HYPOXIA IN THE NORTHERN GULF OF MEXICO: CAUSES AND CONSEQUENCES*

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Abstract

Seasonally severe and persistent hypoxia, or low dissolved oxygen concentrations, occur on the inner to mid-Louisiana continental shelf to the west of the Mississippi River and Atchafalaya River deltas. The areal extent during mid-summer surveys of 1993-1997 ranged from 15,800 to 18,200 km^2. The shelfwide distribution in mid-summer for 1985 to 1992 averaged 8,000 to 9,000 km^2. Hypoxia occurs below the pycnocline from as early as late February through early October, but is most widespread, persistent and severe in June, July and August. The spatial and temporal variability in the distribution of hypoxia exists and is, at least partially, related to the amplitude and phasing of the Mississippi and Atchafalaya discharges. Mississippi River nutrient concentrations and loadings to the adjacent continental shelf have changed dramatically this century, with an acceleration of these changes since the 1950s. An analysis of the diatom, foraminifera, and carbon accumulation sedimentary records supports the inference of increased eutrophication and hypoxia in the Mississippi River delta bight primarily because of changes in nitrogen loading.

Introduction

The inner to mid-continental shelf of the northern Gulf of Mexico, from the Mississippi River birdfoot delta westward to the upper Texas coast, is the site of the largest zone of hypoxic bottom water in the western Atlantic Ocean. The areal extent of this zone during mid-summer surveys of 1993-1997 (estimated at 16,000 to 18,000 km^2 of near-bottom waters ≤ 2 mg/l) rivals the largest hypoxic areas elsewhere in the world's coastal waters, namely the Baltic Sea and the northwestern shelf of the Black Sea. The northern Gulf of Mexico is strongly influenced by the Mississippi and Atchafalaya Rivers, whose combined discharges account for 80% of the total freshwater input (calculated from U.S. Geological Survey streamflow data for 37 U.S. streams discharging into the Gulf of Mexico). The freshwater discharge dictates the physics of the system, and the nutrients delivered by the rivers support high primary production (Sklar and Turner, 1981; Lohrenz et al., 1990, 1994). Decomposition of carbon exported from the upper water column leads to the seasonally severe oxygen depletion in the lower water column and at the seabed.

We have been monitoring the extent of hypoxia since 1985. Mid-summer cruises across the width of the Louisiana shelf, map the extent of bottom water hypoxia, mid-July to early August. Biweekly to monthly data are collected from the southeastern shelf off Terrebonne Bay on a transect C (1985-1986 and 1990-1997). More frequent sampling occurs at station C6A or C6B where there is a moored instrument array.

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Distribution and Dynamics

Historical Background---Hypoxia is operationally defined as dissolved oxygen levels less than 2 mg/l, or ppm, for the northern Gulf of Mexico, because that is the level below which trawlers usually do not capture any shrimp or demersal fish in their nets (Leming and Stuntz, 1984; Renaud, 1986).

The mention of low oxygen conditions from the mid-1930s in the Conseil Permanent International pour l'Exploration de la Mer Bulletin Hydrographique for 1935 were identified in Hedgpeth's Treatise on Marine Ecology and Paleoecology (Brongersma-Sanders, 1957; Richards, 1957) as records from the oxygen minimum zone of deeper waters (e.g., 400-500 m deep). Several authors have shown that there is no physical connection of the oxygen minimum zone with the hypoxia on the inner to mid-continental shelf (Pokryfki and Randall, 1987, Rabalais et al., 1991). Furthermore, the oxygen consumption rates in the oxygen minimum layer are insufficient (by several orders of magnitude) to account for the observed seasonal decline in oxygen concentration on the shelf (Turner et al., 1997).

Prior to the 1970s, there are some anecdotal data from shrimp trawlers in the 1950s-1960s of low or no catches, of "dead" or "red" water, but no systematic analysis of these records. The tendency is to generalize that low oxygen conditions have always been a feature of the system; however, analyses of the sedimentary record (see below) show otherwise. Annual mid-summer surveys over the Louisiana shelf from the Mississippi River birdfoot delta to the upper Texas coast began in 1985. Prior to 1985, the data are mostly ancillary to other studies, and thus do not form complete surveys, either temporally or spatially.

General Characteristics---Critically depressed dissolved oxygen concentrations occur below the pycnocline from as early as late February through early October and nearly continuously from mid-May through mid-September. Hypoxic waters are distributed from shallow depths near shore (4 to 5 m) to as deep as 60 m water depth. During upwelling favorable wind conditions, hypoxic water masses will impinge upon barrier island shorefaces often causing massive fish kills. The more typical depth distribution of hypoxic bottom waters, however, is between 5 and 30 m. The distance offshore to which hypoxic water masses are found is contoured by the slope gradient of the continental shelf. On the southeastern Louisiana shelf, where the shelf slopes more steeply towards the Mississippi Canyon, hypoxia extends only 55 km from shore. On the central and southwestern Louisiana shelf, where the continental shelf is broader and the depth gradient is more gradual, hypoxic bottom waters may extend as far as 130 km offshore.

Mid-summer hypoxia is characterized by a distinct mid-depth pycnocline controlled primarily by salinity. A weaker secondary pycnocline controlled by temperature often dictates the morphology of the hypoxic layer (Wiseman et al. 1997). (See further discussion of the role of stratification below.) Hypoxia is not just a bottom-water condition, but occurs well up into the water column. Depending on the depth of the water, hypoxia may encompass from 10% to over 80% of the total water column. In cases of the higher percentages above, hypoxia may reach to within 2 m of the surface in a 10-m water column, or to within 6 m of a 20-m water column.

Mid-Summer Extent---The quasi-synoptic sampling grid for the shelfwide mid-summer hypoxia survey cruises is similar from year to year, with 60-80 stations between the Mississippi River delta to the upper Texas coast. During the last five years (1993-1997), bottom water hypoxia has been extensive on the Louisiana shelf with bottom horizontal areas estimated at 17,600, 16,300, 18,200, 17,920 , and 15,840 km^2 respectively (1997 distribution is shown in Figure 1).

Total Mississippi River discharge for 1993 was the highest on record and the discharge during late spring to late summer, when flows are normally low, was also the highest on record

(Dowgiallo, 1994). As a result of higher streamflow, there were lower than normal surface salinities, higher surface temperatures, increased stability in the coastal waters, increased overall loading of nutrients, an order-of-magnitude higher than normal total phytoplankton counts, a predicted greater carbon flux, and a significantly lower oxygen content of the lower water column, and an approximately two-fold increase in the areal extent of hypoxia with respect to the 1985-1992 mid-summer average (several papers in Dowgiallo, 1994; Rabalais et al., 1997). Although river freshwater and nutrient fluxes were "normal" in 1994, the areal extent of mid-summer bottom water hypoxia was similar in size and shape to that of 1993. This result suggested the residual effects of the 1993 flood well into 1994. Equally large areas were surveyed in 1995 and 1996 following a peak each year in Mississippi River discharge in late June. Prior to 1993, the average areal extent of bottom water hypoxia in mid-summer was 8,000 to 9,000 km^2.

Another natural experiment in extremes of river flow was provided by the 52-yr record low flow of the Mississippi River in 1988. Discharge began at normal levels in 1988 and quickly 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 (Rabalais et al., 1991). By mid-July, few areas of lower surface salinities were apparent, there was little density stratification, and low oxygen conditions were virtually absent. Mid-summer surface to bottom density differences in 1988 were two to three times less than seen in previous years (Rabalais et al., 1991) (a situation that clearly identifies the need for density stratification in the maintenance of subpycnoclinal oxygen deficiency). Reduced summer flows in 1988 also resulted in reduced suspended sediment loads and increased water clarity across the continental shelf. Although the average Secchi disk depth in 1988 was not statistically different from that in 1986, 1987, 1991 or 1993 (Wiseman et al., 1997), the critical depth for photosynthesis was well below the depth of the seabed. High percent saturation of oxygen and even supersaturation in bottom waters compared to other years with 20% oxygen saturation or less indicated that the weak stratification, which facilitated reaeration, was coupled with the photosynthetic production of oxygen in bottom waters, and the water column was well oxygenated from surface to bottom (Rabalais et al., 1991). The majority flux of organic carbon materials in 1988 was likely in the spring when flows were normal, which led to the formation of hypoxia, but with the lack of stratification and the production of oxygen in bottom waters, hypoxia was not maintained.

Temporal Variability---In March, April and May, hypoxia tends to be patchy and ephemeral; it is most widespread, persistent, and severe in June, July and August (Rabalais et al., 1991, 1994a). The persistence of extensive and severe hypoxia into September and October depends primarily on the breakdown of the stratification structure by winds from either tropical storm activity or passage of cold fronts. While the areal extent of bottom water hypoxia is widespread, its permanence over such an extent is not known, except for consecutive shelfwide cruises (three in July 1993 and two in July 1994). These data showed that the hypoxic water masses persisted over two to three weeks or more and that the extensive areal distribution is not an ephemeral event. Severely reduced oxygen occurs over large areas of the Louisiana-Texas coast for extended periods.

Continuous time series data for station C6 (example in Figure 2 of 1995) show long periods of hypoxia and anoxia, a draw-down of hypoxia in the spring in response to respiration in the lower water column and at the seabed and sediment oxygen demand, vertical mixing and loss of stratification, response to winds (e.g., upwelling of deeper oxygenated waters), and, in other parts of the shelf, the influence of tidal advection (Rabalais et al., 1992, 1994b).

Proximal Causes

The relative magnitude in changes of freshwater discharge and nutrient flux from the Mississippi River to the coastal ocean affects water column stability, surface water productivity, carbon flux and oxygen cycling in the northern Gulf of Mexico. Freshwater discharge from the plumes of the Atchafalaya and Mississippi Rivers rapidly forms the Louisiana Coastal Current, a highly stratified current that flows, on average, westward along the Louisiana coast and southward along the Texas coast. One-third of the flow of the Mississippi River enters the Gulf via the Atchafalaya River. Of the discharge from the Mississippi River delta, approximately 53% flows westward onto the Louisiana shelf (U. S. Army Corps of Engineers, 1974). Freshwater input is more obvious to the west of the Mississippi River delta than to the east in plots of surface salinity, Secchi disk depth and nutrient values (Rabalais et al., 1996) and river plume satellite images (Walker and Rouse, 1993).

Stratification---Water column stability throughout the year is clearly maintained by a strong haline stratification (Figures 1), although cooling of the surface waters in winter may tend to destabilize the water column. Maximum water column stability occurs during spring when run-off is high and during summer when wind mixing is weak and solar heating is strong (Rabalais et al., 1991). The surface salinity signal on the southeastern shelf tracks closely the flow of the Mississippi River (Geyer, 1950; Justic´ et al., 1993; Wiseman et al., 1997) as does the signal on the southwestern Louisiana shelf for the Atchafalaya (Pokryfki and Randall, 1987).

Measures of stratification (either surface-to-bottom differences in sigma t or Δ sigma t/depth) are correlated in time and space with the intensity of hypoxia (Rabalais et al., 1991). The relationships between surface salinity and sigma t gradients are strong ($r^2 = 0.69$ for 1985 shelfwide data in Rabalais et al., 1991). Often (e.g., 1995 data in Rabalais et al., 1991), periods when the surface-to-bottom oxygen differences are greater are those associated with widespread areas of hypoxic bottom waters. This relationship does not always hold, and the depth of the main pycnocline does not always track the depth of the oxycline. The height above the bottom of the 2 mg/l oxygen isopleth is closely correlated with the height above bottom where the sigma t gradient first achieves a value of 0.01 per meter or more (Wiseman et al., 1997). Thus, the existence of a strong near-surface pycnocline is a necessary condition for the occurrence of hypoxia, while the weaker, seasonal pycnocline guides the morphology of the hypoxic domain.

Winds sufficient to cause vertical mixing within the water column will break down the density stratification as well as mix aerated waters from the surface layer with those of the bottom (Rabalais et al., 1992; Wiseman et al., 1992). Intense wind mixing due to cold air outbreaks and frontal passages is active from as early as late September to as late as June. Local squalls and thunderstorms, as well as tropical storms and hurricanes, are important during the summer.

Nutrient Enriched Productivity and Carbon Flux---High biological productivity in the immediate (320 g $C/m^2/yr$) and extended plume (290 g $C/m^2/yr$) of the Mississippi River (Lohrenz et al., 1990; Sklar and Turner, 1981; respectively) is mediated by high nutrient inputs and regeneration, temperature and favorable light conditions. Small-scale and short-term variability in productivity are the consequence of various factors, such as nutrient concentrations, temperature and salinity (Lohrenz et al., 1990). Spatial variation in primary production within a given period is related to salinity and the associated environmental and biological gradients (Lohrenz et al., 1990, 1994). Maximum values of biomass (Turner and Rabalais, unpubl. data) and primary production (Lohrenz et al., 1990) are typically observed at intermediate salinities and coincide with non-conservative decreases in nutrients along the salinity gradient (i.e., biological uptake). Patterns of nutrient depletion provide evidence that riverine inputs of dissolved inorganic nitrogen and its pattern of regeneration ultimately limit the extent of river-enhanced areal productivity and biomass (Lohrenz et al., submitted). The availability of dissolved silicate and its ratio to total inorganic nitrogen are also important in controlling the extent of diatom production and the composition of the diatom community with implications to carbon flux and control of oxygen depletion (Dortch and Whitledge, 1992; Nelson and Dortch, 1996; Rabalais et al., 1996).

Particulate organic carbon flux to the lower water column is high in the extended plume over the inner shelf (approximately 500 to 600 mg $C/m^2/d$ in 15 m water depth; Qureshi 1995; see also Redalje et al., 1994). The fraction of production exported from the surface waters is highly variable, ranging from 10 to 200% of the integrated primary productivity, but averaging about half, with statistically higher percentages in spring. A large proportion of the particulate organic carbon flux reaches the bottom incorporated in zooplankton fecal pellets (55%; Qureshi, 1995), but also as individual cells or in cell aggregates. In a particle trap study at station C6B, the fluxes of fecal pellet carbon, organic carbon and nitrogen, and phytoplankton carbon varied similarly between seasons, with the highest sedimentation in spring and the lowest in summer (Qureshi, 1995). The fluxes of all components were greater in 1991 than in 1992. Seasonal variations in fecal pellet number and carbon fluxes were positively correlated with indicators of high surface water productivity in 1991, but not in 1992. A higher spring freshet of the Mississippi River in 1991 compared to 1992 corresponded to higher fluxes of total particulates, total carbon and fecal pellet carbon in 1991. The carbon fluxed via fecal pellets in spring 1991 was sufficient to deplete the bottom water oxygen reserve in spring, thus creating hypoxic conditions that then prevailed through the stratified summer period. Fecal pellet carbon flux into the bottom trap was low in spring of 1992, and the oxygen depletion rate for this flux was close to the calculated oxygen depletion rate.

Temporal Linkages with Mississippi River Discharge--Seasonal variations in net productivity in the northern Gulf of Mexico are coherent with the dynamics of freshwater discharge (Justic´ et al., 1993). The surface layer (0 to 0.5 m) shows an oxygen surplus relative to the saturation values during February-July; the maximum occurs during April and May and coincides with the maximum flow of the Mississippi River. The bottom layer (approximately 20 m), on the contrary, exhibits an oxygen deficit throughout the year, but reaches its highest value in July. The correlation between Mississippi River flow and surface oxygen surplus peaks at a time-lag of one month, and the highest correlation for bottom oxygen deficit is for the time-lag of two months (Justic´ et al., 1993). These findings suggest that the oxygen surplus in the surface layer following high flow depends on nutrients ultimately coming from the river but regenerated many times. This is an important finding, since a surplus of oxygen relative to the saturation value is a good indicator of net productivity in the surface waters. An oxygen surplus also means that there is an excess of organic matter derived from primary production which can be redistributed within the system; some of this will eventually reach the sediments (which follows Qureshi's (1995) results). Pokryfki and Randall (1987) found a similar two-month lag of bottom water hypoxia on the southwestern Louisiana shelf following peak Atchafalaya River discharge as did Justic´ et al. (1993) for the southeastern Louisiana shelf.

Historical Changes in Eutrophication and Oxygen Stress

Changes in Nutrient Loadings---Mississippi River nutrient concentrations and loadings to the adjacent continental shelf have changed dramatically this century, with an acceleration of these changes since the 1950s (Turner and Rabalais, 1991, 1994a,b; Rabalais et al., 1996). The concentrations of dissolved N and P doubled and Si decreased by 50%, the dissolved Si:N ratio dropped from 4:1 to 1:1, and seasonal trends have changed. The resulting nutrient composition in the receiving Gulf waters shifted towards stoichiometric nutrient ratios closer to the Redfield ratio and more balanced than previously (Justic´ et al., 1995 a,b). N and P are indicated to be now less limiting for phytoplankton growth, while some increase in Si limitation is probable (Justic´ et al., 1994). The effects of these changes on the continental shelf have not been fully explored but are under continuing investigation. An analysis of the diatom, foraminifera, and carbon accumulation sedimentary records supports the inference of increased eutrophication and hypoxia in the Mississippi River delta bight primarily because of changes in nitrogen loadings from agricultural sources (Turner and Rabalais, 1994a; Rabalais et al., 1996; Sen Gupta et al., 1996).

Biological Responses---In spite of a probable decrease in Si availability, the overall productivity of the ecosystem appears to have increased this century. This is evidenced by (1) equal or greater net silicate-based phytoplankton community uptake of silica in the mixing zone, compared to the 1950s (Turner and Rabalais, 1994b), and (2) greater accumulation rates of biogenic silica (BSi) (a surrogate for diatom production) in sediments beneath the plume, but not further away, and in agreement with results found in freshwater systems (Turner and Rabalais, 1994a). The increased % BSi in Mississippi River bight sediments that parallels increased N loading to the system is direct evidence for the effects of eutrophication on the shelf adjacent to the Mississippi River. Individual phytoplankton species composition shifts (heavily-silicified diatoms ---> lightly-silicified diatoms; diatom ---> non-diatom) would indicate some population-level responses to reduced Si supplies and/or changes in nutrient ratios (Rabalais et al. 1996). Finally, an analysis of benthic foraminiferans indicates an increase in oxygen deficiency stress this century, with a dramatic increase since the 1950s (Rabalais et al., 1996; Sen Gupta et al., 1996). Increased bottom-water hypoxia could result from increased organic loading to the seabed and/or shifts in material flux (quantity and quality) to the lower water column.

The importance of the water column physical structure to the development and persistence of hypoxia is clear, and the discharge of the Mississippi River (i.e., amount of flow) since the 1950s has been relatively constant aside from normal decadal scale variations in runoff. The allocation of flow between the Mississippi River proper and the Atchafalaya River has been maintained by the U.S. Army Corps of Engineers according to Congressional mandate. The 1990 to present average discharge rate (decadal time scale) for the lower Mississippi River is remarkably stable near 14,000 m^3/s, but it does show a decrease during the 1950s and 1960s (Bratkovich et al., 1994). The riverine flow delivered to the shelf waters adjacent to Atchafalaya Bay has slowly increased, and the combined flow delivered to the shelf region has also increased, more notably over the last two decades (Bratkovich et al., 1994); however, the results of these effects would be on the southwestern shelf and not the southeastern. Thus, the observed changes in biological responses in the Louisiana bight are probably not due to changes in amount or distribution of freshwater runoff and resultant stratification, but rather changes in water quality.

Changes in Freshwater Inflow---There is a direct connection between river nutrient loading and the hypoxic zones on the Louisiana shelf. River diversions aimed at wetland restoration might be considered a possible management tool to decrease nutrient loading to the offshore waters and thereby raise oxygen concentrations in offshore bottom waters. However, the amounts of river water to be diverted are so small relative to the size of the total discharge that river diversions will have an insignificant effect on the size, frequency and duration of oxygen depletion within bottom waters offshore. For example, river diversions that are currently operating, or being planned to bring large quantities of water from the Mississippi River into adjacent estuaries of Breton Sound, Lake Pontchartrain, and Barataria Bay, will divert less than 10% of the total discharge volume for only one or two months of the year. The reduction in suspended sediment flow due to human-made levees was calculated at 14% during flood years, but only 2.6% during a longer 34-yr period (Kesel, 1988). A 2.6% reduction in suspended sediment (and thus some similar proportion of nutrients) is an insignificant proportion of the total flow, which has also doubled in nitrate concentration. The ability of coastal wetlands to absorb nutrients is not equal among wetland types, and, in fact, most of Louisiana's coastal wetlands appear to export the dissolved nutrient forms that limit phytoplankton growth (Turner and Rabalais, in press). Also, the necessary acreage of suitable wetlands that optimize nutrient removal (i.e., forested freshwater wetlands) is not sufficient to remove even 10% of the historically low nutrient concentration (prior to 1950) through overland flow. Further, diversions of river waters to enclosed water bodies of lower nutrient concentrations, or to shelf areas east or west of the Mississippi River delta may aggravate conditions of eutrophication and/or hypoxia there.

Impacts on Living Resources

Several studies have documented the responses of benthic and demersal communities to varying levels of oxygen stress via benthic cores, remotely operated vehicle video taping and diver observations (Rabalais and Harper, 1991, 1992; Rabalais et al., 1993, 1995; Rabalais and Harper, in preparation). A fairly predictable pattern in responses of components of the community follows a decrease in oxygen concentrations from 2 mg/l to anoxia. Motile fish and crustaceans are generally absent from bottom habitats when the oxygen falls below 1.5-2 mg/l; less motile invertebrates die at oxygen below 1.5 mg/l; infaunal invertebrates display stress behavior below 1.0 mg/l; and a fairly linear decrease in benthic macroinfauna diversity and abundance occurs between 0.5 mg/l and anoxia. Monthly macroinfaunal samples from an area with persistent and severe hypoxia versus an area with intermittent and less severe hypoxia indicate a much reduced abundance, species richness and biomass under conditions of severe hypoxia/anoxia. The more stressed community is characterized by limited taxa (none with direct development, e.g., amphipods), characteristic resistant fauna (e.g., a few polychaetes and sipunculans), a reduced species richness, severely reduced abundance (but never azoic), low biomass, and limited recovery following abatement of oxygen stress. Oxygen stress overwhelms sedimentary characteristics in the structuring of benthic communities. Effects of hypoxia on fishery resources include direct mortality, altered migration, reduction in suitable habitat, increased susceptibility to predation (including by humans), changes in food resources, and susceptibility of early life stages. Fisheries yield is variably affected with a decline from an optimal point to reduced yields and no yields as oxygen depletion progresses from seasonal hypoxia to permanent bottom water anoxia (Caddy, 1993).

Oxygen-depleted bottom waters in the coastal ocean are found worldwide, and the incidence and extent of such areas in coastal waters is apparently increasing (Diaz and Rosenberg, 1995). The patterns of worsening water quality in coastal waters adjacent to the terminus of major rivers undergoing nutrient flux or water quality alterations are consistent with the conditions identified for the Mississippi River.

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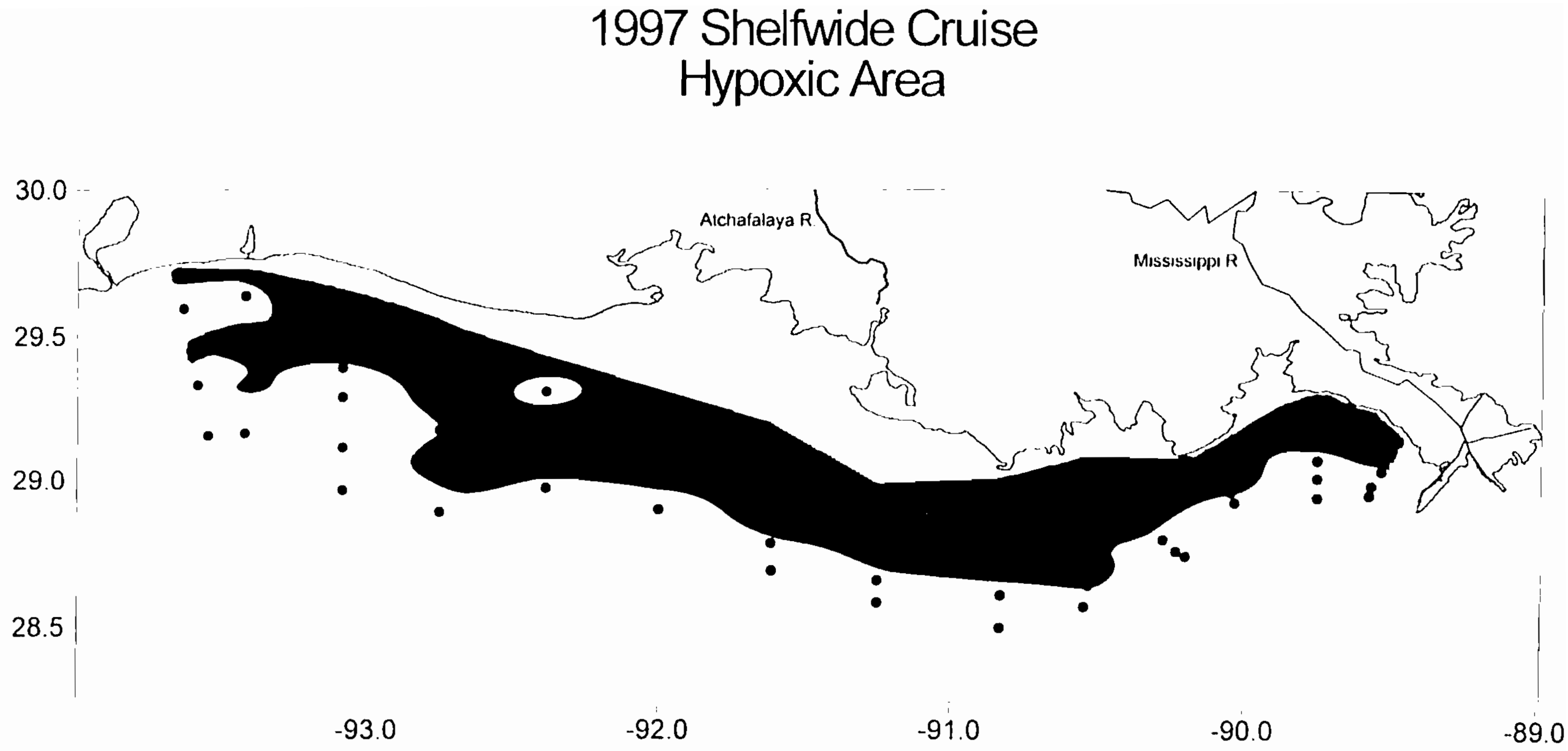

Figure 1. Distribution of near-bottom water hypoxia (dissolved oxygen less than 2 mg/1) in mid-summer for 1997. Data from hypoxia monitoring studies of N.N. Rabalais, R. E. Turner and W. J. Wiseman, Jr.

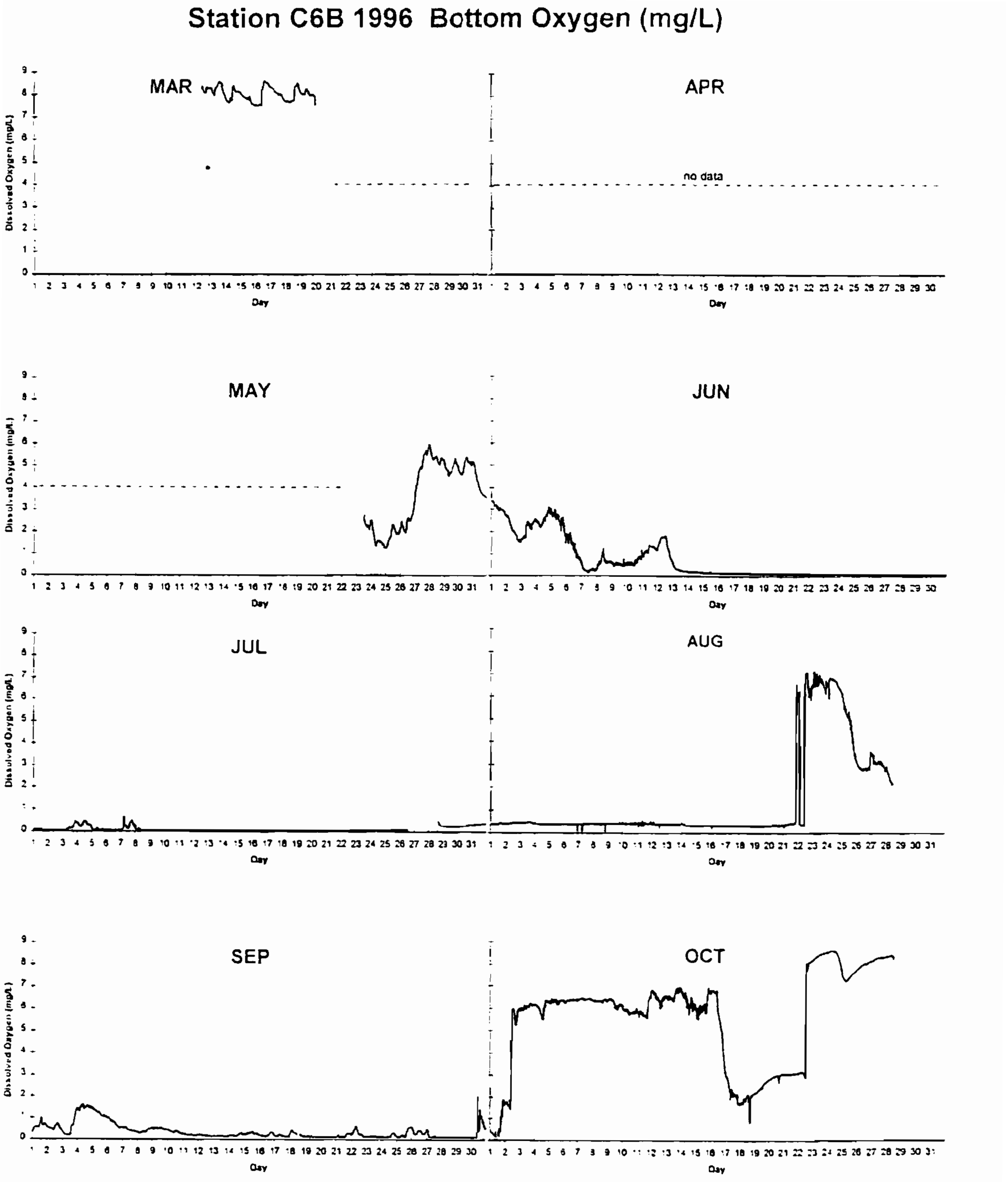

Figure 2. Continuous dissolved oxygen data (15-min intervals) from 19 m depth in a 20-m water column at station C6B on the southeastern Louisiana shelf for 1996. Data from hypoxia monitoring studies of N. N. Rabalais, R. E. Turner and W. J. Wiseman, Jr.

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