2017 Forecast:
Summer Hypoxic Zone Size
Northern Gulf of Mexico

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Abstract

Each year a hypoxic water mass with oxygen concentrations ≤ 2 mg l^{-1} forms in bottom waters of the northern Gulf of Mexico continental shelf. The low oxygen conditions threaten living resources including humans that depend on fish, shrimp and crabs. Nutrients from the Mississippi River watershed, particularly nitrogen and phosphorus, fertilize the Gulf's surface waters to create excessive amounts of algal biomass, whose decomposition in the bottom layer leads to oxygen distress and even organism death in the Gulf's richest waters. Various models use the May nitrogen load of the Mississippi River as the main driving force to predict the size of this hypoxic zone in late July. This prediction is based on one of these models.

The June 2017 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for late July 2017 is that it will cover 26,131 km^2 (10,089 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 23,648 and 28,551 km^2 (9,131 and 11,024 mi^2). This estimate is based on the assumption that there are no significant tropical storms occurring in the two weeks before the monitoring cruise, or during the cruise. If a storm does occur, then the size of the zone is predicted to be 70% of the predicted size without the storm, equivalent to 17,250 km^2 (6,660 mi^2).

The predicted hypoxic area is about the area of Vermont (24,901 km^2) and 93% larger than the average of 13,536 km^2 (all years, including years with storms). If the area of hypoxia becomes as large as predicted, it will equal about five times the size of the goal of the Hypoxia Action Plan (i.e., less than 5,000 km^2). Efforts to reduce the nitrate loading have not been successful.

Caveats: 1) This prediction discounts the effect of large storm events that temporarily disrupt the physical and biological system attributes promoting the formation of the low oxygen zone in bottom waters; 2) The potential space on the shelf where hypoxia occurs is limited by the bathymetry; 3) The predictions assume that there will be no abrupt changes in discharge from now through July; and 4) Unusual weather patterns affecting coastal winds, as experienced in 2009 and 2011, may skew the prediction to be lower.

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Introduction

Hypoxic water masses in bottom waters of the northern Gulf of Mexico occur when the oxygen concentration falls below 2 mg l^{-1}. This hypoxic water is distributed across the Louisiana shelf west of the Mississippi River and onto the upper Texas coast, from near shore to as much as 125 km offshore, and in water depths up to 60 m (Rabalais et al. 2007; Figures 1 and 2). It has been found in all months, but is most persistent and severe in spring and summer (Turner et al. 2005; Rabalais et al. 2007). The July distribution of hypoxic waters most often is a single continuous zone along the Louisiana and adjacent Texas shelf. Hypoxia also occurs east of the Mississippi River delta, but covers less area and is ephemeral. These areas are sometimes called 'dead zones' in the popular press because of the absence of commercial quantities of shrimp and fish in the bottom layer. The number of dead zones throughout the world has been increasing in the last several decades and currently totals over 550 (Díaz and Rosenberg 2008; Rabalais et al. 2010; Conley et al. 2011). The dead zone off the Louisiana coast is the second largest human-caused coastal hypoxic area in the global ocean.

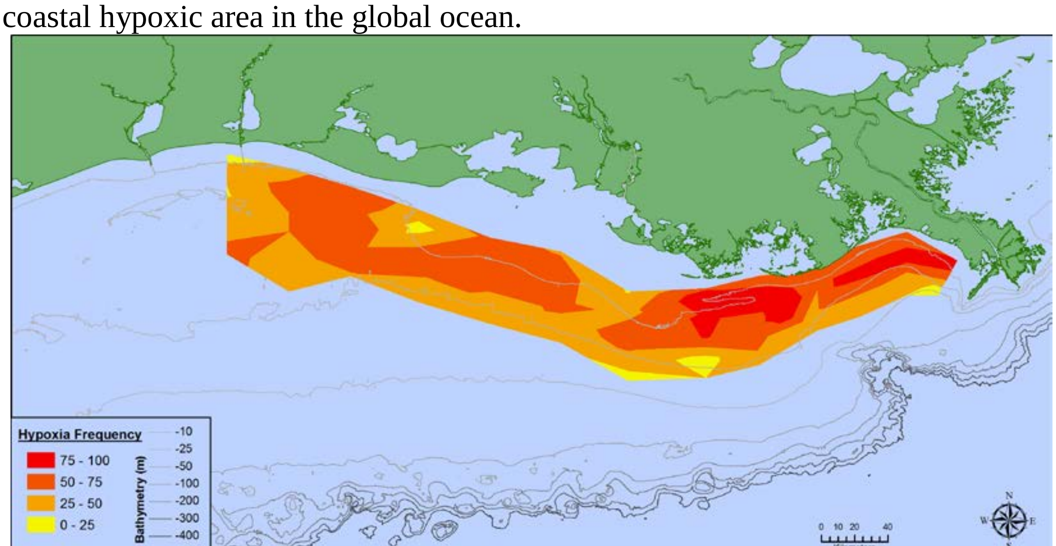


Figure 1. The frequency of mid-summer hypoxia (oxygen ≤ 2 mg l^{-1}) over the 70 to 90 station grid on the Louisiana and Texas shelf during the summer from 1985 to 2014. Updated from Rabalais et al. (2007).

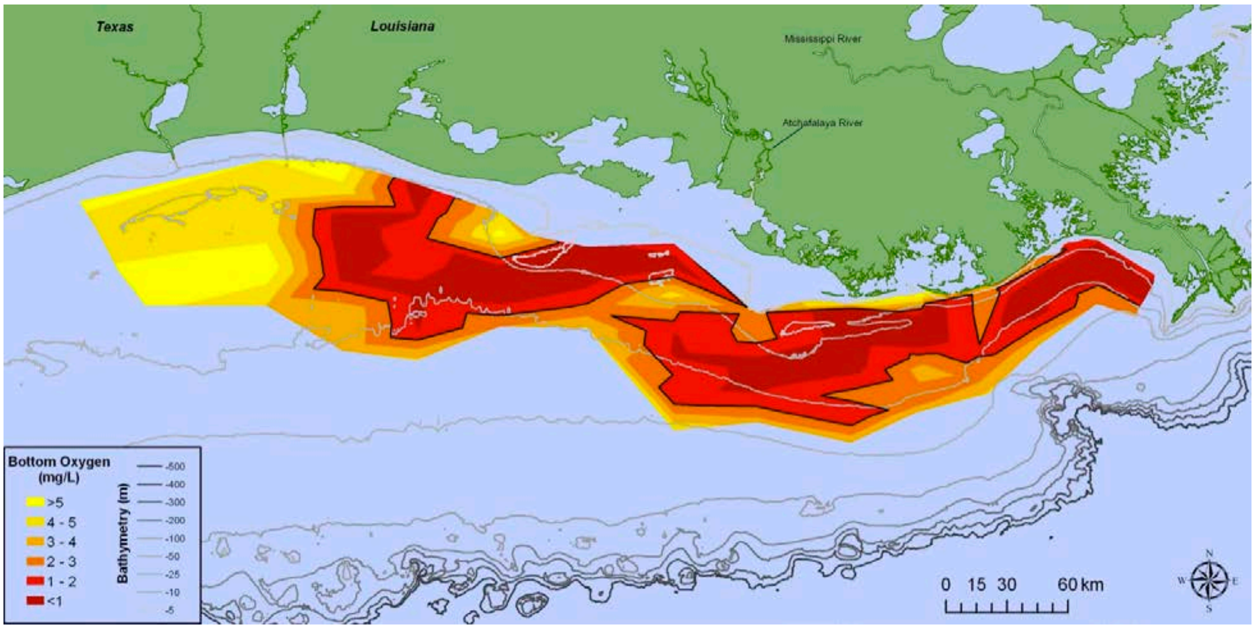


Figure 2. Oxygen concentrations in bottom water across the Louisiana-Texas shelf from July 28 – August 3, 2015. Data source: N.N. Rabalais, Louisiana Universities Marine Consortium, and R.E. Turner, Louisiana State University; funded by NOAA, Center for Sponsored Coastal Ocean Research and EPA Gulf of Mexico Program.

Systematic mapping of the area of hypoxia in bottom waters of the northern Gulf began in 1985. Its size from 1985 to 2015 ranged between 40 to 22,000 km^2 during July and averaged 13,536 km^2 (5,534 mi^2). It was 16,760 km^2 (6,474 mi^2) in 2015. There are few comparable coastwide data for other months, and bi-monthly monitoring on two transects off Terrebonne Bay, LA, and the Atchafalaya delta, LA, ended in 2012.

Hypoxic water masses form from spring to fall on this coast because the consumption of oxygen in bottom water layers exceeds the re-supply of oxygen from the atmosphere. The re-aeration rate is negatively influenced by stratification of the water column, which is primarily dependent on the river's freshwater discharge and accentuated by summer warming. The overwhelming supply of organic matter respired in the bottom layer is from the downward flux of organic matter produced in the surface layer. The transport to the bottom layer is the result of sinking of individual cells, as the excretory products of the grazing predators (zooplankton) that 'package' them as fecal pellets, or as aggregates of cells, detritus and mucus. The respiration of this organic matter declines as it falls through the water column (Turner et al. 1998), but the descent rate is rapid enough that most respiration occurs in the bottom layer and in the sediments.

The amount of organic matter produced in the surface waters is primarily limited by the supply of nitrogen, not phosphorus (Scavia and Donnelly 2007; Turner and Rabalais 2013), and previous indicators of phosphorous deficiency are suspect (Fuentes et al. 2014). The evidence for this conclusion is that the supply, or loading, of nitrogen (primarily in the form of nitrate-N) from the Mississippi River watershed to the continental shelf within the last few decades is positively related to chlorophyll *a* concentration (chl *a*; Walker and Rabalais 2006; R^2 0.30 – 0.42), the rate of primary production (Lohrenz et al. 1997, $R^2 > 0.77$; Lohrenz et al. 2008), and the spatial extent of the hypoxic area in summer (Turner et al. 2012; $R^2 > 0.9$). The size of the shelfwide hypoxic zone has increased since it began occurring in the 1970s, simultaneously with the rise in carbon sequestration in sediments, indicators of increased diatom production, and shifts in benthic foraminiferal communities (Turner and Rabalais 1994; Sen Gupta et al. 1996; Turner et al. 2008). There is, therefore, a series of cause-and-effect arguments linking nitrogen loading in the river to phytoplankton production, bottom water oxygen demand, and the formation and maintenance of the largest hypoxic zone in the western Atlantic Ocean.

The oxygen consumption creates a zone of hypoxia that is constrained by the geomorphology of the shelf, horizontal water movement, stratification and vertical mixing (Obenour et al. 2012; Justić and Wang 2014). The significance of reducing nutrient loads to these coastal waters rests on the coupling between the organic matter produced in response to these nutrients and its respiration in the bottom layer (MRNGoM HTF 2001, 2008; Rabalais et al. 2002, 2007, 2010; SAB 2007). The primary driver of the increased nutrient loading is agricultural land use (Alexander et al. 2008; Broussard et al. 2009), which is strongly influenced by farm subsidies (Broussard et al. 2012). The amount of nutrient loading from the river has remained the same in recent decades, or is increasing (Sprague et al. 2011). Restoration of the coastal waters means, in large part, changing farming practices (Rabotyagov et al. 2014).

Mississippi River Discharge

Hypoxic conditions are dependent on river discharge because of the influence that water volume and salinity have on the physical structure of the water column and on the nutrient load delivered to the coastal zone. The nutrient load is dependent on the concentration of nutrients, primarily nitrogen, and on the discharge. River discharge is, therefore, a key environmental parameter of interest.

The Mississippi River watershed discharge in May 2017 averaged 41,000 $m^3\ s^{-1}$ (cms) (Appendix Figure 2), which is the 44th largest in 49 years from 1968 to 2017. This is about 144% of the average discharge for the interval (Figure 3).

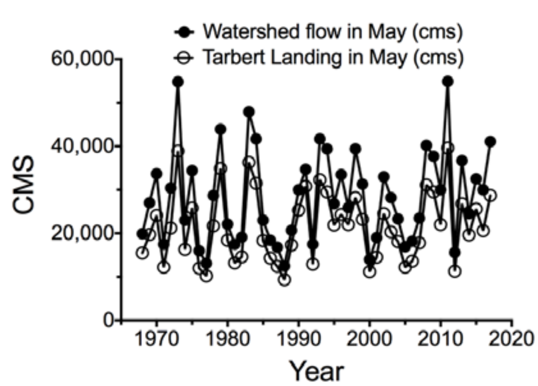


Figure 3. The discharge in May for the Mississippi River watershed and south of St. Francisville, LA at Tarbert Landing, MS. CMS is cubic meters per second, $m^3\ s^{-1}$.

May Nitrogen Loading

The US Geological Survey (USGS) publishes monthly estimates of nitrogen loading and other aspects of water quality from the Mississippi River watershed into the Gulf of Mexico (http://toxics.usgs.gov/hypoxia/mississippi/). The USGS includes information on the data calculations, including an estimate of the 95% confidence range for the nitrogen load. The May nitrite+nitrate (NO2+3) and total nitrogen (TN) load for the Mississippi River watershed for May is shown in Figure 4. Comparative information on the seasonal concentration of dissolved nitrate+nitrite in the Mississippi River at Baton Rouge, LA, is in Figure 5.

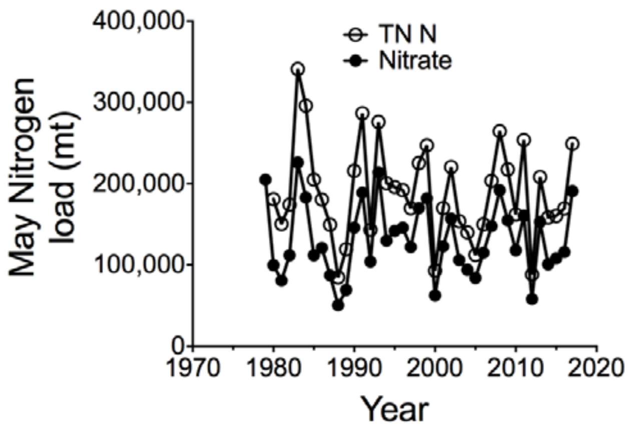


Figure 4. The annual nitrite+nitrate (NO_{2+3}) and total nitrogen (TN) load for the Mississippi River watershed for May. The estimates are from the USGS.

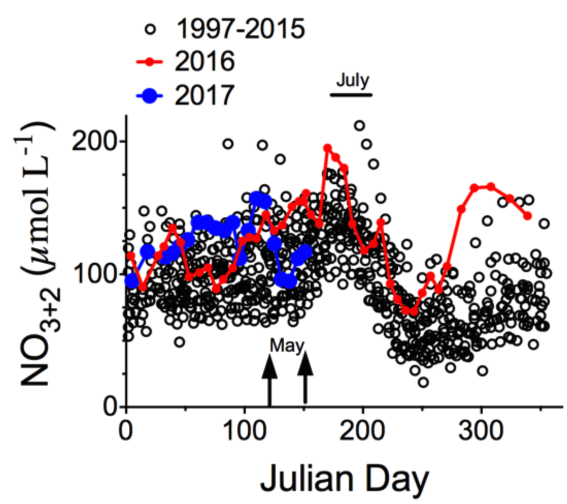


Figure 5. The concentration of nitrite+nitrate (NO_{2+3}) at Baton Rouge, LA from 1997 to present. Unpublished data from Turner et al.

The concentration of nitrite+nitrate at Baton Rouge was above average in the winter of 2017, and but near the highest values in early May since measurements began in 1997. The concentration rose at the end of May and is expected to rise through to the mapping cruise in July. The river discharge was above average, however, to result in a May nitrite+nitrate loading that was equal to 144% of the average value since 1985 when systematic estimates of the hypoxic zone began. The total nitrogen load in May is increasingly dominated by the nitrite+nitrate load (Figure 6).

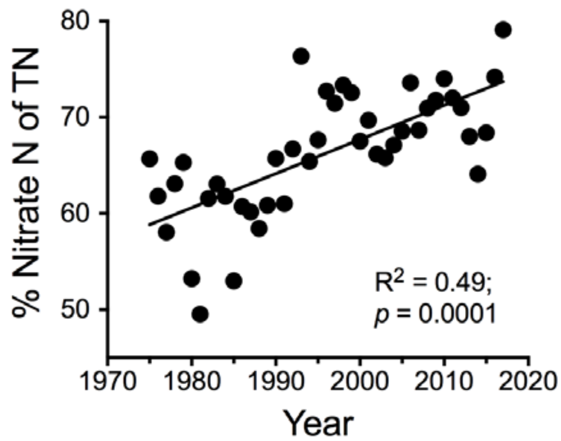


Figure 6. The % nitrite+nitrate load of the total nitrogen load for May in the main channel of the Mississippi River. The estimates are from the USGS.

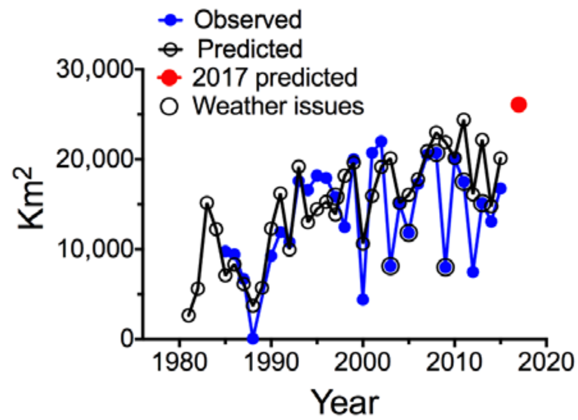
Hypoxic Zone Size

Models for predicting the size of the hypoxic zone rely on July cruise data primarily because there are no comparable shelfwide data for other months. Data on the size of the hypoxic zone in late July from 1985 to 2015 are based on annual field measurements (data available at http://www.gulfhypoxia.net). The 2017 mapping cruise is scheduled for July 24-31, and the data will be posted daily at the same web site. There are no values for 1989 (no funding available) or for 2016 (incompatible ship and with mechanical breakdown); data for 1978 to 1984 are estimated from contemporary field data. The estimates for before 1978 assume that there was no significant hypoxia then and are based on results from various models and sediment core analyses. Data for 7 years were not included in the analysis because there were strong storms just before or during the cruise (1998, 2003, 2005, 2008, 2010, 2011 and 2013). These storms, by comparison of pre-cruise and post-cruise sampling to data collected during the cruise, changed currents, disrupted the stratified water column, and re-aerated the water column. It may take a few days to several weeks, depending on water temperature and initial dissolved oxygen concentration, for respiration to reduce the dissolved oxygen concentration to ≤ 2 mg l^{-1} after the water column stratification is re-established. The average reduction in hypoxia size in years with storms compared to years without storms is 70 ± 9%.

Prediction for 2017

We used several models to forecast the hypoxic zone in the northern Gulf of Mexico in July 2017. The most accurate model prediction, we think, is that it will cover 26,131 km^2 (10,089 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 23,648 and 28,551 km^2 (9,131 and 11,024 mi^2) (Figure 7). This estimate is based on the assumption that there are no significant tropical storms occurring in the two weeks before the monitoring cruise, or during the cruise. If a storm does occur, then the size of the zone is predicted to be 70% of the predicted size without the storm, equivalent to 17,250 km^2 (10,089 mi^2). This is 47% higher than the average of 13,536 km^2 measured from 1985 to 2015.

Figure 7. The measured and estimated size of the hypoxic zone from 1979 to 2015 and the predicted size for 2017.



Hypoxia Models and Model Accuracy

Models are used to summarize information, to test assumptions and to make predictions that may be useful for other purposes, including management. There are multiple models of the size of the hypoxic zone that are useful in evaluating the influence of nitrogen load and variations in ocean currents, climate, etc. These models do not always produce similar results, and model improvement is one focus of ongoing research efforts supported by the NOAA Center for Sponsored Coastal Ocean Research. But the general result from an ensemble analysis using the four model results indicates that a 60% reduction in Mississippi River nitrogen load is required to reach the Hypoxia Action Plan goal, and that a 25% load reduction is required to have a 95% certainty of observing a hypoxic area reduction between consecutive 5-year assessment periods (Scavia et al. in press).

The various statistical models we use to predict the size of the hypoxic zone in July are based on the May total nitrite+nitrate nitrogen load to the Gulf from the main stem of the Mississippi River and the Atchafalaya River. The residence time of the surface waters along this coast is about 2 to 3 months in the summer, hence the 2- to 3-month lag between the loading rate calculated in May and the size of the hypoxic zone in late July. The stability of these models, however, is not fixed, because the ecosystem is evolving. For example, the size of the hypoxic zone for the same amount of nitrogen loading (as nitrite+nitrate) is increasing (Figure 8; Turner et al. 2008, 2012). Further, the models will eventually be adjusted to account for the limited space on the shelf for hypoxia to occur (a physiographic constraint). The rapidly developing process-based ecosystem models are a platform to greatly expand understanding how the physical and biological factors interact over all months (Justić and Wang 2014; Justić et al. 2017), are increasingly accurate, are visually-appealing, and require additional data to validate them as conditions change.

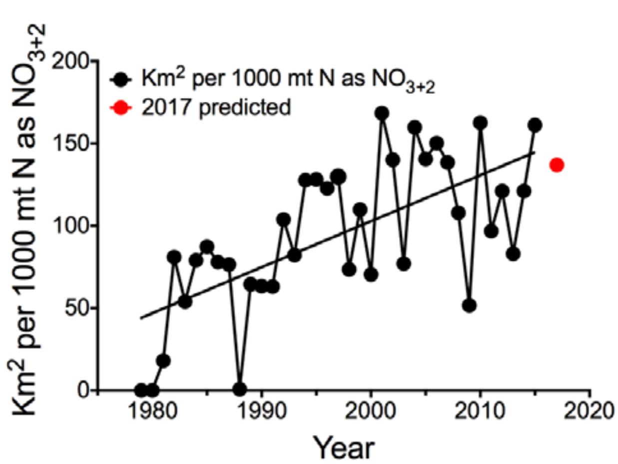


Figure 8. The size of the hypoxic zone per unit May nitrate loading. All years, including strong storm years, are included.

We use several models to predict the size of the hypoxic zone. All of them use the nutrient loading from the Mississippi River in May, which is 2 to 3 months before the annual summer hypoxia cruise that maps its areal extent (note: concentration × discharge equals the nitrite-nitrate load). The unstated hypothesis implied by these models is that the system can be treated as a chemostat limited by N, in the same way that the chlorophyll *a* concentration or algal biomass in lakes might be modeled by P loading to the lake. The Streeter–Phelps type models initiated by Scavia and colleagues also incorporate this nutrient dose:response framework (Scavia et al. 2003, 2004; Scavia and Donnelly 2007) in their predictive schemes. These models assume that the size of the zone is driven mostly by what happens in the current year and that other influences cause variation around a relatively stable baseline suite of factors. An example of secondary influences might be seasonal or annual variations in wind speed and direction or freshwater volume. Our model is based on the nitrate load of the current year. The reference point for calibrating the model is the behavior of the system in recent history. We use the last seven years of data on the relationship between hypoxic zone size and nutrient loading for this model. Others do something similar. The USGS uses the last five years of data to calibrate the 'LOADSET' model, for example, and Scavia and Donnelly (2007) update the coefficients in their model annually by using rolling 3 to 5 year averages for coefficients (Evans and Scavia 2010). Their recent numerical adaptation has the effect of adjusting model input with each year, but not explaining the biological/physical basis for these changes any better than one of our earlier model did with the 'year' term. The year term in our model is, in other words, descriptive, but not explanatory beyond the simple nitrogen loading = oxygen deficit relationship.

The results of our current model are in Figure 7. The nitrate data were transformed into their log10 equivalents to avoid the problem encountered in 2012 when the prediction was much larger than the actual size, which is attributable to using a simple linear regression analysis to fit a curvilinear relationship. If there is significant curvature (bowed downward) without this transformation, then both the lower and upper ends of the data field are overestimated. This effect is more dramatic when the relationship is being extended into a sparse data field at the extremes of nitrogen loading, as happened during 2012, which was a drought with low nitrate loading. The estimate for 2017 overlaps the calibration curve (R^2 = 0.94; Figure 9).

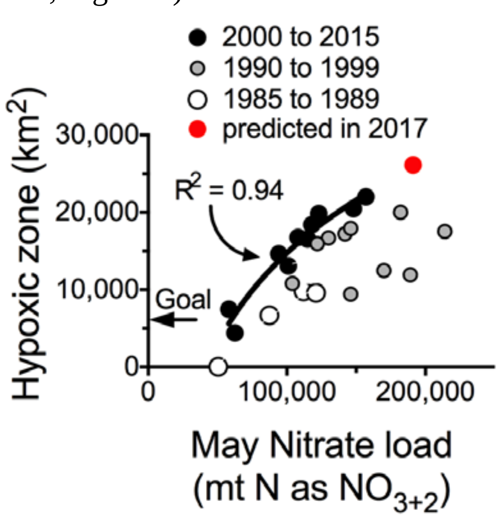


Figure 9. The relationship between nitrate+nitrate loading in May and the size of the hypoxic zone in July. Several intervals are broken out, with the last one (2000 to 2015) being fit to a regression model. The predicted size of the hypoxic zone for 2017 is indicated with the red dot.

Some of the sensitivity to nitrate loading is carried over from one interval to the next. We call these effects ‘legacy’ effects, and they may last decades. A legacy effect can be explained as the result of incremental changes in organic matter accumulated in the sediments one year, and metabolized in later years (Turner and Rabalais 1994), by changes in the percent nitrate of the total nitrogen pool (e.g., Figure 6), or by long-term climate change.

The predicted volume of hypoxia is based on the relationship between hypoxia area and volume (Figure 10). The predicted volume of the hypoxic zone for 2017 is 95 km^3.

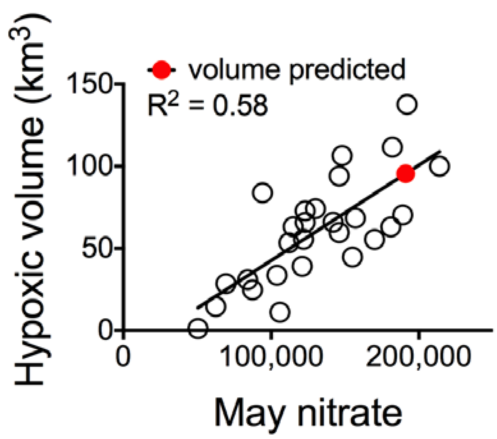


Figure 10. The relationship between nitrate+nitrate loading in May and the volume of the hypoxic zones from 1985 to 2011. The volume data are from Obenour et al. (2013). The predicted size of the hypoxic zone for 2017 is indicated with the red dot (with a 95% confidence interval.)

Our statistical models and their predecessors, are fairly accurate models based on past performance (Turner et al. 2008, 2012). The predictions in 2006, 2007, and 2010, for example, were 99%, 107%, and 99%, respectively, of the measured size. The model used here describes 94% of the variation since 2000 (inclusive; Figure 9). The equivalent model for the Baltic Sea low oxygen conditions explains 49 to 52% of the variation in the interannual variation in bottom water oxygen concentration (Conley et al. 2007).

Nutrient load models are robust for long-term management purposes, but they are less robust when short-term weather patterns move water masses or mix up the water column. The size of the hypoxic zone this year is expected to follow the relationship with nitrogen loading—as long as there is no ‘wildcard’ in the form, for example, of a tropical storm at the time of the annual summer cruise. Some of the variations in the size of the Gulf hypoxic zone result from re-aeration of the water column during storms. The size of the summer hypoxic zone in 2008, for example, was less than predicted because of the influence of Hurricane Dolly. Tropical Storm Don was a similar complication in 2011. The long-term trend, however, is that the area of hypoxia is larger for the same amount of nitrogen loading (Turner et al. 2008, 2012; Figure 8).

Other models predicting oxygen dynamics on this shelf are in Bierman et al. (1994), Justić et al. (2003), Scavia and Donnelly (2007), Forest et al. (2011), Kling et al. 2(014), and Scavia et al. (2003, 2004). The University of Michigan forecast website is: www.sitemaker.umich.edu/scavia. A Virginia Institute of Marine Science estimate will be posted on the internet.

The data from this year’s cruise will be used to quantify the relative merits of the assumptions of the models, and to compare them with other models of various kinds. This is an example of how long-term observations are one of the best ways to test and calibrate ecosystem models, to recognize the dynamic nature of our changing environment(s), and to improve the basis for sound management decisions.

Long-term Trends in Water Quality

The nitrogen loading of the Mississippi River to the Gulf of Mexico has not increased substantially in the last decade, and may have stabilized in some tributaries (Murphy et al. 2013; Stets et al. 2015) despite increasing urban runoff to the river (Baton Rouge Advocate 2017). Stets et al. (2015), for example, reviewed the trends in tributary concentrations across the US from 1945 to 2008 and found some interesting differences shown in Figure 11. The nitrate concentration increased strongly during 1945-1980 at most stations and leveled off from 1981 to 2008. The nitrate concentrations increased at monitoring stations in the Midwest U.S., but less so in the Eastern and Western U.S. During 1945 to 1980, nitrate concentrations in large rivers in the agricultural areas of the Midwest increased up to fivefold. The greatest increases in river nitrate levels coincided with increased nitrogen inputs from livestock and agricultural fertilizer inputs.

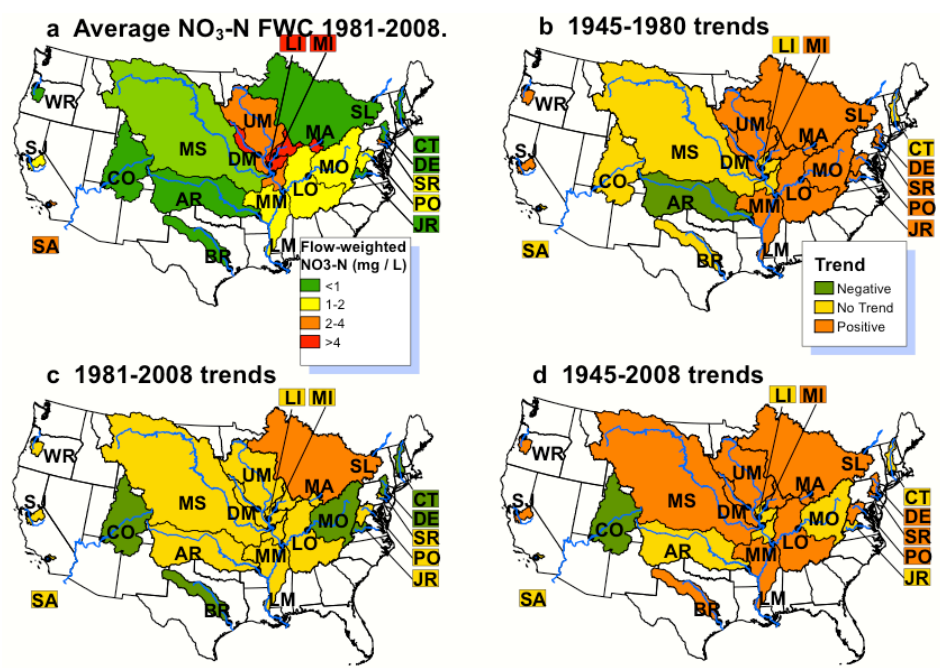


Figure 11. (a) Average flow-weighted nitrate concentration (FW NO_3-N, mg /L) from 1981-2008 at selected monitoring stations. (b-d) Temporal trend in FW NO_3-N significance indicates $p < 0.1$ in Kendall correlation analysis for the specified time period. Station abbreviations are: AR, Arkansas; BR, Brazos; CO, Colorado; CT, Connecticut; DE, Delaware; DM, Des Moines; IL, Lower Illinois; IM, Middle Illinois; JR, James; MA, Maumee; ML, Lower Mississippi; MM, Middle Mississippi; MO, Missouri; OL, Lower Ohio; OM, Middle Ohio; PO, Potomac; SA, Santa Ana; SJ, San Joaquin; SL, St. Lawrence; SR, Schuylkill; UM, Upper Mississippi; WR, Willamette. From Stets et al. (2015).

The increase in nitrate and phosphorus concentration is common to other areas away from the coast and recognized for many decades (Vitousek et al. 1997). Jenny et al. (2016), for example, collected water quality data from over 1,500 European watersheds and identified the relative role of different drivers in initiating hypoxia in lakes. They found a significant acceleration in the spread of lacustrine hypoxia in the 1900s, which occurred before the general use of commercial fertilizers in the mid-20th century and the onset of climate warming in the 1970s. The spread of hypoxia was best explained by urban expansion and the associated intensification of anthropogenic point sources of nutrients that led to enhanced biological productivity and subsequent respiration in bottom waters. Holgrieve et al. (2011) describe the changes in nitrogen in remote watershed of the northern hemisphere (Figure 12). There the isotopes of nitrogen are in concert with the changes in nitrogen application following intense use in agriculture, and coincidentally with rises in climate change gases.

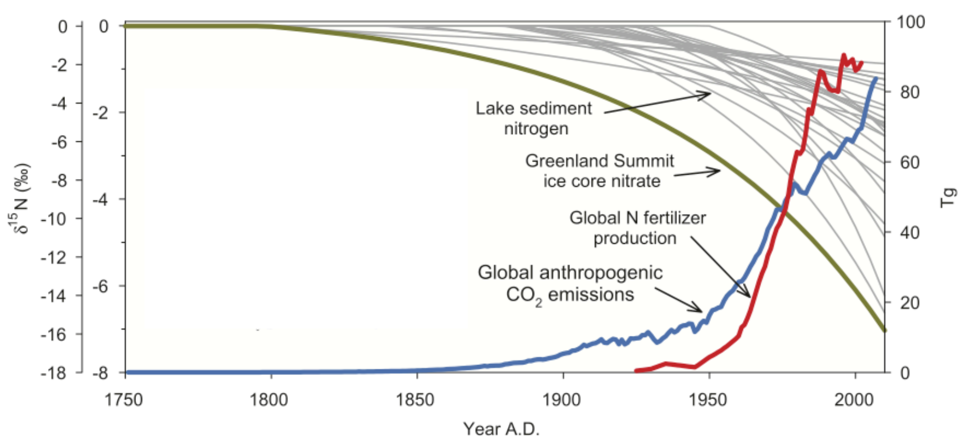


Figure 12. Relative changes in d[15]N isotope ratios in sediments from 25 Northern Hemisphere lakes over the past 260 years (inner left ordinate), standardized to a common asymptotic value. Also shown is the relative change in $d^{15}N$-NO_3 from the Greenland Summit ice core (outer left ordinate), Haber-Bosch N fertilizer production (right ordinate), and global anthropogenic CO_2 (right ordinate, data rescaled by 1/100 for plotting purposes). From Holgrieve et al. 2011.

These changes in nitrogen loading are accompanied by many water quality problems including algal blooms in lakes, with recent notable ones being Lake Erie, Lake Baikal and Lake Utah (Guardian 2016; Michalak et al. 2017; Timoshkina et al. 2016). There are consequences for not improving water quality including higher sewage treatment costs (Dearmont et al. 1998), seafood price increases (e.g., Smith et al. 2017), and compromises to fish reproduction (Tuckey and Fabrizio 2016). There are also documented links between nitrate in drinking water and birth (neural tube and spinal cord, including spina bifida, oral cleft defects and limb deficiencies), bladder cancer, and thyroid cancer. Further, the strictly nutrient related issues are co-developing with other problems (e.g., ocean acidification and climate change) whose cumulative and synergistic interactions may be even more significant socially and ecologically (Moss et al. 2011).

The water quality of sub-watershed streams could improve (Garcia et al. 2016). Water quality has improved in sub-regions of the Mississippi watershed because of conservation (Kling et al. 2014; Markus 2014; McIsaac et al. 2016; Rabotyagov et al. 2014), but clearly a net change has yet to appear 16 years after the 2001 Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico (Mississippi River/ Gulf of Mexico Watershed Nutrient Task Force 2001) to reduce the size of the hypoxic zone to 5,000 km^2.

Post-cruise Assessment

A post-cruise assessment will be made at the end of the summer shelfwide hypoxia cruise and posted on the same website where this report appears (http://www.gulfhypoxia.net).

Acknowledgments

Support was received from the NOAA Center for Sponsored Coastal Ocean Research Grants NA09NOS4780204 to Louisiana Universities Marine Consortium and NA09NOS4780230 to Louisiana State University. Charlie Milan analyzed the nutrient samples for the Mississippi River at Baton Rouge. The hypoxia area data are from http://www.gulfhypoxia.net. We thank Trevor Meckley of NOAA and Brent T. Aulenbach, Mike Woodside and colleagues at the USGS for providing the nitrogen loading data for the Mississippi River.

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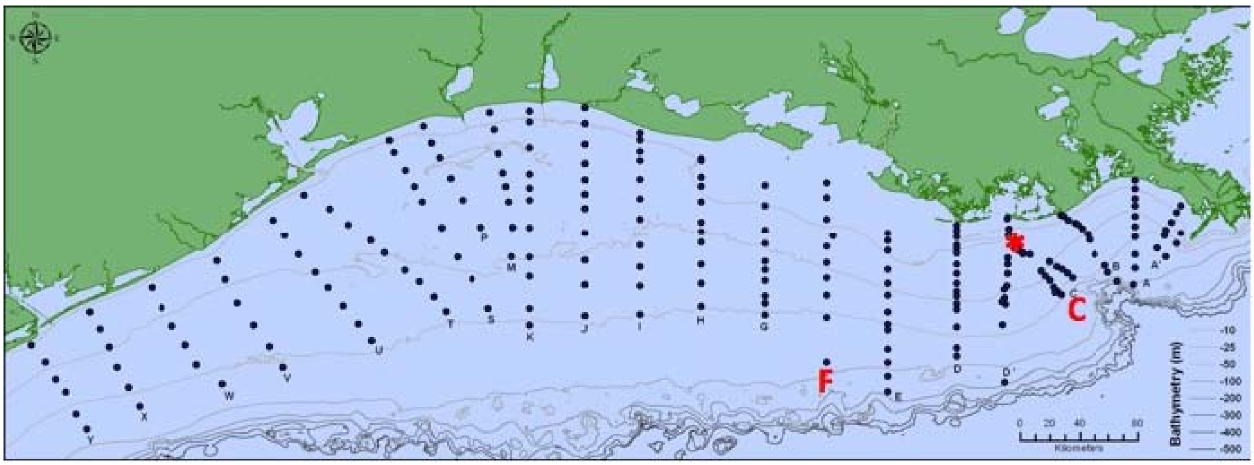
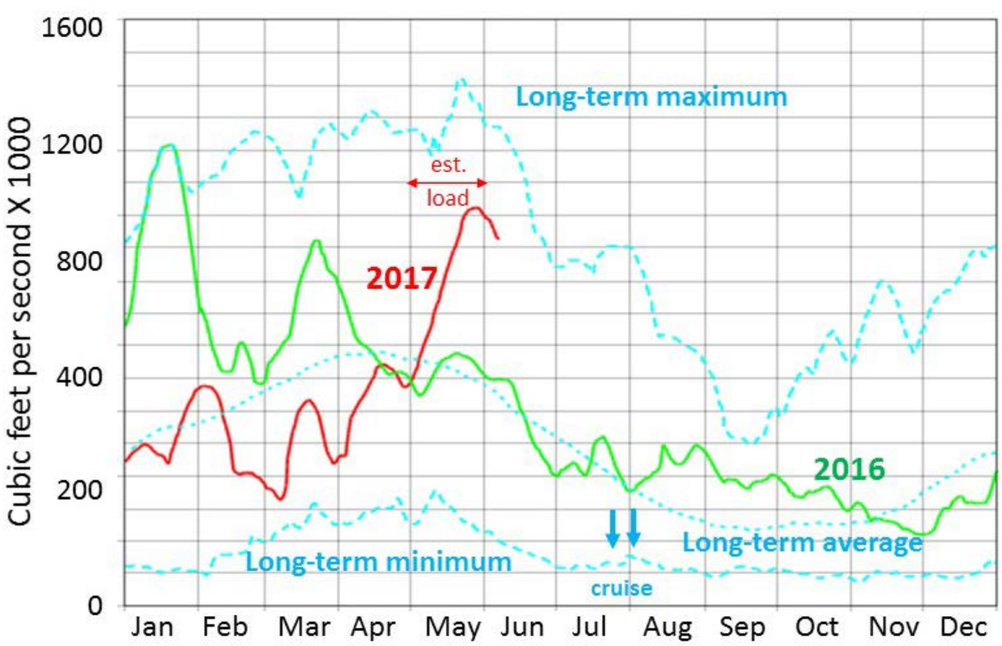
Appendix



Appendix Figure 1. Location of hypoxia monitoring stations sampled in summer (not all every year, depending on location of hypoxic area), the transects off Terrebonne Bay (transect C) and Atchafalaya Bay (transect F), and the ocean observing system (asterisk) off Terrebonne Bay.



Appendix Figure 2. The daily river discharge at Tarbert Landing, LA, from 1935 through 1 Jun 2017. Units are cubic feet per second × 1000. The period of the nitrate load is shown with a red horizontal arrow; the timing of the summer hypoxia cruise is indicated by the blue vertical arrows. Figure modified from http://rivergages.mvr.usace.army.mil/WaterControl/Districts/MVN/tar.gif.