2018 Forecast:
Summer Hypoxic Zone Size
Northern Gulf of Mexico

R. Eugene Turner[1] and Nancy N. Rabalais[1]

Abstract

A hypoxic water mass with oxygen concentrations ≤ 2 mg l^{-1} forms in bottom waters of the northern Gulf of Mexico continental shelf each year. 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. These low oxygen conditions threaten living resources including humans that depend on the fish, shrimp and crabs that are caught there. 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. Our prediction is based on these models.

The June 2018 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for late July 2018 is that it will cover 17,250 km^2 (6,620 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 14,628 and 19,727 km^2 (5,648 and 7,617 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 12,075 km^2 (6,316 mi^2).

The predicted hypoxic area is slightly larger than the State of Vermont (14,357 km^2) and 4% larger than the average of 16,357 km^2 (*n* - 31, including years with storms). If the area of hypoxia becomes as large as predicted, then it will be about three and a half times the size of the Hypoxia Action Plan goal (5,000 km^2). Efforts to reduce the nitrate loading have not yet demonstrated success at the watershed scale.

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 size to be lower than the prediction.

---

[1] Department of Oceanography and Coastal Sciences
Louisiana State University
Baton Rouge, LA 70803
euturne@lsu.edu
nrabal@lsu.edu

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 – something that is of economic consequence to the fishery (Purcell et al. 2017; Smith et al. 2017). The number of dead zones throughout the world has been increasing in the last several decades and currently totals over 500 (Díaz and Rosenberg 2008; Rabalais et al. 2010; Conley et al. 2011; Breitburg et al. 2018). The dead zone off the Louisiana coast is the second largest human-caused coastal hypoxic area in the global ocean.

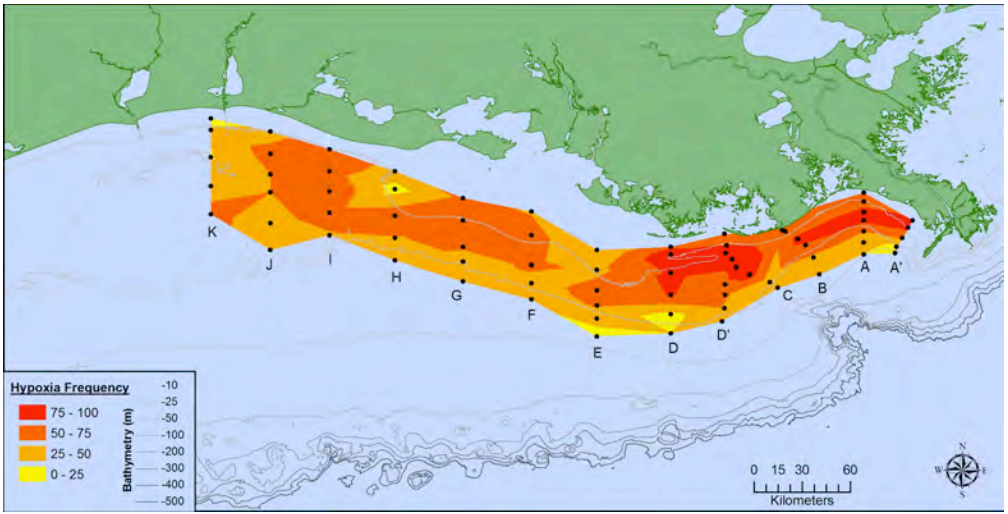


Figure 1. The frequency of mid-summer hypoxia (oxygen ≤ 2 mg l^{-1}) over the 70 to 90 station. grid on the Louisiana and Texas shelf during the summer from 1985 to 2014. The frequency is determined from those stations for which there are data for at least half of all cruises. From Rabalais et al. (2010).

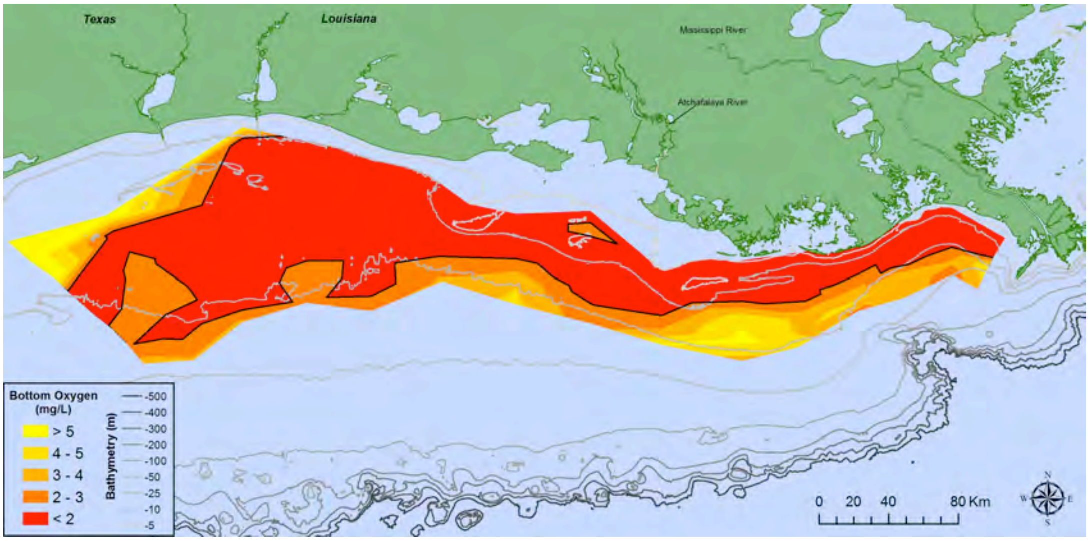


Figure 2. Oxygen concentrations in bottom water across the Louisiana-Texas shelf from July 24 – July 30, 2017. Data source: N.N. Rabalais, Louisiana State University, Universities Marine Consortium, and R.E. Turner, LSU; funded by NOAA, National Centers for Coastal Ocean Science. There was no closure of the hypoxic zone area determination on the western end (funding limitation).

Systematic mapping of the area of hypoxia in bottom waters of the northern Gulf began in 1985 at geographically fixed stations (Appendix 1). Its size from 1985 to 2017 ranged between 40 to 22,720 km^2 during July and averaged 14,042 km^2 (5,424 mi^2). It was 22,720 km^2 (8,776 mi^2) in 2017—the largest measured to date and the cruise ended before the total area was determined. There were no cruises in 1989 and 2016. 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. The number of cruises peaked 20 years ago and is now at the bare minimum (Appendix 2).

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 not as reliable as they were once thought to be (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 (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).

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 daily discharge in May 2018 was 28,500 $m^3 s^{-1}$ (cms) (Appendix 3, Figure 2), which is the 27th largest in 51 years from 1968 to 2018, and equal to about 100 % of the average discharge (in May; 28,433 cms) for the interval (Figure 3).

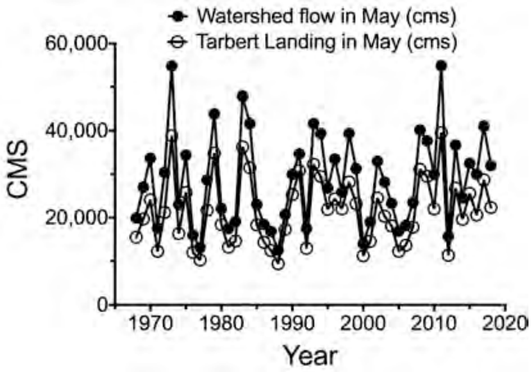


Figure 3. The discharge in May for the Mississippi River watershed and south of St. Francisville, LA at Tarbert Landing, MS. (CMS = cubic meters per second, $m^3 s^{-1}$).

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 provides information on the data calculations, including an estimate of the 95% confidence range for the nitrogen load. The May nitrite+nitrate (NO_{2+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.

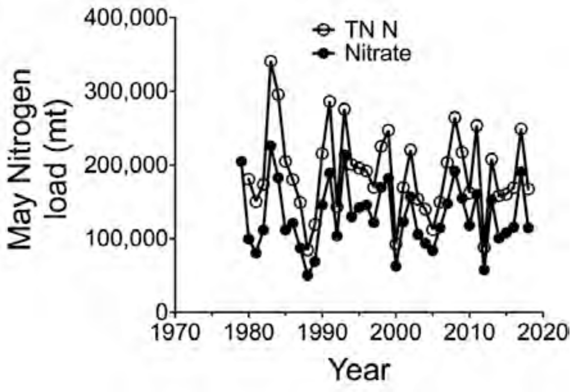


Figure 4. The annual nitrite+nitrate (NO_{2+3}) and total nitrogen (TN) load for the Mississippi River watershed for May. The estimates are from the USGS.

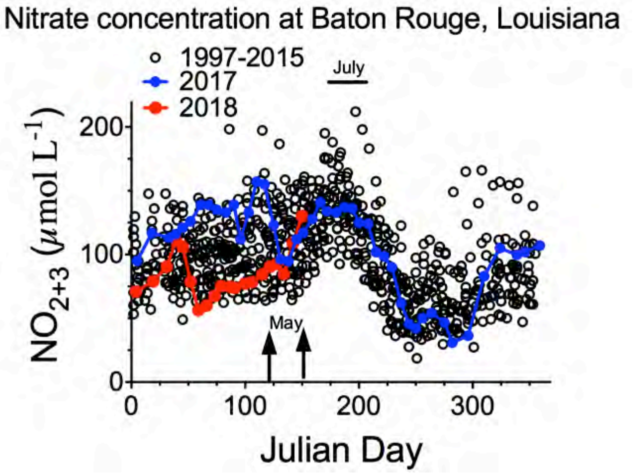


Figure 5. The concentration of nitrite+nitrate (NO_{2+3}) at Baton Rouge, LA from 1997 to present. Unpublished data from RETurner.

The concentration of nitrite+nitrate at Baton Rouge was lower than average in the winter of 2017-18, and but near the higher values for 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 89 % 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).

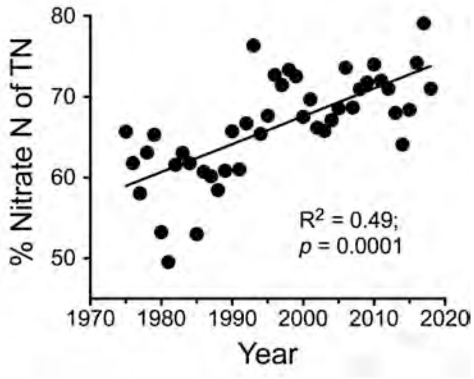


Figure 6. The % nitrite+nitrate load of the total nitrogen load for May in the main channel of the Mississippi River. The estimates are from the USGS for 1968 to 2018

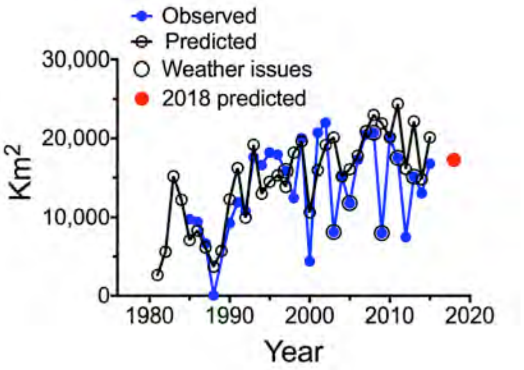
Hypoxic Zone Size

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 2017 are based on annual field measurements (data available at http://www.gulfhypoxia.net). The 2018 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 with mechanical breakdown); data from 2017 was incomplete at the end of the transect; 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 2018

We used several models to forecast the hypoxic zone in the northern Gulf of Mexico in July 2018. The most accurate model prediction, we think, is that it will cover 17,250 km^2 (6,620 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 14,628 and 19,727 km^2 (5,648 and 7,617 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 12,075 km^2 (6,316 mi^2). This is 27% 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 for 2018.



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 National Centers for Coastal Ocean Science. 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 Task Force goal, and that a 25% load reduction is required to have a 95% certainty of observing a hypoxic area reduction within a consecutive 5-year assessment period (Scavia et al. 2017).

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). Hereinafter, the nitrite+nitrate loading will be referred to as "nitrate" loading, because the nitrite component is a minimal component of the two. 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.

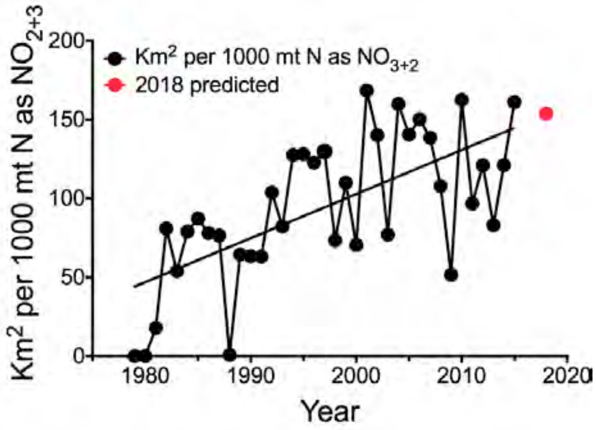


Figure 8. The size of the hypoxic zone per unit May nitrite+nitrate loading. All years, including strong storm years, are included.

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 approximately 2 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 models 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 2018 overlaps the calibration curve ($R^2 = 0.94$; Figure 9).

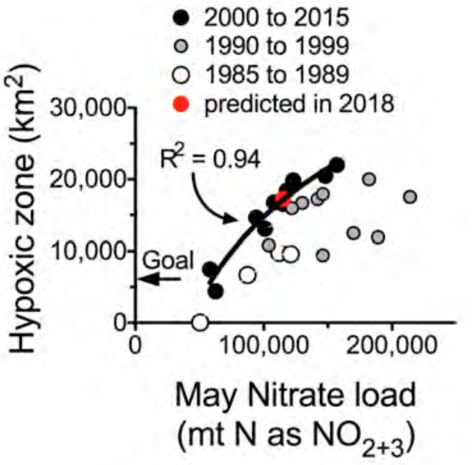


Figure 9. The relationship between nitrate+nitrate loading in May and the size of the hypoxic zone in July. Several intervals are broken out, with the last one (2000 to 2015) being fit to a regression model. The predicted size of the hypoxic zone for 2018 is indicated with the red dot.

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 temperature changes (Turner et al. 2017).

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 2018 is 51.3 km^3.

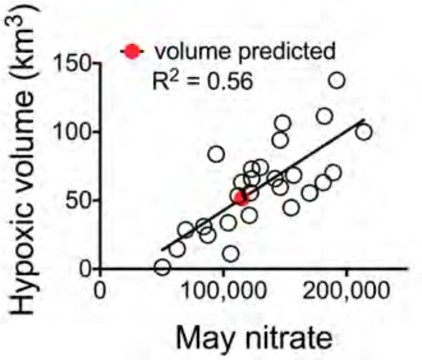


Figure 10. The relationship between nitrate+nitrate loading in May and the volume of the hypoxic zones from 1985 to 2011. The volume data are from Obenour et al. (2013). The predicted size of the hypoxic zone for 2017 is indicated with the red dot (with a 95% confidence interval.)

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 inter-annual variations 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. Climate changes may alter the spring initiation of hypoxia formation, duration and frequency. The timing of hypoxia in the Chesapeake Bay, for example, is earlier with climate warming (Testa et al. 2018). The needed detailed seasonal data necessary to make pheneological comparison are not known. The long-term trend for the northern Gulf of Mexico 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. (2014), Scavia et al. (2003, 2004) and Testa et al. (2017). The annual forecasts for this year are: University of Michigan forecast website (http://scavia.seas.umich.edu/hypoxia-forecasts/); Virginia Institute of Marine Science (http://www.vims.edu/research/topics/dead_zones/forecasts/gom/index.php); Dalhousie University (http://www.noaa.gov/media-releases); North Carolina State University (https://obenour.wordpress.ncsu.edu/); and the NOAA ensemble predictions which is based on these models (http://www.noaa.gov/media-releases).

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. 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 and Restoration

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). Some consequences for water quality degradation include 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).

Water quality improvements have occurred in Massachusetts (Wong et al. 2018), and in many US streams (Keiser and Shapiro 2017). Indeed, the Clean Water Act was formed and succeeded in improving the various 'externalities' of water pollution to those downstream of plants dumping waste into the river. This included the notable Cuyahoga River which caught fire in 1969. The Times magazine (1969) dryly described it: "Anyone who falls into the Cuyahoga does not drown - he decays." But there is much work remaining - half of the US stream and river miles violate water pollution standards (Keiser and Shapiro 2017). Desmit et al. (2018) examined some of these same patterns leading to coastal eutrophication in the Northeast Atlantic. They used models and historical data to demonstrate that water quality improvements would require significant re-connections and re-shaping of the connections between farming and food consumption, less waste-productions and changes from the meat-intensive diets to lower-impact and healthier diets containing vegetal proteins.

Restoration of the coastal waters for the Mississippi River watershed means, in large part, changing farming practices (Rabotyagov et al. 2014). Water quality has improved in some sub-watershed streams of the Mississippi watershed because of conservation (Kling et al. 2014; Markus 2014; Rabotyagov et al. 2014, McIsaac et al. 2016; Garcia et al. 2016), but 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. Van Meter et al. (2018) suggest that there is a legacy effect on improvements that could thwart recovery for decades, presumably through lags in soil water recovery.

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 is from the NOAA National Centers for Coastal Ocean Science. 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 John Wickham of NOAA and Brent T. Aulenbach, Mike Woodside and colleagues at the USGS for providing the nitrogen loading data for the Mississippi River.

References

Alexander, R.B., R.A. Smith, G.E. Schwarz 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. **Environmental Science and Technology** 42: 822–830.

Bierman, V.J., Jr., S.C. Hinz, D. Zhu, W.J. Wiseman, Jr., N.N. Rabalais, R.E. Turner 1994. A preliminary mass balance model of primary productivity and dissolved oxygen in the Mississippi River plume/inner Gulf shelf region. **Estuaries** 17: 886–899.

Breitburg, D., L.A. Levin, A. Oschlies, M. Grégoire, F.P. Chavez, D.J. Conley, V. Garçon, D. Gilbert, D. Gutiérrez, K. Isensee, G.S. Jacinto, K.E. Limburg, I. Montes, S.W.A. Naqvi, G.C. Pitcher, N.N. Rabalais, M.R. Roman, K.A. Rose, B.A. Seibel, M. Telszewski, M. Yasuhara, J. Zhang 2018. Declining oxygen in the global ocean and coastal waters. **Science** 359: eaam7240, 11 pp.

Broussard, W., R.E. Turner 2009. A century of changing land use and water quality relationships in the continental U.S. **Frontiers in Ecology and the Environment** 7: 302-307.

Broussard, W., R.E. Turner, J. Westra 2012. Do federal farm policies and agricultural landscapes influence surface water quality? **Agriculture, Ecosystems & Environment** 158: 103-109. 10.1016/j.agee.2012.05.022

Conley, D.J., J. Carstensen, G. Ærtebjrg, P.B. Christensen, T. Dalsgaard, J.L.S. Hansen, A. B. Josefson 2007. Long-term changes and impacts of hypoxia in Danish coastal waters. **Ecological Applications** Supp. 17: S165-S184.

Conley, D.J., 18 co-authors 2011. Hypoxia is increasing in the coastal zone of the Baltic Sea. **Environmental Science and Technology** 45: 6777–6783. doi.org/10.1021/es201212r.

Dearmont, D., B.A. McCarl, D.A. Tolman 1998. Costs of water treatment due to diminished water quality: A case study in Texas. **Water Resources Research** 34: 849-853.

Desmit, X., V. Thieub, G. Billen , F. Campuzano, V. Dulière, J. Garnier, L. Lassaletta, A. Ménesguen, R. Neves, L. Pinto, M. Silvestre, J.L. Sobrinho, G. Lacroix 2018. Reducing marine eutrophication may require a paradigmatic change. **Science of the Total Environment** 635: 1444–1466.

Díaz, R.J., R. Rosenberg 2008. Spreading dead zones and consequences for marine ecosystems. **Science** 321: 926-929.

Evans, M.A., D. Scavia 2010. Forecasting hypoxia in the Chesapeake Bay and Gulf of Mexico: Model accuracy, precision, and sensitivity to ecosystem change. **Environmental Research Letters** 6: 015001.

Fuentes, S., G.H. Wikfors, S. Meseck 2014. Silicon deficiency induces alkaline phosphatase enzyme activity in cultures of four marine diatoms. **Estuaries and Coasts** 37: 312–324; doi 10.1007/s12237-013-9695-z

Forrest, D.R., R.D. Hetland, S.F. DiMarco 2011. Multivariable statistical regression models of the area extent of hypoxia over the Texas-Louisiana continental shelf. **Environmental**

Research Letters 6: 045002.

García, A.M., R.B. Alexander, J.G. Arnold, L. Norfleet, M.J. White, D.M. Robertson, G. Schwarz 2016. Regional effects of agricultural conservation practices on nutrient transport in the Upper Mississippi River Basin. **Environmental Science and Technology** 50: 6991−7000, doi: 10.1021/acs.est.5b03543

Justić, D., L. Wang 2014. Assessing temporal and spatial variability of hypoxia over the inner Louisiana-upper Texas shelf: Application of an unstructured-grid three-dimensional coupled hydrodynamic-water quality model. **Continental Shelf Research** 72**:** 163-179.

Justić, D., N.N. Rabalais, R.E. Turner 2003. Simulated responses of the Gulf of Mexico hypoxia to variations in climate and anthropogenic nutrient loading. **Journal of Marine Systems** 42: 115-126.

Justić, D., K.A. Rose, R.D. Hetland, and K. Fennel (Eds.) 2017. Modeling Coastal Hypoxia: Numerical Simulations of Patterns, Controls and Effects of Dissolved Oxygen Dynamics. Springer, NY. 433 pp.

Keiser, D.A., J.S. Spiro 2017. Consequences of the Clean Water Act and the demand for water quality. National Bureau of Economic Research Research Paper 23070. Downloaded 5 May 2018, from: http://www.nber.org/papers/w23070.

Kling, C.L., Y. Panagopoulos, S. Rabotyagov, A. Valcu, P.W. Gassman, T. Campbell, M. White, J.G. Arnold, R. Srinivasan, M.K. Jha, J. Richardson, L.M. Moskal, R.E. Turner, N.N. Rabalais 2014. LUMINATE: Linking agricultural land use, local water quality and Gulf of Mexico hypoxia. **European Review of Agricultural Economics** pp. 1-29; doi: 10.1093/erae/jbu009

Lohrenz, S.E., Fahnenstiel, G.L., Redalje, D.G., Lang, G.A., Chen X., Dagg M.J. 1997. Variations in primary production of northern Gulf of Mexico continental shelf waters linked to nutrient inputs from the Mississippi River. **Marine Ecology Progress Series** 155: 45−54.

Lohrenz, S.E., Redalje, D.G., Cai, W.J., Acker, J., Dagg, M.J. 2008. A retrospective analysis of nutrients and phytoplankton productivity in the Mississippi River Plume. **Continental Shelf Research** 28: 1466−1475.

McIsaac, G.F., M.B. David, G.Z. Gertner 2016. Illinois River nitrate-nitrogen concentrations and loads: Long-term variation and association with watershed nitrogen inputs. **Journal of Environmental Quality** 45(4): 1268-75. doi:10.2134/jeq2015.10.0531

Moss, B., S. Kosten, M. Meerhoff, R.W. Battarbee, E. Jeppesen, N. Mazzeo, K. Havens, G. Lacerot, Z. Liu, L. De Meester, H. Paerl, M. Scheffer 2011. Allied attack: climate change and eutrophication. **Inland Waters** 1: 101-105.

MRNGoM HTF (Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force) 2001. *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*; Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency; Washington, DC.

MRNGoM HTF (Mississippi River Nutrient/Gulf of Mexico Hypoxia Task Force) 2008. *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*. Office of Wetlands, Oceans, and Watersheds, U.S. Environmental Protection Agency, Washington, D.C.

Murphy, J.C., R.M. Hirsch, L.A. Sprague. 2013. Nitrate in the Mississippi River and its tributaries, 1980– 2010: An update. **USGS Scientific Investigations Report** 2013–5169. http://pubs.usgs.gov/sir/2013/5169/.

Obenour, D.R., A.M. Michalak, Y. Zhou, D. Scavia 2012. Quantifying the impacts of stratification and nutrient loading on hypoxia in the northern Gulf of Mexico. **Environmental Science and Technology** 46: 5489–5496.

Obenour, D.R., D. Scavia, N.N. Rabalais, R.E. Turner, A.M. Michalak 2013. A retrospective analysis of mid-summer hypoxic area and volume in the northern Gulf of Mexico, 1985-2011.**Environmental Science and Technology** 47: 9808–9815.

Purcell, K.M., J.K. Craig, J.M. Nance, M.D. Smith, L.S. Bennear 2017. Fleet behavior is responsive to a large-scale environmental disturbance: Hypoxia effects on the spatial dynamics of the northern Gulf of Mexico shrimp fishery. **PLoS ONE** 12(8): e0183032. https://doi. org/10.1371/journal.pone.0183032

Rabalais, N.N., R.E. Turner, D. Scavia 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River**. BioScience** 52: 129-142.

Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, D.F. Boesch, P. Chapman, M.C. Murrell 2007. Hypoxia in the northern Gulf of Mexico: Does the science support the plan to reduce, mitigate and control hypoxia? **Estuaries and Coasts** 30: 753-772.

Rabalais, N.N., R.J. Díaz, L.A. Levin, R.E. Turner, D. Gilbert, J. Zhang 2010. Dynamics and distribution of natural and human-caused hypoxia. **Biogeosciences** 7: 585-619.

Rabalais, N.N., L.M. Smith, R E. Turner. 2018. The *Deepwater Horizon* oil spill and Gulf of Mexico shelf hypoxia. **Continental Shelf Research** 152: 98-107.

Rabotyagov, S., T. Campbell, M. White, J. Arnold, J. Atwood, L. Norfleet, C. Kling, P. Gassman, A. Valcu, J. Richardson, R.E. Turner, N.N. Rabalais 2014. Cost-effective targeting of conservation investments to reduce the northern Gulf of Mexico hypoxic zone. **Proceedings of the National Academy of Sciences (USA)** 111(52): 18530-18535 doi: 10.1073/pnas.1405837111.

Scavia, D., N.N. Rabalais, R.E. Turner 2003. Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. **Limnology and Oceanography** 48: 951-956.

Scavia, D., D. Justić, V.J. Bierman, Jr. 2004. Reducing hypoxia in the Gulf of Mexico: Advice from three models. **Estuaries** 27: 419–425.

Scavia, D., K.A. Donnelly 2007. Reassessing hypoxia forecasts for the Gulf of Mexico. **Environmental Science and Technology** 41: 8111-8117.

Scavia, D., I. Bertani, D.R. Obenour, R.E. Turner, D.R. Forrest, and A. Katkin 2017. Ensemble modeling informs hypoxia management in the northern Gulf of Mexico. **Proc. Nat. Acad. Sci. (USA)** 114: 8823–8828. doi/10.1073/pnas.1705293114

Science Advisory Board (SAB) 2007. Hypoxia in the northern Gulf of Mexico, An Update. U.S. Environmental Protection Agency, Science Advisory Board (SAB) Hypoxia Panel Advisory, Report EPA-SAB-08-003, Environmental Protection Agency, Washington, D.C. http://yosemite.epa.gov/sab/sabproduct.nsf/C3D2F27094E03F90852573B800601D93/$Fil e/EPA-SAB-08-003complete.unsigned.pdf

Sen Gupta, B.K., R.E. Turner, N.N. Rabalais 1996. Seasonal oxygen depletion in continental-shelf waters of Louisiana: Historical record of benthic foraminifers. **Geology** 24: 227-230.

Smith, M.D., A. Oglen, A.J. Kirkpatrick, F. Asche, L.S. Bennear, J.K. Craig, J.M. Nance 2017. Seafood prices reveal impacts of a major ecological disturbance. **Proceedings National Academy Sciences (USA)** 114: 1512–1517, doi: 10.1073/pnas.1617948114

Sprague, L.A., R.M. Hirsch, B.T. Aulenbach 2011. Nitrate in the Mississippi River and its tributaries, 1980 to 2008: Are we making progress? **Environmental Science and Technology** 45: 7209-7216. dx.doi.org/10.1021/es201221s

Stets, E.G., V.J. Kelly, C.G. Crawford, 2015. Regional and temporal differences in nitrate trends discerned from long-term water quality monitoring data. **Journal American**

Water Resources Association 51(5): 1394-1407. doi: 10.1111/1752-1688.12321

Testa, J.M, J.B. Clark, W.C. Dennison, E.C. Donovan, A.W. Fisher, W. Ni, M. Parker, D. Scavia S.E. Spitzer, A.M. Waldrop, V.M.D. Vargas, G. Ziegler 2017. Ecological forecasting and the science of hypoxia in Chesapeake Bay. **BioScience** 67: 614–626.

Testa, J.M., R.R., Murphy, D.C. Brady, W.M. Kemp, 2018. Nutrient- and climate-induced shifts in the phenology of linked biogeochemical cycles in a temperate estuary. **Frontiers in Marine Science** 5: 114.doi: 10.3389/fmars.2018.00114

Time Magazine 1969. The Cities: The price of optimism," Time Magazine, August 1.1969. Downloaded 20 May 2018 @ http://content.time.com/time/magazine/article/0,9171,901182,00.html.

Tuckey, T.D., M.C. Fabrizio 2016. Variability in fish tissue proximate composition is consistent with indirect effects of hypoxia in Chesapeake Bay tributaries. **Marine and Coastal Fisheries** 8: 1-15, doi: 10.1080/19425120.2015.1103824

Turner, R.E., N. Qureshi, N.N. Rabalais, Q. Dortch, D. Justić, R. Shaw, J. Cope 1998. Fluctuating silicate:nitrate ratios and coastal plankton food webs. **Proceedings National Academy of Sciences (USA)** 95: 13048-13051.

Turner, R.E., N.N. Rabalais 1994. Coastal eutrophication near the Mississippi river delta. **Nature** 368: 619-621

Turner, R.E., N.N. Rabalais, E.M. Swenson, M. Kasprzak, T. Romaire 2005. Summer hypoxia, Northern Gulf of Mexico: 1978 to 1995. **Marine Environmental Research** 59: 6577.

Turner, R.E., N.N. Rabalais, D. Justić 2008. Gulf of Mexico hypoxia: Alternate states and a legacy. **Environmental Science and Technology** 42: 2323-2327.

Turner, R.E., N.N. Rabalais, D. Justić 2012. Predicting summer hypoxia in the northern Gulf of Mexico: Redux. **Marine Pollution Bulletin** 64: 318-323. DOI: 10.1016/j.marpolbul.2011.11.008

Turner, R.E., N.N. Rabalais, D. Justić 2017. Trends in summer bottom-water temperatures on the Northern Gulf of Mexico continental shelf from 1985 to 2015. **PloS One** 12(9): e0184350. https:// doi.org/10.1371/journal.pone.0184350

Van Meter, P. K.J. Van Cappellen, and N.B. Basu 2018. Legacy nitrogen may prevent achievement of water quality goals in the Gulf of Mexico. **Science** 10.1126/science.aar4462.

Walker, N.D., N.N. Rabalais 2006. Relationships among satellite chlorophyll a, river inputs, and hypoxia on the Louisiana continental shelf, Gulf of Mexico. **Estuaries and Coasts** 29: 1081–1093.

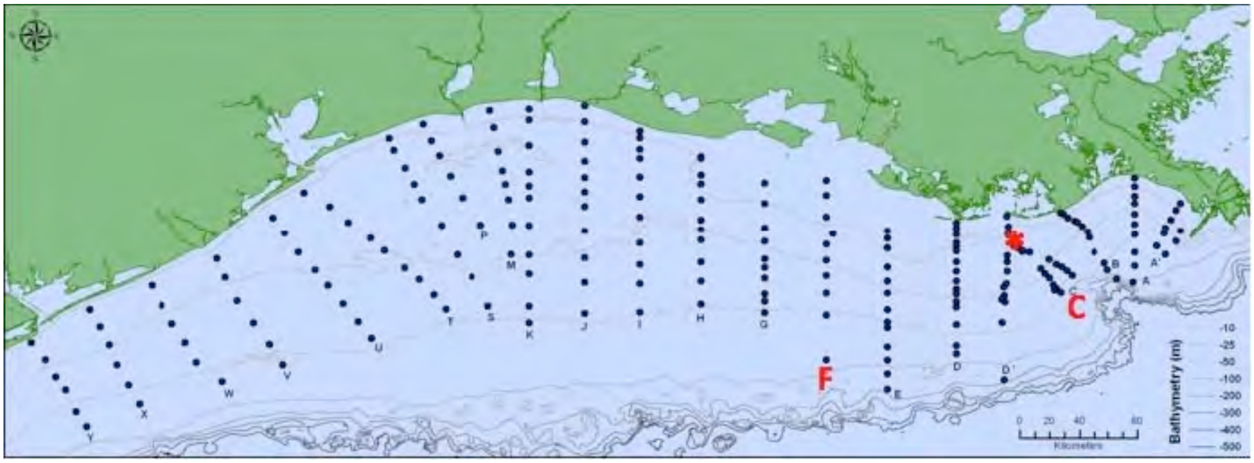
Wong, W.H., J.J. Dudula, T. Beaudoin, K. Groff, W. Kimball, J. Swigor 2018. Declining ambient water phosphorus concentrations in Massachusetts' rivers from 1999 to 2013: Environmental protection works. **Water Research** 139: 108-117.

Contacts for Further Information

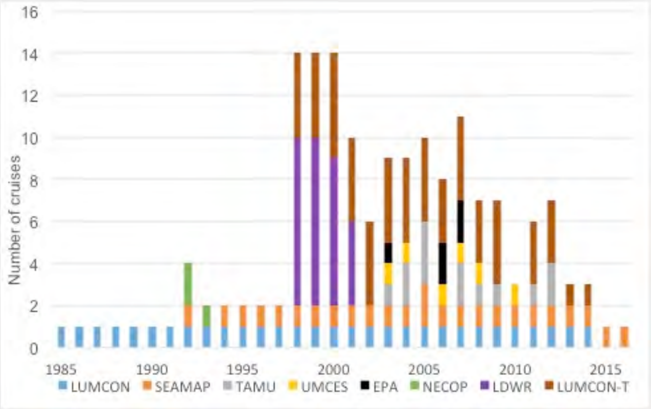
Nancy N. Rabalais (LSU, 225-578-8531 wk, 985-870-4203 c, 985-851-2836 wk); nrabal@lsu.edu)

R. Eugene Turner (LSU, euturne@lsu.edu)

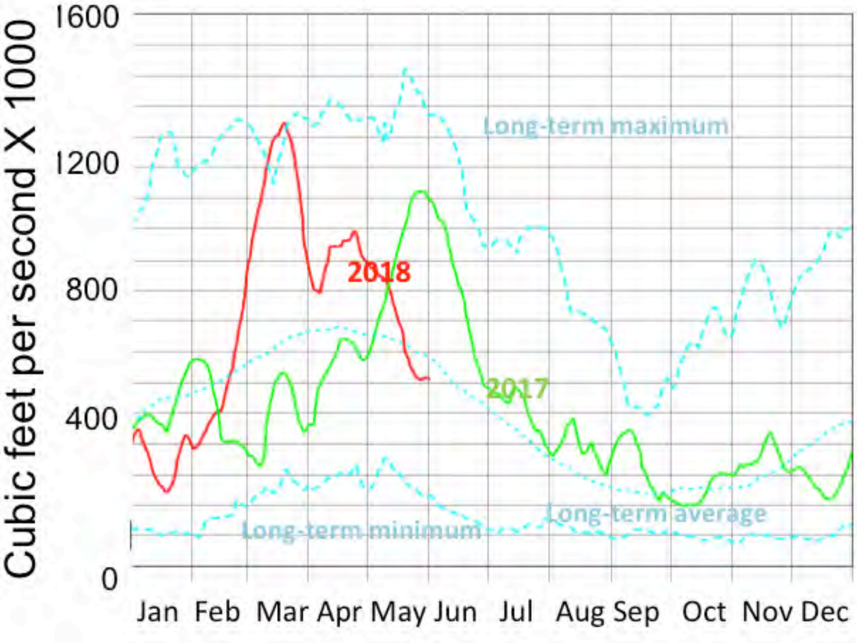
Appendix



Appendix Figure 1. Location of hypoxia monitoring stations sampled in summer (not 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 number of State, Federal and university cruises associated with hypoxia measurements in the northern Gulf of Mexico from 1985 to 2016. LUMCON = Louisiana Universities Marine Consortium; SEAMAP = Southeast Area Monitoring and Assessment Program; TAMU = Texas A&M University; UMCES = University of Maryland Center for Environmental Studies; EPA = U.S. Environmental Protection Agency; NECOP = Nutrient Enhanced Coastal Ocean Productivity; LDWR = Louisiana Department of Wildlife Research; LUMCON-T = transects sampled during the year by LUMCON. The graph was created by Rohith Matli and Dan Obenour, Department of Civil, Construction, and Environmental Engineering, North Carolina State University, and used with permission.



Appendix Figure 3. The daily river discharge at Tarbert Landing, LA, from 1935 through 31 May 2018. Units are cubic feet per second × 1000. Figure modified from http://rivergages.mvr.usace.army.mil/WaterControl/Districts/MVN/tar.gif.