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The last 1000 years of natural and anthropogenic low-oxygen bottom-water on the Louisiana shelf, Gulf of Mexico

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Abstract

The relative abundance of three species of low-oxygen tolerant benthic foraminifers, the PEB index, in foraminiferal assemblages from sediment cores is used to trace the history of low-oxygen bottom-water conditions on the Louisiana shelf. Analyses of a network of box cores indicate that the modern zone of chronic seasonal hypoxia off the Mississippi Delta began to develop around 1920 and was well established by 1960. The pattern of development over the last century is consistent with the interpretation that the formation of modern chronic hypoxia is related to anthropogenic activities resulting in increased transport of nutrients to the Louisiana shelf.

The PEB index in two gravity- and box core pairs (MRD05-4 and 05-6) indicates that low-oxygen bottom-water events have occurred periodically on the Louisiana Shelf for at least the last 1000 ^{14}C years. The pre-1900 low-oxygen bottom-water events are likely caused by intervals of increased Mississippi River discharge and widespread wetland export. The PEB record in gravity cores indicates that the pre-1900 low-oxygen bottom-water events were not as well developed or as geographically extensive as the modern hypoxia zone. We conclude that the development of low-oxygen bottom-water on the Louisiana shelf is a natural process that has been negatively modified by human activities in the last 100 years.
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1. Introduction

Occurrences of oxygen-depleted subsurface-water are well documented in many modern and historic marine systems worldwide (Emerson and Huested, 1991; Wilson and Norris, 2001; Duijnstee et al., 2004; Turner et al., 2005). Hypoxia (dissolved oxygen < 2 mg L-1) develops when the rate of oxygen utilization exceeds the rate of biological production or replenishment by physical processes. The development of low-oxygen conditions in coastal waters is dependent upon a source of bio-available nutrients coupled with a thermally-or density-caused stratified water column. Seasonal or permanent hypoxic conditions have been documented off the mouth of numerous rivers where nutrients and stratification are supplied by river outflow (van der Zwaan, 2000; Daoji et al., 2002; Frascari et al., 2006). Even intermittent seasonal hypoxia can cause marine habitat degradation (Eby et al., 2005).

Several studies have concluded that the development of seasonal hypoxia on the Louisiana shelf is related to increased transport of nutrients (primarily nitrogen, but

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possibly also phosphorous) by the Mississippi River (Rabalais et al., 1994, 1996, 1999; Rabalais and Turner, 2001; Goolsby et al., 2001). The size and area of the hypoxic area, commonly known as the "dead zone," is variable from year to year in terms of duration and extent (over seasons and years). However, since systematic measurement of the extent of the hypoxia zone was begun in 1985, the overall pattern indicates that the dead zone area is increasing in size (Rabalais et al., 1994, 1996, 1999; Turner et al., 2005). The goal of this research is to augment information on the recent expansion of Louisiana shelf hypoxia and to investigate the temporal and geographic extent of the low-oxygen bottom-water conditions prior to 1985.

2. Previous work

Much of the previous research on the record of low-oxygen bottom-water conditions on the Louisiana shelf uses benthic foraminifers. Benthic foraminifers have been shown to be a proxy for bottom-water oxygen content in numerous studies (Sen Gupta et al., 1996; Bernhard et al., 1997; Bernhard and Sen Gupta, 1999; Karlsen et al., 2000; Platon and Sen Gupta, 2001; Duijnstee et al., 2004; Platon et al., 2005; Tsujimoto et al., 2006). Blackwelder et al. (1996) interpreted benthic foraminiferal faunal changes in a sediment core (BL-10) as an indication of increasing hypoxia during the last 90 years caused by increased fertilizer use and transport to the Gulf of Mexico via Mississippi River outflow (Nelson et al., 1994). Sen Gupta et al. (1996) and Platon and Sen Gupta (2001) used abundance of the benthic foraminifers *Ammonia* and *Elphidium* spp. as an index of the increasing occurrence of hypoxia over the last 40 years in 10 Louisiana shelf box cores.

More recently, Osterman (2003) showed that the cumulative percentage of three foraminifers, termed the PEB index (= % *Protononion atlanticum*, + % *Epistominella vitrea*, + % *Buliminella morgani*), in the benthic foraminiferal assemblage was statistically representative of the modern seasonal Louisiana hypoxia zone and could be used as a low-oxygen proxy in retrospective studies. The PEB species are epifaunal opportunists that prefer nutrient-rich environments, and are tolerant of low-oxygen conditions (Blackwelder et al., 1996; Austin and Evans, 2000; Gooday and Hughes, 2002; Jorissen et al., 1992; Ernst and van der Zwaan, 2004). The precise mechanisms used by the PEB species to survive seasonal low-oxygen conditions still remain unknown. However, we infer that these low-oxygen-tolerant species are adapted to live through hypoxic episodes and reproduce or recolonize, whereas other less-tolerant species do not. This adaptation results in a relative increase of the PEB species during recurrent seasonal low-oxygen episodes. Our hypothesis is that in sediment cores, the increased relative abundance of PEB species reflects the past development of seasonal low-oxygen bottom-water events on the Louisiana continental shelf.

Osterman (2003) showed that within the area of the Texas–Louisiana continental shelf subject to the development of hypoxia the PEB species are most abundant (average = 20%) in a restricted depth range, 13- to 70-m water depth (mwd). In other areas of the Louisiana–Texas shelf (< 100mwd), and outside of the hypoxia zone, other coastal and shelf species, *Ammonia parkensoniana*, *Bigenerina irregularis* and *Hanzawai concentrica*, are more common and the PEB species are less common (avg. = 4–5%)(Culver and Buzas, 1981; Osterman, 2003).

Previously, we established variations in the PEB index in four dated box cores and one gravity core from the eastern portion of the modern dead zone (Fig. 1; Table 1; BL-10, MRJ03-2BC, MRJ03-5BC, PE0305-1BC, and PE0305-1GC) (Osterman et al., 2005; Osterman et al., in press). Results from the four box cores identified a trend of increasing PEB over the last 50 years. The trend is consistent with published records of box cores that link the increasing development of hypoxia on the Louisiana shelf since 1985 with increased use of commercial fertilizer in the Mississippi Basin (Blackwelder et al., 1996; Sen Gupta et al., 1996; Platon and Sen Gupta, 2001; Platon et al., 2005). A longer record developed from gravity core PE0305-1GC revealed a number of excursions to high PEB values that occurred prior to 1900. We correlated periodic PEB increases in PE0305-1GC (from 0 to 60 cm) to a 180-year record of Mississippi River discharge from the Vicksburg gaging station (Osterman et al., 2005). In the historical record, we found a close correlation between years of above average Mississippi River flow and higher values of PEB. We concluded that times of increased Mississippi River flow could provide the necessary stratification and nutrients to cause the establishment of seasonal low-oxygen conditions on the Louisiana shelf and thus inferred that stratigraphically older PEB events in core PE0305-1GC were related to older Mississippi River discharge events. However, it is also possible that a combination of natural processes including discharge, coastal wetland erosion and export, as well as anthropogenic activities associated with land clearing, were involved in the development of low-oxygen bottom-water on the Louisiana shelf prior to 1900 (Turner and Rabalais, 2003; Varekamp, 2006).

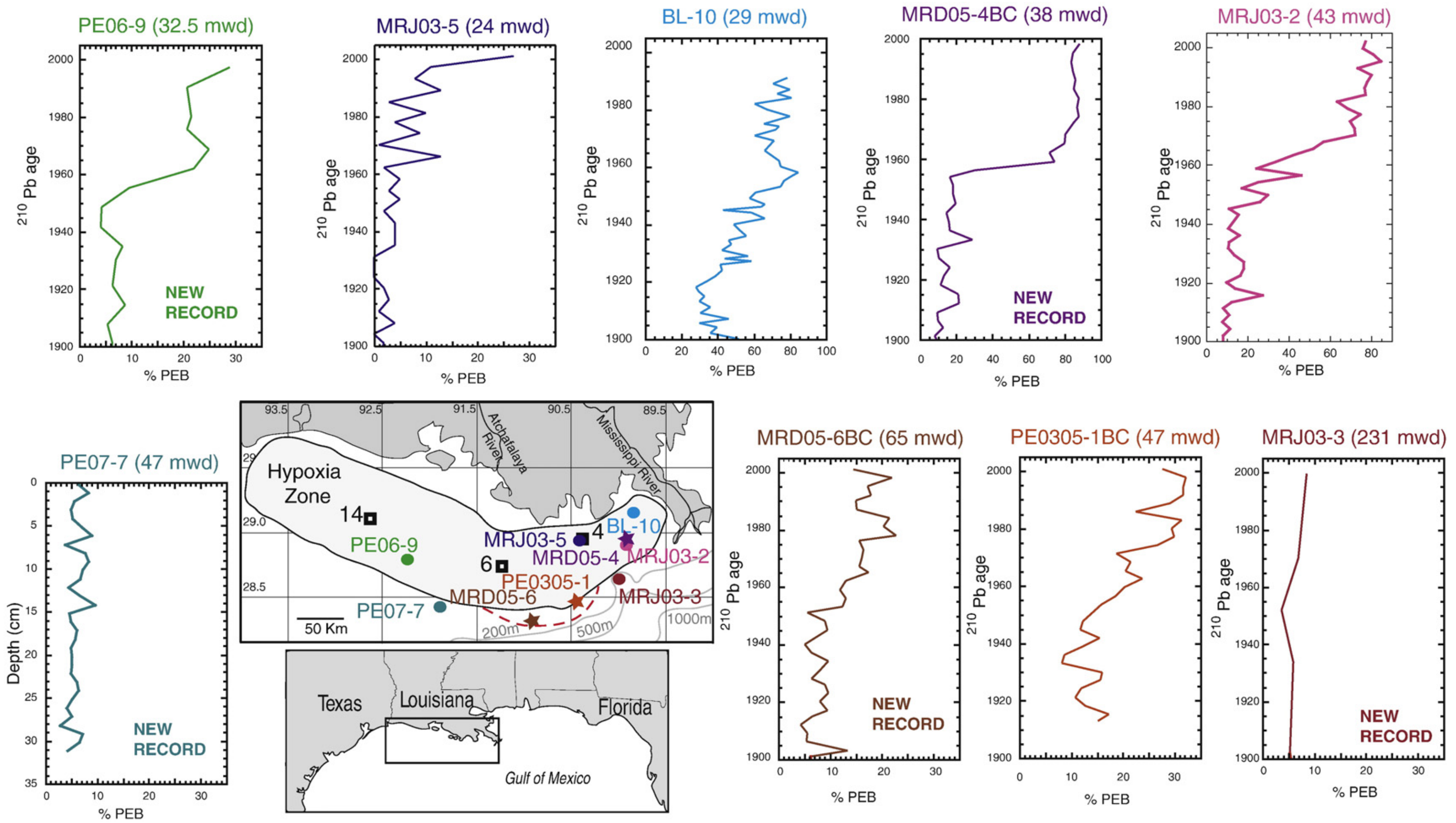

Fig. 1. PEB values (% low-oxygen-tolerant benthic foraminifers) from nine box cores collected from the Louisiana shelf, including four previously published records and five new records. Inset map shows the location (circles) of the box cores shown in relation to the chronically hypoxic zone as reported by Rabalais et al. (1999) and based on measurements since 1985. Box cores are plotted by age (derived from ^{210}Pb chronology) to 1900, except for PE07-7, which is plotted by depth. Also shown are the locations of the three box- and gravity core pairs (stars) (sites MRD05-4, PE0305-1, and MRD05-6), which form the core transect (see Figs. 2 and 3). All box cores, except for PE07-7 (non-hypoxia shelf) and MRJ03-3 (non-hypoxia deeper water), show an increase in the low-oxygen species beginning before 1950. The box cores record environmental changes prior to the instrument record (Turner et al., 2005). Based on the historical record from MRD05-6BC, we propose that the hypoxia zone extends beyond the area measured by Rabalais (dashed line). Core PE07-7BC (47 mwd) records only low numbers of PEB and delimits the extent of hypoxia zone along the southern shelf. Core MRJ03-3BC (226 mwd; sampled at 10 cm intervals) records low numbers of PEB and indicates that only small numbers of PEB species are transported into deeper-water depths. Also shown are the location of three stained surface samples (black boxes) (Table 2).

Table 1

Core name and type	Latitude (decimal)	Longitude (decimal)	Water depth (m)	Core length (cm)/ number of samples	Reference
BL-10 BC	29.1000	89.7250	29.0	51.0	Blackwelder et al., 1996; Osterman et al., in press
MRD05-4GC	28.9317	89.8988	38.5	239.0	this paper
MRD05-4BC	28.9319	89.8961	38.0	41.0	this paper
MRD05-6GC	28.2799	90.9112	65.0	153.0	this paper
MRD05-6BC	28.2791	90.9095	65.0	42.0	this paper
MRJ03-2BC	28.8903	89.8930	43.0	52.0	Osterman et al., in press
MRJ03-3BC	28.6258	90.0009	231.0	58.0	this paper
MRJ03-5BC	28.9251	90.3756	24.0	40.0	Osterman et al., 2005, in press
PE0305-1GC	28.3966	90.4617	47.0	164.0	(0–60 cm only) Osterman et al., 2005, in press
PE0305-1BC	28.3996	90.4528	47.0	31.0	Osterman et al., 2005
PE06-9BC	28.7750	92.3833	32.5	18.0	this paper
PE07-7BC	29.4953	91.9972	47.0	31.5	this paper

BC=box core, GC=gravity core

In this paper, we present the PEB values from an additional five Louisiana shelf box cores that extend our PEB coverage onto previously unsampled shelf regions (Table 1; Fig. 1). These new records corroborate previous results documenting increasing hypoxia over the last 60 years and expand the geographic coverage to the west. We also extend our previous research back in time by reporting on pre-1900 benthic foraminiferal assemblages in two new Louisiana shelf gravity cores (MRD05-4GC and -6GC)(Fig. 1; Table 1). We present a transect of three gravity cores from within the hypoxia zone near the Mississippi Delta to slightly outside of the chronically hypoxic area. Our results document the impact of anthropogenic forcing on the temporal/spatial extent and development of modern hypoxia, and establish the occurrence of pre-anthropogenic low-oxygen conditions on the Louisiana shelf.

3. Materials and methods

Box and gravity cores were collected on the inner Louisiana shelf during four cruises aboard the *R/V Pelican* since 2002 (Fig. 1; Table 1). Sediments from gravity- and box core subcore plastic core liners were extruded and sampled at 1-cm intervals onboard ship. To avoid loss of foraminifers due to post-collection dissolution, samples were processed as soon as possible, but no later than 6 months after collection. Grain-size analyses were determined using a Coulter LS 200 particle-size analyzer. Additional information about core collection, sample processing, total benthic foraminiferal counts, taxonomic notes, and foraminiferal figure references are reported elsewhere (Osterman et al., 2004, 2006, 2007).

The samples were not dried prior to the wet-sieving process. Each 1-cm sediment sample for faunal analyses was soaked in a 5% Calgon solution, slowly agitated for 1–2 h to aid disaggregation, then washed over a stainless steel 63 m sieve. The >63 m fraction was oven dried at 50 °C, then dry sieved at 125 m. Processed samples contained few to abundant benthic foraminifera (1.02 to 729 foraminifers/g). When required, a representative subsample of approximately 300 specimens was obtained for faunal analysis using a microsplitter.

Initial work (Osterman, 2003; Osterman et al., 2005) determined the value of the PEB index to characterize the Louisiana hypoxic zone and recognized large downcore PEB excursion linked to Mississippi river drainage. In the initial gravity core study of PE0305-1GC (Osterman et al., in press), the complete foraminiferal assemblage (>125 m) was separated, identified and counted on standard 60 square slides (Osterman et al., 2005, 2006). However, as the focus of the research switched away from total faunal assemblage identification, in MRD05-6GC and -4GC only the cumulative percentage of three species (% *P. atlanticum*+% *E. vitrea*+% *B. morgani*=PEB index of hypoxia) was used to reconstruct the past record of low-oxygen bottom-water events (Osterman et al., 2007).

In the latter two cores, the >125 m faunal split was spread across a 45 square hole-punched tray. Individual foraminifers were identified and counted as one of four categories (*P. atlanticum*, *E. vitrea*, *B. morgani*, and others) so the relative percentage of the three PEB species in the total assemblage could be tabulated. After identification and counting, each specimen was dropped though a hole in the punched tray onto a stationary 60-square micropaleontological slide placed in a cardboard cutout. With this method, primary results are obtained quickly and total species assemblage identification and counting could be done at a later date, if determined to be necessary. All faunal slides will be curated at the Natural History Museum, Smithsonian Institution at the conclusion of the study.

Because the formation of hypoxia on the Louisiana shelf is highly variable from year to year, the dead zone is divided into smaller areas based on the percentage (>75% etc) of time that hypoxia has been observed during systematic measurements at a grid of monitoring sites since 1985 (Rabalais and Turner, 2001). During each of our box core subcore collections, additional surface sediments were collected, then fixed and stained with Rose Bengal in ethyl alcohol. Examination of the stained surface samples is just beginning but we have preliminary results from three samples that are from three different subareas of the dead zone (Table 2; Fig. 1). In all three samples the number of stained (living or recently dead at the time of collection) is less than half of the total assemblage. However, stained (living) individuals of the PEB species are present in each of the samples. Additionally, in each case the percentage of stained and total (stained+unstained) PEB species is related to the relative frequency of hypoxia at the site. For example, the highest PEB values (stained or total) are found in the sample with the highest (>75%) frequency of hypoxia and the lowest PEB values (stained or total) are found at the site with the lowest (<25%) frequency of hypoxia.

As promising as these initial results appear, we are reluctant to use PEB values as an index of severity of hypoxia at this time. The heterogeneous nature of the Louisiana shelf hydrology and sedimentation complicates the annual picture of hypoxia, which is recorded as frequency of occurrence not severity (Rabalais and Turner, 2001; Turner et al., 2005). Currently, we chose to view increasing PEB as recording increased duration or frequency of low-oxygen conditions, either seasonally or annually, similar to the manner hypoxic conditions are represented by Rabalais and Turner (2001).

3.1. Age models

Sediment geochronologies, in terms of both mass accumulation ($g\ cm^{Š2}\ y^{Š1}$) and sedimentation rates ($cm\ y^{Š1}$), were derived from the box cores using multiple radioactive tracers, including excess ^{210}Pb ($t^{1/2}=22.3$ yr) and ^{137}Cs ($t^{1/2}=30.1$ yr) (Swarzenski et al., 2006; 2007). The MRD05-4 box core record yielded a sedimentation rate of 0.31 $cm\ y^{Š1}$ (mass accumulation rate = 0.18 $g\ cm^{Š2}\ y^{Š1}$), indicating that the last 100 years are represented by approximately the upper 31 cm. The MRD05-6 box core yielded a sedimentation rate of 0.36 $cm\ y^{Š1}$ (mass accumulation rate = 0.21 $g\ cm^{Š2}\ y^{Š1}$), indicating that the last 100 years are represented by approximately the upper 35 cm.

Correlations of several variables, including PEB and trace element geochemistry, between the box and gravity cores indicate that sediment was lost or compressed during the gravity-coring process (PE0305-1, 4 cm; MRD04-6, 13 cm, MRD05-4, 16 cm). However, spliced together the box- and gravity core records are considered to provide a complete sedimentation record.

Table 2

Sample ID	Mwd	Sample split	*P. atlanticum*	*E. vitrea*	*B. morgani*	Other species	Total number of counted foraminifers	PEB %	% Hypoxia occurrence
ST4 (C6B) USGS B- unstained	19.4	37.50	215	4	5	181	405	55.31	>75%
ST4 (C6B) USGS B- stained	19.4	37.50	203	1	101	29	334	91.32	>75%
ST4 (C6B) USGS B- total assemblage	19.4	75.00	418	5	106	210	739	71.58	>75%
ST6 (E2A) USGS C- unstained	15.3	12.50	80	4	7	282	373	24.40	>50%
ST6 (E2A) USGS C- stained	15.3	37.50	257	1	9	60	327	81.65	>50%
ST6 (E2A) USGS C- total assemblage	15.3	50.00	337	5	16	342	700	51.14	>50%
ST 14 (I4) USGS B- unstained	20.6	6.25	67	61	29	255	412	38.11	>25%
ST 14 (I4) USGS B- stained	20.6	37.50	45	4	28	157	234	32.91	>25%
ST 14 (I4) USGS B- total assemblage	20.6	43.75	112	65	57	412	646	36.22	>25%

A more important concern for the longer gravity core record is the loss or gain of sediment associated with storms and mass-movement sediment redistribution, and will be discussed in Section 5.4.

Because clastic sediments dominate the Louisiana continental shelf, it is very difficult to locate sufficient in-situ carbonate material, including mollusks, within discrete horizons to obtain a reliable radiocarbon date. In our gravity cores, only three samples contained enough foraminiferal tests for AMS ^{14}C dates; two from the base of MRD05-04GC (226.5 cm, 1400±140 yrs BP; 228.5 cm 1630±45 yrs BP: Osterman et al., 2007) and one from the base of MRD05-6GC (136.5 cm, 1450±70 yrs BP). The ages are in radiocarbon years (BP) using the Libby half life of 5568 years. Because the cores were collected in 38 and 65 mwd, we applied the standard surface-water reservoir correction of 400 yrs (Poore et al., 2004) to the dates to obtain an average age of 1100 ^{14}C yrs BP for the base of core MRD05-4GC and 1150 ^{14}C yrs BP for the base of core MRD05-6GC. It is likely that sediment accumulation during the last 1000 years at these shelf sites has been variable (Allison et al., 2000; McKee et al., 2004; Draut et al., 2005; Swarzenski et al., 2007). Due to the highly dynamic nature of sedimentation rates on this river-dominated continental shelf, we have not used these basal dates to estimate an average accumulation rate and chronology for these cores.

4. Results

New and previously published PEB records in box cores from the central and eastern portions of the

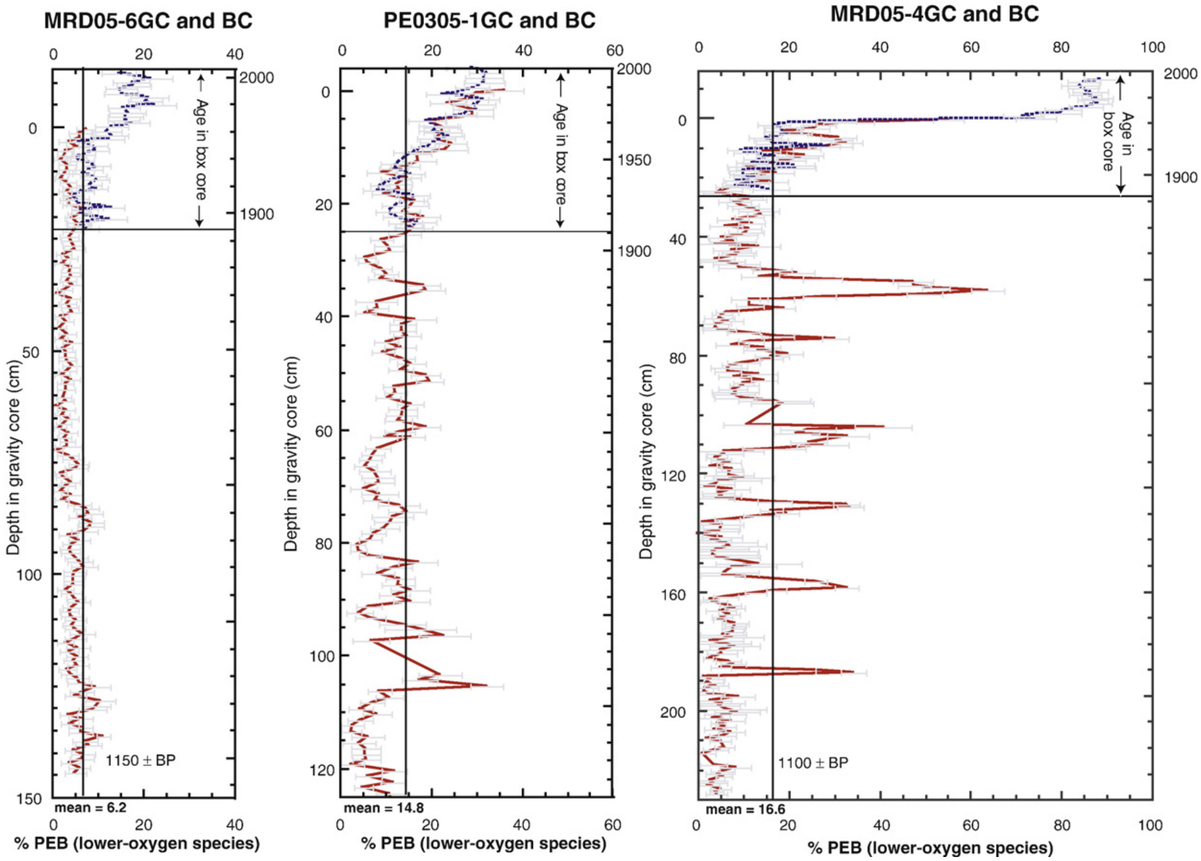

Fig. 2. PEB values (% low-oxygen-tolerant benthic foraminifers) of three Louisiana shelf box- and gravity core pairs (see Fig. 1 for locations). The box cores (dashed blue) are plotted on top of gravity cores (solid red). Depth in each gravity core plotted on the left axis with 0 equal to the top of gravity core. Box core age to 1900 (derived from ^{210}Pb chronology) is plotted on right axis. The depth offsets between the gravity and box cores are based on the PEB values and geochemical data (Swarzenski et al., in press). All three box cores record high PEB values associated with anthropogenic forcing during the last 50 years (also see Fig. 1). The two gravity cores (right), collected closest to the modern hypoxia zone, record evidence for earlier naturally occurring significant low-oxygen bottom-water events. Binomial confidence intervals (Patterson and Fishbein, 1989; Buzas, 1990) on the PEB values are also shown. Solid line represents the mean value for all the data points in each box- and gravity core pair. Also shown are locations of basal radiocarbon dates on two cores.

modern dead zone are shown in Fig. 1. In general, PEB values increase toward the tops of the cores. Box cores with excess ^{210}Pb chronologies show that the PEB index begins increasing about 60 years ago (i.e., at 1950). The record from the westernmost core, PE06-9BC, also indicates that an increase in low-oxygen-tolerant foraminiferal assemblages beginning at 1950. Close to the delta, core BL-10 shows evidence for increased low-oxygen conditions beginning about 80 years ago (at 1920). Cores PE07-7BC and MRJ03-3BC collected outside of the dead zone contain the lowest PEB values.

The box- and gravity core pairs at sites MRD05-4, PE 0305-1, and MRD05-6 provide a transect from the center to the seaward margin of the modern hypoxic zone and extend the PEB record back beyond 1900 (Fig. 1, inset; Fig. 2). The location of site MRD05-4 is within the modern dead zone. The PEB species make up more than 80% of the benthic foraminifer assemblages in the upper part of the box core from this site and then decline to 15–20% in the lower part of the box core, which extends back to about 1900 based on the ^{210}Pb-age model (Figs. 1 and 2). The PEB values in the upper part of the gravity core (0–25 cm), which overlap the box core record, are similar to values in the lower part of the box core. However, the PEB record from deeper parts of MRD05-4GC show periodic excursions to high values that stand out from the overall low background values. Several of the PEB excursions approach values found in the last 50 years, and a number of PEB excursions extends well above the mean for the overall record (Fig. 2). The PEB values and the number of points defining each excursion decrease downcore. In MRD05-4GC, the PEB excursions are quasi-periodic in nature with distinct and multi-point excursions at 55–60 cm, 104–111 cm, 130–133, 156–159 cm, and 186–189 cm.

Site PE0305-1 is located on the seaward edge of the modern dead zone (Fig. 1). The low-oxygen-tolerant species comprise >25% of the assemblage in the last 50 years in both the gravity and box cores. The PEB values below 15-cm depth in the gravity core are low and average about 11% for the gravity core alone, whereas the mean values of both gravity- and box core records is 14.8%. Results from PE0305-1GC show two distinct PEB excursions at 95–96 cm and 103–106 cm.

Site MRD05-06 is just outside the seaward margin of the modern dead zone (Fig. 1). The PEB varies between 15 and 20% in the upper part (1950–present) of the box core record from this site. Lower values of PEB are found in the bottom of the box core and in the entire gravity core (Fig. 2). In addition, overall variability of the PEB record in the lower part of the box core and in the gravity core is subdued with no significant fluctuations.

5. Discussion

5.1. Anthropogenic hypoxia

The network of PEB records with excess ^{210}Pb-derived chronologies (Fig. 1) reveals a consistent pattern of increasing PEB from 1950 to the present over a large portion of the modern dead zone. The pattern indicates more frequent low-oxygen conditions developed from the mid-20th century to the present. This may mean that low-oxygen conditions occurred more frequently, as in the number of years during which hypoxia formed, or the number of times during a particular season, or that an episode of hypoxia may have lasted for a longer time instead of being broken up by physical processes during a particular season. All of these scenarios would result in an increase in PEB species over time. Our results corroborate and extend previous studies based on cores adjacent to the Mississippi Delta (Blackwelder et al., 1996; Sen Gupta et al., 1996; Platon et al., 2005; Osterman et al., 2005). Our network of records indicates that low-oxygen bottom-water conditions may have begun earlier in nearshore areas (core BL-10), whereas clear evidence for low-oxygen bottom-waters extends across a broad area of the Louisiana shelf after 1960 (PE06-9). These data indicate that the occurrence of hypoxia hotspots, similar to those of today, existed on the shelf as far back as the 1920s.

In general, the highest PEB values occur in cores collected closest to the Mississippi River Delta (80%), and PEB values decrease toward the outward extremes of the zone (20–30%). Cores PE07-7BC, collected south of the hypoxia zone, and MRJ03-3, in the Mississippi trench, provides controls with PEB values of <10%. One exception is MRD03-5BC, collected from an area that experienced hypoxia >75% of the time since 1985 (Rabalais et al., 1999). In MRD03-5BC (24 mwd), the PEB values are lower than expected, but still >10%. Shallow, low-salinity surface-water with low-calcium-carbonate saturation, is believed to have contributed to post-depositional dissolution of the lightly calcified PEB species resulting in lower PEB values at this site.

Monitoring and modeling studies completed after 1985 indicate that areal expansion of the dead zone over the last several decades is related to increased use of commercial fertilizer in the Mississippi basin (Nelson et al., 1994; Rabalais et al., 1996; Goolsby et al., 2001). This and other anthropogenic activity (sewage and livestock-derived runoff, etc.) result in elevated levels of nutrients transported down the Mississippi River and subsequently discharged onto the Louisiana shelf. Our results are consistent with the interpretation that the modern increase in hypoxia is related to human activities and indicates that the anthropogenic signal extends back at least to 1950 and perhaps to 1920. In addition, our shelf cores provide a means to measure the geographic extent of hypoxia prior to the post-1985 systematic monitoring efforts. Our data indicate that subsurface low-oxygen conditions in the mid-20th century were occurring seasonally over at least two-thirds of the geographic distribution of the modern hypoxia zone, as measured by Rabalais et al. (1999) since 1985 (Fig. 1).

5.2. Natural low-oxygen bottom-water events

Gravity cores MRD05-04, PE0305-1, and MRD05-6 (Fig. 2) represent a three-core transect, from the center to just beyond the seaward edge of the modern dead zone, that can be used to monitor both the geographic extent and frequency of naturally caused low-oxygen bottom-water on the Louisiana shelf prior to 1985. At least five significant PEB excursions are found at depth in MRD05-4GC, the most proximal site. Although we do not have an age model for this core, AMS ^{14}C dates near the base indicate the record extends back at least 1000 ^{14}C years. The PEB excursions below 40-cm depth in MRD05-4GC do not reach the very high absolute values observed in the upper part of the box core from this site, but the values stand out from background levels of PEB (Fig. 2). The lower absolute values and the number of data points associated with each PEB peak in the gravity core indicate pre-1900 low-oxygen bottom-water episodes were less frequent or less persistent than modern episodes recorded in the box core. Interpolation of the ages of these natural low-oxygen bottom-water events occurring between the ^{210}Pb dated sequence and the basal radiocarbon date is not possible due to uncertainties in sedimentation rates and down core sediment compaction.

At the intermediate site, PE0305-1, excess ^{210}Pb indicates that the gravity and box core are offset by 4 cm centimeters, however, there were not enough foraminifers to allow for radiocarbon dating of the gravity core. (Fig. 2). In both the gravity and box core, the highest PEB values (>20%) occur within the last 50 years, and overall lower PEB values are found below 20-cm depth. Frequent excursions to higher PEB values in PE0305-1GC indicate that lower-oxygen bottom-water conditions occurred periodically on this section of the Louisiana shelf prior to 1900, and frequency of hypoxia seems to have been less than at the proximal site MRD05-4. The total faunal data for PE0305-1GC (Osterman et al., 2006) documents that 40% of the down core assemblage consists of the three PEB species and the two other characteristic shelf species *B. irregularis* and *H. concentrica.* The other 60% of the assemblage is composed of small numbers of 20-to-30 other species. Samples with high PEB values have a relative decrease in the two other characteristic shelf species. This supports our hypothesis that the relative increase in PEB is due to a competitive advantage over other less-tolerant shelf species during the development of low-oxygen conditions.

The distal site, MRD05-6, records the environmental conditions just outside of the modern hypoxic zone. The PEB values throughout MRD05-6GC are consistent with modern non-hypoxia shelf samples (avg. = 6%). The fauna consists of the characteristic nonhypoxic shelf species and no significant PEB excursions are recorded in the gravity core. This indicates that this site did not experience any natural low-oxygen bottom-water conditions during the last 1000 ^{14}C years. However, MRD05-6BC shows an increase in PEB values from normal shelf values (<10% PEB) to lower-oxygen values (PEB of 10–20%) in the last 50 years, indicating the anthropogenically-caused expansion of low-oxygen conditions to this area of the Louisiana shelf.

We now have internally consistent evidence from two cores (proximal and intermediate to the modern dead zone) that record periodic low-oxygen bottom-water on the Louisiana continental shelf. In addition, one core collected outside of the modern dead zone does not record such low-oxygen events. We infer that intervals of high PEB values at depth in MRD05-4GC and PE0305-1GC are related to periods of increased Mississippi River discharge. It is unlikely that these PEB events represent a single “mega”-flood, but instead indicate climatically-caused decade-long intervals of wetter periods and increased discharge from the Mississippi River. Increased Mississippi River discharge would increase the supply of freshwater and nutrient transport to the continental shelf. Naturally occurring nutrients would be supplied by erosion of both upstream and coastal wetlands, which would be a source of labile carbon stimulating marine productivity. These components, low-salinity surface-water stratification, and excess nutrients would foster the development of bottom-water oxygen depletion (Frascari et al., 2006). Extended years of above average discharge and the development of seasonal low-oxygen conditions on the shelf would allow the PEB species to out compete other less tolerant species, resulting in a relative increase in the percentage of the low-oxygen-tolerant species. The pre-1900 PEB excursions in MRD05-04GC and PE0305-1GC are strong evidence for episodes of naturally occurring low-oxygen bottom-water conditions on the Louisiana shelf prior to development of the modern dead zone that has been linked to anthropogenic causes.

5.3. Human impact on expansion of low-oxygen conditions

Transect results also provide insights into the contribution of human activities to hypoxia on the Louisiana continental shelf, in terms of the geographic extent, frequency, and duration. At all three sites, the absolute value of gravity core PEB fluctuations is less than those found during the last 60 years in accompanying box cores, except in one case (PE0305-1GC, 101–103 cm). This indicates that modern hypoxia is more persistent, either longer lasting in frequency (number of times per decade or season) or duration (number of days in length), than the naturally caused low-oxygen conditions in the past. In addition, at site MRD05-6, significantly elevated PEB values are only found in the box core representing the last 50-year time interval. This implies that the modern anthropogenically influenced hypoxia has a larger geographic extent than the earlier natural low-oxygen bottom-water events on the Louisiana shelf. Furthermore, the high PEB values in MRD05-6BC indicate that benthic biota have been negatively impacted by hypoxic conditions slightly outside of the modern measured hypoxia zone. We believe that an enlargement of the modern hypoxia zone is warranted based upon our data (Fig. 1). We conclude that the development of low-oxygen bottom-water on a broad reach of the continental shelf is a natural process that has been negatively modified by human activities during the last 60 years. The record indicates that modern hypoxia is more frequent and more extensive than natural low-oxygen conditions.

5.4. Alternate interpretation of downcore PEB excursions

The Louisiana continental shelf is a passive continental margin modified by the high sediment influx from the Mississippi River and periodic reworking due to extreme-storm events. A potential alternate explanation for the PEB peaks observed in MRD05-4GC is that they represent a geological phenomenon, such as sediment redistribution or sorting by storms or downslope transport. There are multiple reasons why we believe that these peaks are caused by environmental and not sedimentological processes.

First, the foraminiferal assemblage supplies the strongest evidence against sediment redistribution. Wide-scale regional studies of benthic foraminiferal distributions in the Gulf of Mexico over the last 50 years have found repeatedly that benthic foraminiferal distribution parallels bathymetric contours (Phleger and Parker, 1951; Bandy, 1954; Parker, 1954; Culver and Buzas, 1981; Poag, 1981; Osterman, 2003). These studies have documented a coastal (10–30 mwd) assemblage, characterized by *A. parkensoniana* (avg.=35%), which overlaps a shelf assemblage (20–100 mwd), characterized by *H. concentrica* and *B. iregularis* (avg.= 24%). However, within areas prone to hypoxia, the PEB species are most common (13–70 mwd; avg.=20%) (Culver and Buzas, 1981; Osterman, 2003). Cores MRD05-4GC and PE0305-1GC were collected in 38 and 47 mwd, which indicates that the sedimentary particles (including the foraminifers) could not have moved significantly downslope. If sediments were transported from shallower water depths, the samples would include increased numbers of the species common in coastal waters (10–30 mwd), which is not the case in PE0305-1GC. Although it might be possible to increase the overall number of foraminifers in a sample by downslope transport from foraminifer-rich strata into foraminifer-poor strata, it is not possible to increase only the number of select species within an assemblage, and no other, by such a process. It is possible that a PEB-rich fauna could be transported into a nearby barren or PEB-poor assemblage, but this would not negate evidence for the ultimate cause (past low-oxygen conditions) on the continental shelf, just the exact location of such an event on the continental shelf. Given the water depth of MRD05-4GC and the foraminiferal biogeography we believe the most parsimonious explanation is that the high PEB values document in-situ assemblages.

Further support against downslope transport of the PEB species is also shown in the record of MRJ03-3BC, collected outside the hypoxia zone in the Mississippi trench (Fig. 1). At 231 mwd, core MRJ03-3BC lies outside of the preferential depth of the PEB, but in an area of rapidly accumulated sediment transported from the continental shelf and hypoxia zone (Corbett et al., 2004; Bianchi et al., 2006; Swarzenski et al., 2006). The foraminiferal assemblage of MRJ03-3BC is dominated by species found abundantly at that water depth and by consistently low numbers of PEB and other shelf species. Downslope transport of sediments tends to dilute in-situ assemblages with low numbers of misplaced foraminifers (Fig. 1).

In addition, if high-PEB intervals represented sediment transport, then we would expect to see evidence in the sedimentary record of the two gravity cores MRD05-4GC and -6GC. Sand, a minor component of the shelf sediment budget, varies between 0 and 9% in both cores, with MRD05-4GC (the proximal site) containing large PEB excursions and MRD05-6GC (the distal site) containing no PEB excursions. In all cases, the small percentage of sand does not correlate with percent PEB (Fig. 3). Correlation coefficients (using excel) for the percentages of sand and PEB are low, 0.16 for MRD05-6GC and 0.29 for MRD05-4GC. This indicates further that environmental, not sedimentological processes, control PEB values.

Second, the magnitudes of the PEB peaks in the cores are consistent within the known measurements of the hypoxia zone (Turner et al., 2005) and within each gravity cores. Box cores collected from areas with more frequent (>75%) occurrences of hypoxia (BL-10, MRJ03-2, MRD05-4) contain the highest PEB percentage, with the exception of MRJ03-5 as discussed previously. In areas with less frequent hypoxia occurrence (>50% and >25%), maximum PEB values are lower (PE0305-1, MRD05-6, and PE06-9). The lowest PEB values are from cores outside of the hypoxia zone (PE07-7 and MRJ03-3). The PEB peaks in the gravity cores are geographically consistent with the above observation. The highest PEB values are found in MRD05-4 (>75% hypoxia frequency) and all PEB peak values are greater than those in PE0305-1 (>25%), which are in turn greater than those in MRD05-6, which lies outside of the zone of measured hypoxia. If the excursions to high PEB values were to represent reworked sediment in the cores, it is unlikely that the values would be consistent within each core. For example, core MRD05-6GC from outside the hypoxia zone, does not contain peaks of 40–60% such as are found in MRD05-4GC. The PEB excursions within each core vary within a limited range consistent with modern hypoxia occurrence and the maximum-range values decrease, given their location in the dead zone, away from the hypoxia zone. It is unlikely that sedimentary reworking would be so consistent; more variability in the values of PEB within and between cores should be expected if the values resulted from sedimentary processes.

Although we are confident that the elevated PEB values are recording low-oxygen bottom-water conditions in the gravity cores, we cannot unequivocally date these events or correlate them between cores. Louisiana continental shelf sedimentation is variable and complicated. During high Mississippi River flow and storm events, sedimentation on the shelf may have been rapid or even instantaneous. Radioisotopes, geochemistry and sedimentology studies indicate rapid sediment erosion

Fig. 3. Percent of sand (>63 m) and percent of three low-oxygen-tolerant benthic foraminiferal species (PEB) in two new gravity cores from the Louisiana shelf (MRD05-4GC and -6GC; see Fig. 1 for site location). No consistent relation exists between the percent sand and the percent PEB, indicating that the peaks in the species relative abundance in the foraminiferal assemblage are not related to sedimentary processes.

and redeposition can occur during storms or mobile-mud transport over limited distances (Corbett et al., 2004, 2006; Bianchi et al., 2006; Swarzenski et al., 2007). Such physical processes serve to disrupt the sediment record. Developing a better record of the timing of past low-oxygen bottom-water events on the Louisiana shelf requires the study of multiple cores with verifiable chronologies.

6. Conclusions

Bottom-water with low dissolved-oxygen content has occurred periodically on the Louisiana continental shelf for at least the last 1000 years. Naturally caused low-oxygen bottom-water conditions are believed to result from climatically-caused decade-long intervals of wetter periods and increased discharge from the Mississippi River. Increased Mississippi River discharge would increase water column stratification and nutrients supplied by fluvial processes. These components would foster the development of bottom-water oxygen depletion. The geographic extent and frequency of these low-oxygen bottom-water episodes began to change in the 1920 s in the region closest to the Mississippi Delta. By 1950, lower-oxygen conditions were experienced along the Louisiana shelf out to the location of PE06-9BC and had begun impacting areas where no prior low-oxygen bottom-water conditions had occurred during the last 1000 ^{14}C years (MRD05-6GC). Recent expansion of the hypoxia zone has been linked to anthropogenic activities and has been systematically measured since 1985 (Turner et al., 2005). Our results allow a better understanding of the timing and spread of the recent rise in anthropogenic hypoxia before 1985. Low-oxygen bottom-water is a natural phenomenon that has been negatively impacted by human activity during the last 60 years.

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