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Comparison of Continuous Records of Near-Bottom Dissolved Oxygen From the Hypoxia Zone Along the Louisiana Coast

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ABSTRACT: Oxygen depletion is a seasonally dominant feature of the lower water column on the highly-stratified, riverine-influenced continental shelf of Louisiana. The areal extent of hypoxia (bottom waters ≤ 2 mg l⁻¹ dissolved oxygen) in mid-summer may encompass up to 9,500 km², from the Mississippi River delta to the upper Texas coast, with the spatial configuration of the zone varying interannually. We placed two continuously recording oxygen meters (Endeco 1184) within 1 m of the seabed in 20-m water depth at two locations 77 km apart where we previously documented mid-summer bottom water hypoxia. The oxygen meters recorded considerably different oxygen conditions for a 4-mo deployment from mid-June through mid-October. At the station off Terrebonne Bay (C6A), bottom waters were severely depleted in dissolved oxygen and often anoxic for most of the record from mid-June through mid-August, and there were no strong diurnal or diel patterns. At the station 77 km to the east and closer to the Mississippi River delta (WD32E), hypoxia occurred for only 50% of the record, and there was a strong diurnal pattern in the oxygen time-series data. There was no statistically significant coherence between the oxygen time-series at the two stations. Coherence of the oxygen records with wind records was weak. The dominant coherence identified was between the diurnal peaks in the WD32E oxygen record and the bottom pressure record from a gauge located at the mouth of Terrebonne Bay, suggesting that the dissolved oxygen signal at WD32E was due principally to advection by tidal currents. Although the oxygen time-series were considerably different, they were consistent with the physical and biological processes that affect hypoxia on the Louisiana shelf. Differences in the time-series were most intimately tied to the topographic cross-shelf gradients in the two locations, that is, station C6A off Terrebonne Bay was in the middle of a broad, gradually sloping shelf and station WD32E in the Mississippi River Delta Bight was in an area with a steeper cross-shelf depth gradient and likely situated near the edge of a hypoxic water mass that was tidally advected across the study site.

Introduction

Oxygen-depleted bottom waters are seasonally dominant features of the Louisiana continental shelf adjacent to the deltas of the Mississippi and Atchafalaya rivers (Rabalais et al. 1991, 1992). In mid-summer, the areal extent of bottom-water hypoxia (≤ 2 mg l⁻¹ dissolved oxygen (DO)) may cover up to 9,500 km², with spatial configuration of the

zone varying interannually. More frequent sampling along a transect on the southeastern shelf and continuous time-series data off Terrebonne Bay document hypoxic bottom waters as early as February and as late as October, with widespread, persistent, and severe hypoxia-anoxia from mid-May to mid-September.

The Mississippi River system, which empties onto the northern Gulf of Mexico continental shelf, ranks among the world's top ten rivers in terms of

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freshwater and sediment inputs to the coastal ocean (Milliman and Meade 1983), drains 41% of the conterminous United States, and contributes over 90% of the fresh water to the Gulf of Mexico (Dinnel and Wiseman 1986). High flow occurs in March–May. Although river flow is reduced in summer, seasonal wind reversals retain much of the fresh water on the shelf. A productive, stratified system is maintained for the majority of the year (Sklar and Turner 1981; Justić et al. 1993). The vertical distribution of the hypoxic water mass is defined by water-column stratification, which is controlled by riverine freshwater inflow, large-scale circulation, and wind-driven mixing (Rabalais et al. 1991, 1992; Wiseman et al. 1992).

Freshwater discharge from the Mississippi and Atchafalaya rivers rapidly forms the Louisiana Coastal Current, a highly stratified coastal current that flows, in the mean, westward along the Louisiana coast and southward along the Texas coast. During late spring and summer, however, when winds along the south Texas coast are upwelling-favorable, the flow reverses and flows back toward the north and east (Cochrane and Kelly 1986). In some years the reversal penetrates into Louisiana waters during mid-summer. Stratification in the Louisiana Coastal Current, particularly near the two major freshwater sources, is primarily due to salinity. During winter, temperature is destabilizing; from April until October, it is normally stabilizing. Strong wind events interact with the waters of the coastal current throughout the year. Intense wind mixing due to cold air outbreaks and frontal passages is active from as early as late September to as late as June; while local squalls and thunderstorms, as well as tropical storms and hurricanes, are important during the summer months (DiMego et al. 1976). These wind events often result in the complete homogenization of the water-column (Wiseman et al. 1986). At other times, they are not strong enough to fully break down the local stratification, but they result in localized coastal upwelling, which alters the stratification (Dagg 1988).

High biological productivity in the immediate and extended plumes of the Mississippi River (Sklar and Turner 1981; Lohrenz et al. 1990) is mediated by high nutrient inputs and regeneration, and favorable light fields. Subsequent carbon flux (via direct sinking, repackaging, aggregate formation, or advection) is sufficient to deplete the lower water column of oxygen within periods of days to weeks to months (Turner and Allen 1982; Dortch et al. 1994). Once hypoxic water masses have formed, they persist until mixing results from winds and/or thermal cooling, or the advection of oxygenated water during upwelling- or downwell-

ing-favorable conditions. The highest net productivity in the adjacent shelf system lags 1 mo after peak river flow; the most deficient bottom water oxygen lags 2 mo behind peak river flow (Justić et al. 1993).

We have documented interannual variability of oxygen depletion over a large geographic region and monthly or bimonthly variability on a limited spatial scale (Rabalais et al. 1991, 1992). Continuous time-series data from more than a single location were not available until the simultaneous deployment of two oxygen meters in 1990 (Rabalais et al. 1993). The second meter was deployed in the Mississippi River Delta Bight 77 km closer to the outflow of the Mississippi River but in the same water depth as the oxygen meter on a permanent instrument mooring off Terrebonne Bay (Fig. 1). Thus, measurements were obtained from two oxygen meters at 20-m water depth in areas of consistent mid-summer hypoxia, and we were able to assess whether the bottom-water oxygen environment was similar in the two areas and to explore the possible forcing mechanisms of variability.

Methods

STUDY AREA

The study area encompassed the Mississippi River Delta Bight downplume of Southwest Pass of the Mississippi River and the area offshore of Terrebonne Bay (Fig. 1). The oxygen meters were located at WD32E (29°07.63'N, 89°41.46'W; an active oil-production platform) and C6A (28°51.44'N, 90°27.68'W; an inactive platform). Platform-related effects were evident in sedimentary characteristics (physical and chemical) and benthic community structure but not on water-column structure, including oxygen concentrations (Rabalais et al. 1993).

INSTRUMENTATION AND HYDROGRAPHY

Time-series measurements were made using Endeco 1184 pulsed dissolved oxygen sensors sampling at 15-min intervals. Both instruments were deployed within 1 m of the seabed in a 20-m water column. Instruments were deployed from mid-June through mid-October with a probe replacement midway through each deployment. Predeployment and postdeployment calibration of the pulsed DO sensors (accuracy of 0.2 mg l⁻¹) were performed by technicians of Endeco, Inc. according to specifications of the instrument (Endeco, Inc. 1988). An antifouling wax was applied to the center of the DO sensor membrane, and both instruments were resistant to the effects of bio-fouling. With the exception of one deployment period at C6A (6/15/90–7/20/90), there were no indi-

Fig. 1. Map of study area with location of hydrographic survey stations along transects A' through D', oxygen meter locations (closed squares), pressure gauge location in Cat Island Pass at the mouth of Terrebonne Bay (open triangle), and C-MAN wind gauge location at Grand Isle (closed triangle). Stippled area represents spatial extent of near-bottom water hypoxia ($DO \leq 2 \text{ mg l}^{-1}$) during mid-July to late-July 1990. Isobaths in 10 m to 100 m; oxygen isopleths in 1 mg l^{-1} to 6 mg l^{-1} .

cations from the condition of any DO probes that hydrogen-sulfide poisoning had occurred. Postcalibration of the discolored probe (C6A), periodic corroboration of DO data with a Hydrolab Surveyor II (accuracy of 0.2 mg l^{-1}), and collection of similar data following probe exchange, indicated that the values for the first part of the deployment at C6A were accurate and usable.

Bottle samples for determination of DO by Winkler titration (Parsons et al. 1984) were taken periodically during deployment of the instruments. Supplemental DO data were obtained during frequent hydrographic surveys of the study areas using a Hydrolab Surveyor II or a SeaBird CTD/DO (accuracy of 0.1 ml l^{-1}) system. Numerous discrete samples and hydrographic profiles indicated that oxygen meters were, for the most part, representative of the near-bottom DO conditions at the point of instrument placement

and within a 1,000-m radius of the instrument. Postdeployment corrections to the Endeco 1184 DO concentrations were made if Winkler titrations and Hydrolab measurements showed a consistent offset for any deployment period, as was the case for a portion of the WD32E record.

The DO concentration below which waters were considered "hypoxic" was designated as 2 mg l^{-1} , based on the absence of demersal finfish and crustaceans in trawl catches when dissolved oxygen falls below that level (Pavela et al. 1983; Leming and Stuntz 1984; Renaud 1986; N. N. Rabalais personal observation).

BOTTOM PRESSURE AND WINDS

Time-series analyses were conducted to compare dissolved oxygen with bottom pressure records collected from within the Cat Island Pass entrance to Terrebonne Bay (Fig. 1). Tide gauge data for

Grand Isle were not available, but prior studies (Murray 1976) suggest that the tide does not vary significantly between Grand Isle and the entrances to Terrebonne Bay. A ScaBird SBE 26 pressure gauge, set to sample at 15-min intervals, was deployed and serviced at regular intervals. The accuracy and resolution of the instrument are 46.5 Pa and 1.24 Pa, respectively. No effort was made to correct pressure gauge data for atmospheric pressure to recover sea-level records. Our primary concern was with the tidal periods where the bottom pressure signal is significantly greater than the atmospheric pressure signal. Also, bottom pressure, which includes atmospheric pressure and baroclinic signals, is a more fundamental measurement relating to bottom water movement than is water level. Wind data were obtained from the C-MAN station at Grand Isle (Fig. 1). The winds were rotated 45° to be more nearly longshore near the instrument deployment at C6A.

DATA ANALYSES

Hourly data were entered into spreadsheets for calculations of frequency of records and duration of events at various DO levels, and determination of daily DO minima, maxima, ranges, and averages. The 4-mo record for DO time-series were divided into equal monthly intervals for each station for calculation of monthly values. Spectra for the entire 4-mo DO time-series were estimated to determine the energy containing scales of various observables. The periodogram was calculated from the discrete Fourier transform (Cooley and Tukey 1965). The power spectrum was then estimated by smoothing the periodogram with an 11-point triangular running filter giving four equivalent degrees of freedom for the spectrum estimates. (A curve was then smoothed through these estimates to provide spectra as in Fig. 5 used later in this paper.) Coherence squared estimates between time-series were estimated from the discrete Fourier transforms. These were estimated by averaging across five adjacent bands giving ten degrees of freedom to each estimate.

Results and Discussion

OXYGEN TIME-SERIES

Continuous time-series data for near-bottom dissolved oxygen concentrations at the two locations are shown in Fig. 2. The near-bottom dissolved oxygen environments were usually very different between the two stations.

Extended periods of hypoxic and anoxic near-bottom waters were recorded at station C6A off Terrebonne Bay (Fig. 1), particularly in the first 2 mo of the record, that is, mid-June through mid-August (Fig. 2). DO concentrations fell below 2 mg

l⁻¹ for 80% of the total record and below 1 mg l⁻¹ for 71% of the total record, and were anoxic for 60% of the total record (derived from Table 1). The DO was almost always anoxic (or sometimes hypoxic) until August 19. The frequency of normoxic water (DO > 2 mg l⁻¹) increased dramatically in the third and fourth months of the record (Table 1) with two extended periods of reoxygenation in mid-August to early September and again from early to mid-October. After October 2, the DO was above 2 mg l⁻¹ for the remainder of the record.

The oxygen time-series in the Mississippi River Delta Bight at station WD32E was much different with periodic fluctuations above and below 2 mg l⁻¹ DO (Fig. 2). Hypoxia occurred overall for 50% of the total record, and more frequently in the first and third months (derived from Table 1). The duration of hypoxic events was longer in the first month of the record than in the subsequent three months.

Hypoxic events, at all levels considered (DO = 0 mg l⁻¹, 0 mg l⁻¹ < DO ≤ 1 mg l⁻¹, 0 mg l⁻¹ < DO ≤ 2 mg l⁻¹) were longer in duration at station C6A than at WD32E (Table 1). For the first 2 mo of the record, the daily DO minima and DO maxima were significantly lower at station C6A than at WD32E (Table 1). The daily DO minima and maxima were lower at C6A than WD32E in the second 2 mo of the record but not always significantly. The daily range in DO values was significantly greater at station WD32E than at C6A for the first 3 mo of the record. The daily DO average was lower at station C6A than at WD32E for the first 2 mo of the record.

HYDROGRAPHY

In addition to the obvious differences in the DO time-series for the two stations, the water-column structure at mid-month intervals through the period of instrument deployments also differed. Dissolved oxygen minima were observed in the lower water column below a strong thermocline or halocline for all mid-month surveys (four shown in Fig. 3). All station data from the WD32E site during the course of the summer, five profiles, indicated a mid-depth oxygen minimum (three shown in Fig. 3). Some profiles exhibited more than one such minimum and others showed a near-bottom oxygen minimum. From mid-June through mid-September, upper water-column temperatures were cooler at station WD32E than at C6A; WD32E is considerably closer to the effluent of the Mississippi River than C6A (Fig. 1). For the same time period, upper water-column salinities were also lower at station WD32E than at C6A. Profiles for mid-October for both stations showed a relaxation in

Fig. 2. Time-series plots of near-bottom dissolved oxygen concentration (mg l^{-1} in 1-h intervals) at stations C6A and WD32E (closed triangles indicate beginning of month indicated).

the strength of the thermocline as a result of seasonal cooling (Fig. 3).

We created oxygen versus salinity, temperature versus salinity, and depth versus salinity plots for all mid-month profiles at station WD32E (Fig. 4). Where well-developed mid-depth oxygen minima occur (e.g., Fig. 4, June 15, 1990), they are associated with strong haloclines in the depth versus salinity plots and temperature versus salinity plots which cross the lines of constant density at large angles. Water disperses preferentially along isentropic surfaces rather than across them (Montgomery 1938). This suggested that the mid-depth min-

ima were advecting or diffusing offshore along pycnoclines from near-bottom source regions closer to shore. The pycnoclines were not associated with the same density surface throughout the summer. In particular, waters in June were colder and denser at a given salinity than they were in July, August, or September. This is consistent with previous observations of the seasonal variation of water mass properties in the region (Wiseman et al. 1982). It is also consistent with the distribution of hypoxic bottom waters found inshore of WD32E in July 1990 (Fig. 1) and during other mid-summer synoptic surveys (see below).

TABLE 1. Comparison of time-series of dissolved oxygen (DO) measurements (mg l^{-1}) from two locations, station C6A and station WD32E, in the zone of hypoxia on the Louisiana shelf.

Station: Period:	C6A June 15, 1990–July 14, 1990	C6A July 15, 1990–August 14, 1990	C6A August 15, 1990–September 15, 1990	C6A September 16, 1990–October 15, 1990	WD32E June 15, 1990–July 14, 1990	WD32E July 15, 1990–August 14, 1990	WD32E August 15, 1990–September 15, 1990	WD32E September 16, 1990–October 16, 1990
Frequency of Events								
DO = 0	71%	99%	30%	42%	1%	0%	0%	0%
0 < DO ≤ 1	22%	1%	14%	8%	33%	6%	13%	13%
1 < DO < 2	6%	0%	25%	5%	33%	24%	55%	21%
2 < DO	1%	0%	32%	45%	33%	70%	32%	65%
Duration of Events: $\bar{x} \pm \text{SE}$ (n)								
DO = 0	29.8 ± 12.5 (17)	245.0 ± 180.9 (4)	57.5 ± 20.5 (4)	62.0 ± 27.0 (5)	3.0 (1)	N/A (0)	N/A (0)	N/A (0)
0 < DO ≤ 1	222.7 ± 214.2 (3)	744 (1)	42.0 ± 19.0 (8)	184.5 ± 169.5 (2)	14.2 ± 5.7 (17)	4.5 ± 1.5 (10)	26.7 ± 12.5 (20)	14.7 ± 5.8 (7)
0 < DO ≤ 2	236.0 ± 210.7 (3)	744 (1)	129.2 ± 67.5 (4)	134.7 ± 113.4 (3)	43.0 ± 21.4 (11)	14.8 ± 5.1 (15)	8.1 ± 3.3 (10)	16.5 ± 7.7 (17)
Daily DO Concentration: $\bar{x} \pm \text{SE}$ (n = 30 or 31)								
Minimum	0.1 ± 0.0	0.0 ± 0.0	1.1 ± 0.2	1.7 ± 0.4	1.1 ± 0.2*	1.8 ± 0.2*	1.3 ± 0.1	2.0 ± 0.2
Maximum	0.5 ± 0.2	0.2 ± 0.0	1.7 ± 0.2	2.7 ± 0.5	2.3 ± 0.2*	3.4 ± 0.2*	2.2 ± 0.1*	3.3 ± 0.2
Range	0.4 ± 0.2	0.2 ± 0.0	0.5 ± 0.1	1.0 ± 0.2	1.2 ± 0.1*	1.5 ± 0.2*	0.9 ± 0.1*	1.4 ± 0.1
Average	0.2 ± 0.1	0.0 ± 0.0	1.4 ± 0.2	2.2 ± 0.4	1.8 ± 0.2*	2.7 ± 0.2*	1.7 ± 0.1	2.6 ± 0.2

* Significantly different from paired monthly mean at station C6A, $p < 0.05$, paired *t*-test.

SPECTRAL AND COHERENCE ANALYSES

Spectra of the continuous 4-mo dissolved oxygen records from stations C6A and WD32E are shown in Fig. 5. While no obviously significant peaks were present in the spectrum for C6A, a significant peak appeared in the record from WD32E in a band near the diurnal frequency. While suggested in Fig. 5, the periodogram (not shown) clearly showed that the strongest peaks were in the bands containing the K_1 (period = 23.9 h) and the O_1 (period = 25.8 h) tides. Given the length of the available record, it was not possible to separate the K_1 signal from the 24-h period due to solar insolation. Thus, the signal in this band could be due to advection by the K_1 tidal currents or to phytoplankton activity in response to the day-night cycle of insolation. The fact that the O_1 dissolved oxygen signal at WD32E was slightly higher than the K_1 signal, as observed in the bottom pressure record from Cat Island Pass (see Fig. 5), suggested that the dissolved oxygen signal was due principally to advection by tidal currents. The lowest frequencies, that is, processes with periods longer than 4 d, were the most energetic at both stations. These processes tend to be associated with weather-driven events such as wind-driven mixing, upwelling, and downwelling.

The dissolved oxygen records were not coherent with each other at the 95% significance level. They were also not coherent with coastal bottom pressure or surface wind. At the 80% significance level, however, there were isolated bands of coherence. In particular, the dissolved oxygen record from sta-

tion WD32E was coherent with the coastal bottom pressure in the diurnal band. There were also other isolated bands of coherence, including a narrow band near semidiurnal frequencies. Coherence of the DO record with the winds was not particularly strong, although narrow isolated bands of coherence existed in both records. Both oxygen records appeared coherent with winds in the 3-d and the 15-d bands.

Past efforts to seek statistically significant coherence between bottom current records and bottom dissolved oxygen at C6A have proven futile. Seasonal and shorter scale variations in current structure appear to be strongly influenced by a variety of processes. The diurnal tidal signals are often confounded with inertial oscillations (Daddio et al. 1978) and internal tides (Science Applications International Corporation 1989). The former are most important during the energetic winter season and the latter during the stratified summer season. Furthermore, the alongshore coherence of cross-shelf currents along the Louisiana shelf appears to have extremely short spatial scales (F. J. Kelly personal communication). We have analyzed two records of near-bottom currents in a diurnal band (23-h to 26-h periods), which included the K_1 , O_1 , and inertial periods, and a semidiurnal band (12-h to 13-h periods). The filtered records showed the expected strong temporal variability in envelope amplitude. Descriptive statistics are presented in Table 2. Over 12 h of onshore flow, an rms speed of 1 cm s^{-1} would displace a water parcel approximately 0.4 km. When added to the displacement

STATION C6A

STATION WD32E

Fig. 3. Water-column vertical profiles of salinity (‰), temperature (°C), and dissolved oxygen (mg l⁻¹) for stations C6A and WD32E for dates indicated.

Fig. 4. Plots of oxygen (mg l⁻¹) versus salinity (‰), temperature (°C) versus salinity (‰), and depth (m) versus salinity (‰) with constant density (sigma-t) curves superimposed for dates indicated at station WD32E. Vertical lines through each plot identify oxygen minima and related temperature and salinity features.

TABLE 2. Descriptive statistics for tidal band, near-bottom currents at station C6A.

Year	Duration (d)	Band ^a	Component	Mean Speed (cm s ⁻¹)	Maximum (cm s ⁻¹)	Minimum (cm s ⁻¹)	Θ ^b
1989	272	D	East	1.52	5.91	-5.91	7.5°
1989	272	D	North	1.47	5.04	-5.02	
1989	272	D					
1989	272	S	East	1.26	4.71	-4.72	-33.5°
1989	272	S	North	0.99	4.57	-4.57	
1989	272	S					
1990	211	D	East	1.00	3.56	-3.56	50.2°
1990	211	D	North	1.10	3.71	-3.71	
1990	211	D					
1990	211	S	East	1.25	3.45	-3.45	-21.0°
1990	211	S	North	0.71	2.40	-2.39	
1990	211	S					

^a D indicates the diurnal band and S indicates the semidiurnal.

^b Θ is the orientation of the principal axis of the variance ellipse, measured positive counterclockwise from east.

associated with a semidiurnal flow of 1 cm s⁻¹ speed over 6 h, an additional 0.2 km displacement is to be anticipated. Maximum displacements of roughly 3 km might be expected due to diurnal and semidiurnal currents (including inertial currents) during extreme events.

The distribution of near-bottom oxygen gradients and extent of mid-summer hypoxia on the southeastern Louisiana shelf are detailed in Fig. 1. The extent of hypoxia near WD32E in 1990 was constricted to a narrow depth range between the birdfoot delta and Grand Isle. The interface of normoxic-hypoxic waters is often near stations A3 and A4, as it was in 1990, with similar distributions for 1987, 1989, and 1991 (Rabalais et al. 1992, unpublished data). Based on the mid-summer synoptic surveys, it appears that there is more variability in the configuration of the hypoxic area within the Mississippi River Delta Bight than in the area off Terrebonne Bay. Stronger bathymetric gradients nearer the delta (Fig. 1) imply that short cross-gradient excursions may move oxygenated water across the measurement area. Comparison of oxygen gradients and bathymetric contours near WD32E (transect A for mid-summer 1990) indicated that a 1 mg l⁻¹ difference in oxygen concentration could occur within 0.9 km to 2 km of the oxygen meter. This is within the calculated distance

←

Fig. 5. Smoothed periodograms of dissolved oxygen time-series at C6A (upper panel), dissolved oxygen time-series at WD32E (middle panel), and bottom pressure at mouth of Terrebonne Bay (lower panel). The smoothing was done with a symmetric, 11-point triangular filter and the results multiplied by a constant factor so that the units of the resultant plots represent estimates of energy spectra. O₁ and K₁ peaks as indicated.

Fig. 6. Comparison of daily near-bottom DO average for station C6A (open circle) and a 2-d lagged average for station WD32E (closed triangle) for the period Julian days 231–252.

of spatial displacement based on near-bottom currents (see above). Mean monthly-averaged daily ranges of DO at WD32E were $0.9 \pm 0.1 \text{ mg l}^{-1}$ to $1.5 \pm 0.2 \text{ mg l}^{-1}$ (Table 1). Similar calculations for station C6A, which occurs on a broader, more gently sloping shelf, indicate that a parcel of water must be displaced 15 km to 18 km to realize a 1 mg l^{-1} difference in oxygen concentration.

Lack of strong winds (until late September to early October) capable of breaking down the locally strong stratification gradients suggests that the reoxygenation at either station (C6A in mid-August to early September, and WD32E for most of the record) resulted from lateral advection rather than vertical mixing. Chuang and Wiseman (1983) analyzed data collected by Gordon (1982) at the Exxon Offshore Test Site near station C6A. They concluded that the near-bottom currents during summer, those that would advect hypoxia, were not strongly driven by local winds. This is again consistent with the weak coherence between wind and dissolved oxygen.

CORRELATION BETWEEN SHORTER RECORDS

The spectral and coherence analyses described above utilized the entire 4-mo period of record. Because so much of the record at station C6A was anoxic, a smaller subset of both records was re-examined for correlation. There was only one extended period in each of the two 4-mo DO time-series when the oxygen concentration was high enough to analyze for correlation in changes between the oxygen concentration at one station and the other. This period was during late August and early September, from Julian day 231 to 252; the DO was above zero at both stations (Fig. 2). The daily average oxygen concentration at station WD32E and the average oxygen concentration at C6A 2 d later are shown in Fig. 6. There was a significant correlation (adjusted $r^2 = 0.47$, $p = 0.0003$) between DO changes between stations.

When the oxygen concentration is rising or falling at station WD32E, the oxygen concentration follows a similar pattern 2 d later at station C6A.

There are at least two explanations for the observed coherence in oxygen concentration between the two stations in this period. First, the distance between stations is 77 km, so the transit time of 2 d between the two stations could be covered by a surface current velocity of 45 cm s^{-1} , if surface water parcels travelled in an assumed downfield and longshore flow. Chuang and Wiseman (1983) measured westward moving surface currents of this velocity in the region during summer. One explanation of the lagged correlation between the two stations is to assume that, all other factors being equal, similar organic loading to the bottom layer from similar parcels of water, but 2 d and 77 km apart, are likely to reach similar equilibrium points for oxygen concentration. A second explanation is that hypoxic waters are formed in the region of WD32E and transported to C6A. Near-bottom currents measured at C6A, however, indicate speeds predominantly $<10 \text{ cm s}^{-1}$, and a longer theoretical transit time (8 d) than the lag observed in oxygen concentrations. Also, mean bottom currents at C6A for 1990 were not statistically indistinguishable from zero (Wiseman et al. 1992).

Conclusions

Continuously recording oxygen meters were placed within 1 m of the seabed in 20-m water depth at two locations on the Louisiana continental shelf. They recorded considerably different oxygen conditions for a 4-mo period from mid-June through mid-October. At station C6A off Terrebonne Bay, bottom waters were severely depleted in dissolved oxygen and often anoxic for most of the record from mid-June through mid-August. Severe hypoxia also persisted for much of the month of September. There were no strong diurnal or diel patterns in the oxygen time-series at C6A. In contrast, at station WD32E, which is 77 km east of C6A and closer to the birdfoot delta of the Mississippi River, $\text{DO} \leq 2 \text{ mg l}^{-1}$ occurred for only 50% of the total record, hypoxic events were shorter in duration than at C6A, and there was a strong diurnal pattern in the oxygen time-series. The record of dissolved oxygen was most coherent with the diurnal bottom-water pressure signal, which suggested the importance of tidal advection in the variability of the oxygen record.

Although the oxygen time-series were considerably different from each other, they were consistent with the processes and conditions relevant to the formation and maintenance of hypoxia on the Louisiana shelf (Rabalais et al. 1991). A highly stratified water-column was present during most of

the periods of record. Wind-induced mixing was insufficient to reoxygenate the water-column prior to the outbreak of cold air fronts in late September and early October, at which time a relaxation in the stratification also occurred due to thermal cooling. Lack of strong winds capable of breaking down the stratification suggested that reoxygenation (at C6A in late August and at WD32E for most of the record) resulted from lateral advection. The depth gradient is gradual at C6A so that the hypoxic area is much broader in a cross-shelf direction and the oxygen meter was less likely to be impinged by a normoxic water mass during upwelling- or downwelling-favorable conditions. The steeper depth gradient in the Mississippi River Delta Bight and the occurrence of mid-water oxygen minima for several of the mid-month hydrographic surveys indicated that the WD32E oxygen meter was often near the edge of a hypoxic water mass and was periodically exposed to hypoxia.

The data analyses presented here focused on high frequency events. Clearly, the obvious temporal signal on the shelf is the annual recurrence of extended periods of hypoxia in mid-summer. On a broader geographic scale and a longer time period, the ecosystem response of the Louisiana continental shelf to the combined riverine influence of the Mississippi and Atchafalaya river effluents is apparent in usually disjunct zones of bottom-water hypoxia that mirror somewhat, in a downplume direction, the surface salinity field and surface phytoplankton biomass concentrations that result from the major freshwater inputs (Rabalais et al. 1991, 1992). The period during which the two oxygen meters were deployed did not capture the formation of bottom-water hypoxia. On a broader seasonal scale, the oxygen deficit in the bottom waters on the southeastern shelf off Terrebonne Bay is significantly correlated with river flow, implying a time-lag of 2 mo from peak flow in April (Justić et al. 1993). Fluxes of organic matter resulting from primary production (which lags peak river flow by 1 mo) are likely to be high and sufficient to induce hypoxia in a highly stratified water-column (Justić et al. 1993). A similar 2-mo lag of bottom-water oxygen depletion to Atchafalaya River flow was found for the southwestern Louisiana shelf (Pokryfki and Randall 1987).

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