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The *Deepwater Horizon* oil spill and Gulf of Mexico shelf hypoxia

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ABSTRACT

The oil/water/dispersant mixture from the 2010 *Deepwater Horizon* oil spill was juxtaposed on the Louisiana continental shelf with the annual development of oxygen-depleted bottom waters. There was uncertainty whether the oil from the spill might worsen the extent or severity of the seasonal hypoxic area formation in 2010. The surface and bottom water hydrocarbons in May were elevated compared to in June and July, while the bottom-water dissolved oxygen concentrations were higher in May and June compared to in July. The degradation of oil in the water column or sediments was not known. The results of an empirical orthogonal functions (EOF) analysis of the progression of hypoxia development in May, June and July 2010, and an analysis of conditions in July compared to a 27-year background database, indicated no difference in oxygen concentrations for May, June or July 2010, with or without oil data included, nor any difference in July 2010 compared to other years. The analysis instead indicated that, in all years compared, the hypoxic area increased with higher river discharge, higher nitrate-N load, an easterly (westward) wind and reduced wind speed. Although the analyses did not demonstrate that the oil spill affected, or did not affect, the size of the 2010 hypoxic zone, there was evidence that the 2010 hypoxia season did not differ from the long-term record.

1. Introduction

Multiple stressors, including the riverine input of nutrients from the Mississippi River Basin, affect the northern Gulf of Mexico continental shelf off Louisiana, Texas and Mississippi. These stressors are expressed as noxious algal blooms in surface waters, low dissolved oxygen conditions in bottom waters (Rabalais et al., 2007a), and an eroding delta and associated coastal land loss occurring at an alarming rate (Couvillion et al., 2011). Increasing nitrogen and phosphorus loads from the Mississippi River Basin exacerbate the low oxygen conditions on the inner to mid continental shelf (Rabalais et al., 2007a; Turner et al., 2012). The 50% reduction of suspended sediments in the last century, along with intrusive human activities in the deltaic plain, result in a delta unable to keep up with sea-level rise (Blum and Roberts, 2009). These features occurred within an area of extensive onshore and offshore oil and gas development and collided with the oil/dispersant/water mixture from the *Deepwater Horizon* oil spill in the spring and summer of 2010.

Hypoxia (defined as dissolved oxygen concentration equal to or less than 2 mg l^{-1}) on the northern Gulf of Mexico continental shelf has been monitored systematically since 1985 (with the exception of 1989 and 2016; Rabalais et al., 2007a). The mechanisms driving the interannual variation are well established (Justić et al., 2002, 2007; Rabalais et al., 2007a), and hypoxia dynamics and distribution can be modeled and predicted with a high level of accuracy (Turner et al., 2012; Justić and Wang, 2014). The development of hypoxia on the Louisiana shelf in 2010 was consistent with the long-term seasonal cycle of higher nitrate-N load in spring, higher river discharge in spring and summer, subsequently higher phytoplankton biomass, and then respiration-driven reduction in dissolved oxygen below a strong pycnocline.

The development of hypoxia and its distribution over the continental shelf west of the Mississippi River delta coincided both spatially and temporally with the progression of oil residue from the *Deepwater Horizon* oil spill across the shelf and its movement onshore and along shore (Fig. 1). The release of 5 million barrels (or 210 million gallons) (McNutt et al., 2012) from the Macondo well at a depth of approximately 1500 m (Lubchenco et al., 2012) over nearly three months followed the *Deepwater Horizon* well explosion on April 20, 2010. The oil/dispersant/water mousse from the *Deepwater Horizon* oil spill extended across the Louisiana continental shelf offshore and onshore to Atchafalaya Bay (Fig. 1). Either the oil-water mousse or oil sheens were observed in surface waters during research cruises in May through July (N.N. Rabalais, personal observations).

Hydrocarbon-degrading bacteria responded to the presence of the

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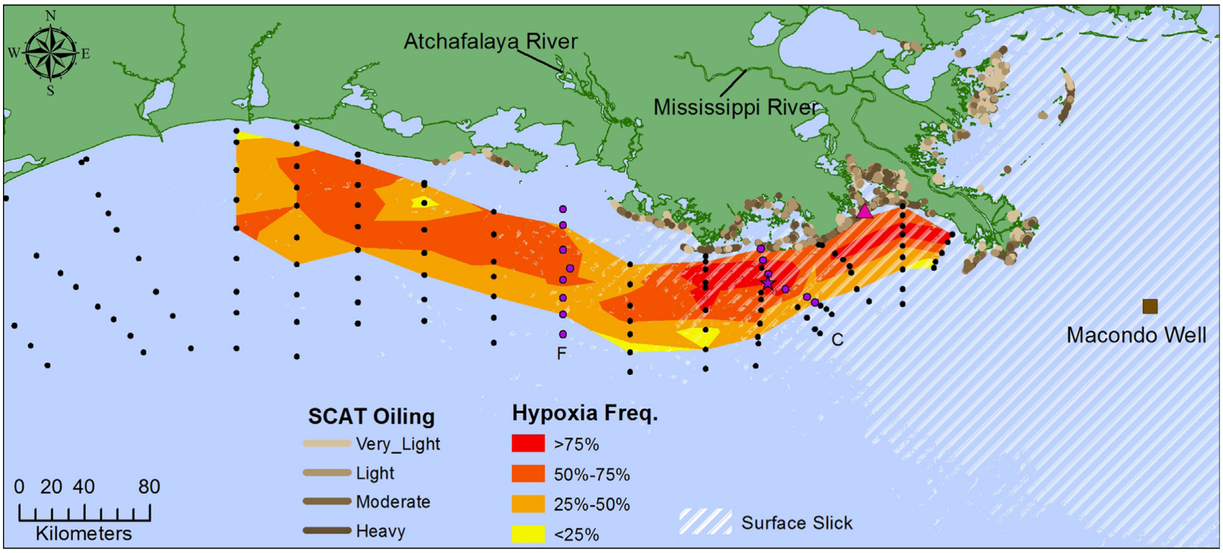

Fig. 1. General area of bottom-water hypoxia in the northern Gulf of Mexico east of the Mississippi River delta. The station grid represents the area where hypoxia has been mapped in mid-summer since 1985 through 2017 (not all stations in all years). The frequency of bottom-water hypoxia occurrence from shelf wide hypoxia mapping from 1985 through 2014 (updated from Rabalais et al. (2007b)) is shown in shades of yellow to red; frequency is determined from stations for which there are data for at least half of all cruises. The extent of the surface slick (white lines) from the Macondo well (brown square) is computed from all of the individual Texture Classifying Neural Network Algorithm (TCNNA) days from Synthetic Aperture Radar (SAR) satellite polygons collected during the spill (http://gomex.erma.noaa.gov/ Accessed 5 May 2017). The Shoreline Cleanup Assessment Technique (SCAT) map for May 2010 to May 2012 (light and brown shading) documents the level of oiling along the shoreline. Stations from transects C and F used in the analyses (purple circles), station C6C (purple star) and the Grand Isle, Louisiana, wind gauge (pink triangle) are identified. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

oil at the well head. Their respiration generated small oxygen anomalies in the water column (Camilli et al., 2010) and in areas down-plume from the well head at 1200 m (Du and Kessler, 2012). The permanent oxygen minimum layer at 400–800 m in the Gulf of Mexico (Rabalais et al., 2002) was "re-discovered" and was thought to potentially affect continental shelf hypoxia (Du and Kessler, 2012), but this was not the case given the earlier described mid-water oxygen minimum layer (Rabalais et al., 2002). Neither the oxygen anomalies nor the oxygen minimum layer approached dissolved oxygen concentrations as low as those associated with the continental shelf hypoxia.

There were scintillating observations of a possible oil degradation signal in bottom waters in the Louisiana bight west of the Mississippi River during a July 2010 cruise that were manifested by a significant deviation from all other years in the relationship between apparent oxygen utilization (AOU) and dissolved inorganic carbon (DIC) (Hu et al., 2016). There were also suggestions from the popular press that, "the BP oil spill was making it even worse. But few people paid much attention to this 25-year-long environmental disaster…." (Wallace, 2010). Some conjectured that the presence of oil coincident with the usual distribution of hypoxia (Fig. 1) could affect the severity and distribution of summer hypoxia on the Louisiana continental shelf in 2010 (e.g., Schmickle, 2010).

The exposure of the surface waters of the Louisiana shelf to residues of *Deepwater Horizon* oil/dispersants is not well quantified, although it can be indirectly suggested from satellite imagery of oil distributions (Fig. 1). Knowledge of the flux of oil from the surface waters to the seabed on the continental shelf where hypoxia forms is minimal. Sediment samples collected in 2010 were in water depths greater than 200 m (Montagna et al., 2013). Sediments from the continental shelf (13–83 m) collected in August 2011 were considered to be "relatively uncontaminated" with very low, often undetectable, levels of oil (Balthis et al., 2013).

Therefore, we applied multivariate techniques to the data associated with the development and distribution of low dissolved oxygen (DO) conditions in 2010, before, during and after the oil spill, along with surface- and bottom-water hydrocarbon samples. These analyses provided information as to whether the 2010 hypoxia during the oil spill in 2010 was anomalous in terms of hypoxia distribution, areal extent, or driving mechanisms as compared to the historical baseline data. Although such an analysis cannot assign cause, or no cause, of oil-mediated hypoxia, it can provide insight as to whether the events and circumstances can be seen as correlated or associated.

2. Methods

2.1. Study area

The Louisiana and upper Texas shelf of the Gulf of Mexico has been sampled systematically in mid-summer since 1985 (with the exception of 1989 and 2016) for the presence of hypoxia and associated environmental factors. The sample area typically extends from the mouth of the Mississippi River at Southwest Pass westward through the eastern Texas shelf (Fig. 1). Transects extend from 5-m water depth to as far offshore as necessary to delineate the distribution of hypoxia, usually 30- to 40-m deep. The transects are routinely extended to generate a more complete dataset for a 50- to 60-m depth contour. The C transect (Fig. 1) is located approximately 100 km west of the Mississippi River delta, and the F transect (Fig. 1) is located perpendicular to the boundary of Atchafalaya Bay and 250 km west of the Mississippi River delta. Transects C and F were sampled in all spring and summer months of 2010 to document the effects of the 2010 Mississippi River flood on hypoxia (purple circles in Fig. 1). Historically, transect C was monitored almost monthly for the period 1997–2011, and transect F was sampled bimonthly during 2002–2011.

The typical mapping from the Mississippi River to the west was modified in 2010 because a tropical storm passed through the eastern part of the study area at the time the cruise was to begin, inhibiting the survey of the eastern area until the storm passed. Mapping began on July 25, 2010 off the Atchafalaya River at transect F (Fig. 1), moved west, and then back towards transects on the eastern part of the study area.

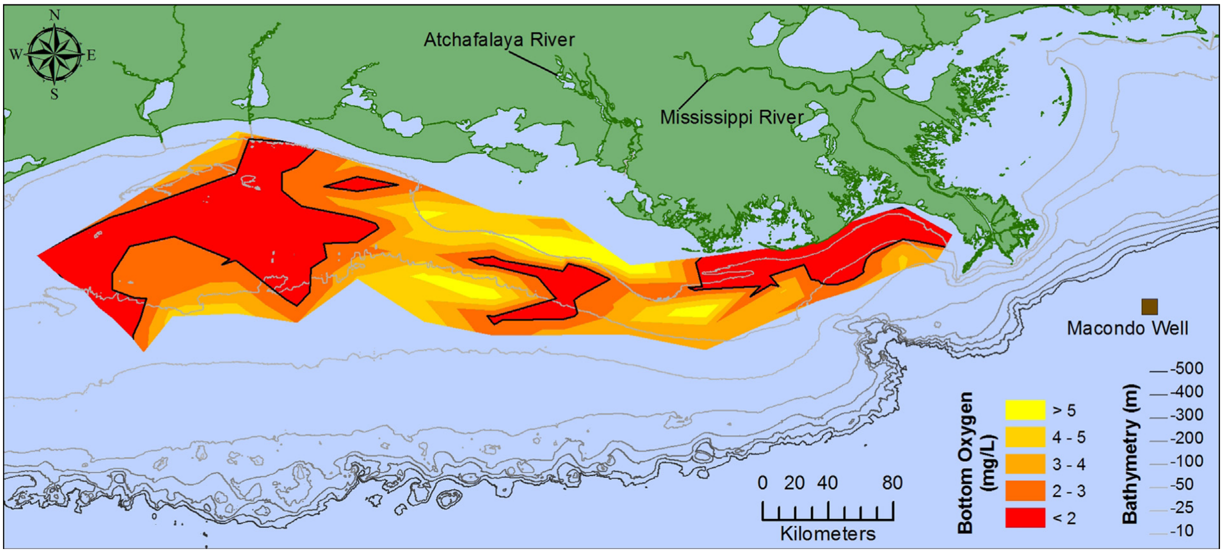

Fig. 2. Bottom-water dissolved oxygen concentration for July 25–31, 2010. The hypoxic area is denoted by the black contour line of 2 mg O_2 l^{-1}. Contour map was created in ArcGIS v10.3.1 using the 3D Analyst Toolbox Triangulated Irregular Network (TIN) interpolation method. The TIN method interpolates data between points by creating a series of non-overlapping triangles and interpolating linearly along each edge. There was no closure of the western boundary of hypoxia due to time limitations.

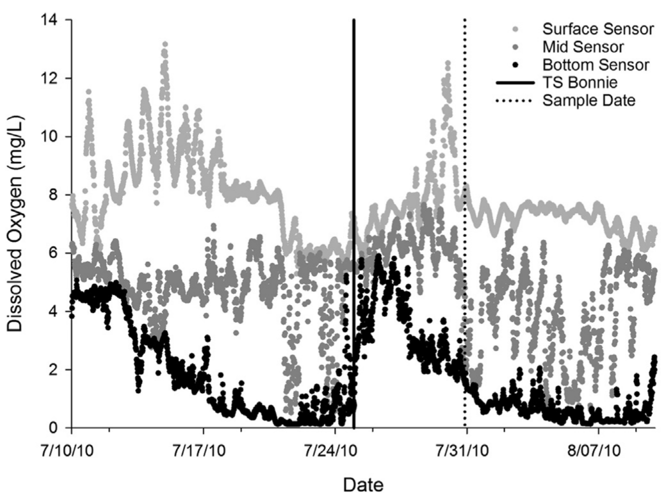

Fig. 3. Continuous dissolved oxygen concentrations (mg l^{-1}) at station C6C (see Fig. 1) from July 10 to August 10, 2010. YSI 6600 sondes were located near the surface (3 m), mid-water (11 m), and near the bottom (19 m). The solid vertical line indicates when TS Bonnie passed over the station; the dashed line indicates station C6C sampling date.

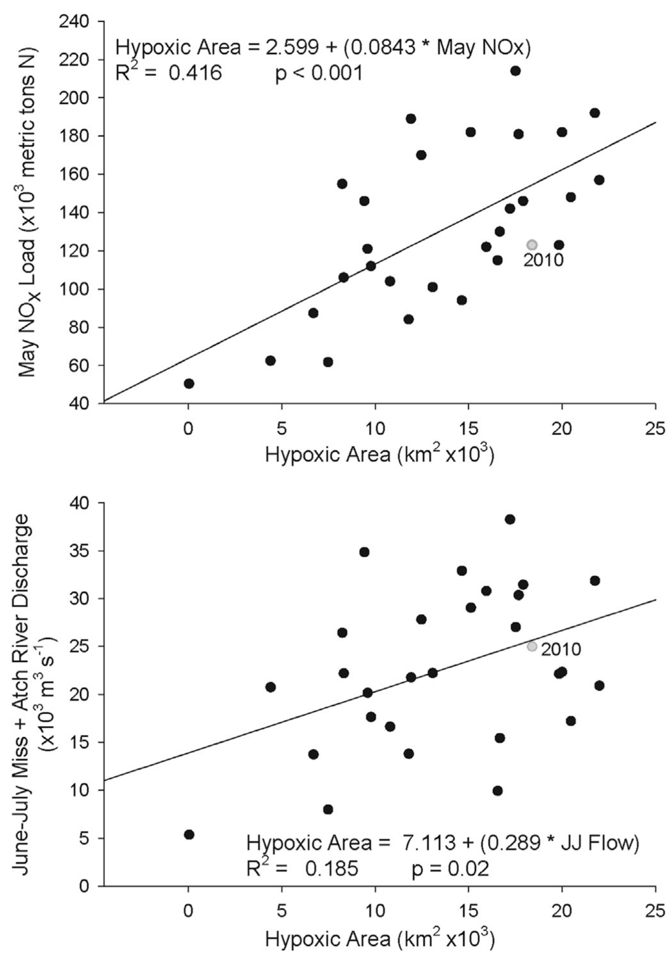

Fig. 4. Comparison of Mississippi-Atchafalaya May nitrate-N load (upper panel) and June-July river discharge (lower panel), and hypoxic area for 1985 through 2014. The data for 2010 are identified by a lighter shade circle.

2.2. Field and laboratory methods

Research vessels, oceanographic and laboratory instrumentation, and analytical methods have changed over the 30-y period that the shelf wide hypoxic area has been sampled, but consistent quality assurance/quality control has been applied to the data generated by the same principal investigators. The more recent instrumentation and methods are described below. The data and metadata can be accessed at the National Oceanic and Atmospheric Administration, National Center for Environmental Information (formerly, the National Oceanographic Data Center).

Hydrographic data for most shelf wide cruises were obtained using the R/V *Pelican* SeaBird SBE91 + CTD system (or equivalent for historic data), which included a SBE 43 dissolved oxygen sensor along with sensors measuring conductivity, temperature, depth, as well as other environmental parameters. The CTD unit included a 12-carousel rosette with 5-L Niskin bottles and was deployed from 1.5 to 2 m below the surface to within 1.5–2 m of the bottom depending on sea state and

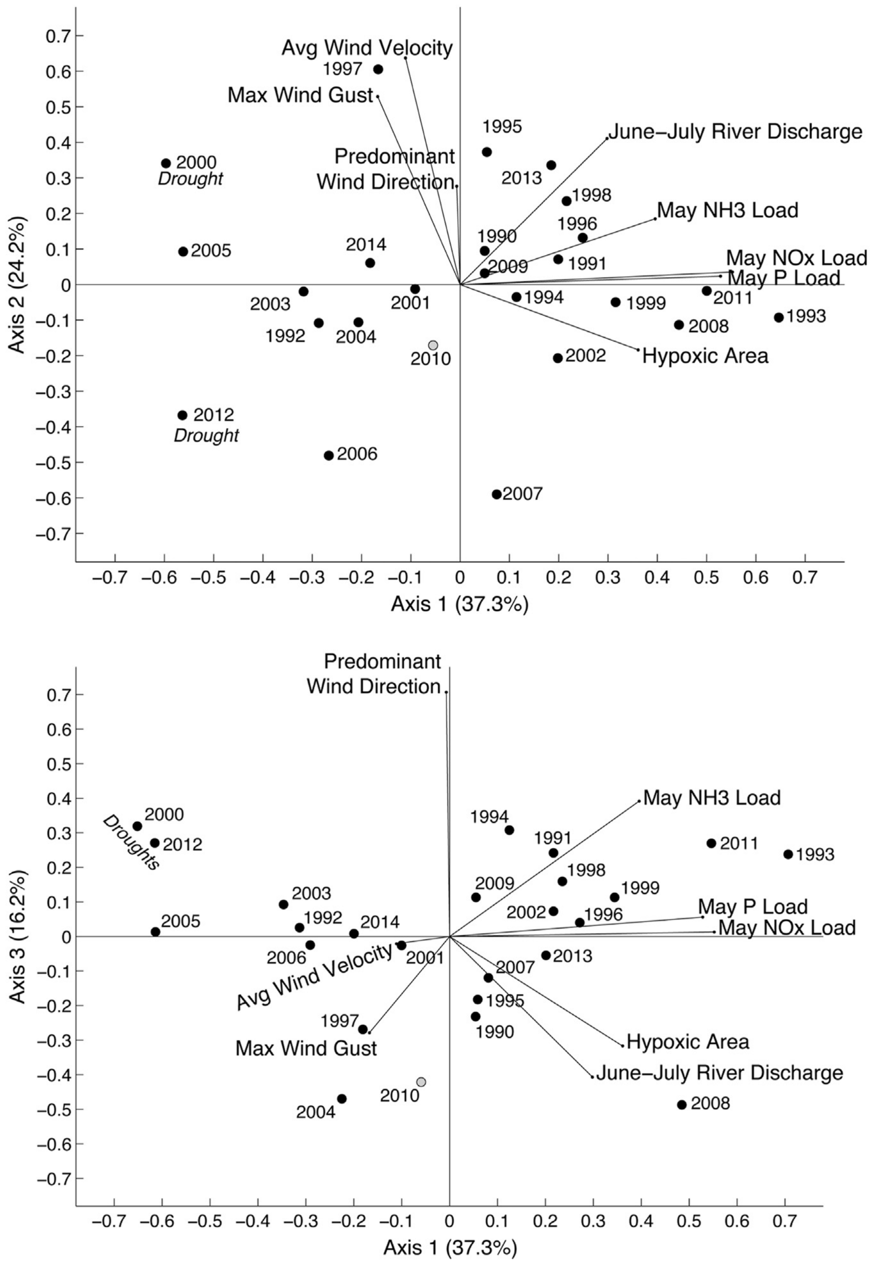

Fig. 5. Empirical Orthogonal Function (EOF) biplot of hypoxic area and related variables as vectors (n = 8) for 1990–2014 (n = 27). Factors include June 15 – July 15 river average daily discharge from the Mississippi-Atchafalaya River watershed. May nitrate + nitrite (NOx), orthophosphate (P) and ammonium (NH3) loads, June 15 – July 15 average daily discharge from the Mississippi-Atchafalaya watershed, and predominant wind direction, wind speed and maximum wind gust within two weeks before and during the cruise. Note that larger magnitude wind values on the plot indicate a westerly wind. Each axis represents the new composite dimension created in the analysis to view the data; the percentage represents the overall variation of the system captured by that axis. Axes are ordered from most to least variance explained. Note, that within the biplot the element with the largest magnitude for each axis is forced to be positive. All other signs for the axis are modified accordingly. Points that are closer together are more similar than those farther away. Similarly, vectors with similar angles are more correlated. Vectors pointing in opposite directions have a strong negative correlation. Vector length (EOF Loading) indicates the strength of that factor in explaining the variation along each axis. Expansion coefficients are plotted as individual data points and represent the transformed variable values for the given axis. Drought years are labeled.

Table 1
EOF loadings by axis for inter-annual shelf wide analysis. Variance explained by each axis is given in parentheses. EOF loadings represent values derived from a correlation matrix along that axis. Numbers are interpreted similarly to correlation coefficients where negative and positive values represent negative and positive correlations, respectively. Values > ± 0.5 are considered strong and are in bold.

	Axis 1 (37.3%)	Axis 2 (24.2%)	Axis 3 (16.2%)
May NOx Load	**−0.5522**	0.0352	−0.0130
June-July River Discharge	−0.2981	0.4104	0.4068
Predominant Wind Direction	0.0071	0.2761	**−0.7066**
Average Wind Velocity	0.1109	**0.6374**	0.0210
Maximum Wind Gust	0.1673	**0.5286**	0.2783
Hypoxic Area	−0.3610	−0.1837	0.3170
May NH3 Load	−0.3957	0.1848	−0.3918
May Ortho P Load	**−0.5282**	0.0236	−0.0561

operator. A YSI 6820 (or equivalent for historic data) was deployed separately at 0.5-m intervals to capture water quality data missed by the CTD rosette within 2 m of the surface and within 2 m of the bottom. Prior to having access to the R/V *Pelican* for monthly cruises, a YSI 6820 (or equivalent) was used to collect data at 1.0-m intervals, or at more narrow intervals where gradients were steep. SeaBird data were post-processed with an "align-CTD" protocol and reported at closest depth to 1-m intervals, or more frequently during steep gradients. SeaBird sensors were maintained via routine factory calibration; YSI 6820 sensors were calibrated in-house per manufacturer specifications. Dissolved oxygen concentration (mg l^{-1}) from both the SBE and YSI sensors were corrected as necessary with data from Winkler titrations; salinity data were corrected with PortaSal (AutoSal equivalent for historical) salinity determinations. Density (kg m^{-3}) was calculated from temperature, pressure and corrected salinity measurements from the CTD unit. Stratification ($\Delta\rho$) was calculated as the difference between surface and bottom density.

Surface and bottom water samples were collected and analyzed for chlorophyll, phaeopigments, a suite of inorganic nutrients and

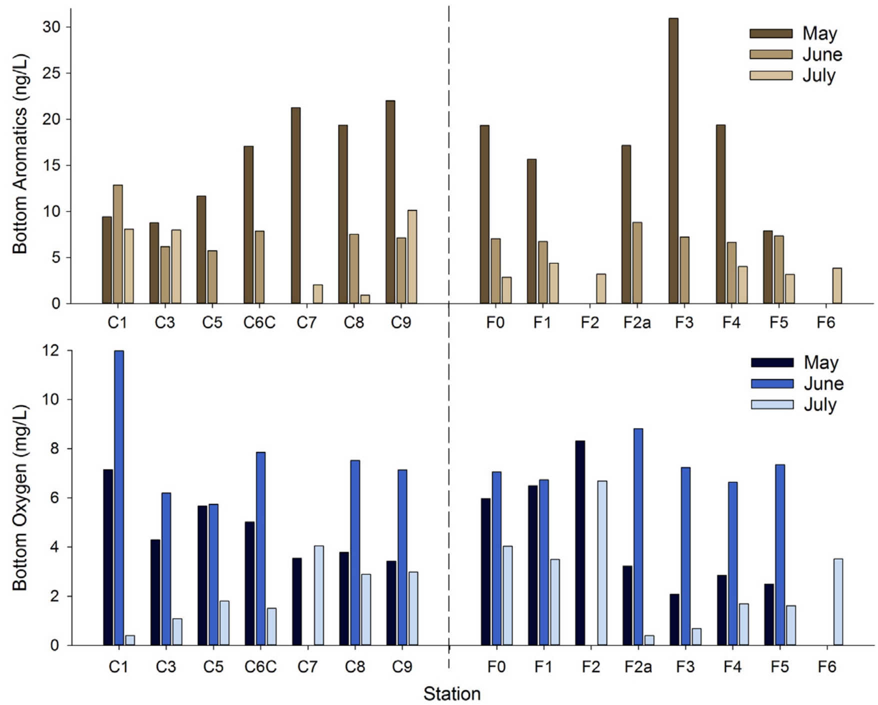

Fig. 6. Bottom-water aromatic hydrocarbon concentrations for transects C and F in May, June and July 2010 (upper panel) and bottom-water dissolved oxygen concentrations for the same months (lower panel).

hydrocarbons. Surface water samples were collected with a surface bucket to capture the often steep salinity, chlorophyll biomass and nutrient characteristics in the uppermost sea surface layer. Bottom water samples were collected using a 5-l Niskin bottle deployed to capture bottom water as close to the sea floor as possible.

Chlorophyll and phaeopigment concentrations (µg l^{-1}) were determined on replicate 10–100 ml water samples filtered through GF/F (0.7 µm) filters, fixed in 5 ml of DMSO/90% acetone (40/60) solution, and extracted for at least 2 h. The solution was measured pre- and post-acidification on a Turner Model 10 AU fluorometer.

Nutrient concentrations (µM) were determined from frozen (4 °C), unfiltered water samples and analyzed in the laboratory within two weeks using EPA methodology (353.2, 350.1, and 365.2) on a Lachat auto-analyzer II system (8000 series) equipped with an autosampler (ASX-400 series). Ammonium concentration was determined using Lachat Instrument's QuikChem method 31–107-06-1-B.

Hydrocarbon water samples were analyzed by the Louisiana State University – Response and Chemical Assessment Team (LSU-RCAT), which has been the primary chemical hazard assessment and analytical support team for NOAA's Office of Response and Restoration. Additionally, the team has analyzed samples from most spills in US Coast Guard jurisdictions over the last 25-years, as well as characterizing a variety of samples of Macondo oil. Samples were collected using accepted standard operating and QA/QC procedures to prevent contamination and avoid sample degradation (Turner et al., 2014). The samples were analyzed by GC/MS (gas chromatography/mass spectrometry) to identify the normal and branched saturated hydrocarbons (from C10 to C35), the one- to five-ringed aromatic hydrocarbons and their C1 to C4 alkyl homologs, and the hopane and sterane biomarkers. All GC/MS analyses used an Agilent 7890 A GC system configured with a 5% diphenyl/95% dimethyl polysiloxane high-resolution capillary column (30 m, 0.25 mm ID, 0.25-micron film) directly interfaced to an Agilent 5975 inert XL MS detector system. The MS was operated in the Selective Ion Monitoring (SIM) to maximize the detection of the target constituents unique to crude oil. Surface and bottom water aromatics (ng l^{-1}) were used in this analysis.

The bottom-water area of hypoxia (km^2) was determined by interpolating between sampling locations and hand-contouring parallel to isobaths over a calibrated (planimeter) grid. Bottom oxygen (mg l^{-1}) concentration data from the YSI 6820 were used for each sampling location. It should be noted that, at times within the historical data, the bottom-water dissolved oxygen data from the CTD and the hand-held YSI 6820 equivalent were not collected together. When only the CTD data were available, then its bottom-water oxygen values were adjusted to extend from the CTD measured depth (roughly 2-m above the bottom) to a bottom depth more similar to the YSI according to relationships between the dual CTD and YSI data (Obenour et al., 2013). If these calculations changed any of the original spatially generated maps of N.N. Rabalais, then the estimate of bottom-water hypoxia was re-calculated. The percentage difference of those not changed and those changed over a 27-y period was 0.006%. Recalculated area estimates by N.N. Rabalais were used in this analysis (http://www.gulfhypoxia.net).

2.3. Additional parameters

Wind direction data were from the coastal NOAA National Data Buoy Center (NDBC) station on Grand Isle, Louisiana (Fig. 1). Data were available from station GDIL1 from 1990 to 2005 when the station received extensive damage during Hurricane Katrina, and station GSIL1 (replacement for damaged GDIL1) from 2005 to 2014 (NBDC http://www.ndbc.noaa.gov/). The values of pre-dominant wind direction were calculated for the 2-wk period before the start of each mid-summer cruise and for the duration of the cruise. Wind data were converted from degree direction (e.g., 90° to cardinal direction) for each day, with the most common wind direction (mode) selected for each time period.

The average wind speed (m s^{-1}) data were collected from the same instruments as used for wind direction. Before averaging, the wind speed values were calibrated to the standard height of 10 m using the logarithmically varying wind profile equation (Mears et al., 2001). Average wind speed data for the shelf wide cruise analyses included the two weeks prior to and during the cruise as a unique data point for the analyses. Average wind speed for the transects C and F analyses were a running average for the two weeks prior to each day of the three 2010 monthly cruises.

Average wind gust (m s^{-1}) data were collected from the same instruments as used for wind direction and speed. Wind gusts were

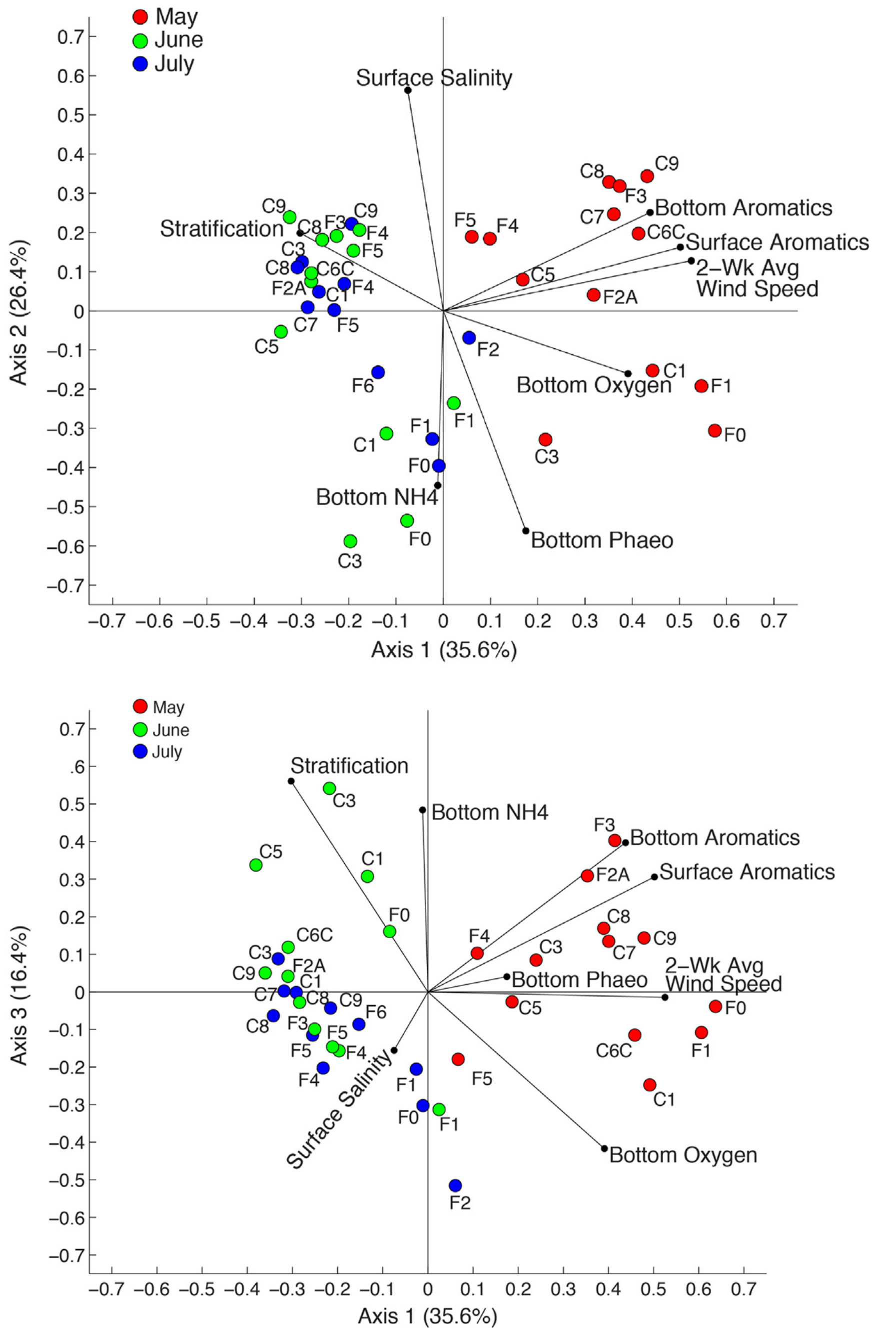

Fig. 7. Empirical Orthogonal Function (EOF) biplot of the May-July C + F transect data with oil included. Factors include bottom-water oxygen, ammonium (NH4), phaeopigments and aromatic hydrocarbons, surface-water salinity and aromatics, stratification and average wind speed for two weeks before the day of sampling. See Fig. 5 for a full description of the biplots.

calculated from the maximum 5-second peak gust during each measurement hour, averaged for each day over the period of two weeks prior to and during the shelf wide cruises, from which the maximum wind gust value over the 3 + -wk period was used. The values ranged from 4.4 to 18.2 m s^{-1} and provided a shelf wide indicator of how high winds during a cruise could disrupt water column stratification.

Mississippi River nutrient load data for 1985–2014 were obtained from the US Geological Survey (USGS, toxics.usgs.gov) long-term water quality stations at St. Francisville, Mississippi (Mississippi River basin) and at Melville, Louisiana (Atchafalaya River basin, which includes the combined flow from the Old River Control Structure outflow and the Red River). The loads were estimated by USGS through the adjusted maximum likelihood estimation (AMLE) method using the LOADEST program, and represented the total Mississippi-Atchafalaya basin load delivered to the Gulf of Mexico in metric tons (https://toxics.usgs.gov/pubs/of-2007-1080/sources.html). The nitrate load is reported as NO2 + NO3 (metric tons as N) the ammonia load, as NH3 (metric tons as N); and the orthophosphate load, as OrthoP (metric tons as P). The load of $NO_3 + NO_2$ is typically referred to as the ‘nitrate’ load, despite the inclusion of nitrite, because the concentration of nitrite is minimal.

The river discharge ($\times\ 10^3\ m^3\ s^{-1}$) data for 1985–2014 were obtained from the US Army Corps of Engineers (rivergages.mvr.usace.army.mil) stations on the Mississippi River at Tarbert Landing, MS (station 1100) and Atchafalaya River at Simmesport, LA (station 3405).

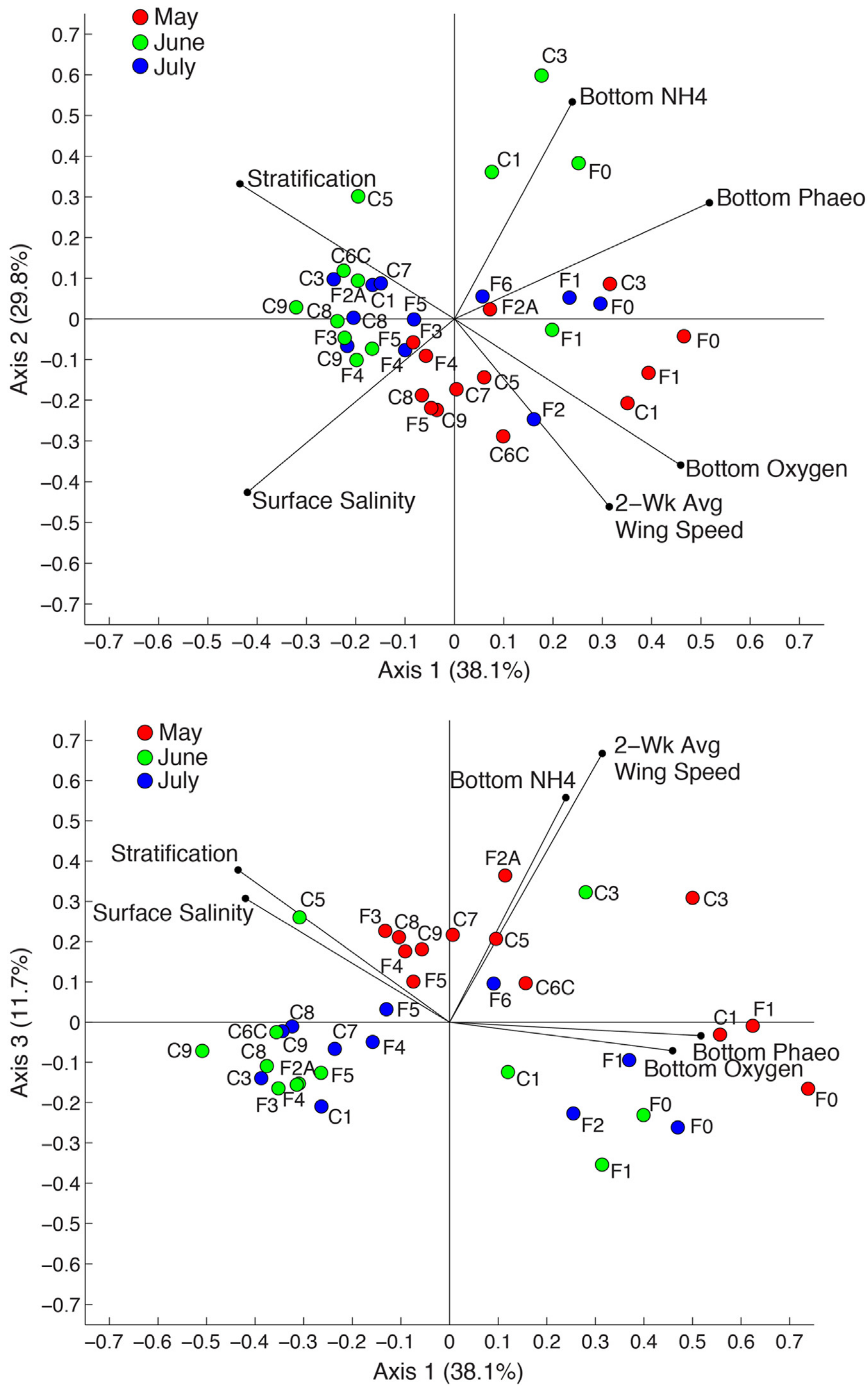

Fig. 8. Empirical orthogonal function (EOF) biplot of the May-July C+F transect data without oil data. Factors used in this analysis are the same as Fig. 7, with the exception that surface and bottom oil data were excluded. See Fig. 5 for a full description of the biplots.

Both stations are downstream of the Old River Control Structure that diverts about one-third of the Mississippi River flow to the Red River to form the Atchafalaya River. The sum of the two stations represents the total discharge for the Mississippi-Atchafalaya River Basin. Average daily river discharge data from June 15 to July 15, just prior to the late July shelf wide cruise were used in the statistical analysis. It should be noted that May river discharge data are a component of the May nutrient load calculation; as such, the data were not included as a parameter in this analysis. June-July discharge data were included in the analysis in order to examine the influence of continued discharge into the summer that would influence stratification.

2.4. Multivariate statistical analysis

The data were normalized and detrended to compare variables measured on different scales and units. Correlation biplots were created using the empirical orthogonal function (EOF) analysis function in MATLAB 7.10.0 (R2010a) to determine relationships among environmental variables, and between stations and years.

An empirical orthogonal function (EOF) analysis is a powerful statistical tool used to understand the interactions within a complex system by examining them in terms of a smaller number of prominent modes of variability (Hannachi et al., 2007). This technique is used widely in oceanographic, atmospheric and climate analyses given the

Table 2

EOF loadings by axis for 2010 monthly analysis. Variance explained by each axis is given in parentheses. EOF loadings represent values derived from a correlation matrix along that axis. Numbers are interpreted similarly to correlation coefficients where negative and positive values represent negative and positive correlations, respectively. Values > ± 0.5 are considered strong and are in bold.

May-July 2010 C+F analysis without oil			
	Axis 1 (38.1%)	**Axis 2 (29.8%)**	**Axis 3 (11.7%)**
Bottom Oxygen	0.4589	−0.3599	0.0710
Bottom Phaeopigments	**0.5175**	0.2856	0.0334
Bottom NH4	0.2393	**0.5333**	**−0.5577**
Surface Salinity	−0.4199	−0.4263	−0.3072
Stratification	−0.4350	0.3319	−0.3779
2-week wind average	0.3142	−0.4612	**−0.6676**
May-July 2010 C+F analysis with oil			
	Axis 1 (35.6%)	**Axis 2 (26.4%)**	**Axis 3 (16.4%)**
Bottom Oxygen	0.3908	0.1604	−0.4170
Surface Aromatics	**0.5020**	−0.1620	0.3063
Bottom Aromatics	0.4376	−0.2506	0.3971
Bottom Phaeopigments	0.1747	**0.5612**	0.0403
Bottom NH4	−0.0115	0.4451	0.4839
Surface Salinity	−0.0751	**−0.5625**	−0.1554
Stratification	−0.3031	−0.1984	**0.5608**
2-week wind average	**0.5250**	−0.1276	−0.0146

complexity of these systems (Hannachi et al., 2007; Monahan et al., 2009). An EOF analysis can be viewed as synonymous with a Principal Components Analysis (PCA) as both analyses transform a multivariate dataset into a series of orthogonal basis functions. An EOF analysis differs from a PCA, however, in that it is also able to tease apart the spatial and temporal patterns in the data (Hannachi et al., 2007). This difference makes an EOF analysis preferable for long-term data covering a broad spatial extent.

An EOF analysis of the historical data ($n = 27$ y) was conducted using data from the mid-summer shelf wide cruises collected from 1990 through 2014. The breadth of shelf wide data that could represent processes involved in the shelf wide distribution of hypoxia was limited. We used variables in the inter-annual comparison that would test against "average" bottom-water area of hypoxia. These variables were restricted to those that would characterize an area estimate, and not individual stations as in the monthly comparison. The analysis did not cover the full extent of the historical data set (since 1985) because of limited wind data and the missed sampling in 1989.

An analysis of monthly 2010 data included data from May, June and July for C and F transects. An EOF analysis was conducted on surface and bottom water parameters both with and without the inclusion of oil data. The parameters analyzed included bottom oxygen concentrations and hypoxia-related environmental data - stratification, surface salinity, bottom ammonium, bottom phaeopigments and average wind speed from two-weeks prior to sample date. Similar to variables in the historical data analysis, the variables in the 2010 monthly analysis were selected because they had been previously described as associated with the formation of hypoxia. The surface salinity was included as an in situ indicator for the distribution of river discharge, the bottom-water phaeopigments as an indicator of dead phytoplankton biomass available for respiration, and the bottom water ammonium data as an indicator of organic matter remineralization under hypoxic conditions. Water column stratification and wind speed were included because of their well-established relationship with hypoxia formation in the Gulf of Mexico; they support the physical characteristics under which respiration and oxygen depletion can occur, or because they re-aerate the water column to alleviate the symptoms of hypoxia (Rabalais et al., 2007a). Stratification and surface salinity were both included because two density layers in the late summer can be influenced by surface salinity and cooler, lower water column temperatures (Rabalais et al., 2007a).

3. Results

The size of the mapped hypoxic area in 2010 (Fig. 2) was estimated at 18,400 km^2 (Rabalais and Turner, 2010) but was larger than the 1985–2015 average of 13,752 km^2 (Rabalais and Turner, 2015). Some contributing factors to the smaller than expected size were the disruption of hypoxia due to Tropical Storm Bonnie, and the lack of time to finish the western end of the survey area.

The overall hypoxic area may have been more continuous along the shelf in the absence of the tropical storm. Evidence of the storm's effect can be observed in the high wave height data from station C6C (=CSI-6, http://wavcis.csi.lsu) and from the re-aeration of the bottom water (Fig. 3) at the time of the storm. Hypoxia was re-established on the eastern part of the study area, by July 30, 2010 when those stations were sampled. The sampling nearer the Mississippi appears to have been sufficiently delayed (5 days) to allow stratification to re-form and bottom oxygen to decrease (Fig. 3).

3.1. Comparison with the Long-Term Data

The estimated area of bottom-water hypoxia (1985–2014, n = 29) varied in parallel with the May nitrate loading ($R^2 = 0.416$, $p < 0.001$) from the Mississippi-Atchafalaya watershed and the June-July river discharge ($R^2 = 0.185$, $p < 0.02$) (Fig. 4). Drought years, such as 2000, were characterized by low discharge and nitrate loading and a small hypoxic area, while flood years, such as 1993, with high discharge and nitrate loading, were characterized by a large hypoxic area (Rabalais et al., 2007a). Anomalous years, such as 2003, were related to hurricane or tropical storm events occurring within two weeks before the sampling cruise or during the cruise that de-stratified the water column and re-aerated bottom waters.

The results from the Empirical Orthogonal Functions (EOF) analysis indicated that, in general, the hypoxic area increased with higher discharge, higher nutrient loads (nitrate and orthophosphate), lower wind velocity before the cruise and an easterly (westward) wind (Fig. 5). The June-July river discharge and May nutrient load were correlated along axes 1 and 2, which collectively explained more than 75% of the variation in the data (Table 1). The year 2010 (light gray dot with black outline) falls within the data cloud of other years within the 27-y data, and aligns most closely to other years with high river discharge and easterly (westward) winds. Anomalous years in the analysis were years known to have had droughts (2000 and 2012).

3.2. Conditions in May, June and July 2010 (transects C and F)

The bottom-water aromatic hydrocarbon concentrations were highest during the mid-May cruise, which was approximately one month after the spill began (Fig. 6). The concentrations were sharply lower during the June cruise at most stations and again in July (Fig. 6). Spatially, the highest concentrations were observed at the offshore stations of transect C (C6C to C9), and inshore portion of the F transect (F0–F4). The dissolved oxygen concentrations for bottom water were typically lower in May than in June, with bottom waters of transects C and F being mostly hypoxic in July.

The EOF analyses for monthly 2010 data were conducted with and without oil data. The May station data were distinctly separate from the June and July station data in the EOF analysis when the oil data were included (Fig. 7). Conversely, when the oil data were not included in the analysis, the May station data were within the cloud of the other two months of data (Fig. 8). May station data were strongly and positively associated with wind speed and a correspondingly negative association with stratification, indicating an aerated water column (Fig. 8). Irrespective of oil, the oxygen concentrations in June and July were correlated with stratification, wind speed and surface salinity (Figs. 7 and 8). These forcing factors paralleled the influence of stratification on the overall hypoxic area observed for the 27-y data (Fig. 5) (Table 2).

4. Discussion

4.1. Comparison of 2010 with the Long-Term Data

The long-term data associated with hypoxia studies since 1985 provided a sound baseline for comparison with the conditions of similar parameters during the exposure of the Louisiana continental shelf to the *Deepwater Horizon* oil/water/dispersant mixture. An analysis of these data provides a means to identify interannual variability and causal mechanisms.

Parsons et al. (2015) compared the May-October 2010 phytoplankton data with similar collections from the 1990–2009 hypoxia dataset. The phytoplankton abundance was 85% lower in 2010 versus in the baseline, and the species composition shifted from ciliates and phytoflagellates towards diatoms and cyanobacteria. This analysis of phytoplankton abundance and community composition data shows a difference in years, but with an inference for indirect evidence suggesting that the *Deepwater Horizon* oil spill may have had an impact on Louisiana coastal waters west of the Mississippi River. The shift from a 'summer' phytoplankton community composition to a 'spring' phytoplankton composition in summer 2010 may reflect conditions during the 2010 Mississippi River flood in summer that were more typical of a 'spring' condition over the longer term (Dortch et al., 2001). Additional toxicological studies may help refine the field data.

In the case of our study of hypoxia, there was no adequate way to compare whole ecosystem indicators through any manipulation. By comparing 27-y baseline data, however, we can state that the area and conditions of hypoxia in the shadow of oiled continental shelf waters were similar to other years, providing indirect evidence to suggest no impacts on hypoxia size. The multivariate analysis of the historical data, including the 2010 data, identified similar factors in all years associated with the area of hypoxic bottom waters. Overall, hypoxia on the Louisiana-Texas shelf during the shelf wide survey of 2010 was as would be expected within the context of the 27-y dataset, i.e., hypoxia developed during periods of stratification following spring nutrient-enhanced organic matter flux of phytoplankton as cells or zooplankton fecal pellets to the seabed (Rabalais et al., 2007b). The parameters responsible for 75% of the variation in the data (axes 1 and 2) were: higher river discharge from 15 June to 15 July, the strength of stratification; higher May nutrient load, responsible for the amount of organic matter flux that drives respiration and depletion of oxygen; and an easterly (westward) wind that pushes the hypoxic water mass toward the west leading to a larger footprint for hypoxia (Cochrane and Kelly, 1986; Rabalais et al., 2007a).

4.2. Oil Presence in 2010

Hydrocarbons, either as sheen or mousse, were observed by cruise participants in May, June and July of 2010, and also quantified for surface and bottom waters. The stations furthest offshore along transect C, closer to the Mississippi River delta and the observed oil plumes, had higher concentrations of aromatic hydrocarbons than those closer to shore. Conversely, at the F transect off the Atchafalaya River, the concentrations of aromatic hydrocarbons were higher closer to shore. These distributions are similar to those modeled as oil was injected into the Louisiana bight and then became entrained in the alongshore Louisiana Coastal Current (Justić et al. unpubl.). The aromatic hydrocarbon concentrations were highest in the bottom waters of the shelf during May. This coincided with a time in which high winds prevailed and the water column was well mixed – circumstances under which hypoxia does not form. Hydrocarbon concentration dropped off sharply in July, a time of increasing stratification and decreasing bottom oxygen concentrations. Results of Balthis et al. (2013) suggest that the flux of surface oil to the seabed (where hypoxia is formed) was limited in these offshore shelf waters following the spill, with sediments exhibiting normal background levels of PAHs and other hydrocarbons over broad areas of the shelf including ones coinciding with the present study area.

Hu et al. (2016), sampled the inorganic chemistry of the water column concurrently with our 2010 shelf wide sampling and conjectured that the microbial metabolism of oil was the reason for four stations (A5, A7, B9, C9) falling outside of the main relationship between AOU (apparent oxygen utilization, µmol kg^{-1}) and DIC (dissolved inorganic carbon, µmol kg^{-1}) according to organic matter reaction stoichiometry. There were, however, 81 other stations that were consistent for the main AOU and DIC relationship for 2010 and four other years with July data, similar to the long-term data for the continental shelf where hypoxia forms.

5. Conclusion

The multivariate analyses identified the representative and overall factors driving the formation and maintenance of hypoxia in the Gulf of Mexico adjacent to the Mississippi River. We can be confident, therefore, that 2010 indeed was not an anomalous year within the context of the greater dataset (1990–2014). The size of hypoxia in summer 2010 was related to similar processes – nitrogen loading, river discharge, wind direction, and the presence of a tropical storm. This lack of difference in the 2010 oil spill hypoxia season may have been related to: (1) the timing of the spill and diminishing hydrocarbon concentrations from May to July, (2) insufficient oil exposure data and time series across the broad area of hypoxia, and (3) the underlying mechanisms that fuel hypoxia – the river flow and nutrient load leading to organic loading to the sea floor –overshadowed any impact of the remaining oil during July. We consider the conditions of the hypoxic area during 2010 to be "business as usual."

The presence of the oil spill at a time when hypoxia develops drew public attention to more water quality issues in the northern Gulf of Mexico than the oil spill. It is imperative that safety controls and enhanced offshore oil development procedures prevent more serious oil spills from deeper water production. It is also imperative that application of mitigation efforts within the Mississippi River basin also work to reduce nitrogen loads and minimize hypoxia and its effects on living resources. Finally, this analysis is only possible because of the long-term baseline data stemming from a 30-year funded series of hypoxia studies in the northern Gulf of Mexico. Funds for the hypoxia program and others like it are becoming rarer amid calls for better background data to better define oil spill impacts. The opposite should be the case.

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0129417, 0162101, 0162440, 0161219, 164298). Data specific to 2010 can be found at NODC Accession 0117436, also doi: 10.7266/N7W66HP0. The river discharge data for 1985–2014 were obtained from the US Army Corps of Engineers (rivergages.mvr.usace.army.mil) stations on the Mississippi River at Tarbert Landing, MS (station 1100) and Atchafalaya River at Simmesport, LA (station 3405). Mississippi River nitrate, orthophosphate and ammonium load data for 1985–2014 were obtained from the US Geological Survey (USGS, toxics.usgs.gov). Wind data were available from station GDIL1 on Grand Isle, LA from 1990 to 2005 at [NOAA National Data Buoy Center (NDBC), doi: gov.noaa.nodc:0117682]. Wind data were available from station GSIL1 (replacement for damaged GDIL1) from 2005 to 2014 (NBDC http://www.ndbc.noaa.gov/).

Contributors

N. N. Rabalais and R. E. Turner have been Co-Principal Investigators of northern Gulf of Hypoxia hypoxia studies from 1985 to present, designed the study, and provided all 'hypoxia' data. L.M. Smith collected all ancillary data, conducted the statistical analyses, and generated the figures. They have collaboratively collected and analyzed all data. All authors have approved the final article. Neither NOAA nor GoMRI participated in the study design, analyses, and interpretation of the data or development of the publication.

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