Reconstructing a 180 yr record of natural and anthropogenic induced low-oxygen conditions from Louisiana continental shelf sediments

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ABSTRACT

Hypoxia on the Louisiana continental shelf is tied to nutrient loading and freshwater stratification from the Mississippi River. Variations in the relative abundance of low-oxygen-tolerant benthic foraminifers in four sediment cores from the Louisiana shelf provide a proxy record of low-oxygen events. Core chronologies are obtained using ^{210}Pb dating techniques. The foraminiferal data are consistent with previous studies indicating that the intensity of hypoxic events (oxygen <2 mg/L) has increased over the past 50 yr owing to the higher nutrient loading associated with the use of commercial fertilizer, and also reveal several low-oxygen events between A.D. 1817 and 1910, prior to the widespread use of fertilizer. The pre-1910 low-oxygen events are associated with high Mississippi River discharge rates, indicating that these low-oxygen episodes are related to natural variations in river drainage that enhance transport of nutrients and freshwater to the continental shelf. Our data show that the low-oxygen events of the past few decades were more extreme than any that occurred in the previous ~180 yr, and support the interpretation that the increased use of fertilizer has amplified an otherwise naturally occurring process.

Keywords: hypoxia, Louisiana continental shelf, benthic foraminifers, PEB index, ^{210}Pb.

INTRODUCTION

During summer months a large area of water on the Louisiana continental shelf becomes depleted in oxygen concentration; <2 mg/L is defined as hypoxic (Rabalais et al., 1999; Rabalais and Turner, 2001; Committee on Environment and Natural Resources [CENR], 2000; Fig. 1). Oxygen concentrations decline when the uptake of oxygen by respiration exceeds its resupply. The occurrence of hypoxia is increased with nutrient loading or greater stratification (Van der Zwaan, 2000; Rabalais, 2002). Nutrients stimulate marine surface phytoplankton blooms, whose organic matter upon death may sink to the bottom and decay. Oxygen is consequently removed from the water column, and marine organisms become distressed, evacuate the area, or die (Diaz and Solow, 1999). The size of the hypoxic zone has increased in recent years, and in 1993 a historic Mississippi River flood event caused the hypoxic zone to double in size (Rabalais et al., 1999). The development of hypoxia has become an important economic and environmental issue to commercial and recreational fisheries in the Gulf of Mexico.

Systematic surveys of oxygen across the Louisiana continental shelf only began in 1985 (Rabalais et al., 1999; Fig. 1). However, proxy studies of biological, chemical, and mineral properties of shelf sediments can be used to reconstruct previous low-oxygen or hypoxic events. This paper discusses the use of low-oxygen-tolerant benthic foraminifers to reconstruct a 180 yr record of natural and anthropogenic induced low-oxygen events, including hypoxia on the Louisiana shelf.

HYPOXIA FAUNAL PROXY

Benthic foraminifers are proxies of bottom-water hypoxia (Van der Zwaan and Jorissen, 1991; Bernhard et al., 1997; Bernhard and Sen Gupta, 1999; Duijnstee et al., 2004). Blackwelder et al. (1996) reported evidence in the Louisiana hypoxia zone for an increased hypoxia caused by increased fertilizer use (Nelson et al., 1994); Sen Gupta et al. (1996) and Platon and Sen Gupta (2001) recorded increasing hypoxia during the past 40 yr in 8 cores with 2 additional cores containing records greater than 50 yr, but used a method that is most effective in water depths shallower than 30 m.

Analyses of continental shelf core-top samples from Texas and Louisiana indicate that the cumulative percentage of three foraminifers, named the PEB index (*Pseudononion atlanticum*, *Epistominella vitrea*, and *Buliminella morgani*), was highest in the surface sediment samples collected in the Louisiana hypoxia zone (Osterman, 2003). The PEB species are opportunists that prefer nutrient-rich environments, are tolerant of low oxygen and high sedimentation rates, and are believed to be epifaunal in these environments (Jorissen et al., 1992; Blackwelder et al., 1996; Gooday and Hughes, 2002; Ernst and Van der Zwaan, 2004).

The total loss of oxygen (anoxia) will result in death for many species, but a few opportunistic, hypoxia-tolerant foraminiferal species have adapted to withstand short intervals (days to weeks) of anoxia (Moodley et al., 1998; Duijnstee et al., 2004). Because only gametes are capable of recolonization, it is clear that any benthic foraminifers (>125 μm) living in hypoxic-area sediments must have survived the previous hypoxic episode while the other species, and gametes, less tolerant to low-oxygen conditions did not survive. Given the highly variable temporal and spatial distribution of seasonal hypoxia on the open Louisiana shelf (Rabalais et al., 1999), we infer that hypoxia-tolerant PEB species continue to live through hypoxic episodes, whereas other species and gametes die, resulting in a relative increase of the PEB species during recurrent episodes of hypoxia. Our interpretation is that an increased relative abundance of PEB species in sediment cores reliably records the development of seasonal low-oxygen and

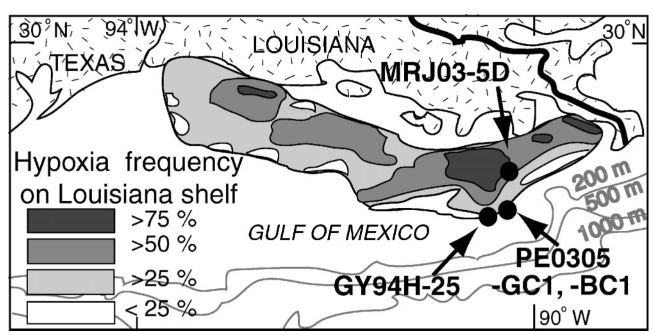

Figure 1. Locations of four cores discussed herein. Locations of hypoxia zone frequency taken from Committee on Environment and Natural Resources (2000), based on measurements done by N. Rabalais since 1985.

TABLE 1. CORE LOCATIONS

Core	Core Type	Lat (°N)	Long (°W)	Length (cm)	mwd	^{210}Pb rate (cm/yr)
GY94H-25	Box	28 21.352	90 30.457	25	48	–
PE0305-GC1	Gravity	28 23.796	90 27.701	144	47	0.33
PE0305-BC1	Box	28 24.108	90 26.484	31	47	0.34
MRJ03-5D	Box	28 55.508	90 22.538	40	24	0.3

Note: mwd—m water depth.

even hypoxia events on the Louisiana continental shelf. However, the PEB index cannot be used to determine the precise value of oxygen concentration (above or below 2 mg/L). Thus we discuss the PEB values in terms of ''low-oxygen events,'' rather than as a strict definition of ''hypoxic events.''

MATERIALS AND METHODS

The current study is based on the PEB index in four cores collected within and adjacent to the area of recurrent hypoxia on the Louisiana continental shelf (Table 1; Fig. 1) (CENR, 2000). Information about core collection, sample processing, benthic foraminifer counts, taxonomic notes, figure references, and the PEB hypoxia index were reported in Osterman (2003) and Osterman et al. (2004).

Lead isotope sediment geochronologies were derived by modeling excess ^{210}Pb activities, using two techniques. Core PE0305-BC1 sediments were analyzed, using an integrated gamma-spectroscopy system (Nittrouer et al., 1979). In cores PE0305-GC1 and MRJ03-5D the ^{210}Pb ($t_{½}$ = 22.3 yr) activities were determined by alpha counting of polonium (Brenner et al., 1993; Appleby, 2001).

The precise definition of a flood event for the Mississippi River is highly subjective. For example, historic flood events can be isolated to specific tributary basins (i.e., Ohio vs. Missouri River), and the socioeconomic impact can be affected by factors such as population, levee breakage, timing, and duration. In this study, flood events are determined by using the measurement of water discharge from the U.S. Geological Survey stream gage at Vicksburg, Mississippi. Poore et al. (2001) showed that the Vicksburg average annual discharge record provided a 181 yr composite record for the entire Mississippi River drainage from 1817 through 1998. During this recorded interval, the mean annual discharge was 16,908 m^3 s^{-1}. We identified 26 high-flow (flood) years that exceeded the mean annual discharge for the recorded historic record by one (+1 SD) or two (+2 SD) standard deviations (Table 2). Table 2 also identifies multiyear high-flow events. The past 53 yr of the record contain one-half (13) of the highest discharge events, 4 multiyear high-flow events, and 2 +2 SD flow events (1993 and 1950). The earlier 128 yr of the record contain 13 high-discharge events, 1 multiyear event, and 3 +2 SD flow events (1927, 1844, and 1823).

RESULTS: ^{210}Pb AND PEB ANALYSES

The sediment cores examined for this study were collected at two water depths within and adjacent to the area of most severe hypoxia (Rabalais et al., 1999; Fig. 1). One of us (Osterman, 2003) indicated that although the PEB species occur within the hypoxia zone, they prefer the mid-shelf (30–70 m water depth, mwd). Because the complete removal of oxygen (anoxia) will result in the absence of all foraminifers, sampling locations on the fringe of the maximum hypoxia zone provide the most continuous record of hypoxia-sensitive foraminifers and were selected for this study (Fig. 1; Table 1).

The stratigraphic distributions of PEB values from the four cores show similar patterns (Fig. 2). The striking similarity in PEB values in the upper 31 cm of PE0305-GC1 and PE0305-BC1 indicates that bioturbation is not a significant problem. PEB values in the three dated cores show a series of fluctuations superimposed on a trend of decreasing values from the surface down to the ~1960 horizon. In the shallow

TABLE 2. YEARS WITH +1 SD ANNUAL FLOW AT VICKSBURG, MISSISSIPPI (1817–1998)

Calendar year	Average flow (m^{3}s^{-1})
1998	22677.35
1994	**20533.32**
1993	**26571.48**
1991	20805.55
1985	**20616.17**
1984	**21574.69**
1983	**22148.01**
1979	23607.64
1975	**21981.36**
1974	**23074.86**
1951	**22780.91**
1950	**24702.35**
1945	23100.33
1929	22002.31
1927	25626.89
1907	20954.58
1903	20756.36
1890	21690.82
1882	20671.41
1858	23559.74
1850	**20586.46**
1849	**23871.23**
1848	**21011.21**
1844	26816.20
1828	23984.50
1823	24465.89

Note: Shading denotes years of >+2 SD (standard deviation) annual flow, bold indicates consecutive years of +1 SD flow.

core (MRJ03-5D), the PEB values trend from 27% to 3%. In deeper water cores GC1 and BC1, the PEB values trend from ≥27% to ~9%–15%. Between the ~1960 and ~1910 horizons, PEB values vary in a narrow range (0%–5% in MRJ03-5D and 10%–15% in GC1 and BC1) and do not show a clear trend. PEB values in levels older than ca. 1910 show more variability with several significant excursions to +1 SD values (≥7.9% in MRJ03-5D; ≥16.7% in GC1). The pattern of PEB values with depth in core GY94H-25 is similar to the pattern in the other three cores, and we have used correlations with the PEB pattern to tentatively extend the ~1960, ~1910, and ~1880 horizons to core GY94H-25 (Fig. 2).

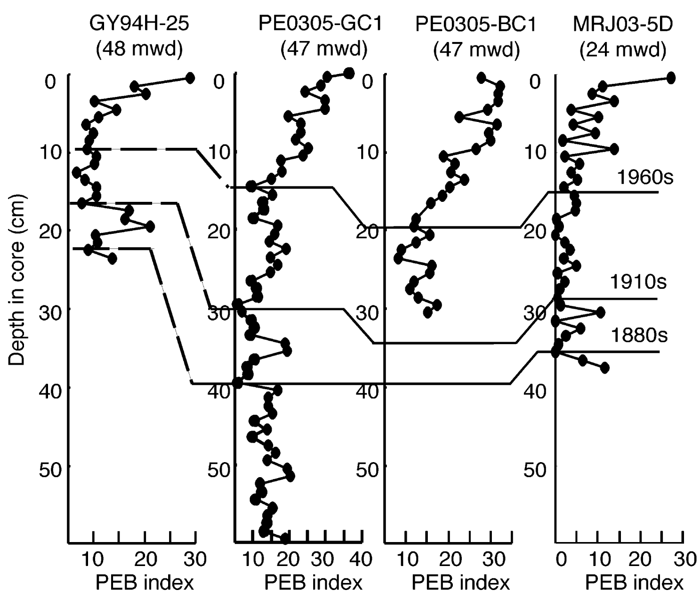

Figure 2. PEB (see text) index values for four Louisiana shelf cores. Possible age correlations (ca. 1960, ca. 1910, and ca. 1880), based on ^{210}Pb derived geochronologies, are shown by solid lines between three cores on right. Extrapolated chronologies to GY94H-25 core are shown with dashed lines. Error bars on PEB ratio average 3.5%; mwd—meters water depth.

DISCUSSION

Although there are a number of possible sources of nitrogen to the Mississippi River, at present the largest sources are estimated to be from fertilizer use and soil mineralization. The only primary source that has changed recently is the contribution from fertilizer use, which has increased more than sixfold since 1950 (Goolsby et al., 2001). The resulting increased flux of nitrogen through river outflow results in higher nutrient concentrations in surface waters (e.g., Rabalais and Turner, 2001). Thus, the recent increase in hypoxic conditions on the Louisiana shelf has been attributed primarily to anthropogenic activities (Rabalais et al., 1994, 1996; Nelson et al., 1994). The increasing trend in the PEB index from the ~1960 horizon to the surface in our cores is most likely related to increased use of nitrogen-rich fertilizer.

The most interesting result of this research is the relatively high PEB excursions in three cores prior to ca. 1910. The values of the pre-1910 PEB excursions are comparable to PEB values in each core during the 1970s, when the recent expansion of the Louisiana hypoxia zone began to occur (Justić et al., 2003; Turner et al., 2005). This result implies that low oxygen was occasionally present in the bottom water of the Louisiana shelf prior to the extensive use of fertilizer in the Mississippi River Basin, and that the concentration of oxygen in the water may have dipped low enough to be defined as hypoxic. Turner and Rabalais (2003) suggested that increased nutrient loading on the Louisiana shelf in the late 1800s was associated with increased soil mineralization from deforestation and land clearing. The occurrence of increased nutrient loading prior to 1910 is consistent with our observations of increases in the PEB low-oxygen indicator. However, while anthropogenic activities such as land clearing may explain the source of nutrients, they do not necessarily explain the variability of the low-oxygen indicators shown by our data (Fig. 2). It is possible that both natural processes and anthropogenic activities were involved in the development of widespread algal blooms and resulting low-oxygen bottom water on the Louisiana continental shelf prior to 1910. It is also important to note that the data indicate that the pre-1910 elevated PEB values did not reach the very high PEB values found since 1960, and therefore are consistent with the interpretation that significant nutrient enhancement related to increased use of fertilizer has caused the recent intensification of hypoxia.

Historic measurements show that the flux of nitrate from the Mississippi River to the Gulf of Mexico is related to mean annual discharge of the river (Goolsby et al., 2001). We infer from recent observations that excursions to relatively high values in the PEB index prior to 1910 reflect hydrologic extremes (i.e., extended wet intervals and major floods) that enhanced transport of nutrients through the river basin. To test the hypothesis that pre-1910 elevated PEB values represent times of increased river flow, we assigned ages, based on constant sedimentation rates, to individual samples in the two cores with pre-1910 ^{210}Pb chronologies and compared the occurrences of pre-1910 high PEB samples with the tabulation of above-average flow values from the Vicksburg discharge record (Fig. 3). The highest pre-1910 Vicksburg discharge events occurred in 1823 and 1844, closely followed by the multiyear 1848–1850 events. These high-discharge years in the Vicksburg record correspond with +1 SD PEB values in core PE0305-GC1, with age estimates of 1819 (59.5 cm) and 1844–1847 (50.5–51.5 cm) (Fig. 3). The other pre-1910 +1 SD PEB value in core PE0305-GC1 has an estimated age of 1893–1896, close to the high-discharge event of 1890 in the Vicksburg annual flow record (Fig. 3). In the lower part of core MRJ03-5D, estimated dates for the hypoxic events are 1901 and 1881. These intervals coincide with high-flow intervals in the Vicksburg annual flow record in 1903 and 1882 (Fig. 3). The slight offset between the years of elevated discharge and estimated ages of the high PEB values is considered well within the likely errors in the chronology, owing to possible accumulation rate changes in the cores.

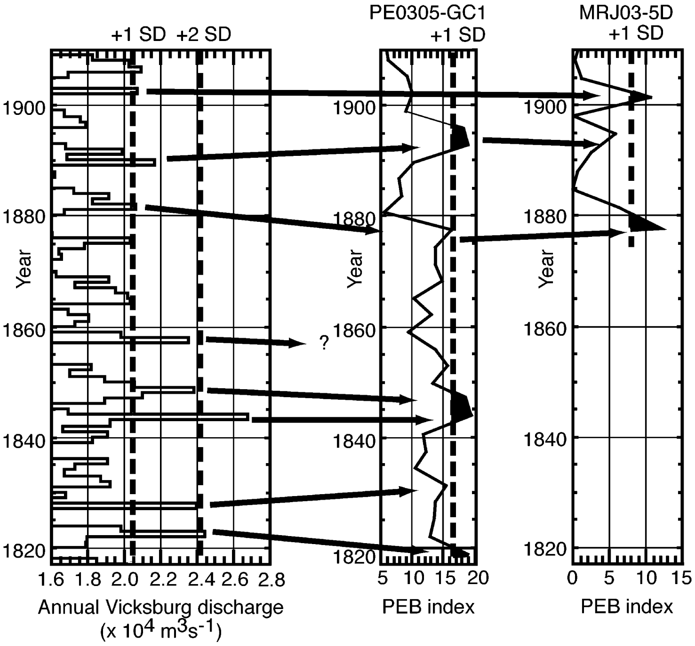

Figure 3. Left: Average annual Mississippi River flow measured at Vicksburg, Mississippi, greater than mean for years 1910–1817. Dashed vertical lines are +1 and +2 SD (standard deviation) over mean. Years of significantly high annual flow rates are given in Table 2. PEB (see text) values for cores PE0305-GC1 (middle) and MRJ03-5D (right) with +1 SD PEB peaks are indicated by shaded area to right of dashed +1 SD line. There are three significant +1 SD peaks (>16.7%) in pre-1900 PEB values of core PE0305-GC1 (34.5–35.5 cm, 50.5–51.5 cm, and 59.5 cm) and a value of 16.3% (nearly +1 SD) at 40.5 cm. In lower part of core MRJ03-5D there are two intervals with +1 SD (>7.9%) PEB values at 30.5 cm and 37.5 cm.

Therefore, we find that samples with significant +1 SD PEB values in the sediment cores match closely with measured high-discharge rates from the Mississippi River, with two exceptions. In one case, river discharge was very high in 1858, but the PEB values from core PE0305-GC1, estimated to be from ca. 1858, are near the mean values for the lower interval of the core. In another case, the high discharge of 1903 corresponds with high PEB values in core MRJ03-5D, whereas the PEB values in core PE0305-GC1 are not elevated. The development of hypoxia depends on a variety of factors (flood origin, timing, duration, and onset of stratification or storm-induced physical mixing of surface waters) that could influence the geographic extent, duration, and intensity of hypoxic events such as in 1858. In the second case, 1903, it is possible that hypoxia may have developed only in shallow waters, as indicated by core MRJ03-5D, and not in deeper waters, as indicated by core PE0305-GC1.

SUMMARY AND CONCLUSIONS

Hypoxia is ultimately caused by an increased delivery of fluvial nutrients (either natural or anthropogenic) to stratified continental shelf waters. These fresh nutrients stimulate surface phytoplankton blooms that eventually sink to the bottom and decay, removing oxygen from the water column. The increased occurrence and intensity of hypoxic events on the Louisiana shelf over the past few decades is related in part to increased use of nitrogen-rich fertilizer (Goolsby et al., 2001; Rabalais and Turner, 2001). Our proxy record contains evidence for low-oxygen events on the Louisiana shelf prior to the use of commercial fertilizer (ca. 1910) in the Mississippi River Basin. A comparison of the estimated dates of pre-1910 low-oxygen events in our cores with the discharge record from Vicksburg indicates that low-oxygen events are associated with above-normal discharge from the Mississippi River. The flood events enhanced the transportation of nutrients to the shelf and increased stratification, which resulted in the development of hypoxic conditions. Our proxy data from the Louisiana continental shelf support the conclusion that the intensity or duration of hypoxia has increased over the past 50 yr and indicates that hypoxic events of the past few decades were more extreme than any that occurred in the past ~180 yr. The increased use of commercial fertilizer has amplified an otherwise naturally occurring process. Any future climate change that intensifies the hydrologic cycle in the Mississippi River Basin also will likely increase the occurrence and geographic extent of hypoxia on the Louisiana continental shelf.

ACKNOWLEDGMENTS

We thank N. Slowey and D. Bean (Texas A&M University) for providing access to the GY94H–25 core. M. Kulp, K. Clayton, J. Motti, and T. Williams (University of New Orleans), M. Lobegeiger and S. Del la Rue (Louisiana State University), and B. Boisvert (U.S. Geological Survey) assisted in the collection of cores PE0305-GC1 and PE0305-BC1. Suggestions made by P. Blackwelder, C. Brunner, S. Culver, D. Hollander, C. Larsen, M. Podwysocki, and B. Sen Gupta improved the manuscript.

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Manuscript received 12 November 2004
Revised manuscript received 21 December 2004
Manuscript accepted 22 December 2004

Printed in USA