring peaks in nitrate-N. The pattern for transect F is for higher chlorophyll *a* in surface waters nearshore to mid-transect increasing through spring to maximal concentrations in summer to a decrease in the fall. There is a secondary peak in dissolved inorganic nitrogen followed by higher chlorophyll concentrations on transect C that is not evident on transect F.

The development of hypoxia along transect C occurs earlier in spring compared to transect F in summer and extends into September as opposed to August for transect F. Vertical profiles of oxygen concentrations along the two transects (not depicted) indicate that hypoxia takes up less of the lower water column along transect F than transect C, and hypoxia covers less of the bottom and occurs less frequently along transect F (N.N. Rabalais unpubl. data). Further models that compare the response of the coastal ecosystem to varying and long-term nutrient loads, nutrient ratios, different light characteristics, and physical hydrographic structure will benefit from the multiple transect data.

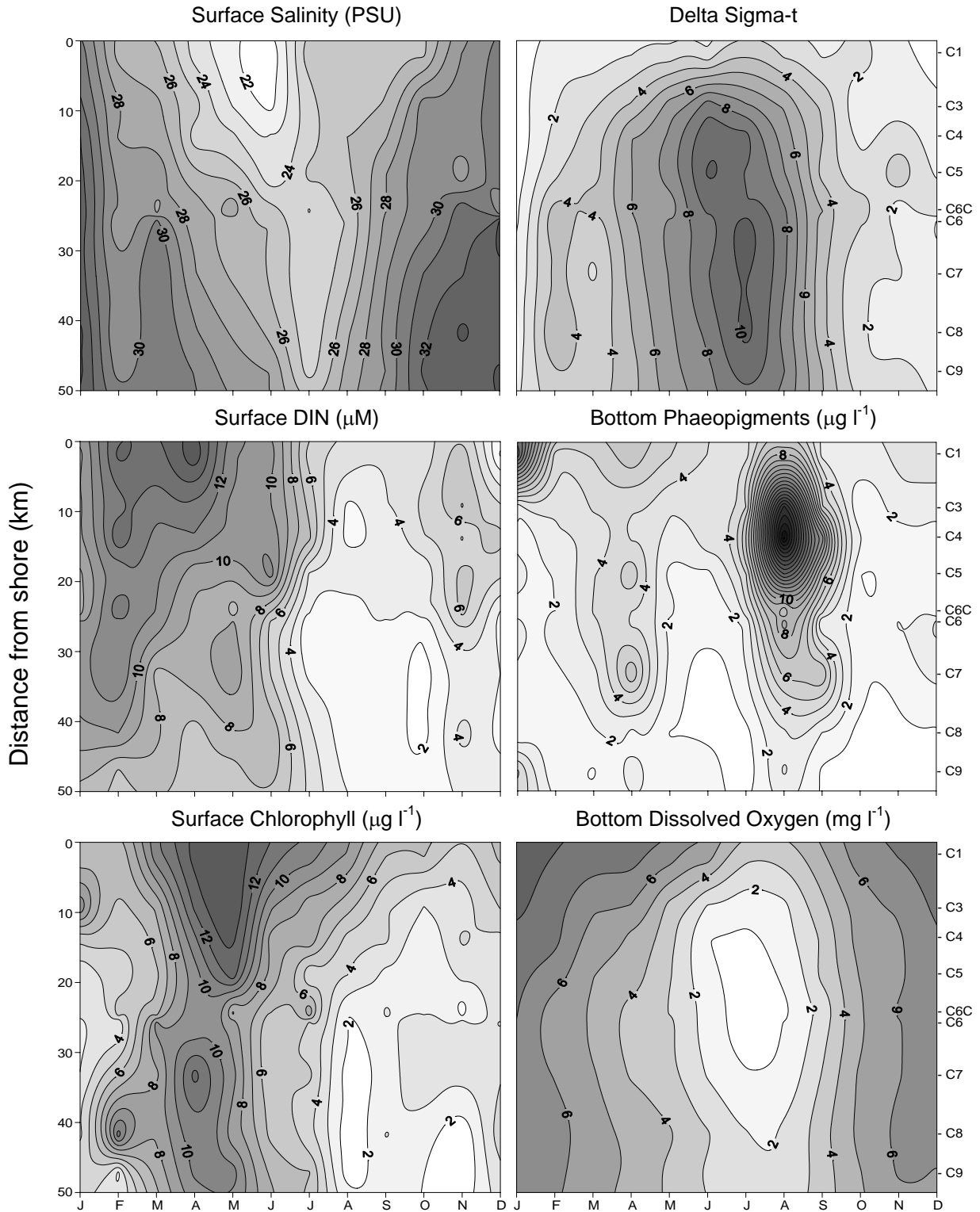


Figure 5. Water column parameters along transect C from station C1 inshore to C9 offshore, Jan-Dec, 1985-1997. Y axis is distance from shore (km). Unpublished data of Rabalais et al. (see Fig. 3 for location of transect).

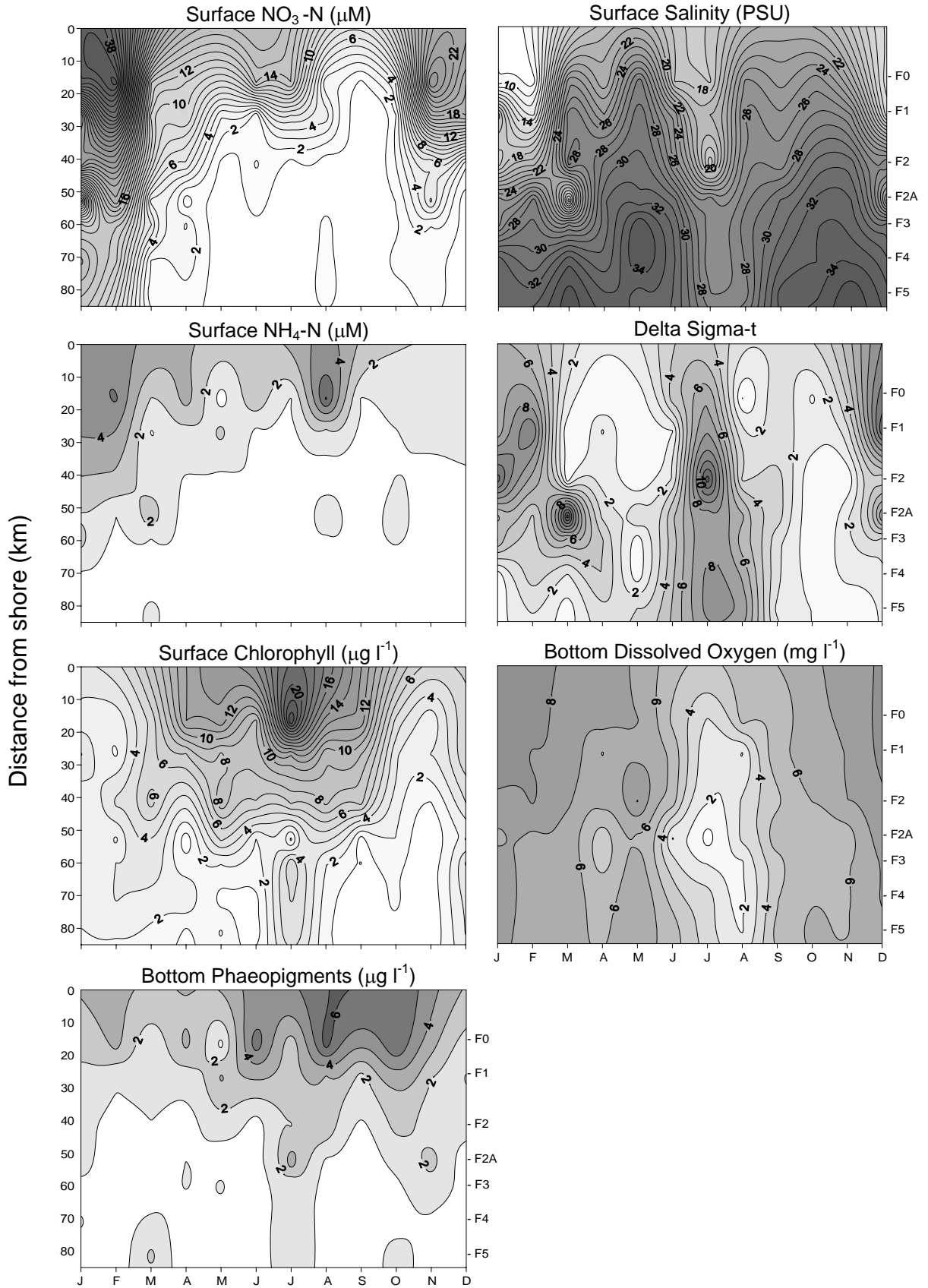


Figure 6. Water column parameters along transect F from station F0 inshore to F5 offshore, Jan - Dec, 2001-2005. Depth range is from 5 m at F0 to 30 m at F5. Unpublished data of Rabalais et al., Atchafalaya series (see Fig. 3 for location of transect).

Much of the onshore-offshore variability in distribution can be attributed to wind-induced cross-shelf advection or tidal advection (Rabalais et al. 1991, 1994, Wiseman et al. 2004). Data from an acoustic Doppler current profiler (ADCP) deployed in 20 m on transect C from mid-March to mid-November 2002 (Wiseman et al. 2004) demonstrated the strong dominance of the alongshore currents compared to cross-shelf flow. Long periods of eastward flow contrary to the expected westward flow regime were observed in May through July in 2002. The offshore cross-shelf flow during the westward flow is consistent with a wind-driven downwelling regime as would be expected under the predominantly southeasterly winds affecting the region. Intermittent periods of an upwelling favorable regime during winds from the north push surface waters offshore and thus move bottom waters and the hypoxic water mass onshore and closer to the barrier island shore. These opposing patterns explain much of the cross-shelf variability.

MOORED INSTRUMENT TIME SERIES

Oxygen time series (15-min interval) near the bottom at a 20-m station on transect C where hypoxia frequently occurs demonstrate the seasonal pattern of hypoxia (Fig. 7). The decline of bottom-water oxygen observed during spring is apparent with respiration rates exceeding rates of resupply of oxygen from the surface waters. Strong mixing events of the stratified water column associated with cold fronts in spring and fall and tropical storms and hurricanes in summer result in an almost immediate increase in bottom-water oxygen levels from near anoxic to often above 6 mg l^{-1} . Following a mixing event and reoxygenation of bottom waters, a gradual decline of bottom oxygen concentrations recommences and continues as long as the stratification is maintained. As long as mixing does not occur and stratification persists, periods of oxygen concentrations less than 1 mg l^{-1} or near anoxia last from one-half to two months in May-September. Short-lived increases in bottom-water oxygen during summer are usually the result of intrusions of higher oxygen content water from depth during upwelling-favorable wind conditions followed by a relaxation of the winds and movement of the low oxygen water mass offshore. Weather associated mixing events increase in frequency after September, and the bottom waters usually remain normoxic, values of 6 to 8 mg l^{-1} through February. The frequency of cold fronts begins to lessen in March, stratification persists for longer periods, and respiration of fluxed carbon draws down the oxygen concentration in the lower water column. At the same time, the volume of fresh water and nutrient loads increase and affect the stratification and the nutrient-enhanced production that both contribute to the next seasonal cycle of hypoxia.

Additional time series data (observing system site in Fig. 3) for just dissolved oxygen or that combine multiple parameters with dissolved oxygen—nitrate, silicate, turbidity, chlorophyll, salinity, temperature, ADCP—continue to be analyzed to advance understanding of physical/chemical/biological interactions within the hypoxic zone.

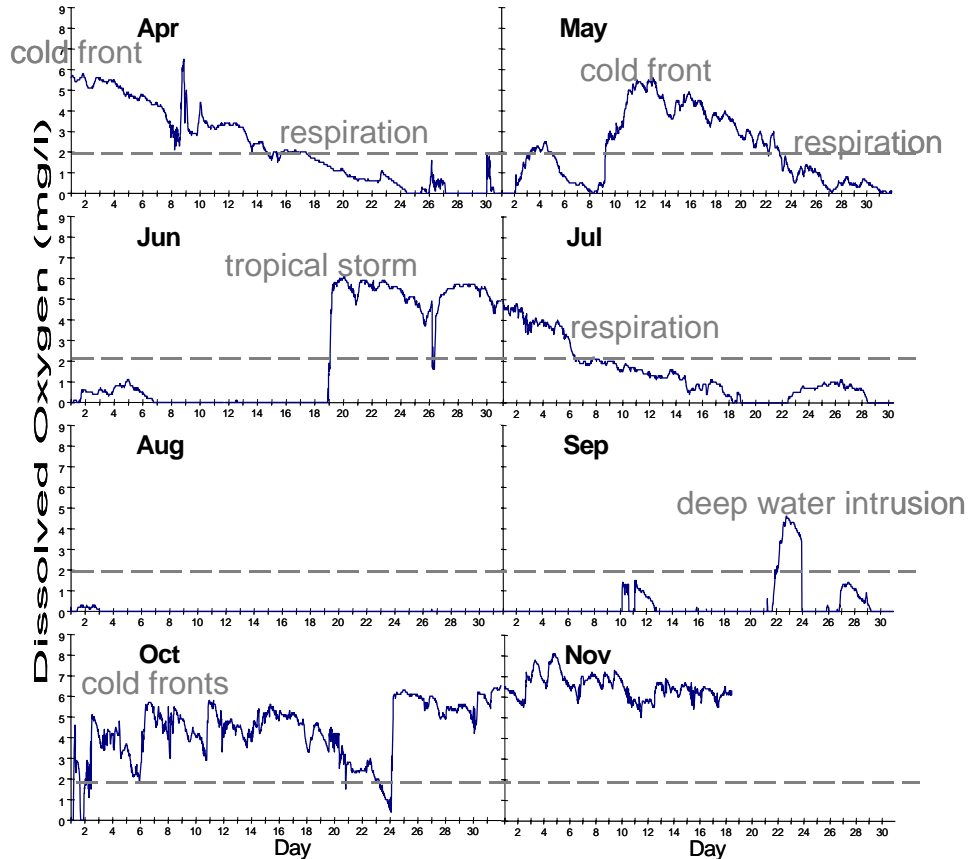


Figure 7. Continuous bottom-water dissolved oxygen in 20-m depth on the continental shelf west of the Mississippi River (April–November 1993) (mooring site in Fig. 3). The horizontal dashed line defines hypoxia. (From Rabalais and Turner 2006.)

CLIMATE-DRIVEN VARIABILITY IN SIZE

Conditions during extreme events such as the 1993 flood or the 1988 or 2000 droughts emphasize the importance of climate-driven river discharge and nutrient load in defining the mid-summer extent of hypoxia (Rabalais et al. 1998, Rabalais and Turner 2001). The influence of the Mississippi River system was magnified during the 1993 flood with above normal discharge from late spring into early fall. Flood conditions resulted in a higher flux of nutrients to the Gulf, higher concentrations of dissolved nutrients in Gulf surface waters, lower surface water salinity, higher surface water chlorophyll *a* biomass, increased phytoplankton abundance, modeled greater carbon export from the surface waters, increased bottom water phaeopigment concentrations (an indicator of fluxed degraded surface water chlorophyll *a* biomass), lower bottom water oxygen concentrations compared to the long-term averages for 1985–1992 and a doubled size of the hypoxic zone (Rabalais et al. 1998).

A 52-yr low-river flow of the Mississippi River occurred in 1988 (derived from data for 1988 at <http://www.mvn.usace.army.mil/eng/edhd/>). Discharge began at normal levels and dropped to some of the lowest levels on record during the summer months. In early June 1988,

hydrographic conditions on the southeastern Louisiana shelf were similar to those observed in previous years, i.e., a stratified water column and some areas of oxygen-deficient bottom waters. A typical seasonal sequence of nutrient-enhanced primary production and flux of organic matter progressed in the spring and led to the formation of hypoxia in early June. Density stratification was not maintained during the summer extreme low discharge, and low oxygen conditions were virtually absent in the mid July mapping (Rabalais et al. 1999).

Drought conditions throughout the watershed in spring 2000 resulted in decreased discharge (derived from data for 2000 at <http://www.mvn.usace.army.mil/eng/edhd/>) and nutrient flux so that the typical effects of water discharge and nutrient flux on productivity, phytoplankton biomass and carbon flux were diminished. Less productivity, coupled with windy spring weather that prevented the usual development of stratified waters, resulted in little development of hypoxia in the spring. Discharge increased and exceeded the previous 70-yr average in June and hypoxia eventually developed although over a smaller area (4,400 km²) (Rabalais and Turner 2001). While the total discharge in 1988 and 2000 between the months of January-May was similar, the timing of high discharge affected the sequence of production, organic matter accumulation and degree of stratification, and the distribution of mid-summer hypoxia was quite different in the two years.

The influence of tropical storms and hurricanes on the distribution and size of mid-summer hypoxia was demonstrated by the summers of 2003 and 2005 (discussed above). The predicted size of mid-summer hypoxia (by several models) was larger than the size measured during the mapping cruise. The result of tropical storms on the water column structure, mixing and re-oxygenation of the water column is evident in the bottom-water oxygen time series in Fig. 7. The tropical storm that led to the rapid re-aeration of the bottom water in mid June 1993 (Fig. 7) was 1000 km away in the Gulf of Campeche, but caused 3 to 4 m waves at the instrumented observing station.

ADEQUACY OF DATA

Obtaining the data necessary to determine the size of mid-summer hypoxia with regard to the goal of the Action Plan (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001) requires at least one quasi-synoptic period (5-6 days) in mid- to late-July consistent with the long-term data (Rabalais et al. 1999). Finer-scale resolution of dissolved oxygen conditions obtained with a towed Scanfish in 2003 and 2004 immediately after the hydrographic surveys (W. Boicourt and M. Roman, unpubl. data) provided an order of magnitude increase in the cross-shelf vertical resolution of properties compared to traditional profiles. Initial results from the 2003 and 2004 surveys indicate that, as far as the areal extent of the hypoxic region is concerned, the advantages of the Scanfish over traditional CTD surveys are relatively modest, with a slightly greater survey speed afforded by continuous steaming (Rabalais unpubl. report 2005). A disadvantage of this instrument was that profiles from the Scanfish excluded the upper and lower 1-2 m of the water column where strong gradients in dissolved oxygen and associated parameters are common.

The towed Scanfish, on the other hand, increased the resolution of smaller-scale features and provided additional insight into the important biological-physical interactions on the shelf.

The Gulf of Mexico is a region of rapid mesoscale variability, with highly time-dependent sources of fresh water, nutrients, and sediments driving the buoyant Mississippi and Atchafalaya Plume and the Louisiana Coastal Current and with meandering frontal jets, eddies, and fluctuating wind-driven currents on the continental shelf. In the western portion of the hypoxic region, the changes in hydrography were more gradual than near the river sources in the east. Within the western region the differences between the traditional CTD survey and high-resolution Scanfish survey reflected more the expected time variability during the one-week interval between cruises than any small-scale processes. However, smaller-scale structure was especially evident in the dissolved oxygen transects over the eastern portion of the survey region, nearer the Mississippi-Atchafalaya sources (transects C and F in Fig. 3; Rabalais unpubl. report 2005). Much remains to be learned from the finer temporal and spatial data from towed multi-parameter instruments, monthly transects and instrumented observing systems with regard to interacting biological and physical processes in the development and maintenance of hypoxia.

Other metrics could be used to determine the extent, duration and intensity of hypoxia. Volume measurements are typically used in the Chesapeake Bay as a measure of change and in developing empirical relationships with river discharge (e.g., Hagy et al. 2004). Preliminary volume calculations for the northern Gulf of Mexico hypoxic zone correlate with the bottom-area estimates (Fig. 8, N. N. Rabalais et al. unpubl. data). [N.B. Both the volume and area estimates are being refined to determine a uniform and best method for calculation.] Average hypoxic volume for the northern Gulf of Mexico ($6 \times 10^{10} \text{ m}^3$) is about an order of magnitude greater than average hypoxic volume for the Chesapeake Bay and approached $1 \times 10^{11} \text{ m}^3$ in 2002, the year of the largest area to date (N. N. Rabalais et al. unpubl. data).

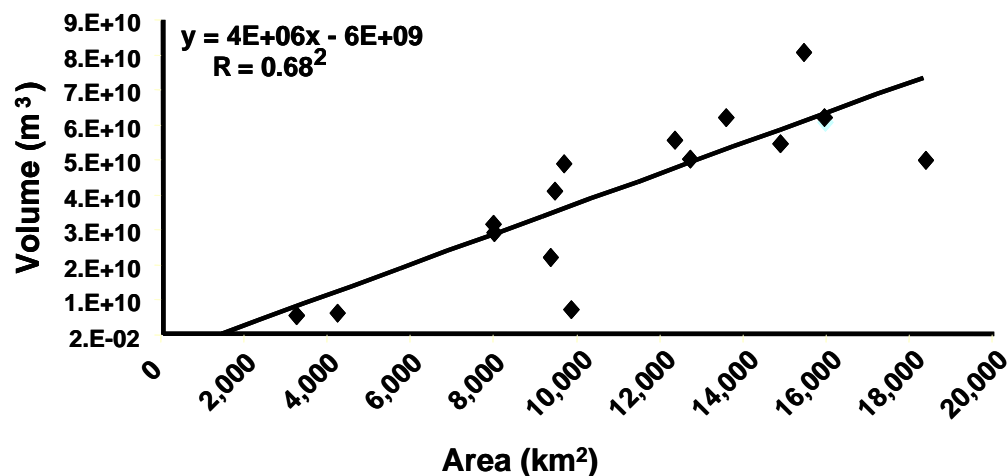


Figure 8. Preliminary estimates of hypoxic water volume ($< 2 \text{ mg l}^{-1}$) for 15 survey years of mid-summer surveys between 1985 and 2001 versus the estimated areal extent of hypoxia along the Louisiana/Texas shelf (N. N. Rabalais et al. unpubl. data.)

Area or volume estimates of dissolved oxygen concentrations less than a certain value (e.g., $< 2 \text{ mg l}^{-1}$, moderate hypoxia, and $< 1 \text{ mg l}^{-1}$, severe hypoxia) do not capture the total oxygen deficiency of the water column. Dissolved oxygen 'condition' can be determined as a deficit (or a surplus) of oxygen below (or above) 100% saturation at a known temperature and salinity (Justić 1991). Such calculations would be useful in models that link changes in nutrient

management to a more comprehensive status of ecosystem condition with regard to oxygen supplies.

Other nutrient management strategies identify ecological goals to determine steps to achieve those goals. For instance, the Tampa Bay National Estuary Program set a goal of increase in percent cover of turtle grass, *Thalassia testudinum*, and other native seagrasses in Tampa Bay over a 20-year period (summarized in National Research Council 2000). Nitrogen loading reductions in tons per year were proposed that would lead to a specified improved level of water clarity (caused by reducing phytoplankton biomass) that was needed to achieve increased acreage of seagrasses. The New York State Department of Environmental Conservation, besides mapping area of dissolved oxygen levels, determines the weekly bottom-water oxygen levels, and from that determines the number of days of hypoxia ($< 3.5 \text{ mg l}^{-1}$) per year. Length or frequency of oxygen concentrations below a specified level is used to characterize a degraded ecological condition (National Research Council 2000). Other restoration or management concerns determine 'swimable, fishable, drinkable' standards for water use or levels of dissolved oxygen below which specific organisms are physiologically stressed, die, or are unable to sustain healthy population levels.

The current method of assessing the mid-summer extent of hypoxia is sufficient to support of the Action Plan in assessing whether the five-year running average of the hypoxic area is less than $5,000 \text{ km}^2$, the metric of concern. It also has the advantage that it is a reflection of the early history of research in the area, can be consistently acquired, and satisfies a public interest of size in understandable terms. More frequent measurements of simple metrics (e.g., area and volume) from late spring through late summer, however, would ensure that the metric is representative of the system in any given year. A series of years with active tropical storm seasons may skew the area or volume data to less than representative of the river discharge, nutrient flux, and conditions of stratification, such as when the water column is disrupted by a storm within a week or two of the mapping survey (e.g., 2003 and 2005). Such a misrepresentation of the annual cycle of hypoxia formation and maintenance could negatively influence management plans for reducing shelf hypoxia. In addition to the assessment metric of hypoxia, greater resolution of hypoxia features should be emphasized in future research plans in order to facilitate understanding of the causes and impacts of Gulf hypoxia and enhance model development and validation.

Long-Term Trends in Hypoxia: Multiple Lines of Evidence

The Integrated Assessment concluded that "hypoxia in the northern Gulf of Mexico is caused primarily by the excess nitrogen delivered from the Mississippi-Atchafalaya Basin in combination with stratification of Gulf waters" (CENR 2000). This conclusion was based on an understanding of the role of nutrients in controlling the production of organic matter, the decomposition of which causes bottom-water oxygen depletion, and the documented substantial increase in the loadings of nutrients, particularly nitrate, from the rivers since the 1960s. Because there were no comprehensive, direct measurements of oxygen in the region prior to 1985, indirect evidence of the intensification of hypoxia from the sediment record also provided support for the conclusion that regularly occurring and widespread hypoxia became a common feature of the northern Gulf shelf only after nutrient loading increased during the last half of the

twentieth century. Considerable additional research has been conducted since the Integrated Assessment. The results of these studies lend further credence to the conclusions of the Integrated Assessment and enrich our understanding of the long-term changes that have occurred. This new information is summarized under five lines of evidence.

MINING OF OTHER DATASETS

Rabalais et al. (1999) reviewed various reports of shelf hypoxia prior to the beginning of systematic monitoring in 1985. They noted that documented shelf hypoxia dates back to 1972 based on relatively localized and discontinuous measurements. Two recent reports examined trends in dissolved oxygen in bottom waters in datasets that began prior to 1985. Turner et al. (2005) examined an 18-year monitoring record (1978-1995) associated with the Louisiana Offshore Oil Port (LOOP) facility located west of the Mississippi River delta and 30 km southeast of Belle Pass off Port Fourchon. This area generally corresponds to transect B (see Fig. 3) of the shelf-wide surveys and frequently experiences mid-summer hypoxia since those surveys began in 1978. Dissolved oxygen concentrations during June, July and August were rarely hypoxic ($< 2 \text{ mg l}^{-1}$) prior to 1984, but frequently hypoxic after that time (Fig. 8). Using the relationship between total Kjeldahl nitrogen (TKN, largely organic nitrogen) measured at the LOOP stations and the shelf-wide area of hypoxia between 1985 and 1995, and the relationship between TKN at the LOOP stations and Mississippi River spring nitrate flux, Turner et al. (2005) hindcasted that there would have been “no substantial hypoxia” on the Louisiana shelf before the 1970s when river nitrate flux began to rise.

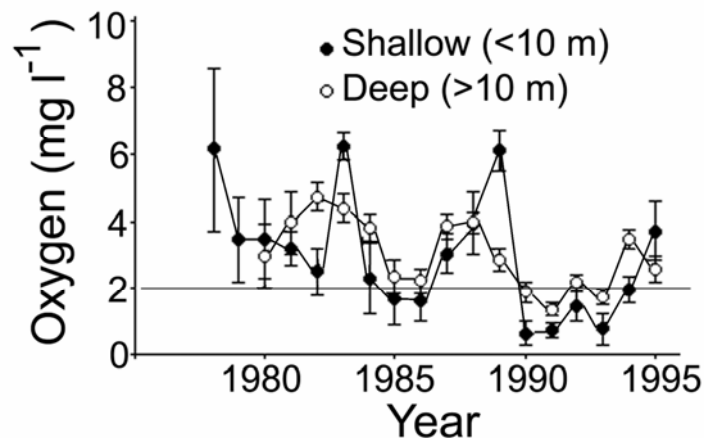


Figure 8. Bottom water oxygen concentration (mg l^{-1}) for shallow and deep water stations for June, July and August (mean ± 1 S.E.) (from Turner et al. 2005).

Stow et al. (2005) examined water quality data from the Southeast Area Monitoring and Assessment Program (SEAMAP) fisheries-independent trawl surveys conducted from 1982-2002 over the entire Louisiana shelf ($< 50 \text{ m}$ depth). They used a general additive model to fit the trend of declining bottom dissolved oxygen on the Louisiana shelf during this period (Fig. 9). They found that the difference of surface and bottom salinity (influencing density stratification) is an important predictor of hypoxia, exhibiting a threshold, where the probability of hypoxia increases rapidly, at approximately 4.1 psu. Using a Bayesian change-point model, they showed that this stratification threshold decreased from 1982 to 2002, indicating the degree of stratification needed to induce hypoxia has gone down, implicating a long-term factor or factors

transcending flow-induced stratification differences. Stow et al. (2005) did not specifically address the influence of increased nitrate loading on the declining threshold, but pointed out other factors, including increasing surface temperature (and its influence on oxygen solubility) that could also play a role.

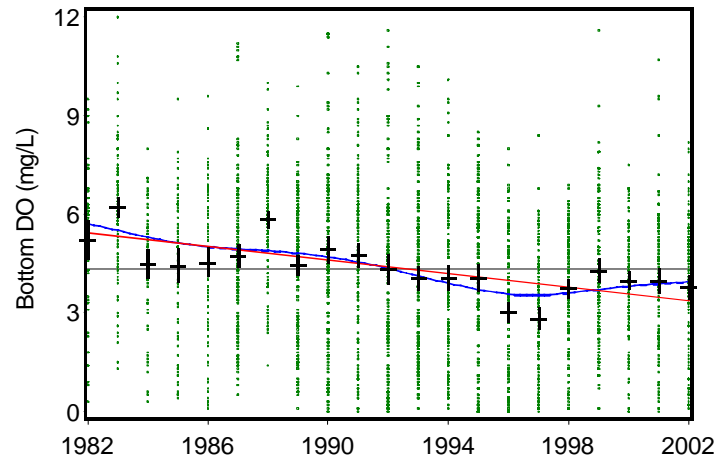


Figure 9. Bottom dissolved oxygen (DO) versus year for SEAMAP surveys (Southeast Area Monitoring and Assessment Plan, National Marine Fisheries Service). Yearly mean is depicted by black horizontal bars ($\pm 2SE$) through the green points, the black line indicates the overall DO, the red line is an ordinary least squares regression fit, and the blue line is a GAM fit (from Stow et al. 2005).

STATISTICAL ANALYSES

There are many challenges in discerning the influence of various inputs from the Mississippi and Atchafalaya rivers, including fresh water, nutrients and other materials, on the development of hypoxia because they strongly co-vary with river flow. The two studies just reviewed (Turner et al. 2005; Stow et al. 2005) add further evidence that, while freshwater inflows and their influence on density stratification are important determinants of bottom oxygen depletion, other factors influence the long-term increase in hypoxia. Turner et al. (2006) performed statistical analyses to discern the relative strengths of the loading of various forms of nitrogen, phosphorus, dissolved silicate and their molar ratios on the variance in the size of the summertime low oxygen zone. A stable multiple regression that included as variables Year and river nitrate + nitrite loading for the two months prior to the measurement of the hypoxic zone described 82% of variation in the size of the hypoxic zone from 1978 to 2004 (Fig. 10). The inclusion of the time variable Year is consistent with the documented increase in carbon stored in sediments after the 1970s (Rabalais et al. 2004, Turner et al. 2004). The variable Year is also negatively correlated with the TN:TP ratio (currently fluctuating around 20:1) in a way that suggests N, not P, has become more important as a factor limiting phytoplankton growth in the last 20 years. Nitrogen (specifically nitrate + nitrite) not phosphorus, dissolved silicate, or their molar ratios, appears to be the major driving factor influencing the size of the hypoxic zone on this shelf. Hind casting this relationship also lends credence to the limited observational and historical sediment record that hypoxia was limited in extent in the early 1970s (Fig. 11).

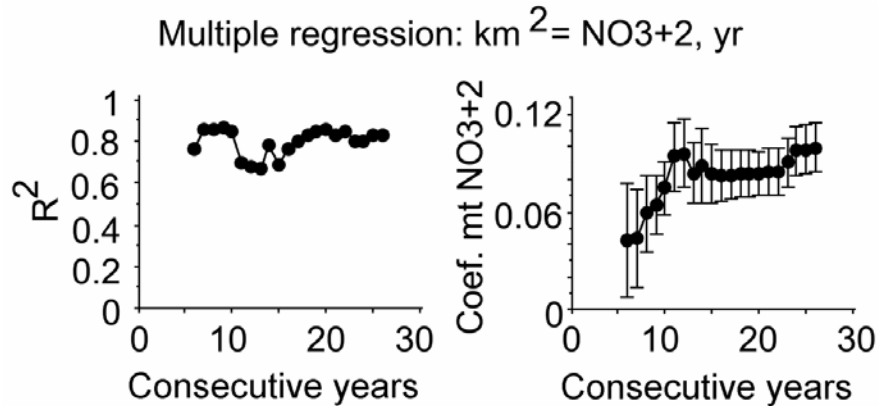


Figure 10. The coefficient of determination (R^2) and the coefficient for the variable NO_3+2 for each year of the model, based on the data available after the sixth year of the data collection (1985-2004) (from Turner et al. 2006).

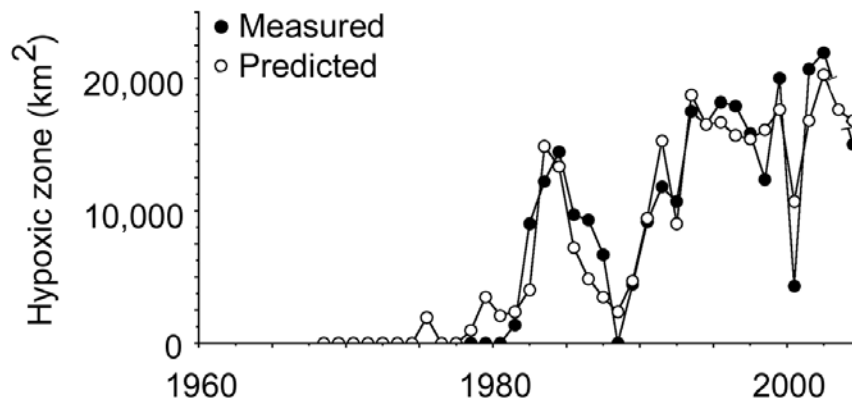


Figure 11. The results of a final model predicting the size of the hypoxic zone from 1968 to 2004, and the estimates over the whole shelf. The equation is $y (\text{km}^2) = -1337953.4 + 672.1589 * \text{Year} + 0.0998 * (\text{May flux as } \text{NO}_3+2)$. The hindcast values plotted as zero before 1978 are negative values in the model. (From Turner et al. 2006.)

EMPIRICAL MODELS

The Integrated Assessment (CENR, 2000) relied on a relatively simple mass balance model (Bierman et al. 1994, in the CENR Topic 4 report by Brezonik et al. 1999) to forecast the responses of dissolved oxygen and chlorophyll concentrations to reductions of nitrogen and phosphorus loadings. This model simulates summer steady-state, three-dimensional, food-web-nutrient-oxygen dynamics and is further discussed by Bierman et al. (2003). Subsequent to the Integrated Assessment, Justić et al. (2002, 2003) developed a simpler model that simulates two-layer, time-dependent, oxygen dynamics for one location off the Louisiana coast, driven by meteorological conditions and nitrogen loads. Model forcing functions include monthly values of the Mississippi River runoff, nitrate concentration, nitrate flux, ambient water column temperature, and surface winds. Scavia et al. (2003) published an even simpler model that simulates summer steady-state, one-dimensional horizontal dynamics of nutrient-dependent production, respiration of organic matter, and resulting oxygen balance. It is driven by May-June total nitrogen loads, calibrated to 17 years of data between 1985 and 2002, and used to simulate, hindcast, and forecast hypoxic zone length and area in response to changes in nitrogen

loads. The model simulates concentrations of subpycnocline oxygen-consuming organic matter and dissolved oxygen downstream from the Mississippi and Atchafalaya Rivers.

The three modeling approaches (referred here as the Bierman, Justić and Scavia models, although some of the investigators were involved in more than one model application) capture very different aspects of the physics, chemistry, biology, and ecology of the northern Gulf. These models were compared in a collaborative paper by the lead modelers (Scavia et al. 2004). One question they addressed was: when did large-scale hypoxia start in the Gulf of Mexico? Hindcasts of the areal extent of hypoxia by the Scavia model suggest that large hypoxic regions were not likely to have occurred prior to the mid 1970s and that the size of those regions grew between the mid-1980s and have since fluctuated. Hindcasts of subpycnocline oxygen concentrations by the Justić model suggest that subpycnocline summer-minimum oxygen concentrations offshore of Terrebonne and Timbalier Bays were fairly constant at approximately 6 mg l^{-1} between 1955 and 1969, decreased during the 1970s, and consistently dropped below 2 mg l^{-1} in most years since 1978. Scavia et al. (2004) concluded that, taken together, their models suggest that large-scale regions of hypoxia were not likely to be present prior to the 1970s, similar to the results of Turner et al. (2005, 2006).

NEW STUDIES OF THE SEDIMENT RECORD

Indicators of increased biological production and decreased oxygen availability in the sediment record provided information in support of the conclusions of the Integrated Assessment that hypoxia had intensified in the last half of the 20th century as a result of increased nutrient loading (Rabalais et al. 1999, 2002a, CENR 2000). These indicators included increased accumulation of organic matter and biogenic silica in sediment deposits (reflecting increased primary production) and increased glauconite (a mineral indicative of reducing environments) as a percentage of coarse-grained sediments, decreased diversity of ostracods and benthic foraminiferans, and changes in the species composition of benthic foraminiferans (all indicative of depleted oxygen conditions) (Fig. 12). These trends show that while there are signs of increased production and oxygen depletion earlier in the 20th century, the most dramatic changes have occurred since the 1960s. Most of this information came from sediment cores taken from depositional environments in the Louisiana Bight, west of Southwest Pass. These historical data analyses are useful for assessing the time course of increased frequency and intensity of hypoxia in the Louisiana Bight. There are few net-depositional areas regularly affected by hypoxia farther west along the shelf that yield a fairly undisturbed sediment record. Limited core data from the southwestern shelf include similar patterns of increasing carbon, diatom remains as biogenic silica and chloropigment storage with time, but there are, as yet, no data on shifts in oxygen deficiency (Rabalais et al. 2004, Turner et al. 2004).

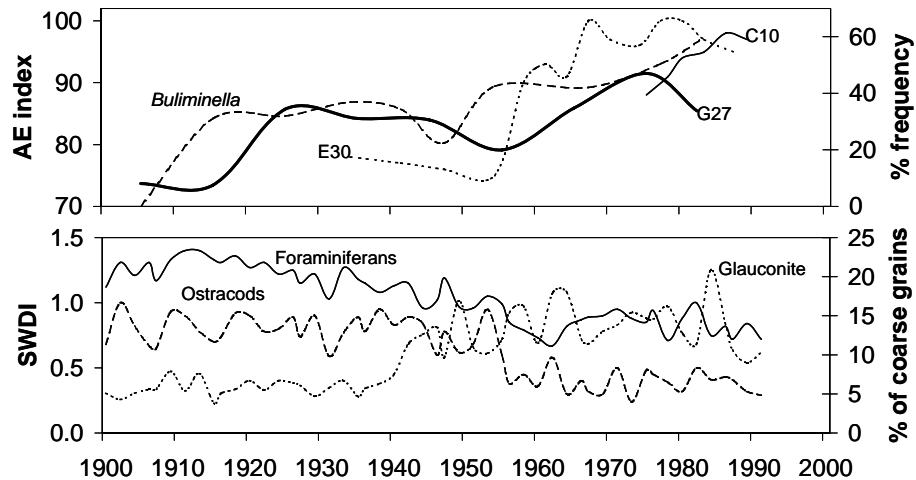


Figure 12. Top panel: A-E index (see text) for cores C10 (3-yr running average), E30, G27 (Sen Gupta et al. 1996); % frequency of *Buliminella morgani* in core G27 (Rabalais et al. 1996). Bottom panel: SWDI (Shannon-Wiener Diversity Index) for foraminiferans and ostracods (Nelsen et al. 1994, unpublished data); % glauconite of coarse grains (Nelsen et al. 1994). (Modified from Rabalais et al. 2002a.)

Microfossils and other biomarkers have been used by several workers as paleohypoxia tracers on the Louisiana Shelf. Particular attention has been given to benthic foraminifers, because (1) severe oxygen stress decreases their diversity and alters species proportions within the community, and (2) their shells are preserved well in sediments. In the sedimentary record of the Louisiana Bight, a benthic foraminiferal diversity reduction in historical times is documented by Shannon-Wiener Diversity Index data of Nelsen et al. (1994) and Platon et al. (2005), and also by species richness data of Platon et al. (2005). These species diversity measures show a substantial reduction that began between the late 1930s and the early 1950s (e.g., Fig. 12), although the specific trends differ at different coring sites or water depths. Relative abundances of agglutinated and porcelaneous groups of Foraminifera declined conspicuously in the 20th century. The well-known porcelaneous genus *Quinqueloculina* was a noticeable member of the fauna from 1700 to 1900 (Rabalais et al. 1996), but it has almost disappeared from parts of the Louisiana Bight in the past 50 or 60 years (Platon et al. 2005). The abundances of several hyaline species e.g., *Bulimina marginata*, *Cancris sagra*, and *Uvigerina hispidocostata*, have also declined in the past century (Platon et al. 2005). In contrast, the relative abundance of *Buliminella morgani*, a hypoxia-tolerant endemic species of the Gulf of Mexico, has increased markedly in recent decades; the species now dominates the benthic foraminiferal community (> 50%) within areas of chronic seasonal hypoxia (Blackwelder et al. 1996; Rabalais et al. 2000; Platon and Sen Gupta, 2001) (Fig. 12). Osterman et al. (2005) suggest that the percentage of *B. morgani*, when combined with those of two other hypoxia tolerant species, *Pseudonion atlanticum* and *Epistominella vitrea*, serves as a measure (the 'PEB index') that can be used to identify 'low-oxygen events' in the Louisiana Bight. Overall, an increasing trend of the PEB index agrees with earlier reports that hypoxia has worsened in the past 50 years (Osterman et al. 2005). At present, the PEB index shows high values in surface-sediment foraminiferal assemblages from the Louisiana shelf as well as the southern Texas coast (Osterman 2003).

The hypoxia proxy that has drawn most attention in Gulf of Mexico foraminiferal studies is a simple index based on the abundances of *Ammonia* and *Elphidium*, two common coastal genera. This *Ammonia-Elphidium* index (or A-E index) was defined by Sen Gupta et al. (1996) as $[N_A/(N_A+N_E)] \times 100$, where N_A and N_E are the respective numbers of individuals of the two genera in a sediment sample, but the index can also be computed from relative abundance (species proportion or percentage) data (Fig. 10). The arguments for the dependability of this index are explained elsewhere (Sen Gupta and Platon, in press), but, in brief, the index is trusted as a relative measure of past hypoxia because (1) observed values correlate with sedimentary organic content (Sen Gupta et al. 1996) and bottom-water O_2 level (Thomas et al. 2000), and (2) live individuals of *Ammonia*, but not of *Elphidium*, have been found in anoxic or nearly-anoxic waters (Platon and Sen Gupta 2001). It must be emphasized, however, that *Elphidium* is not intolerant of hypoxia, but *Ammonia* is more tolerant. Thus, they may co-occur in hypoxic areas, but the A-E index rises as hypoxia worsens. Using the A-E index and the PEB index, Brunner et al. (2006) infer occurrence of hypoxia south of the Mississippi-Alabama barrier islands in the 1950s. The A-E index has also proven to be a strong, consistent oxygen-stress signal in the Chesapeake Bay (Karlsen et al. 2000) and Long Island Sound (Thomas et al. 2000). In the Louisiana Bight, data from multiple cores (Rabalais et al. 1996; Sen Gupta et al. 1996; Platon and Sen Gupta 2001) show that (1) as a paleohypoxia tracker, the A-E index works best in sediments deposited in waters shallower than 30 m, and (2) oxygen stress increased (in intensity or duration) over much of the 20th century, and especially in the last half century (Fig. 10).

Additional studies of indicators of planktonic production and composition have also been conducted. Turner et al. (2004) observed increases in the accumulation of biogenic silica in cores collected in a number of locations in the Louisiana Bight, again the most marked increases began in the 1960s. Parsons et al. (2002) reported a pronounced increase in the abundance of diatoms of the genus *Pseudo-nitzschia* in sediments deposited after 1960.

Phytoplankton pigments that are deposited in sediments reflect not only the composition of the phytoplankton, with some pigments being specific to certain algal or cyanobacterial taxa, but also reflect oxygen availability at the seabed, as this affects the degree of decomposition of the pigments. In the Louisiana Bight Rabalais et al. (2004) found a general increase in accumulation of chlorophyll *a*, phaeopigments, zeaxanthin, fucoxanthin and most carotenoids over time, with a gradual change from 1955 to 1970, followed by a fairly steady increase to 1997. The highest chloropigment concentrations were found in cores likely to be exposed to seasonal hypoxia, which reduces pigment breakdown. Interestingly, in one core taken on the inner shelf off southwestern Louisiana, this increase in chloropigment accumulation appeared to occur later, in the 1990s. Other pigment biomarkers reflect the presence of phototrophic bacteria that live under oxygen-poor conditions. Chen et al. (2001) found that the downcore distribution of bacteriopheophytin-*e* and bacteriopheophytin-*e* homologues indicated the highest concentrations occurred in sediments deposited since 1960. These bacteriopigments were not detected prior to the early 1990s.

The accumulated body of evidence from a variety of fossil and chemical biomarkers from the Louisiana Bight shows trends of increased production in the twentieth century that was accompanied by more severe or persistent hypoxia beginning approximately in the 1960s and becoming most pronounced in the 1990s. This is consistent with the observational data on

hypoxia, including the newly analyzed LOOP and SEAMAP data, with the well-documented increase in nitrate export from the Mississippi River. Because of the paucity of sediment indicators beyond the Louisiana Bight, the growth in the extent of hypoxia along the shelf cannot be documented. However, limited core data from the southwestern Louisiana shelf (Rabalais et al. 2004, Turner et al. 2004), coupled with the model results of Scavia et al. (2003), suggest that hypoxia spread from the proximal Louisiana Bight somewhat later, particularly during the 1980s and 1990s.

COHERENCE WITH EVENTS IN OTHER REGIONS

Soon after the completion of the Integrated Assessment (CENR 2000), four global syntheses of hypoxia and eutrophication were published. Diaz (2001) and Diaz et al. (2004) produced an update of the earlier synthesis of Diaz and Rosenberg (1995) on marine benthic hypoxia. Cloern (2001) published a conceptual model of coastal eutrophication, and Boesch (2002) presented an overview of efforts underway to reduce coastal eutrophication by controlling anthropogenic inputs of nutrients. Diaz (2001) indicated that there was evidence of worsening hypoxia over time in 24 of the 43 coastal systems that had experienced aperiodic, seasonal or persistent hypoxia, including the Louisiana shelf, the German Bight of the North Sea, Long Island Sound, Chesapeake Bay, the Kattegat and Baltic Sea, Japanese harbors, the northern Adriatic Sea, and the northwest shelf of the Black Sea. Similarly, Diaz et al. (2004) increased once again the number of documented coastal areas of hypoxia. Cloern presented many examples of increased nutrient loading (N and P), increased primary production, loss of macrovegetation, increased incidence of harmful algal blooms, and increased hypoxia in these systems and others since 1960. Boesch added to Cloern's inventory and attempted to bracket exactly when the changes in these eutrophying coastal ecosystems began. In almost all cases, the 'tipping points' fell within a twenty year period between 1960 and 1980, a period during which there was a dramatic increase in the amount of fixed nitrogen being added to the biosphere, mainly from industrially fixed fertilizers (Fig. 13).

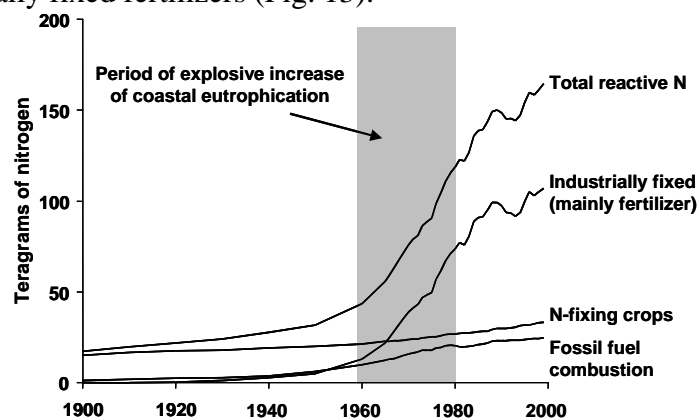


Figure 13. Period of the explosive increase in coastal eutrophication around the world in relation to global additions of anthropogenically fixed nitrogen (from Boesch 2002).

A particularly analogous situation to the Louisiana shelf is the northwest shelf of the Black Sea, because it too is an exposed shelf rather than an enclosed embayment, and it is fed by large rivers, including the Danube. Bottom-water hypoxia on the northwestern shelf of the Black Sea adjacent to the Danube River was first documented in 1973 (Zaitsev, 1992). By 1990 the

areal extent of hypoxia was 40,000 km² (Fig. 12, upper left). There is substantial evidence that eutrophication in the Black Sea is the result of large increases in the discharge of nitrogen and phosphorus to the Black Sea from the 1960s and 1970s (Mee 2001). The typical scenario followed with increased nutrients triggering dense phytoplankton blooms, a decrease in seawater transparency and an increase in the load of organic detritus reaching the seafloor (Tolmazin 1985, Mee 1992, 2001, Zaitsev 1992). The high organic loading led to the expansion of oxygen-deficient waters over the northwestern shelf in depths of 8 to 40 m and over areas of the seafloor up to 40,000 km². As a result of the economic collapse of the former Soviet Union and declines in subsidies for fertilizers, the decade of the 1990s witnessed a substantially decreased input of nutrients to the Black Sea (Fig. 14 lower left; Mee 2001, Lancelot et al. 2002). For the first time in several decades oxygen deficiency was absent from the northwestern shelf of the Black Sea in 1996, and receded to an area less than 1,000 km² in 1999 (Fig. 14, right panel).

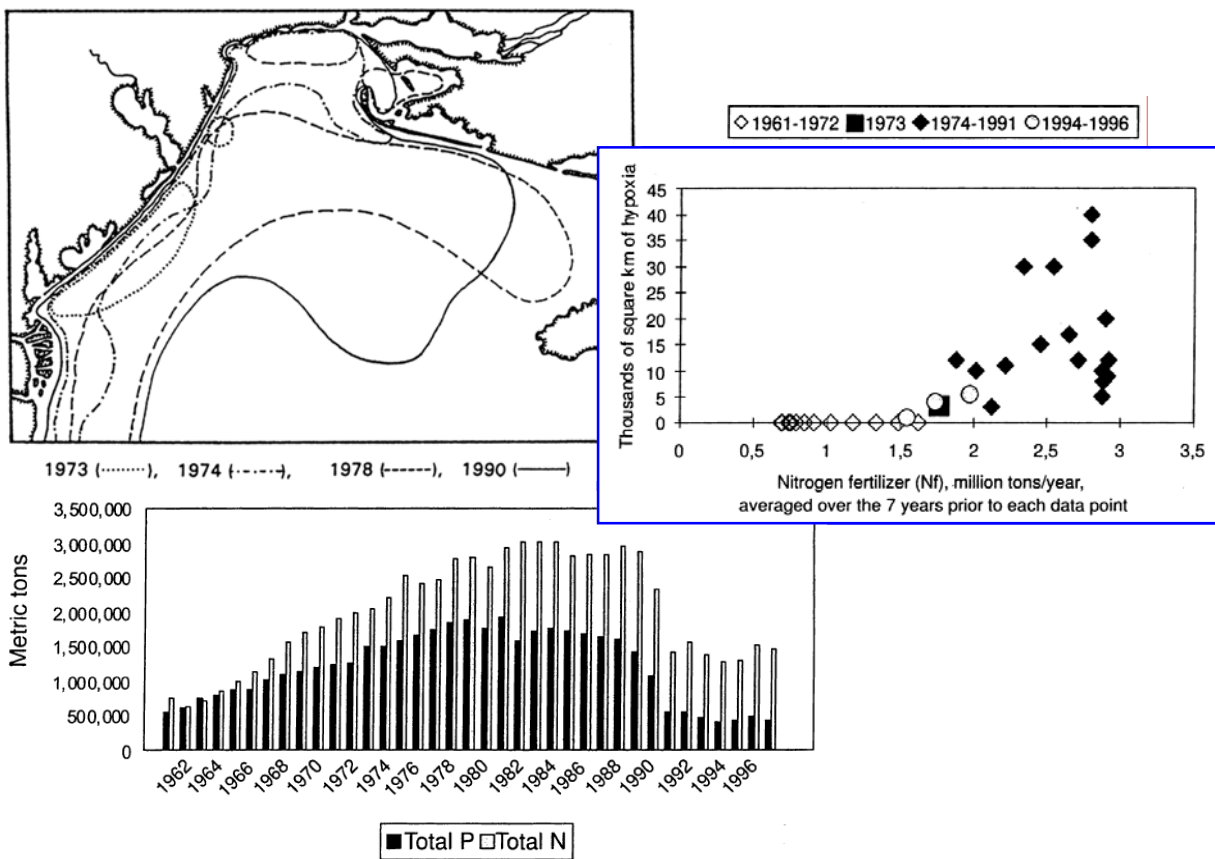


Figure 14. Upper left panel: development of hypoxia on the northwestern shelf of the Black Sea (from Zaitsev 1992). Lower left panel: Nitrogen and phosphorus fertilizer trends for use in the watersheds draining to the northwestern shelf of the Black Sea. The nitrogen and phosphorus loads corresponded to fertilizer use. (From Mee 2001). Right panel: Change in the areal extent of bottom-water hypoxia on the northwestern shelf of the Black Sea in relationship to groupings of years with differing use of nitrogen fertilizer in the Danube River watershed (from Mee 2001).

However, just when Black Sea researchers were convinced that the northwestern shelf was moving towards recovery, late rainfall and higher temperatures triggered a new large-scale hypoxic event (Mee et al. 2005). Now that many central and eastern European countries have

joined, or are in the process of joining, the European Community, the Black Sea will be influenced by the Community's common policies and regulations. As new member countries seek to have the same technologies and modernized agriculture of other members, the slow recovery of the northwestern Black Sea shelf will be endangered (Mee et al. 2005).

The parallel developments coincident with increased nutrient loading in other ecosystems further present compelling evidence in addition to the other lines of evidence based on more extensive observational, historical and mechanistic evidence above that shelf hypoxia in the northern Gulf became a severe and recurrent stress in this ecosystem over the past 30 years or so as a result of increased nutrient loading from the land.

Mississippi River Discharge and Nutrient Flux

A more detailed consideration of Mississippi River flow and constituent loads is presented in (Turner et al. manuscript). Summarized information is presented here in order to compare changes in the coastal ecosystem with changes in the Mississippi River system and its contributions to the northern Gulf of Mexico.

VOLUME OF DISCHARGE

Bratkovich et al. (1994) conservatively estimated the discharge rate of the Mississippi River system [the sum of the discharges at Tarbert Landing (for the lower Mississippi) and Simmesport (for the Atchafalaya)] to be slightly over $19,000 \text{ m}^3 \text{ s}^{-1}$ for the 1930-1997 period. Goolsby and Battaglin (2001) estimated this combined annual stream flow to be approximately $22,000 \text{ m}^3 \text{ s}^{-1}$ between 1980 and 1999. The long-term peak flow occurs in March, April and May, and the long-term low flow is in summer and early fall. Monthly average flow of the Mississippi River above the diversion point for the Atchafalaya River in spring is 25,000 to 30,000 and decreases to below $8,500 \text{ m}^3 \text{ s}^{-1}$ in August (Goolsby et al. 1999). Although flow is reduced in summer, large-scale circulation patterns facilitate the retention of the fresh water on the shelf during that period in support of continued stratification (Rabalais et al. 1999).

There is significant interannual variability in discharge (Fig. 15), but the 1820-1992 average rate (multi-decadal time scale) for the Mississippi River at Vicksburg has been relatively stable near $17,000 \text{ m}^3 \text{ s}^{-1}$ (Turner and Rabalais 2003). Within decades there are upward and downward trends in river discharge; but the long-term average since 1820 has not appreciably changed. Bratkovich et al. (1994) examined a shorter interval of Mississippi River discharge and found that the early 1990s annual discharge rate increased by 30% from the 1950s, but only 15% since 1900. Karl and Knight (1998) reported an increase in precipitation by about 10% across the contiguous United States between 1910 and 1997, including parts of the Mississippi River basin. To date, however, there has not been a published analysis linking changes in Mississippi River stream flow to secular climate change.

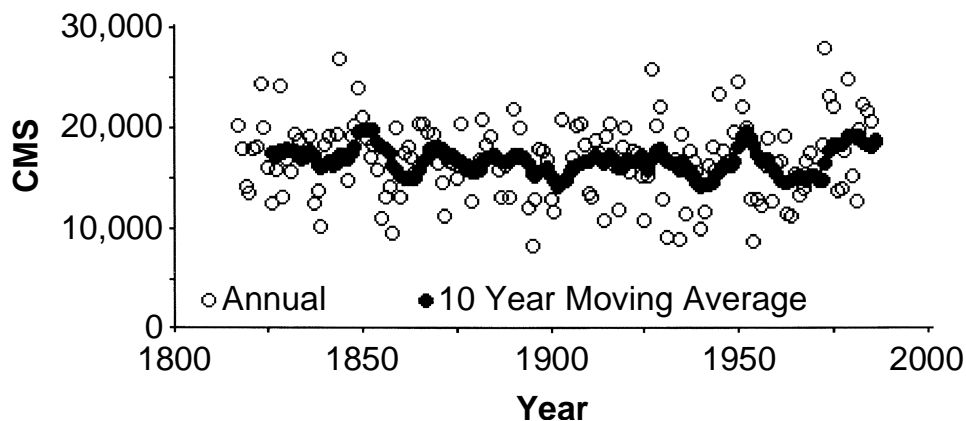


Figure 15. The annual discharge of the Mississippi River at Vicksburg, Mississippi with a 10-year moving average superimposed (data from U.S. Army Corps of Engineers) (from Turner and Rabalais 2003).

Because the amount of fresh water delivered to the northern Gulf of Mexico influences both the nutrient loads and the strength of salinity stratification on the shelf, climate-induced variability in river discharge will influence the extent and severity of hypoxia. Nitrate load increased about 300% from the 1950s to the mid 1990s (Goolsby et al. 1999, Goolsby and Battaglin 2001), whereas stream flow from the basin increased only 30% (Bratkovich et al. 1994). Clearly, the most significant driver in the change in nitrate load is the increase in nitrate river concentration, not freshwater discharge (Justić et al. 2002). Using two different approaches, Donner et al. (2002) and Justić et al. (2003) both concluded that only 20 to 25 percent of the increased nitrate load between the mid-1960s to the mid-1990s was attributable to greater runoff and river discharge, with the rest due to increased nitrogen concentrations in the lower river. Nonetheless, with nitrate concentrations in the lower Mississippi River remaining near 100 μM since the early 1990s (Turner et al. 1998), climate-driven changes in discharge are likely to have a significant influence on the seasonal formation of and interannual variability in hypoxia in contrast to the period between 1970-1990 when nitrate concentrations were rapidly increasing. This is consistent with the results of Stow et al. (2005) that demonstrated declining thresholds for hypoxia formation as a function of salinity stratification during that period.

Future climate change, within the range likely to occur in the 21st century, could have profound consequences to hypoxia in the northern Gulf of Mexico (Justić et al. 2003, 2005). To the degree to which these changes result in increased precipitation, river discharge, and nitrogen loading, hypoxia is expected to be more extensive, persistent and severe. Greater reductions in up-basin nutrient sources would be required to achieve the hypoxia reduction goals of the Action Plan. At the same time, efforts to increase the use of biofuels, such as ethanol, as alternatives to fossil fuels may increase the production of corn and other crops requiring high nitrogen subsidies.

NUTRIENT LOADS

Turner and Rabalais (1991) and Justić et al. (1995) examined water quality data for the lower Mississippi River for dissolved inorganic nitrogen (as nitrate), phosphorus (as total phosphorus) and silicon (as silicate). The mean annual concentration of nitrate was

approximately the same in 1905-1906 and 1933-1934 as in the 1950s, but it has doubled (or tripled depending on the comparative periods) from the 1950s and 1960s values. These results were corroborated by Goolsby et al. (1999) who documented that the average mean nitrate concentration at St. Francisville during 1980-1996 was more than double the average concentration during 1955-1970. The mean annual nitrogen flux, determined by Goolsby et al. (1999) from discharge weighted regression models, approximately tripled in the last 30 years with most of the increase occurring between 1970 and 1983. The increase in total nitrogen is almost entirely due to changes in nitrate concentration (Goolsby and Battaglin 2001).

The mean annual concentration of silicate in the lower Mississippi River was approximately the same in 1905-1906 as in the early 1950s, then it declined by 50% (Turner and Rabalais 1991). Justić et al. (1995) documented a 30% decrease in silicate concentration between the periods 1960-1962 and 1981-1987. Goolsby et al. (1999) noted a 40% decline in silicate concentrations from the 1950s to the mid-1970s when they stabilized. They further noted that there was no long-term trend in silicate load as observed for nitrate. Concentrations of nitrate and silicate appear to have stabilized, but trends are masked by increased variability in the 1980s and 1990s data.

There are no regular and reliable records of total phosphorus concentrations in the lower Mississippi River before 1973 and subsequent values vary greatly among years. Goolsby et al. (1999) found no long-term trend in orthophosphate or total P from 1973 to 1996. Turner and Rabalais (1991) noted a similar temporal change in orthophosphate consistent with temporal nitrate changes, but stated that extreme variability in the data made it unlikely that a statistical trend could be identified. Justić et al. (1995) estimated a two-fold increase in total P concentration, but this was based on extrapolation of a regression back to the past, rather than actual measurement.

Thus, there is agreement that nitrate concentration and flux have increased three-fold since the turn of the century and the 1950s-1960s and that levels have plateaued but exhibit considerable variability from year-to-year. There is also agreement that the concentration of silicate decreased, anywhere from 30 to 50% depending on the period of record, but that the load remains similar. The phosphorus data are of shorter duration, beginning in 1973, with no turn-of-the-century or 1930s data, and less robust for determination of long-term trends, for which there is not a consensus regarding the significance and rate of change between the 1960s and 1980s.

An important management issue is the relative influence of nitrogen versus phosphorus loads in controlling bottom-water dissolved oxygen on the Louisiana inner shelf. Model forecast results indicated a general tendency for responses to be somewhat greater for nitrogen load reductions than for phosphorus load reductions (Limno-Tech, Inc. 1995). Nitrogen is considered to be relatively more important than phosphorus in limiting primary productivity on the Louisiana inner shelf, but both phosphorus and silica may also be limiting at times and in certain locations, or combinations of nutrients may be limiting (Rabalais et al. 1999, 2002a, CENR 2000). Further investigation appears warranted for nitrogen and phosphorus as well as the inclusion of silica into water quality models.

CHANNELING AND DIRECTION OF FLOW

In addition to the intensification of agriculture and steady population increase within the Mississippi basin, human activities have changed the natural functioning of the Mississippi River system in many other ways (Turner and Rabalais 2003). Dams, navigation, channelization and flood control through leveeing along the length of the river are clearly important watershed alterations that affect the delivery of water, and dissolved and particulate matter. Other significant alterations in landscape (e.g., deforestation, conversion of wetlands to cropland, loss of riparian zones, expansion of artificial agricultural drainage) have affected both the timing of runoff, especially the peaks, and trapping of sediments and nutrients. In particular, the dramatic proliferation of agricultural land under artificial drainage during the 20th century (Mitsch et al. 2001) interacted with increased fertilizer applications in the later half of the century to result in high rates of nitrate losses. In addition, the flow in the lower river has been trained by levees and managed to flow down certain paths, both between the Atchafalaya and lower Mississippi and among the distributaries of the birdfoot delta. Spring flow that historically traversed through several active distributaries and across the vast wetlands of the Mississippi Deltaic Plain is now largely constrained to enter as point sources. Furthermore, a significant amount of the coastal wetlands of the Mississippi Deltaic plain have been lost to sinking, erosion and dredging. What have been the effects of these changes in channels and direction of water flow on the historical development of hypoxia in the northern Gulf?

For the most part, most of the structural hydrological changes affecting the river occurred prior to the 1960s and prior to the advent of recurrent hypoxia on the shelf. Some exceptions may be construction of dams on the Missouri River, continued isolation of bottom-land flood plains along the river and expansion of artificial drainage of agricultural lands. All of these may affect the delivery of water and nutrients from the upper basin rather than the distribution of discharges and loads through the river delta. Flows down the Atchafalaya had gradually grown to present day levels after massive log rafts were cleared in 1860, such that the proportion of the Mississippi and Red river flow that had been captured equaled or exceeded the presently regulated 30% flow well before the time of completion and operation of the Old River Control Structure in 1962 (Reuss 1998).

Levees that extended down the lower Mississippi River almost to the Head of Passes prevented broad spring flooding across the wetlands even earlier than that. Bayou Lafourche, which had been an active distributary, was closed in 1935. The loss of coastal wetlands has compromised the potential of the deltaic plain to trap nutrients before reaching the Gulf, but in reality this has not mattered because of levees that prevented overflow through those wetlands. On the other hand, actions taken to manage the distribution of river flow through the Mississippi-Atchafalaya delta in the future could be of major consequence to the development and distribution of hypoxia on the continental shelf and these effects should be taken into account in integrated ecosystem-based management approaches that address both coastal wetland loss and hypoxia (Boesch 2006). For example, river diversions contemplated to restore wetlands could affect some degree of nutrient trapping, although the amount of nitrate that would be lost or converted even in the most ambitious efforts would be only a small part of the nutrient reduction requirements of the Action Plan (Mitsch et al. 2001). Furthermore, management decisions that

direct more flow from Southwest Pass, presently a major conduit to the shelf edge, onto the inner shelf either to the east or west of the birdfoot delta, or that increase the flows down the Atchafalaya would have major consequences for shelf hypoxia. Most occurrences of hypoxia east of the Mississippi River are during periods of high Mississippi River flow (Rabalais et al. 1992) and would increase with this flow; more fresh water and nutrients delivered to shallow water west of the birdfoot delta would intensify stratification and nutrient-enhanced production there; and historic sediment data down plume of the Atchafalaya outflow indicate that primary production has increased and hypoxia worsened (Turner et al. 2004; Rabalais et al. 2004) as more lower Mississippi River water was shifted through the Old River Control Structure.

OTHER NUTRIENT OR CARBON SOURCES

The Mississippi River also delivers a complement of different nitrogen and carbon forms in the dissolved phase as well as particulate matter (Turner et al. manuscript). Recent estimates of the dissolved organic carbon (DOC) loading to the Gulf of Mexico is $3.1 \times 10^3 \text{ Pg yr}^{-1}$ (Bianchi et al. 2004) and is $0.80 \times 10^9 \text{ kg yr}^{-1}$ for particulate organic carbon (POC) and $0.078 \times 10^9 \text{ kg yr}^{-1}$ for particulate nitrogen (PN) (Duan and Bianchi 2006). The estimate for POC is within the range of previous estimates ($8.0 \times 10^9 \text{ kg C yr}^{-1}$, Milliman and Meade 1983; $2.5 \times 10^9 \text{ kg C yr}^{-1}$, Trefry et al. 1994; $0.21 \times 10^9 \text{ kg N yr}^{-1}$, Goolsby et al. 2000). A potential carbon or nitrogen source from eroding wetlands appears to be relatively small compared to the river-derived carbon or nitrogen loading spread out over the same continental shelf (Turner et al. manuscript). The relative availability of various carbon and nitrogen forms depends on their reactivity, lability, susceptibility to uptake and transformation, and the physical regime in which these processes occur. Continued increase in knowledge of the biological importance of constituents, such as dissolved organic phosphorus and urea (Dyhrman and Ruttenberg 2006; Glibert et al. 2006), particularly within the lower salinity, higher suspended sediment portion of the river plumes, dictate increased need for monitoring of these constituents.

Direct atmospheric deposition to the offshore surface waters is a small amount of the total nitrogen budget (1-2%, Goolsby et al. 1999). Upwelled flow of nitrate from deeper waters may be important at the shelf edge at depths of 100 m, but there are limited physical transport mechanisms for enhancing continental shelf processes and no documented role for it in controlling the severity or size of the hypoxic zone. Groundwater discharges directly to the Gulf are unlikely to be important because of the lack of shallow aquifers along the Louisiana coast and the low potential for transfer in a cross-shelf direction. Saline groundwater seeps through bottom sediments on the inner to mid Louisiana shelf, but the source and composition of this groundwater is uncertain (Krest et al. 1999). Another study indicates that oil and gas formation water, geothermal convection, and seawater recirculation are the major sources of ground water on the Louisiana shelf, with a minimum input of terrestrially derived topography driven flow (D. R. Corbett unpubl. data, McCoy et al. manuscript).

The best current knowledge, confirming the Integrated Assessment, is that the outflows of the Mississippi and Atchafalaya rivers dominate the nutrient loads to the continental shelf where hypoxia is likely to develop.

Conclusions

Data and publications from 1999 through 2006 add to our understanding of hypoxia dynamics oxygen-depleted waters along the Louisiana/Texas coast. The quasi-synoptic shelfwide mapping of the hypoxic area and its associated biological, chemical and physical variables on a consistent grid in mid-summer are adequate and represent a valuable means of measuring 'hypoxic condition' in support of the Action Plan. Increased coverage of hypoxia shelfwide distributions during summer months would provide complementary and compensatory data to account for pre-cruise events in years when the consistent mid-summer grid follows storms. Finer resolution of features, more frequent surveys over shelf-scale areas, and high frequency observations at key locations across the shelf are needed to better understand the biological, chemical and physical processes that support the formation and maintenance of hypoxia.

Other metrics of 'hypoxic condition' that can be constructed with existing data may provide additional insight into hypoxia dynamics. However, hypoxic area as a long-term indicator has advantages of being relatively simple to calculate, and is a measure that is readily grasped by the public. For longer-term indication of ecosystem response to changes in nutrient loads (anthropogenic increases, managed reductions or climate-induced), a fairly simple expression of the extent and severity of hypoxia would benefit the public discourse on remediation and prevention. Additional considerations are the cost, the degree of complexity, and continued consistency in collection of the data that support the 'indicator.'

The long-term data on hypoxia, sources of nutrients, associated biological parameters, and paleoindicators continue to verify and strengthen the relationship between the nitrate-N load of the Mississippi River, the extent of hypoxia, and changes in the coastal ecosystem (eutrophication and worsening hypoxia) that reflect the increased nitrogen loads. Multiple lines of evidence, representing a wide array of data sources, provide a consistent 'big picture' scenario of increased eutrophication resulting from increased nutrient loading and manifesting as increased size and severity of hypoxia. The additional findings broadly reinforce the science supporting the Action Plan that aims to reduce nutrient loads, primarily nitrogen, as a means of reducing hypoxia in the northern Gulf of Mexico.

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