



Recently Observed Seasonal Hypoxia within the Gulf of Mexico in the Chandeleur Sound of Southeastern Louisiana and Mississippi Bight of Coastal Mississippi

Andreas Moshogianis, B.S., John Lopez, Ph.D., Theryn Henkel, M.S., Andy Baker, M.S., and Ezra Boyd, Ph.D.

Introduction

The Chandeleur Sound is the shallow-water area located between the Chandeleur Islands and the Biloxi Marsh, north of the Mississippi River delta and south of the barrier islands (Cat Island and Ship Island) along the Mississippi Coast. The Chandeleur Sound extends southward behind remnants of the Curlew and Gosier Barrier Islands and connects to Breton Sound to the south. The two sounds are separated by the Mississippi River Gulf Outlet (MRGO) conveyance. At the north end of Chandeleur Sound, the seafloor forms a broad trough which slopes seaward toward the Gulf of Mexico and narrows westward to the Cat Island Channel south of Cat Island, Mississippi. The Lake Pontchartrain Basin Foundation (LPBF) has monitored water quality in the Sound in 2008, 2010, 2011 - working in partnership with the Marine Research Assistance Council (MRAC) and the Louisiana Universities Marine Consortium (LUMCON) - and 2012. MRAC is a volunteer organization of mariners based in New Orleans which conducts scientific and environmental research and education. The cumulative observations to date have revealed that an area of hypoxia develops in this area seasonally. LPBF will continue seasonal monitoring in 2013. Reports outlining the results of the 2008, 2010, and 2011 monitoring can be found at <http://saveourlake.org/PDF-documents/our-coast/Chandeleur-2011-Hypoxia-FINAL-Jan2012.pdf>. This report summarizes the 2012 water quality observations collected by LPBF.

Hypoxia

Hypoxia, or oxygen depletion, is an environmental phenomenon that occurs when dissolved oxygen concentrations in the water are reduced to a point detrimental to aquatic organisms living in the system. In the northern Gulf of Mexico, hypoxia is defined as a concentration of dissolved oxygen below 2 mg/L (Rabalais et al., 2010; EPA, 2012). Hypoxic waters, often termed “dead zones” are most prevalent in the coastal waters of the United States from late spring through late summer and are becoming more frequent, widespread, and persistent (Committee on Environment and Natural Resources, 2010; Rabalais et al., 2010).

The formation of hypoxia (**Figure 1**) may be a result of a number of factors, from both natural and anthropogenic sources, but are mainly driven by excess nutrients to a system (eutrophication – see below), and stratification of the water column due to salinity and temperature gradients (EPA, 2012; LUMCON, 2012). Freshwater discharge from rivers introduces nutrient-rich water into an ecosystem. Phytoplankton, or algae, feed on these nutrients and sink because of their increased size and biomass (Bricker et al., 1999). Throughout the water column, zooplankton eat algae. As the phytoplankton are consumed, zooplankton excrete fecal pellets which sink to the seafloor where bacteria decompose the nutrient-rich fecal pellets and algae. This process known as bacterial respiration, consumes most of the life-giving oxygen supply in the bottom waters, resulting in organism stress and mortality (Howarth et al., 2011). In the Gulf of Mexico, the increased turbidity from the Mississippi River discharge limits phytoplankton production in bottom waters because light does not penetrate this region of the water column, therefore phytoplankton cannot produce oxygen through photosynthesis in the bottom waters (Bricker et al., 1999; Anderson et al., 2002; Howarth et al., 2011).

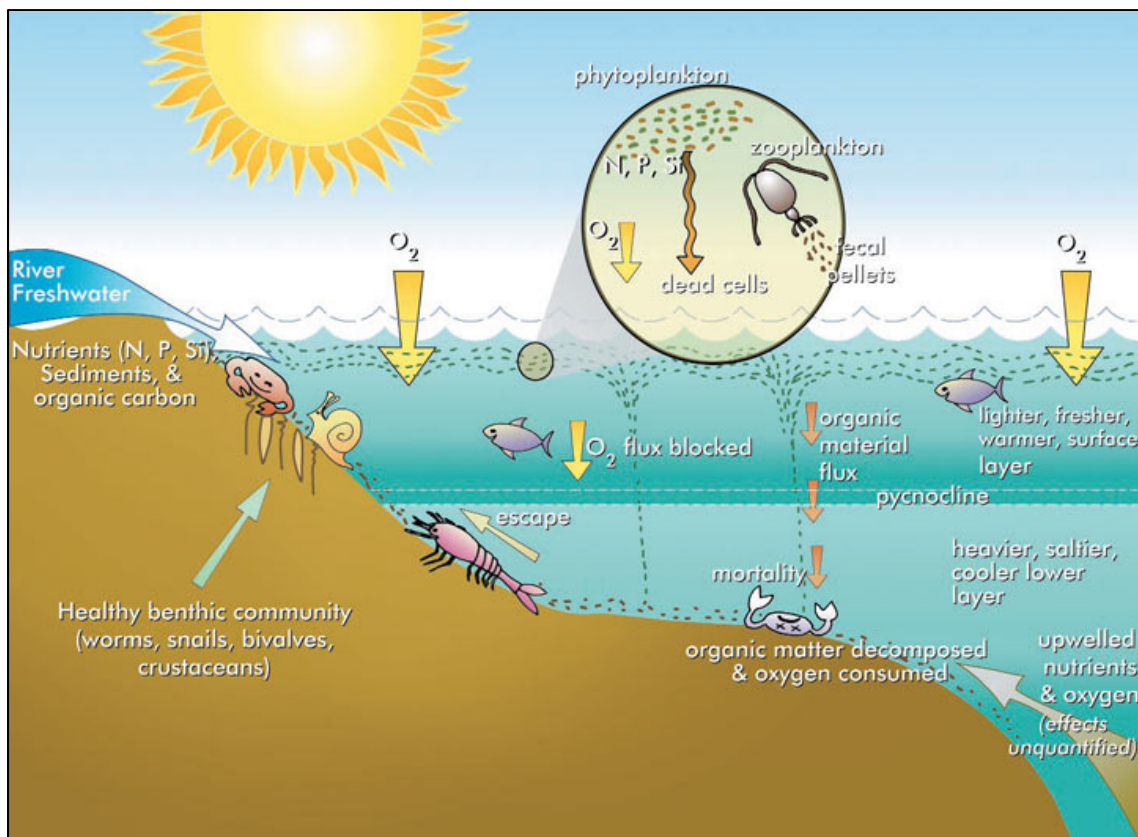


Figure 1. Schematic showing how hypoxia can develop at depth in the water column.

Source: <http://water.epa.gov/type/watersheds/named/msbasin/hypoxia101.cfm>

In addition to eutrophication, stratification of the water column is essential in the development of hypoxia. Freshwater discharge contains fresh (zero salinity) water which is less dense than the saline and cold bottom water of the ocean. As river discharge brings warmer, fresh water to a coastal environment, the freshwater floats on top of the more dense (higher

salinity, lower temperature) oceanic water. This process causes a pycnocline to develop, or layer where the density gradient is greatest, which prevents vertical mixing of oxygen-rich surface water with oxygen-depleted bottom water of the Gulf (EPA, 2012).

As a result of seasonal stratification of the water column in the absence of strong winds or currents, oxygen consumption rates in the bottom water easily exceeds the rate of resupply of oxygen from both primary production, and diffusion of oxygen from the atmosphere into the lower reaches of the water column, resulting in hypoxia, or low dissolved oxygen concentrations (Howarth et al., 2011). During the fall and winter, a strong storm like a hurricane or cold front, can induce strong mixing which is the most rapid and efficient mechanism to deliver oxygen to the bottom (LUMCON, 2012).

Eutrophication

Eutrophication is an increase in the rate of supply of organic matter and chemical nutrients (primarily nitrogen and phosphorus) to an ecosystem to an extent that increases the primary productivity of the ecosystem. Although eutrophication is a natural process, in recent years eutrophication has been accelerated by human or anthropogenic activities where the release of sewage effluence and agricultural run-off carrying fertilizers is introduced to an aquatic system (Jorgensen and Richardson, 1996; Bricker et al., 1999).

Summary of 2008, 2010, and 2011 Results

In 2008, two marine surveys fortuitously documented the occurrence of a low oxygen layer in Chandeleur Sound. In June 2008, the University of Southern Mississippi was conducting shark research and collected environmental data and water quality data in the Chandeleur Sound. Later that month, the Nekton Research Laboratory at the University of New Orleans was en route to do research around the Chandeleur Islands and collected water quality data while crossing the Chandeleur Sound. These two data sets were provided to LPBF and are shown on **Figure 2**.

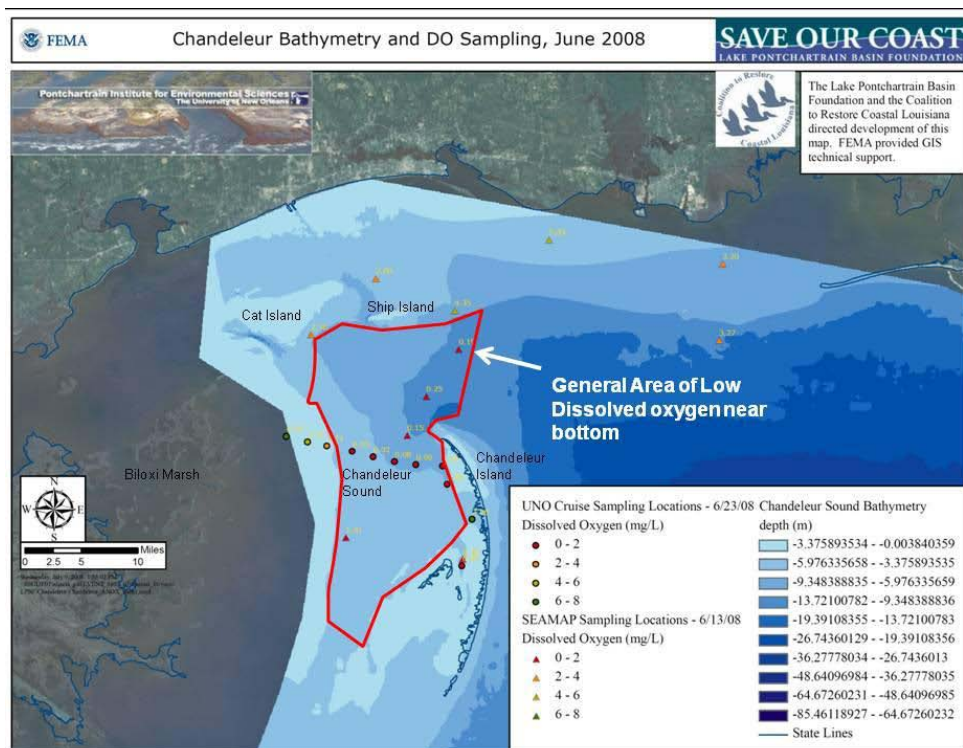


Figure 2. Map of the Chandeleur Sound area and the approximate location of low dissolved oxygen observed in 2008 by University of New Orleans and the University of Southern Mississippi.

In July 2010, LPBF, in partnership with MRAC, developed a water quality monitoring protocol for the Chandeleur Sound which was surveyed to ascertain if the low dissolved oxygen detected in 2008 was an anomaly for that year or if it was a reoccurring phenomenon. Briefly, Two transects were selected which crossed the deepest axial through portions of the Chandeleur Sound. One transect ran through the Cat Island Channel to the deep hole near the northern end of Chandeleur Sound. The other transect ran from eastern Ship Island southward to the central area of the Chandeleur Sound. A YSI Pro-2030 meter with a 90 foot cable was used to measure salinity, temperature, and dissolved oxygen concentrations. The YSI cable was marked at two-foot intervals. First, the total depth was determined using two on-board acoustic depth finders. Next, the probe on the instrument was lowered to take measurements at three depths; two feet

beneath the surface, at mid-depth, and one foot from the seafloor. Hypoxia was detected again in the Chandeleur Sound area (**Figure 3**).

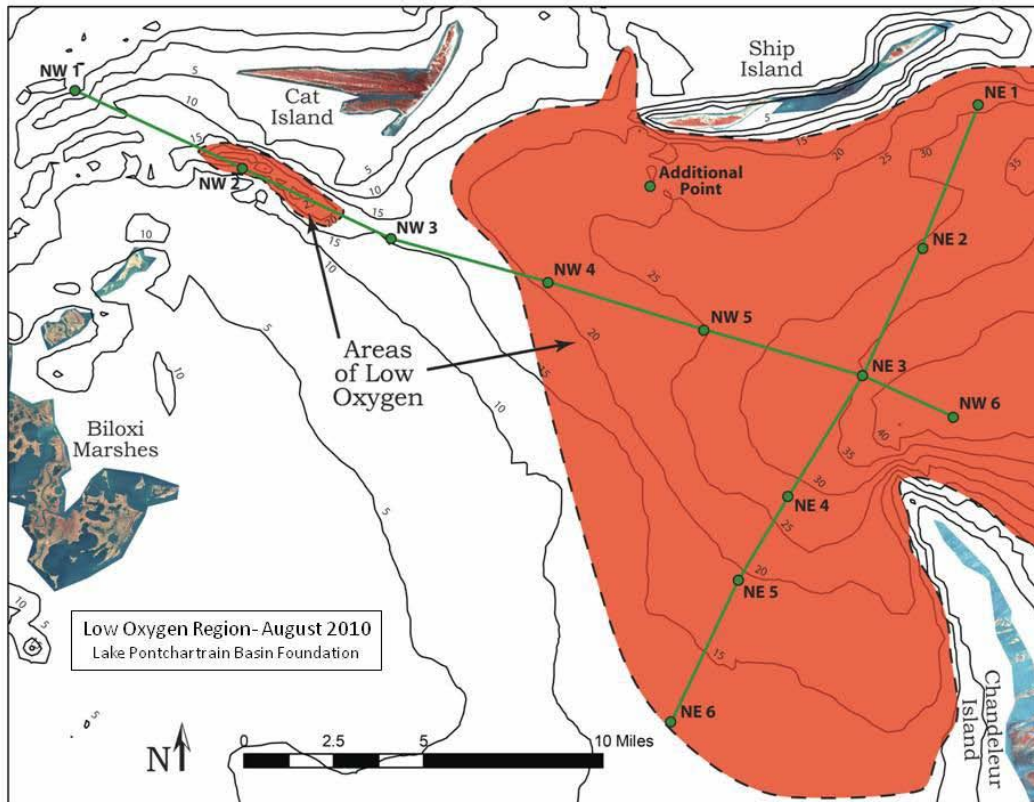


Figure 3. Map of Chandeleur Sound with the area of hypoxia observed in August 2010.

In July 2011, a joint effort between LPBF and MRAC measured and collected water quality data and observations using the same transects (**Figure 4, circles**), sampling protocol, and sampling frequency plan developed in 2010. A total of 15 stations were acquired in July 2011. Additional data was collected by LUMCON which monitored water quality off the coast of Mississippi during the same time period in July 2011. LUMCON surveyed an area in the Gulf of Mexico starting 8 miles from the coast of Mississippi to 24 miles into the Gulf (**Figure 4, triangles**). The survey was conducted in deeper waters on the continental shelf to measure hypoxia and other water quality parameters. The specific data collected by LUMCON is not included in this report but the extent of hypoxia that was detected by LUMCON has been combined with the hypoxia detected by LPBF-MRAC to gain a total picture of the area of hypoxia off of the coast of Southeast Louisiana and coastal Mississippi.

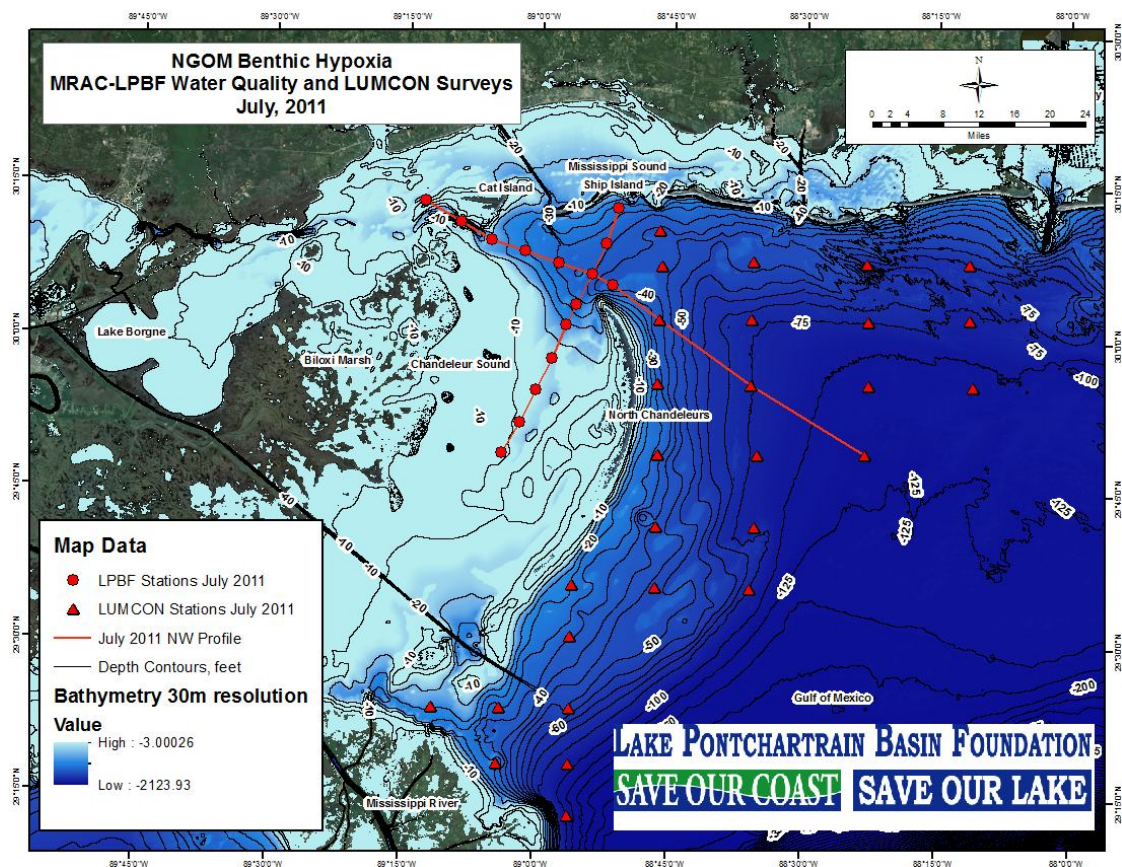


Figure 4. Map of LPBF-MRAC and LUMCON sampling locations in the Chandealeur Sound, Mississippi Bight, and the Gulf of Mexico.

As a result of the July 2011 water quality sampling, a large area of bottom water hypoxia was detected in the vicinity of the Chandealeur Islands extending into the Gulf of Mexico (**Figure 5**). The area of the detected hypoxia was approximately 1,050 square miles. However, the hypoxic zone was most likely larger as data collection did not extend past the Mississippi/Alabama border. A total of 43 points were surveyed between the LPBF-MRAC and LUMCON sampling efforts (**Figure 4**). Of these 43 points, hypoxia was measured in the bottom water as 25 sites, over half of the points surveyed.

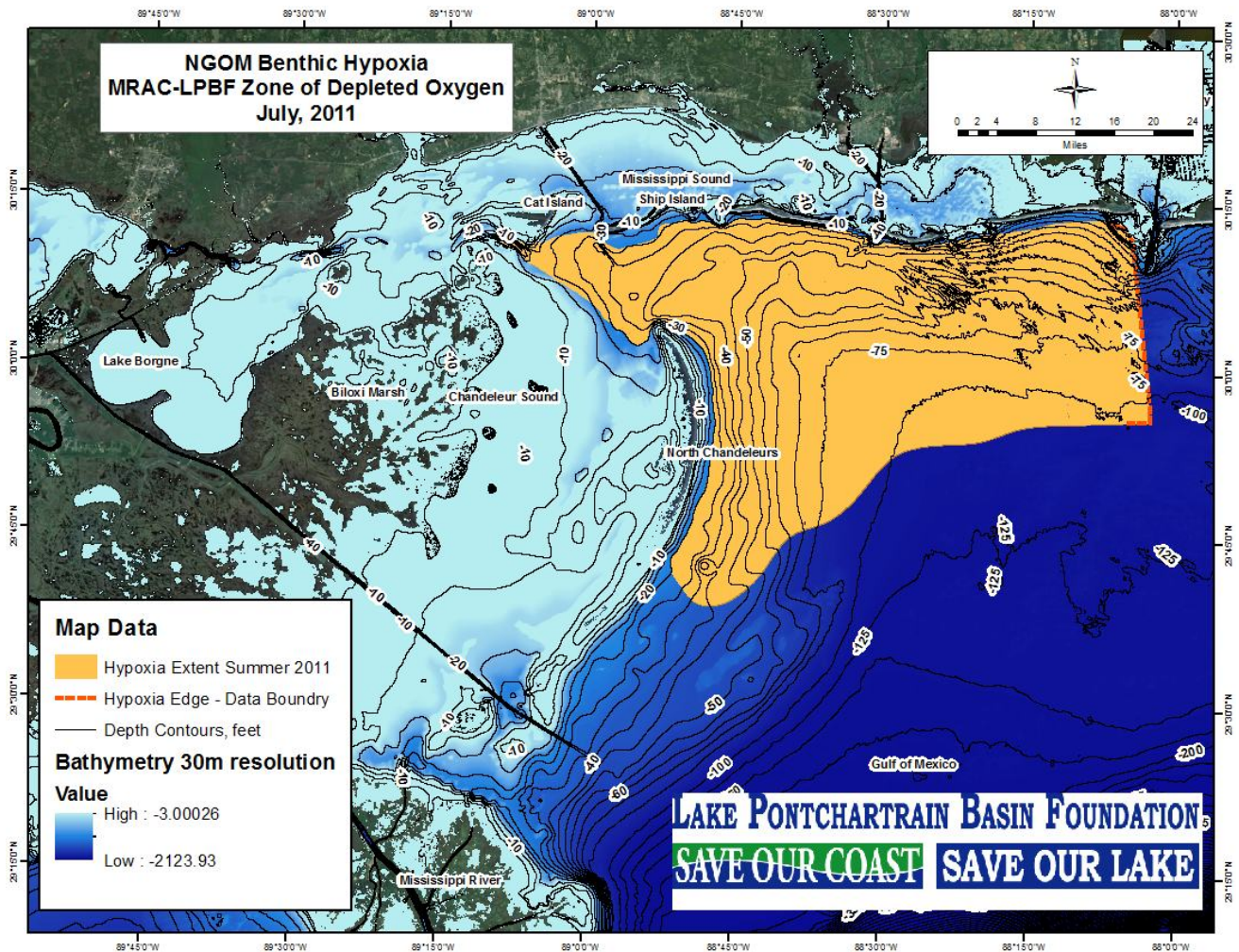


Figure 5. Map showing the area of hypoxia detected in LPBF-MRAC and LUMCON surveys in July of 2011. The area of hypoxia most likely extends further east but the survey was terminated at the Mississippi/Alabama boarder.

2012 Methods

In July 2012, LPBF measured and collected water quality data and observations using the same transects (**Figure 4, circles**), sampling protocol, and sampling frequency plan developed in 2010. The two transects named NW## (yellow pushpins) and NE## (green pushpins) were sampled, as well as, five new alternative stations (ALT##; red pushpins) were also sampled to better capture the extent of hypoxia west of the Chandeleur Islands (**Figure 6**).

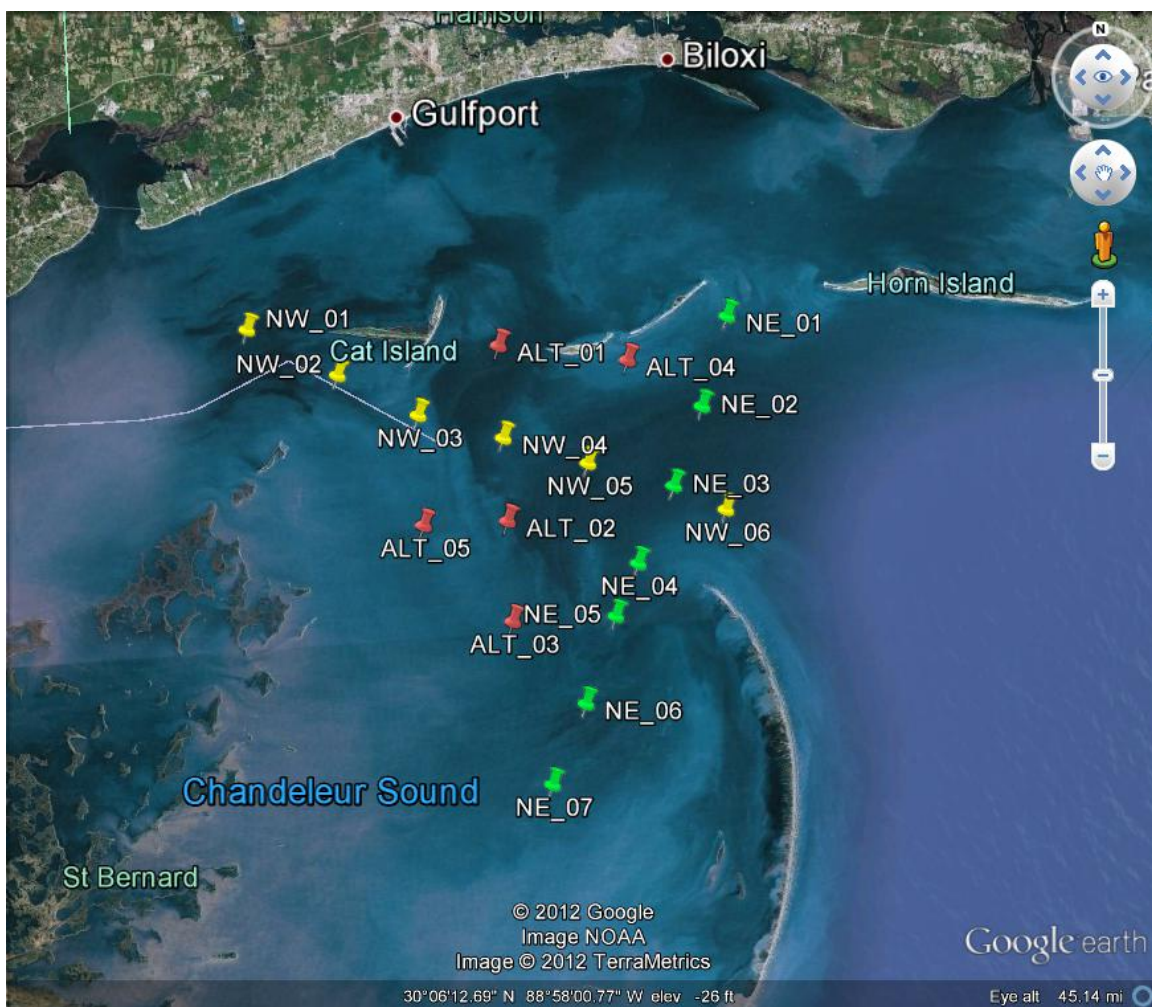


Figure 6. Map of locations of July 2012 LPBF sampling stations.

Results

A hypoxic zone at depth was detected in July 2012 in the Chandeleur Sound and Mississippi Bight, at the intersection of the NW and NE transects (**Figure 7**). The area detected was approximately 70 square miles. The hypoxic zone was most likely larger, similar to results from previous years, however, data collection for 2012 did not extend past the Chandeleur Sound and the Ship Island/Horn Island Pass. A total of 18 locations were sampled by LPBF, of which

five of these stations demonstrated oxygen concentrations considered to be hypoxic, less than 2 mg/L.

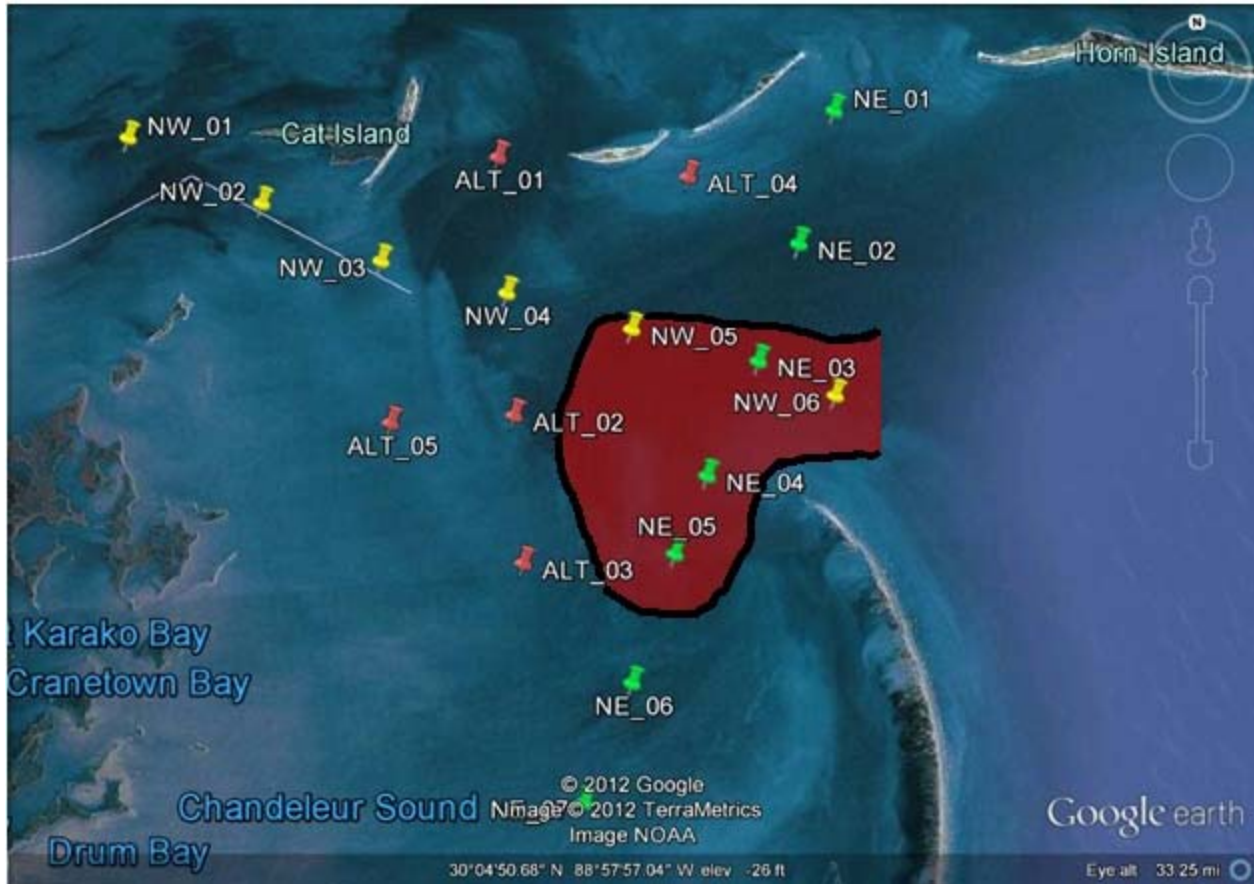


Figure 7. Map showing the sampling stations for LPBF surveys in July of 2012 and hypoxic area. Low oxygen concentrations were measured at five stations and the red area indicates the estimated extent of hypoxia as a result of the sampling. The eastern extent of hypoxia is unknown.

Figures 8, 9, and 10 illustrate the depth-dependent segregation of dissolved oxygen, salinity, and temperature data, which demonstrates the development of a pronounced boundary between lower salinity, oxygen-rich waters above, and higher salinity, oxygen-depleted waters below.

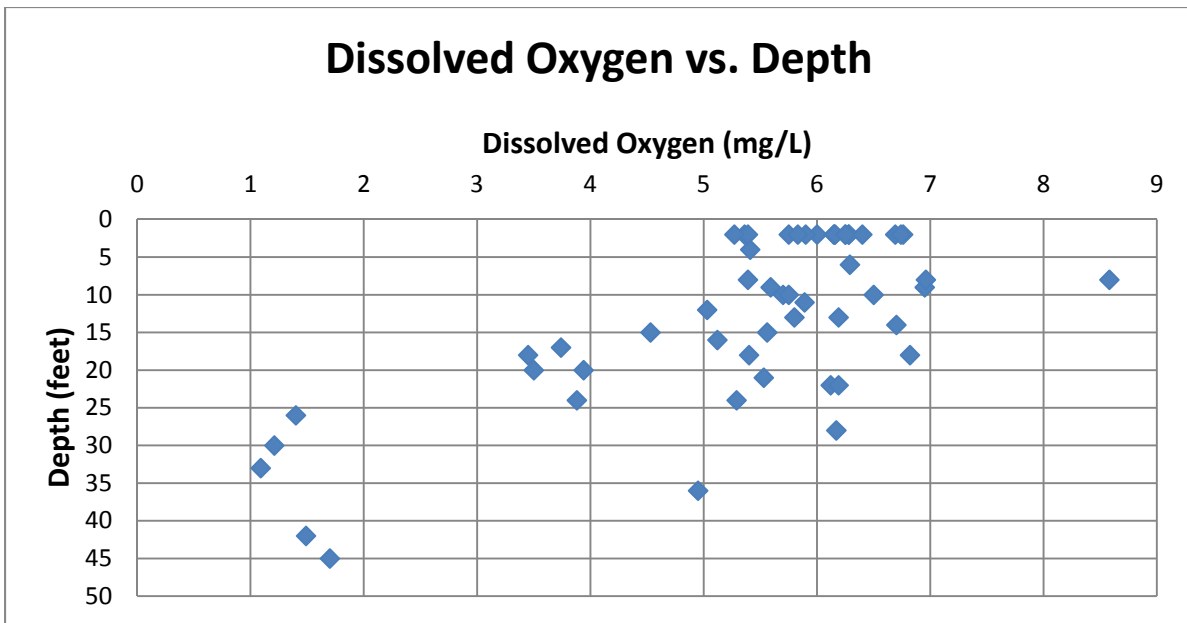


Figure 8. Graph showing dissolved oxygen with depth in 2012, using LPBF data. Notice a decline of dissolved oxygen with depth.

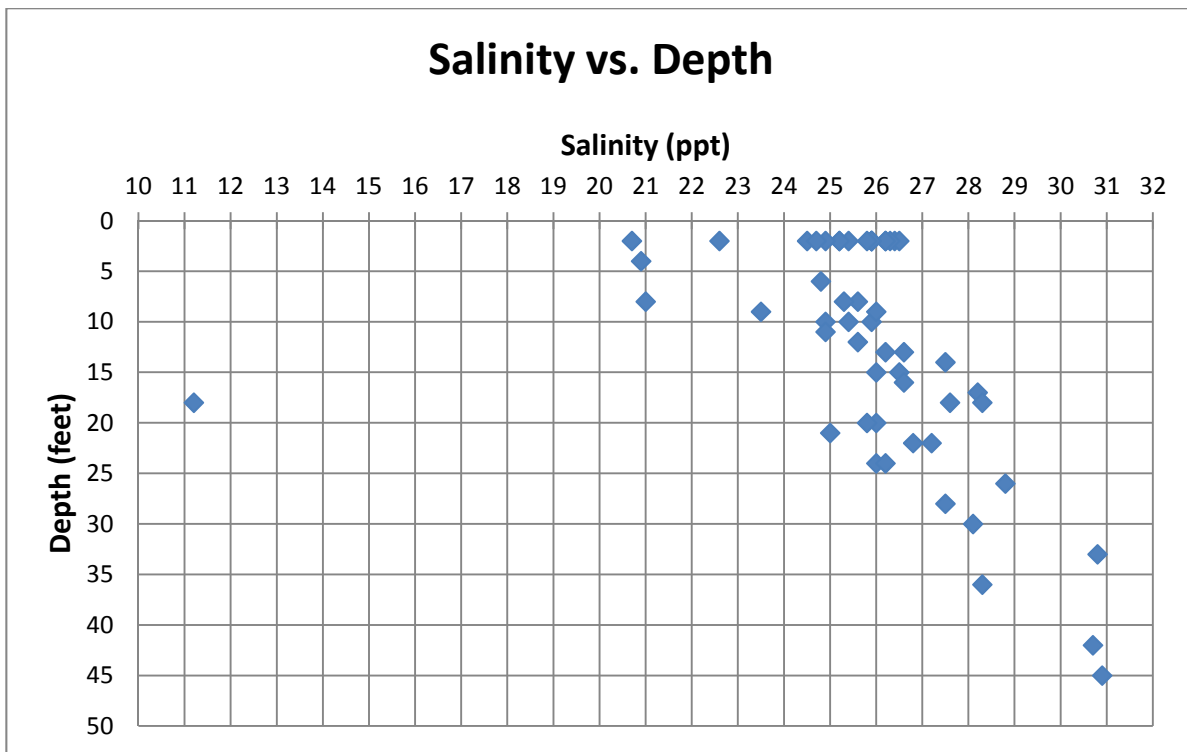


Figure 9. Graph showing changes in salinity with depth in 2012, using LPBF data. Notice the increase in salinity with depth. The anomaly, or outlier, at 11 ppt and 18 feet deep was measured three separate times with two different instruments, therefore confirming the accuracy of this point. This measurement was taken one foot from the seafloor at station NW-02.

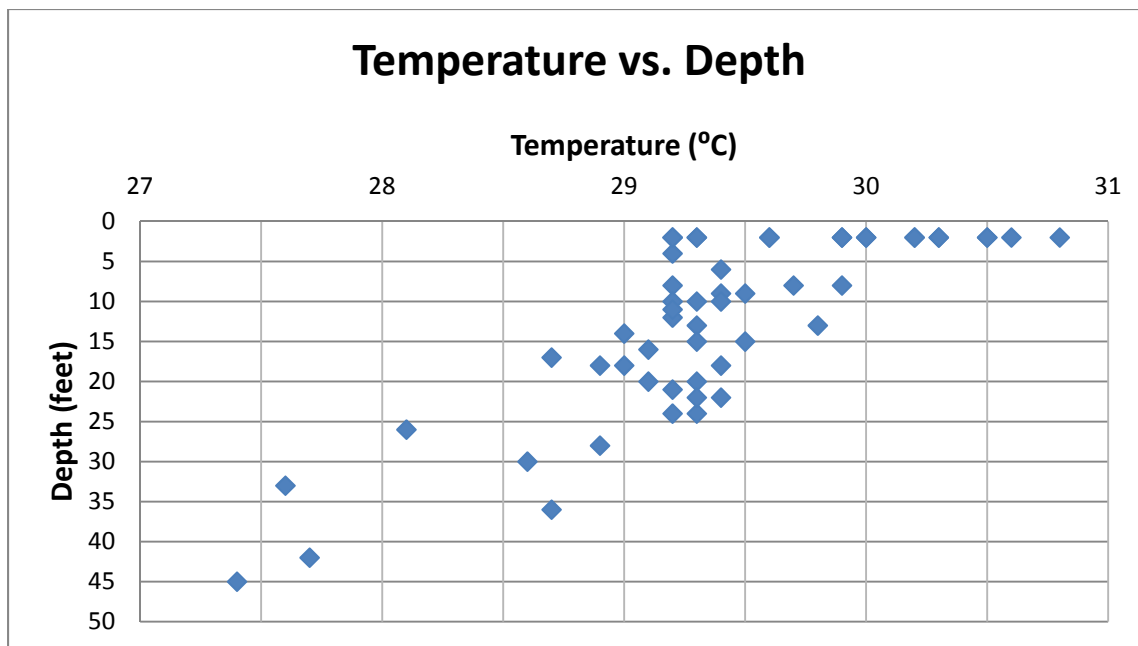


Figure 10. Graph showing change in water temperature with depth in 2012, using LPBF data. Notice the cooler temperatures with depth, as expected.

In the hypoxic zone, the lower layer had an average of 4.5 mg/L lower oxygen concentration, 3.7 ppt increase in salinity, and 2.3 °C decrease in temperature (**Table 1**). In the area where hypoxia was not present, the differences between the upper layer and lower layer in dissolved oxygen, salinity, and temperature were negligible as the water column was fairly-well mixed between the upper and lower layers (**Table 2**).

Table 1. Average difference in dissolved oxygen, salinity, and temperature between the upper and lower layers of the water column in 2012 in the hypoxic zone.

Hypoxic Area (5 out of 18 stations)			
	Average D.O. (mg/l)	Average Salinity (ppt)	Average Temperature (°C)
Upper layer	5.89	26.2	30.2
Lower layer	1.38	29.9	27.9
Difference	-4.51	3.7	-2.3

Table 2. Average difference in dissolved oxygen, salinity, and temperature between the upper and lower layers of the water column in 2012 in the area of no hypoxia.

Non-hypoxic Area (13 out of 18 stations)			
	Average D.O. (mg/l)	Average Salinity (ppt)	Average Temperature (°C)
Upper layer	6.17	24.9	29.9
Lower layer	4.85	24.8	29.1
Difference	-1.32	-0.1	-0.8

In July 2012, hypoxia developed in waters deeper than 24 feet. The hypoxia continued into deep water but always developed near the bottom with the hypoxia boundary (pycnocline) growing deeper with increasing water depth. **Figures 11 and 12** show the depth profile and the depth of the pycnocline for data collected by LPBF along the two transects, NW and NE, shown in **Figure 6** as yellow and green, respectively.

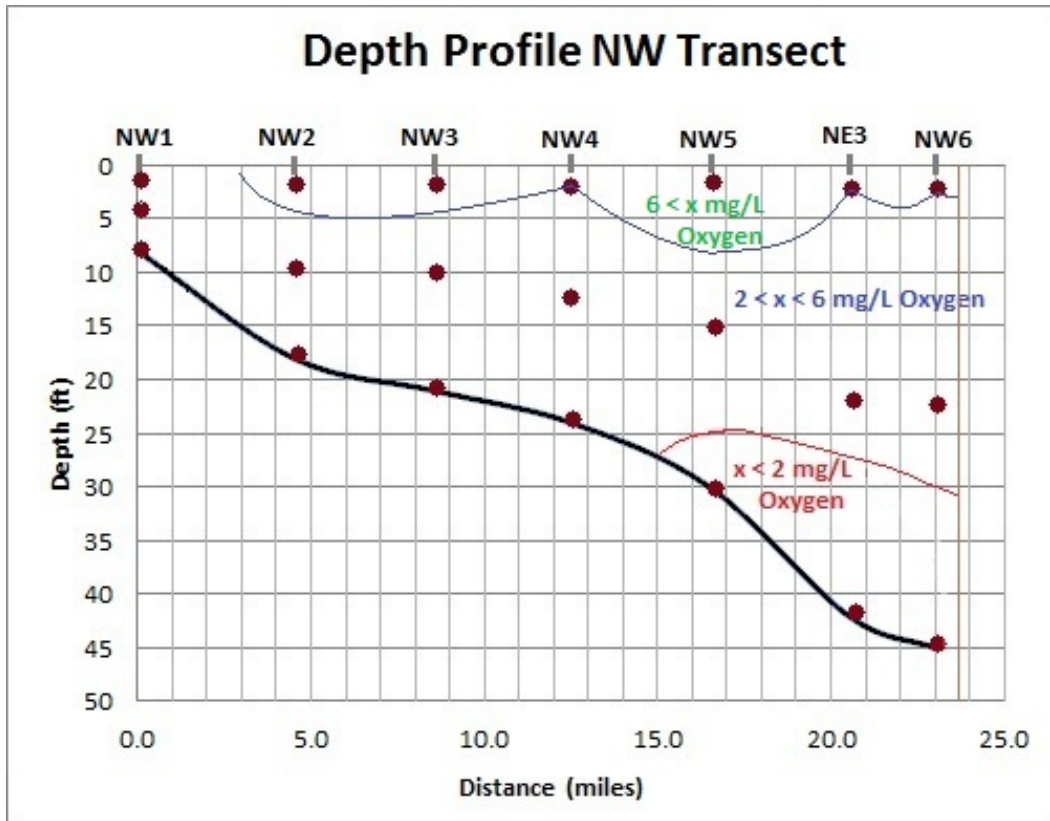


Figure 11. Depth profile created from data taken along the transect running from the northwest near Cat Island to the southeast crossing just north of the Chandeleur Islands.

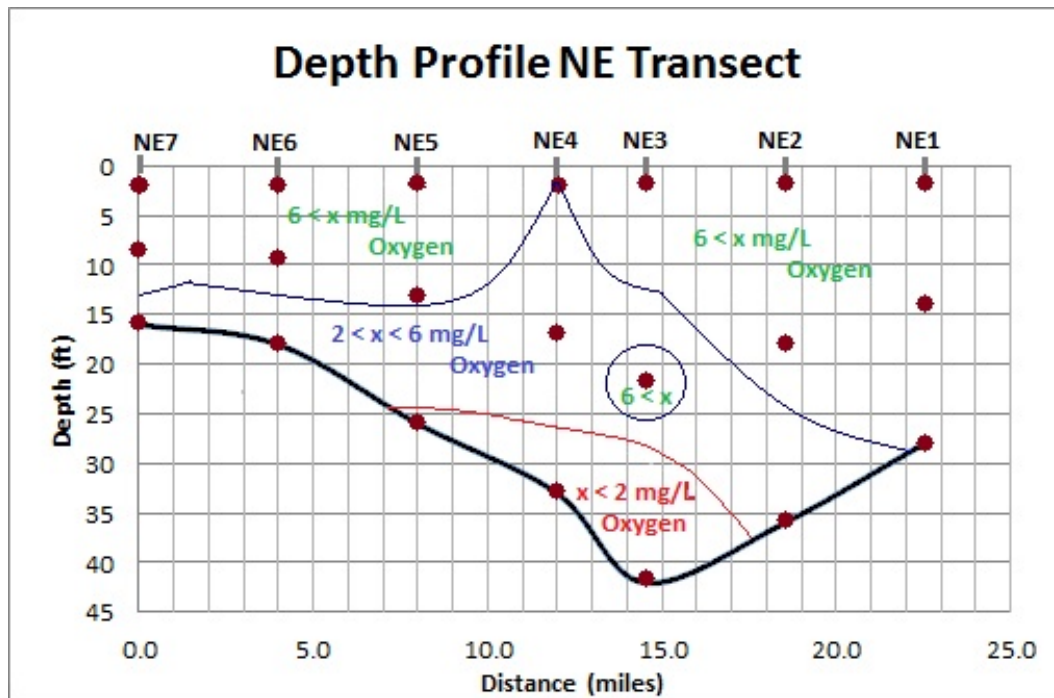


Figure 12. Depth profile created from data taken along the transect running from the southwest in the Chandeleur Sound to the northeast near Ship Island.

Discussion

In 2008, the hypoxia detected was detected in June. In 2010, the early stages of hypoxia were detected in May, which became more prevalent in July, and was even more extensive in August. By October, strong mixing of the Gulf caused oxygen concentrations in bottom waters to increase, therefore terminating the existence of the hypoxic water mass. The development of hypoxia is most likely seasonal and occurs in the summer months when coastal waters become heated. The stratification, and therefore hypoxia, is most likely disrupted by cold fronts, strong storms and hurricanes that are prominent in the area during late summer and early fall. The full extent of the effect of these hypoxic events on the organisms and ecology of the region is unknown. The impacts on fish are most likely small as they can move into more oxygenated waters. Less mobile organisms like shrimp, crabs, and other crustaceans, that live near the bottom may become stressed and eventually suffocate under hypoxic conditions in the bottom water, depending on the length of exposure to the oxygen-poor environment.

The well-documented dead zone along the Louisiana coast in the Gulf of Mexico is thought to be triggered by excess nutrients and stratification of the water column which is a seasonal phenomenon occurring in the summer months (Rabalais et al., 2002). Prior to the closure of the Mississippi River Gulf Outlet (MRGO), the well-documented dead zone in Lake Pontchartrain was triggered by high salinity water which had been allowed to enter Lake Pontchartrain via the MRGO and the Industrial Canal (Poirrier, 1978; Poirrier et al., 1984; LPBF 2006). In both the Gulf and Lake dead zones, a lack of circulation and cumulative demand on oxygen within the water column, have conspired to create very low oxygen concentrations in bottom waters. Many sessile organisms that inhabit the bottom are very likely to suffocate and

die, even with minor exposure to the low oxygen environments. Hence these are referred to as “dead zones”. In Lake Pontchartrain, the dead zone was evident by the absence of large lake clams (*Rangia cuneata*), simply because clams were killed before they could mature (Poirrier et al., 1984).

At this time it is still speculative to draw conclusions, but a few relevant observations can be made. In 2008, there was unusually high water on the Mississippi River, and the Bonnet Carré Spillway was opened which discharged nutrient-rich river water into Lake Pontchartrain which eventually made its way through Lake Borgne, and eventually into the Chandeleur Sound. This occurred prior to the low oxygen observations in June. In addition, algal blooms did occur in Lake Pontchartrain in 2008 (Mofatt and Nichol, 2010). The spillway opening undoubtedly added freshwater and nutrients (stratification and eutrophication) to Chandeleur Sound, and may have contributed to the low oxygen event in 2008. In 2010, the Bonnet Carré Spillway was not opened, however, the Mississippi River had an extended period of high water. Also in 2010, due to the British Petroleum (BP) oil spill response resulting from the Deepwater Horizon blowout, freshwater diversions such as Caernarvon were opened to their maximum operable capacity for an extended period of time to create a freshwater plume to prevent oil from coming into the coastal waters of Louisiana and Mississippi. The additional nutrient rich, fresh river water in 2010 may have contributed to the low oxygen concentrations observed during this time period. The hypoxia appears to have developed between May and July in 2010, and in early August, there were unofficial reports of “red tide” in the Chandeleur Sound indicating the possibility of excess nutrients, enough to maintain hypoxic water masses in the bottom waters (Times-Picayune, 2010).

In 2011, the Bonnet Carré Spillway was again opened at full capacity for 42 days in May and June. No significant algal blooms occurred in Lake Pontchartrain in 2011, possibly due to a lower ratio of phosphorus and nitrogen in the river water (Nguyen et al., 2011; Roy et al., 2011). However, there are some rivers that flow into the Gulf of Mexico off of the Mississippi coast, such as the Pearl River, Mobile River, and Pascagoula River, which may have introduced high concentrations of nutrients to coastal waters. These excess nutrients could have also entered the Chandeleur Sound and contributed to the formation of deepwater hypoxia in this area in 2011. However, it is unrealistic that the high nutrient concentrations remained high enough to cause hypoxia extending all the way to the Mississippi/Alabama border. In addition, the high salinity of the upper layer suggests that the freshwater influence was minimal. Therefore, it is questionable whether high nutrient concentrations are the primary cause of hypoxia, and perhaps other hypotheses should be considered.

It appears that the cause of the formation of hypoxia may be a naturally induced phenomenon simply due to the lack of wind and wave energy available to mix the coastal waters with deep Gulf of Mexico water, therefore causing density driven stratification to develop on a seasonal basis (**Table 1**).

The hypoxic area is a reentrant that appears to be isolated from ocean currents prevalent in the open Gulf of Mexico. **Figure 13** indicates that the region where hypoxia develops is bypassed by the prevailing currents in the Gulf of Mexico. The hypoxia also sets up at a time of the year when winds are low in the summer. The combination of low winds and a lack of horizontal surface currents (**Figure 14**), creates a low energy environment which allows for stratification of the water column to develop. **Figures 13 and 14** show both, that low speed currents are present in the summer, or in this case when hypoxia was observed in July 2012, and how the hypoxic area east of the river is out of the main path of prevailing Gulf of Mexico currents. Low wind velocity is in direct correlation with lack of vertical mixing and therefore stratification and hypoxia develops (McCardell and O'Donnell, 2006).

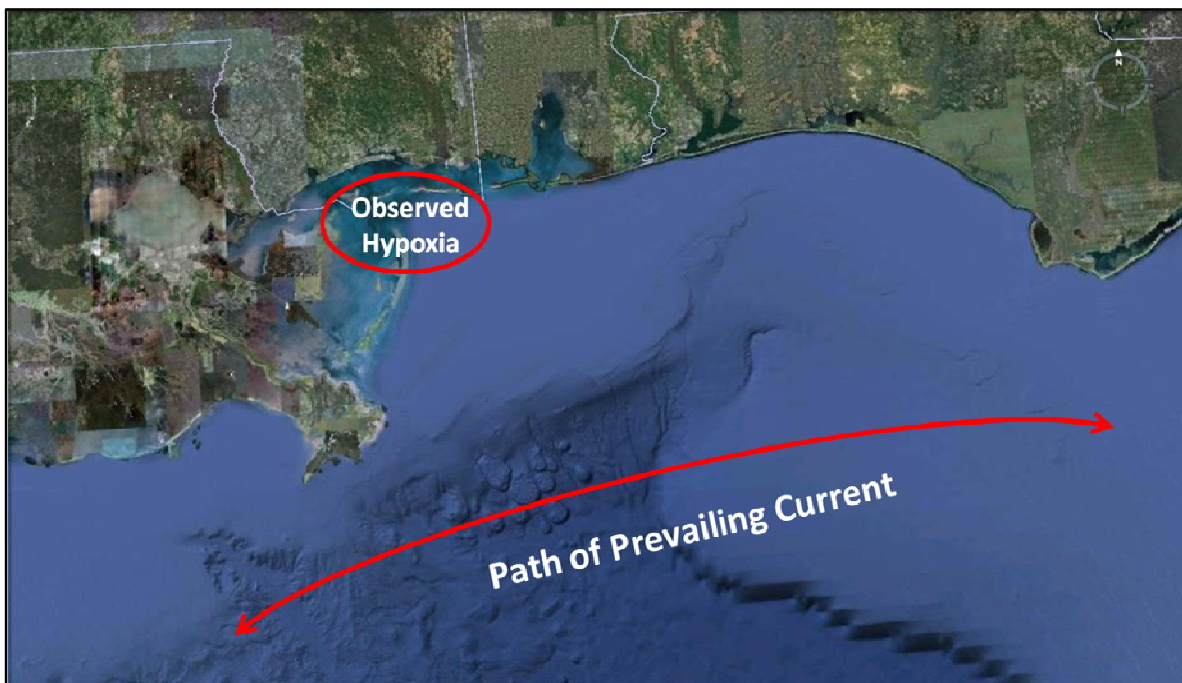


Figure 13. Location of seasonal hypoxia observed east of the Mississippi River, in a regional context, showing how the hypoxic area is out of the path of the prevailing Gulf of Mexico currents.

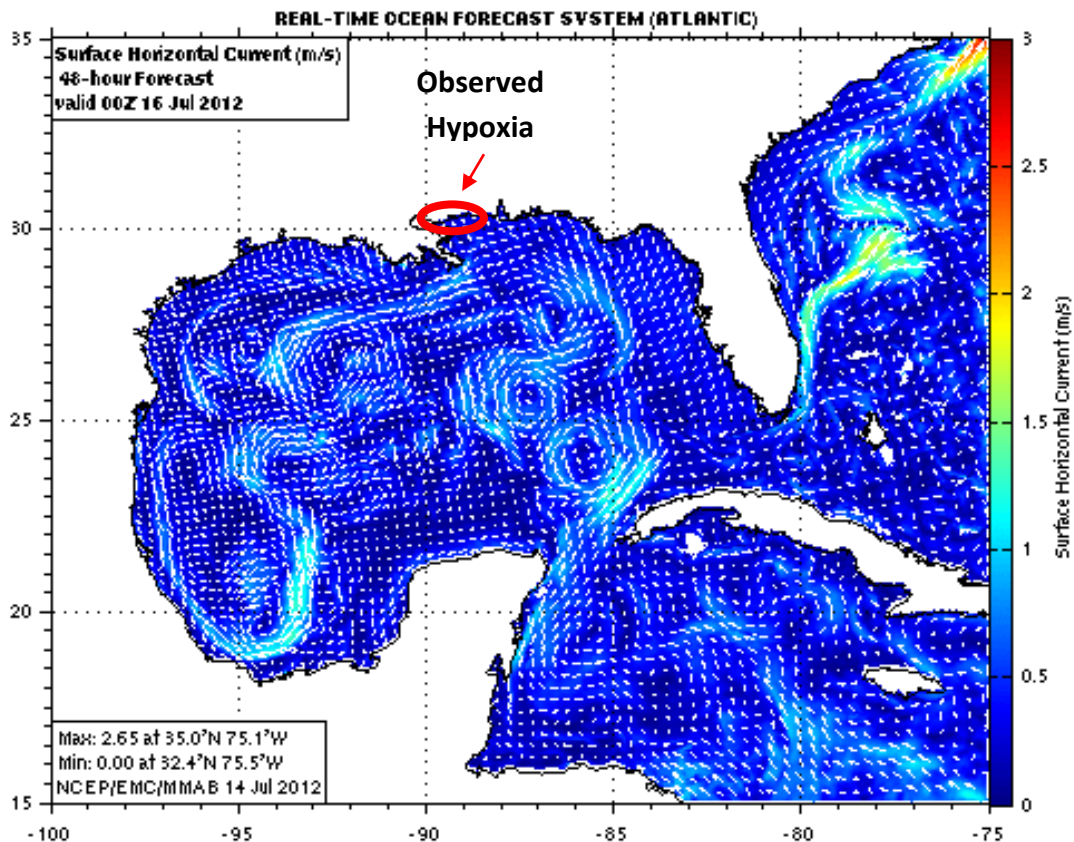


Figure 14. Horizontal surface currents in the Gulf of Mexico on July 16, 2012. Notice the low speed currents that are present and how the hypoxic area east of the river is out of the main current. (Image source: NOAA: EMC Modeling and Analysis Branch, <http://polar.ncep.noaa.gov/ofs/viewer.shtml?-gulfmex-cur-0-small-rundate=20120716>).

The low oxygen layer in the Chandeleur Sound is much smaller than the typical annual dead zone in the Gulf of Mexico, however, its re-occurrence over a significant portion of the Chandeleur Sound may be of ecological significance. In several years of this study, (2008, 2010, and 2011), there has been potential sources of excess nutrients entering the system. The excess nutrients and seasonal stratification may be the contributing factors to the development of hypoxia in a manner similar to the development of the “dead zone” off of the Louisiana-Texas shelf (Rabalais et al., 2002). Although the cause of the development of hypoxia in the Chandeleur Sound and coastal Mississippi may be natural, anthropogenic, or a combination of both, the exact permutation of factors that leads to the development of hypoxia still remains unknown.

Due to conditions present in the hypoxic zone in the summer time (low winds, outside of prevailing current path, warm shallow waters) it is probable that the observed stratification develops on a consistent basis due to existing natural conditions, regardless of anthropogenic nutrient inputs. The question remaining seems to be whether excess nutrients are necessary to increase the biological oxygen demand (BOD) and deplete oxygen in the stratified water over the short seasonal time period that it develops. It is intriguing that the exact opposite energy condition prevails within a tropical system. Tropical systems, or hurricanes/tropical depressions,

have strong east or southeast winds which tend to focus water through the reentrant (hypoxic) area. These events undoubtedly cause significant mixing and likely terminate seasonal hypoxia. An example of this effect was Tropical Storm Lee, in early September, which most likely ended the bottom water hypoxia event in 2011.

In 2012, hypoxia was detected in the bottom waters at 5 of the 18 stations sampled. The eastern extent of the hypoxic area is still unknown as sampling efforts did not take place past east of the Ship Island/Horn Island Pass, however, because of the low winds in the summer months, warm shallow waters, and the fact that this region is outside of the prevailing current path (**Figure 14**), it is more than likely that the hypoxic area east of the Mississippi River extended past the Ship Island/Horn Island Pass, further into the Mississippi Bight, similar to the observations in 2011. However, based on LPBF observations, the hypoxic zone observed in the Chandeleur Sound in 2012 was smaller than the zone observed in 2011. A similar study conducted by Nancy Rabalais at LUMCON discovered the same results on the Louisiana-Texas shelf, stating that the “dead zone” that develops every spring and summer in the Gulf of Mexico is smaller than usual this year. It is suggested that the dead zone west of the river is small this year as a result of less eutrophication from rivers. The record drought across the country meant fewer nutrients were washed into the river which would have limited the amount of nutrients into the coastal areas of Chandeleur Sound and the Mississippi Bight, and furthermore the Gulf of Mexico (NOAA, 2012).

Another factor that could have inhibited the growth and development of hypoxia in the Chandeleur Sound and Mississippi Bight in 2012 was Tropical Storm Debby which formed in the northern Gulf of Mexico on June 23rd. Debby remained in the Gulf for several days until making landfall on the eastern Florida panhandle on June 26th. Tropical storms (in addition to hurricanes and cold fronts) can disrupt stratification throughout the water column which temporarily replenishes the bottom waters with oxygen and reduces hypoxic conditions (Ariyama and Secor, 2010; LUMCON, 2012). As a result of the drought throughout the Mississippi River watershed and disruption of the water column as a result of Tropical Storm Debby, the dead zone in 2012 was smaller than expected.

It is important to move forward from speculation of the development of hypoxia and discover the actual cause of this phenomenon. To ascertain the cause of the hypoxia in the Chandeleur Sound and Mississippi Bight, LPBF will continue seasonal monitoring in 2013 to characterize the water quality and better understand the nature of the low oxygen event which may provide a basis for recommendations to reduce the occurrence or environmental impact of the Chandeleur Sound dead zone. The goal is to expand the research program to include multiple samplings throughout the year, and through the duration of the hypoxic event to determine when hypoxia develops and when it disappears, and the changes throughout the season. LPBF will investigate the predicted local and regional currents to determine if the hypoxic area is indeed outside of the prevailing current path and therefore stratification develops readily. LPBF will collaborate with other agencies to ascertain the full extent of the hypoxic area off of the Mississippi and Alabama coast. This will be a larger collaborative sampling effort as samples will need to be collected around the same time following similar protocols so the data can be combined and compared. Additionally, studies into the effects of hypoxic events on the marine ecology will also need to be included. Finally, the Chandeleur hypoxic zone will be compared to other hypoxic events, such as the one along the Louisiana-Texas shelf, west of the

Mississippi River, in addition to other global hypoxic events like the Chesapeake Bay and Long Island Sound, to better understand the drivers and causes of this phenomenon locally.

References

- Anderson, D.M., P.M. Gilbert, and J.M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* **25**(4b): 704-726.
- Ariyama, H. and D.H. Secor. 2010. Effect of environmental factors, especially hypoxia and typhoons, on recruitment of the gazami crab *Portunus trituberculatus* in Osaka, Japan. *Fisheries Science* **76**: 315-324.
- Bricker, S.B., C.G. Clement, D.E. Pirhalla, S.P. Orlando, and D.R.G. Farrow. 1999. National Estuarine Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries. NOAA, National Ocean Service, Special Projects Office and the National Centers for Coastal Ocean Science. Silver Spring, MD: 71 pp.
- CENR. (Committee on Environment and Natural Resources). 2010. Scientific assessment of hypoxia in U.S. coastal waters. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC. September 2010.
- EPA. (Environmental Protection Agency). 2012. Hypoxia 101. *Mississippi River Gulf of Mexico Watershed Nutrient Task Force*. United States Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds. August 2012. Available at: <http://water.epa.gov/type/watersheds/named/msbasin/hypoxia101.cfm>
- Howarth, R., F. Chan, D.J. Conley, J. Garnier, S.C. Doney, R. Marino, and G. Billen. 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. *Front. Ecol. Environ.* **9**(1): 18-26.
- Jorgensen, B.B. and K. Richardson. 1996. Eutrophication: definition, history, and effects. In: *Coastal and estuarine studies: Eutrophication in coastal marine ecosystems*, pp. 1-20. American Geophysical Union, Washington, DC.
- LPBF (Lake Pontchartrain Basin Foundation). 2006. Comprehensive Habitat Management Plan, SaveOurLake.org.
- LUMCON (Louisiana Universities Marine Consortium). 2012. Hypoxia in the Northern Gulf of Mexico. August 2012. Available at: www.gulfhypoxia.net.
- McCardell, G. and J. O'Donnell. 2006. Vertical mixing rates and hypoxia in Western Long Island Sound. *Long Island Sound Research Conference Proceedings 2006*.
- Moffatt and Nichol. 2010. Review and analysis of Pontchartrain estuary water quality as impacted by opening of the Bonnet Carré Spillway. *Submitted to: U.S. Army Engineer District, New Orleans, Louisiana.* (PI: Dr. Mark Dortch).

- Nguyen, N.T., E.D. Roy, S.J. Bentley, and J.R. White. Effects on the 2011 Bonnet Carré Spillway opening on Lake Pontchartrain sediment phosphorus loading and concentrations with potential for release to the water column. *Basics of the Basin Research Conference Proceedings*. SaveOurLake.org.
- NOAA. (National Oceanic and Atmospheric Administration). 2012. NOAA Scientists: Midwest drought brings fourth smallest Gulf of Mexico 'dead zone' since 1985. National Ocean and Atmospheric Administration, United States Department of Commerce. July 27, 2012. Available at:
http://www.noaa.gov/stories2012/20120727_midwestdrought.html
- Poirrier, M.A. 1978. Studies of salinity stratification in southern Lake Pontchartrain near the Inner Harbor Navigation Canal. The proceedings of the Louisiana National Academy of Sciences. Vol. XLI, pp. 26-35.
- Poirrier, M.A., T.M. Soniat, Y. King, and L. Smith. 1984. An evaluation of the southern Lake Pontchartrain benthos community. Final Report to the Louisiana Department of Environmental Quality:79.
- Rabalais, N.N., R.E. Turner, and D. Scavia. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. (Articles). *BioScience*. Feb 2002; 52, 2; Research Library pg. 129.
- Rabalais, N.N., R.J. Diaz, L.A. Levin, R.E. Turner, D. Gilbert, and J. Zhang. 2010. Dynamics and distribution of natural and human-caused hypoxia. *Biogeosciences* 7:585-619.
- Roy, E.D., J.R. White, S. Bargu, S.J. Bentley, C.Y. Li, and N. Walker. 2011. Nutrient dynamics in Lake Pontchartrain during and after the 2011 Bonnet Carré Spillway opening. *Basics of the Basin Research Conference Proceedings*. SaveOurLake.org.
- Times-Picayune. 2010. Algae choking Breton, Chandeleur Sounds. Published in: *Times Picayune*. Wednesday, August 11, 2010, New Orleans, LA. Available at:
http://www.nola.com/news/gulfoilspill/index.ssf/2010/08/algae_choking_breton_chandeleur.html