2019 Forecast:
Summer Hypoxic Zone Size
Northern Gulf of Mexico

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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 depletion. The low oxygen conditions in the Gulf's most productive waters stresses organisms and may even cause their death to threaten living resources, including humans depending on the fish, shrimp and crabs 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 one of these models.

The June 2019 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for late July 2019 is that it will cover 22,557 km^2 (8,717 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 20,433 and 24,821 km^2 (7,889 and 9,583 mi^2). This estimate is based on the assumption that there are no significant tropical storms 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 13,847 km^2 (5,346 mi^2).

The predicted hypoxic area is about the size of the land area of New Hampshire (23,227 km^2) and 67% larger than the average of 13,536 km^2 (n = 34, including years with storms). If the area of hypoxia becomes as large as predicted, then it will be about 4.5 times the size of the Hypoxia Action Plan goal to reduce the zone to less than 5,000 km^2. No reductions in the nitrate loading from the Mississippi River to the Gulf of Mexico has occurred in the last few decades.

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 prediction assumes 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, 2011, and 2018, may reduce the hypoxic zone size to be lower than predicted.

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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 far 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.

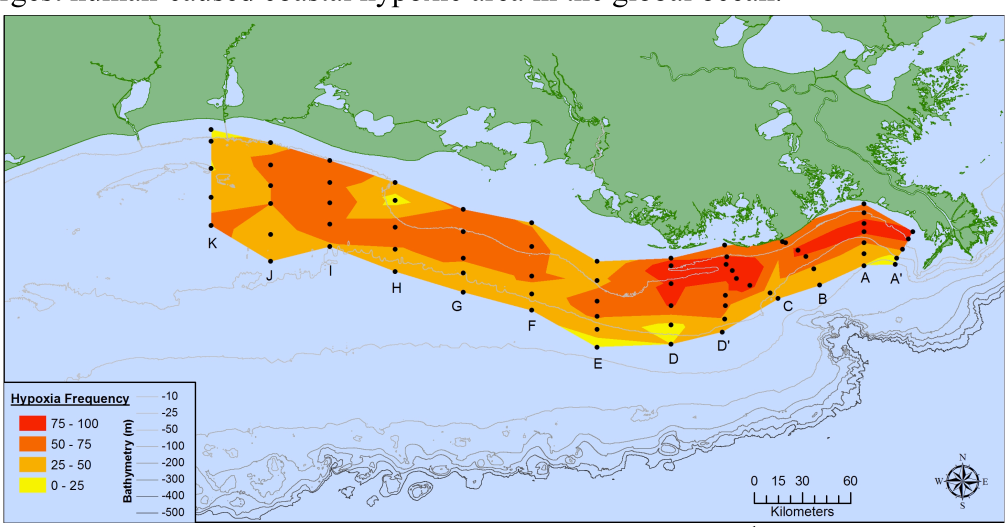


Figure 1. The frequency of mid-summer hypoxia (oxygen ≤ 2 mg l^{-1}) over the 70 to 90 station grid on the Louisiana and Texas shelf during the summer from 1985 to 2014. The frequency is determined from those stations for which there are data for at least half of all cruises. From Rabalais et al. (2010).

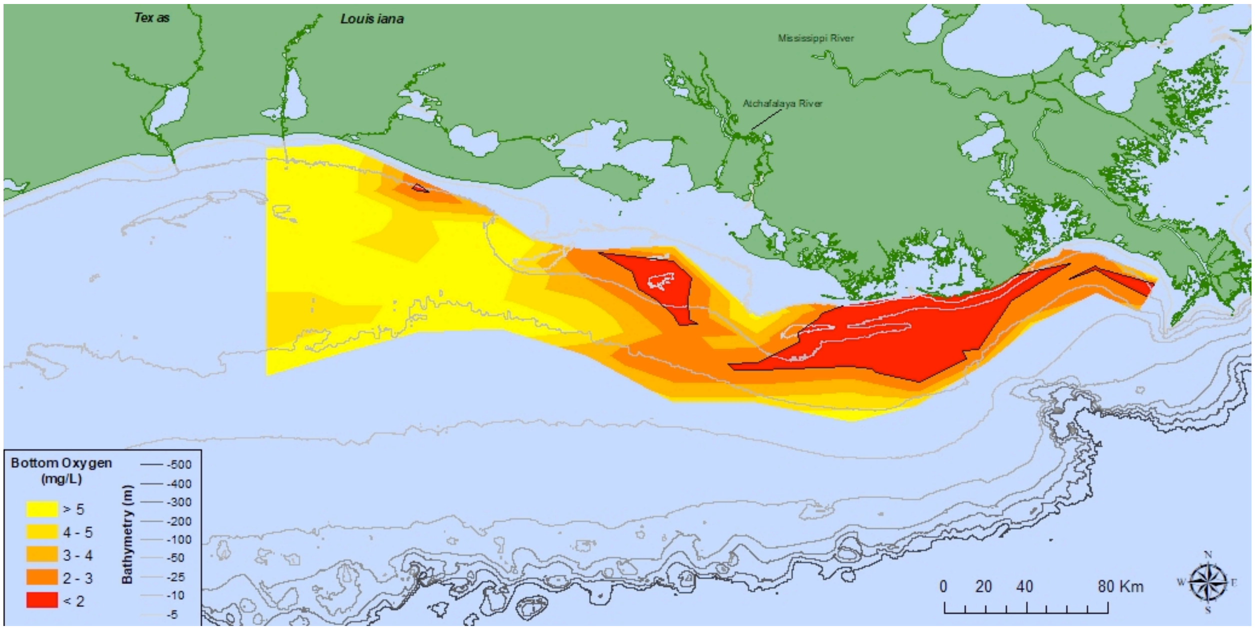


Figure 2. Oxygen concentrations in bottom water across the Louisiana shelf from July 23 – July 30, 2018. Data source: N.N. Rabalais, Louisiana State University, Universities Marine Consortium, and R.E. Turner, LSU; funded by NOAA, National Centers for Coastal Ocean Science.

Systematic mapping of the area of hypoxia in bottom waters of the northern Gulf began in 1985 at geographically fixed stations (Appendix Figure 1). Its size from 1985 to 2018 ranged between 40 to 22,720 km^2 during July and averaged 14,042 km^2 (5,424 mi^2). There were no cruises in 1989 and 2016, and the area was incompletely mapped in 2017. 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 (Maiti et al. 2018; Appendix Figure 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 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 (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 1) the rise in carbon sequestration in sediments, 2) indicators of increased diatom production, and 3) 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.

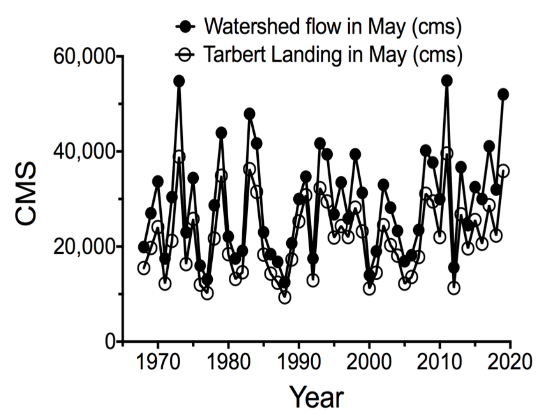
The oxygen consumption creates a zone of hypoxia that is constrained by the geomorphology of the shelf, horizontal water movement, stratification and vertical mixing (Obenour et al. 2012; Justić and Wang 2014). The significance of reducing nutrient loads to these coastal waters rests on the coupling 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: 1) concentration of nutrients, primarily nitrogen, and 2) river discharge. River discharge is, therefore, a key environmental parameter of interest.

The Mississippi River watershed daily discharge in May 2019 was 52,000 $m^3 s^{-1}$ (cms) (Figure 2), which is the 3rd largest in 52 years from 1968 to 2019, and equal to about 182% of the average discharge (in May; 28,886 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.

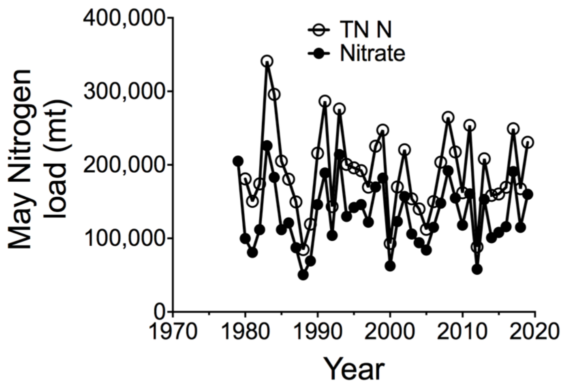


Figure 4. The annual nitrite+nitrate (NO_{2+3}) and total nitrogen (TN) load for the Mississippi River watershed for May. The estimates are from the USGS.

Comparative information on the nitrate concentration in May for 2017, 2018 and 2019 in the Mississippi River at Baton Rouge, LA, is in Figure 5. These data are the hourly concentrations of nitrate from the USGS gage for 2017 and 2019. The May nitrate load in 2019 is 84% of that in 2017 when the hypoxic zone size was at least 23,720 km^2. The predicted amount for 2017 was higher, but measurements were truncated because of under-funding.

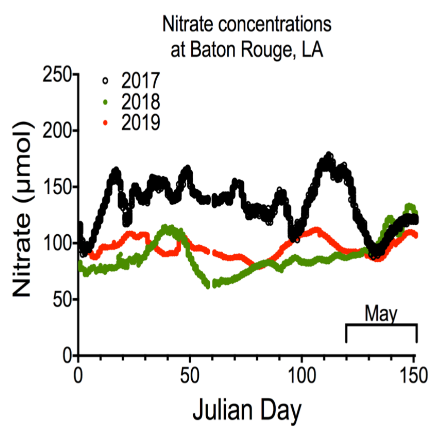


Figure 5. The daily concentration of nitrite+nitrate (NO_{2+3}) at Baton Rouge, LA from 1 January 2017 to 30 May 2019. from the USGS automated sampling gage. (https://waterdata.usgs.gov/la/nwis/uv/?site_no=07374000&agency_cd=USGS

The total nitrogen load in May is increasingly dominated by the nitrite+nitrate load (Figure 6).

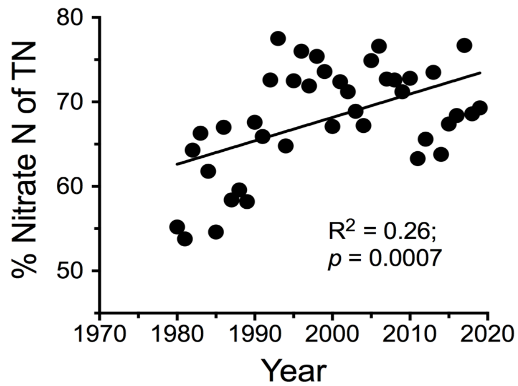


Figure 6. The % nitrite+nitrate load of the total nitrogen load for May in the main channel of the Mississippi River at St. Francisville, LA. The estimates are from the USGS for 1980 to 2019.

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 2018 are based on annual field measurements (data available at http://www.gulfhypoxia.net). The 2019 mapping cruise is scheduled for July 22-31, 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 were 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 8 years were not included in the analysis because there were strong storms or unusual wind conditions just before or during the cruise (1998, 2003, 2005, 2008, 2010, 2011, 2013 and 2018). These storms or unusual wind conditions, 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 2019

We used several models to forecast the hypoxic zone in the northern Gulf of Mexico in July 2019. The most accurate model prediction, we think, is that it will cover 22,577 km^2 (8,717 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 20,433 and 24,821 km^2 (7,889 and 9,583 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 13,847 km^2 (5,346 mi^2). This 'non-storm' estimate is 27% higher than the average of 13,536 km^2 measured for all years from 1985 to 2018, and the 2nd largest measured since systematic sampling began in 1985.

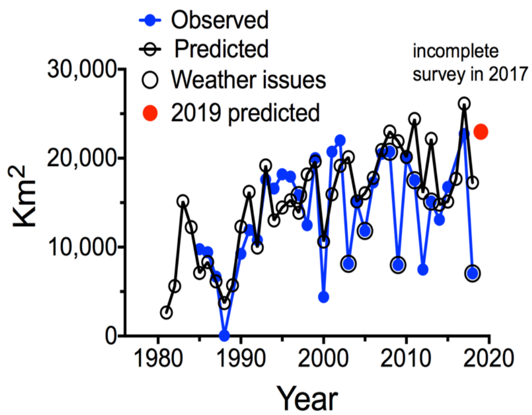


Figure 7. The measured and estimated size of the hypoxic zone from 1979 to 2018 and the predicted for 2019.

The Mississippi River discharge has been exceptionally high this spring, the Bonnet Carré spillway above New Orleans was opened twice, and the Morganza Spillway is anticipated to be opened in early June to reduce flood threats to New Orleans. The Bonnet Carré diverts riverwater into Lake Pontchartrain on the east bank and the Morganza Spillway is used to increase riverflow to the west, through the Atchafalaya Swamp and into the Gulf of Mexico near Morgan City. Both diversions will affect the prediction for 2019. The movement of water to the east through Bonnet Carré, will probably have a minimal effect on the eastern end of the study area. But, moving water through the Morganza spillway and to the west may help maintain hypoxia on the western region of the study area or extend it further to the west.

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Hypoxia Models and Model Accuracy

We use several models to predict the size of the hypoxic zone in July that are based on the May total nitrite+nitrate nitrogen load (note: concentration × discharge equals the nitrite+nitrate 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). The nitrite+nitrate loading will be referred to here 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 throughout the year.

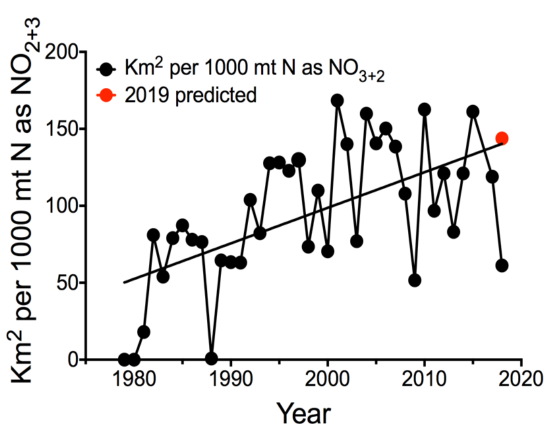

Figure 8. The size of the hypoxic zone per May nitrite+nitrate loading. All years, including strong storm years, are included.

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 only the current year. The reference point for calibrating the model is the behavior of the system in recent history. We use the last several 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 year with low nitrate loading. The estimate for 2019 is in Figure 9.

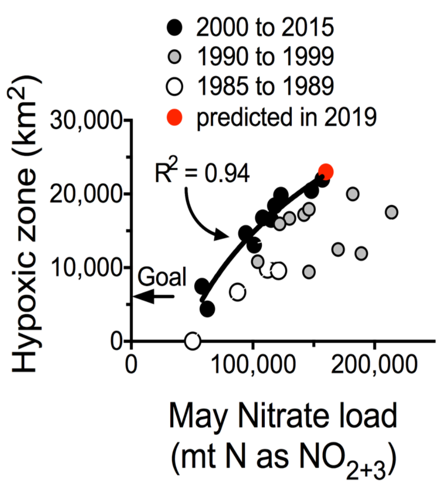

Figure 9. The relationship between nitrate+nitrate loading in May and the predicted size of the hypoxic zone in July. Several intervals are broken out, with the last one (2000 to 2015) being fit to a regression model. The predicted size of the hypoxic zone for 2019 is indicated with the red dot.

Some of the sensitivity to nitrate loading is carried over from one interval to the next to create a 'legacy' effect that 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).

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 (Rabalais et al. 2018). 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 phenological 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).

The prediction in 2018 was noteworthy for the great disparity between the much larger size of the hypoxic zone predicted by *all* models and the actual size. The predicted size of the forecast from four models ranged from 12,949 to 17,523 km^2, but the measured size was 2,720 km^2. The post-cruise model of the hypoxic zone size revealed a strong change in wind patterns at the time of the cruise (Figure 10). This wind field change along the A' and A transects resulted in a short-lived decrease in water column stratification and then oxygenation of the bottom layer, particularly on the eastern end of the mapped area.

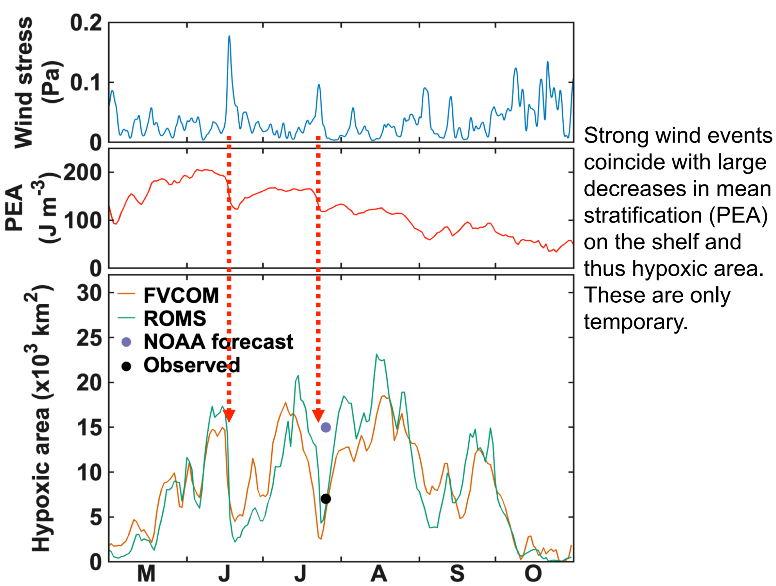

Figure 10. The ecosystem model output describing the hypoxia layer size (km^2) from March to October in 2018 (bottom panel). The panel above is an index of the degree of stratification (PEA = joules per m^2), and wind stress (atmospheric pressure). Graph from D. Justic´, and used with permission).

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), Testa et al. (2017), Laurent et al. (2018) and Fennel and Laurent (2018). The two other forecasts for this year will be from the University of Michigan (http://scavia.seas.umich.edu/hypoxia-forecasts/), Dalhousie University (http://memg.ocean.dal.ca/news/), and the Virginia Institute of Marine Science (http://www.vims.edu/research/topics/dead_zones/forecasts/gom/index.php). The NOAA ensemble predictions are based on these models (http://www.noaa.gov/media-releases). 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 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 Water Quality Trends, Consequences, 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). The average annual nitrate concentration at St. Franciville, LA, has been stable from 1992 to 2015 (https://nawqatrends.wim.usgs.gov/swtrends/).

Some consequences of 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 documented links between nitrate in drinking water and birth defects [neural tube and spinal cord including spina bifida, oral cleft defects and limb deficiencies (Brender et al. 2013)] and bladder and thyroid cancer (Ward et al. 2018). Furthermore, 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 socially and ecologically significant (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, including flammables causing the Cuyahoga River to catch 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 plant proteins.

Restoration of the coastal waters for the Mississippi River watershed means, in large part, changing farming practices (Rabotyagov et al. 2014). The nitrate yield from Iowa streams is directly related to farming (Crumpton et al. 2006) and much of the total nitrogen yield is a result of tile drainage, as implied or stated in various reports (e.g., Kaspar et al. 2003; McIsaac and Hu 2004; Malone et al. 2007; Nangia et al. 2008; Tomer et al. 2003; Randall and Gross 2008; Jha et al. 2010; Agen 2011). Tiling fields does not account for all of the increased nitrate yield, of course. Some nitrate comes from mineralized soil or the atmosphere. Much research has been done at the local scale to determine the effect of tile depth and spacing on nitrate yield. Nangia et al. (2008), for example, used 14 years of field data from northeastern Iowa (the Raccoon River watershed) to determine what controls variations in the nitrate yields for similar fields under different drainage. They found that a simple rearrangement of the fertilizer application (no reduction in fertilizer application) caused a 21% reduction in nitrate yield. Randall and Gross (2008) showed that there was a close correspondence between tile drain water yield and nitrate yield. This is why McIsaac and Hu (2004) found that the 1945–1961 riverine nitrate flux in an extensively tile drained region in Illinois averaged 6.6 kg N ha^{-1} $year^{-1}$, compared to 1.3 to 3.1 kg N ha^{-1} $year^{-1}$ for the non-tile drained region, even though the nitrogen application was greater in the non-tile drained region.

These yields can be reduced with both agronomic and field nutrient reduction techniques that land under tile drainage can be a part of. Some alternatives are discussed in Agren (2011) in greater detail. The use of cover crops figures prominently in these discussions. The nitrogen fertilizer application rate and timing, and crop rotation, when combined with tile drainage and other factors, impact nitrogen yield (Randall and Mulla 2001; Dinnes et al. 2002). Tile drainage can go into buffer strips before they reach streams, drain into wetlands, or even not be used if row cropped fields are converted to perennials. A major example is provided by Liebmann et al. (2013) and Davis et al. (2012) who conducted a 7-year field trial of alternative cropping systems for corn-soybean rotations at Iowa State University. Some key findings were that, by using cover crops for 4 years, there was 50% or more reduction in fossil fuel use, a doubling of employment, and the profits remained unchanged. There was also a 91% reduction in fertilizer use and 97% reduction in herbicide use.

We conclude from these observations, and others, that the hypoxic zone is considerably larger over time as nitrate-N loads increased as a result of farming practices, including from the effects of tiling farm fields. Cropping choices can be changed to reduce the quite high nitrate yields characteristic of the region which contributes to the size of the hypoxic zone forming on the continental shelf near the end Mississippi River. These nitrate yields contribute to a variety of natural resource management problems, including those of water quality inland and offshore, soil health, and wetland restoration. Water quality improvements, therefore, can be made at scales ranging from the farm level to the watershed.

Although 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), a net change has yet to appear 17 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 over a 5-year running average

Post-cruise Assessment

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

Acknowledgments

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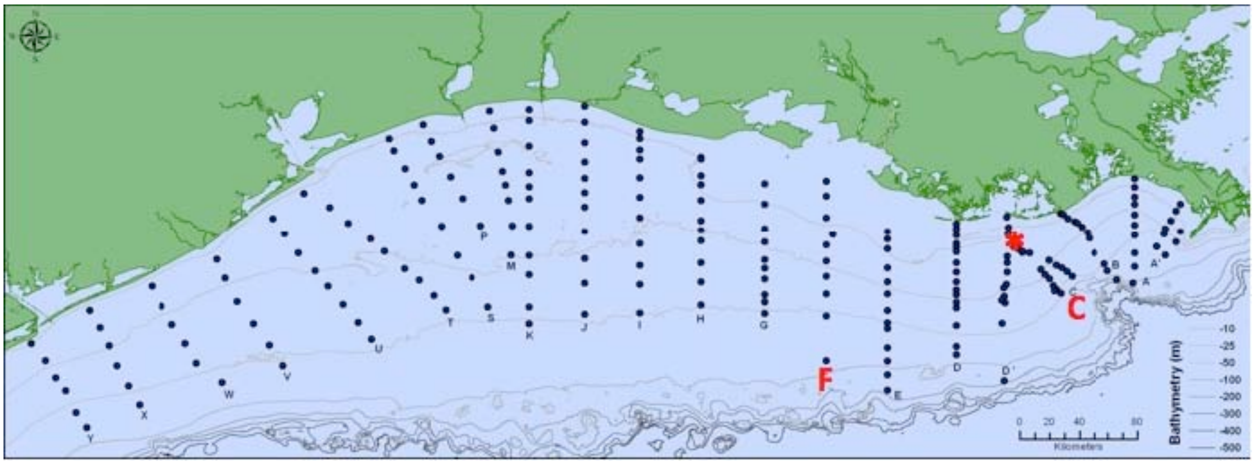
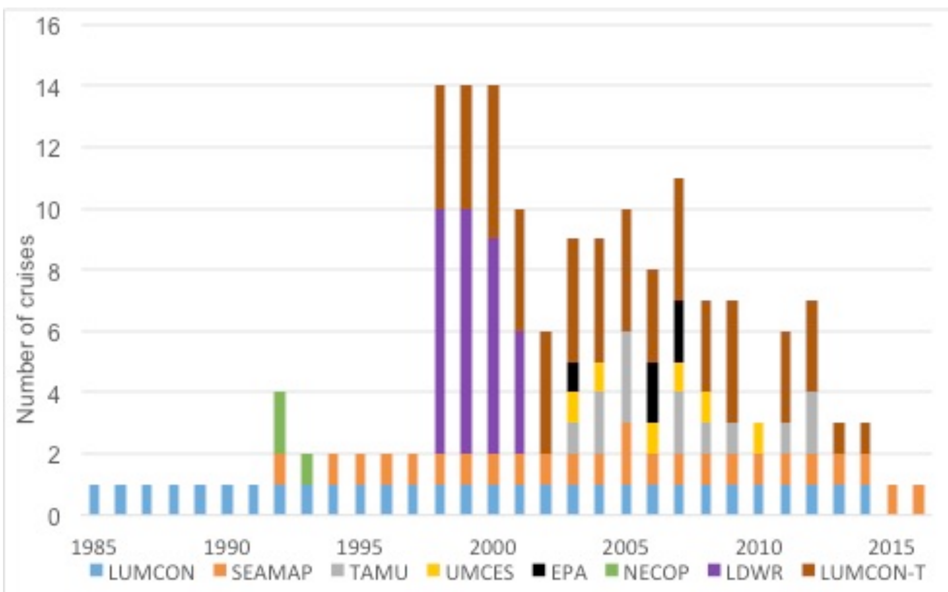
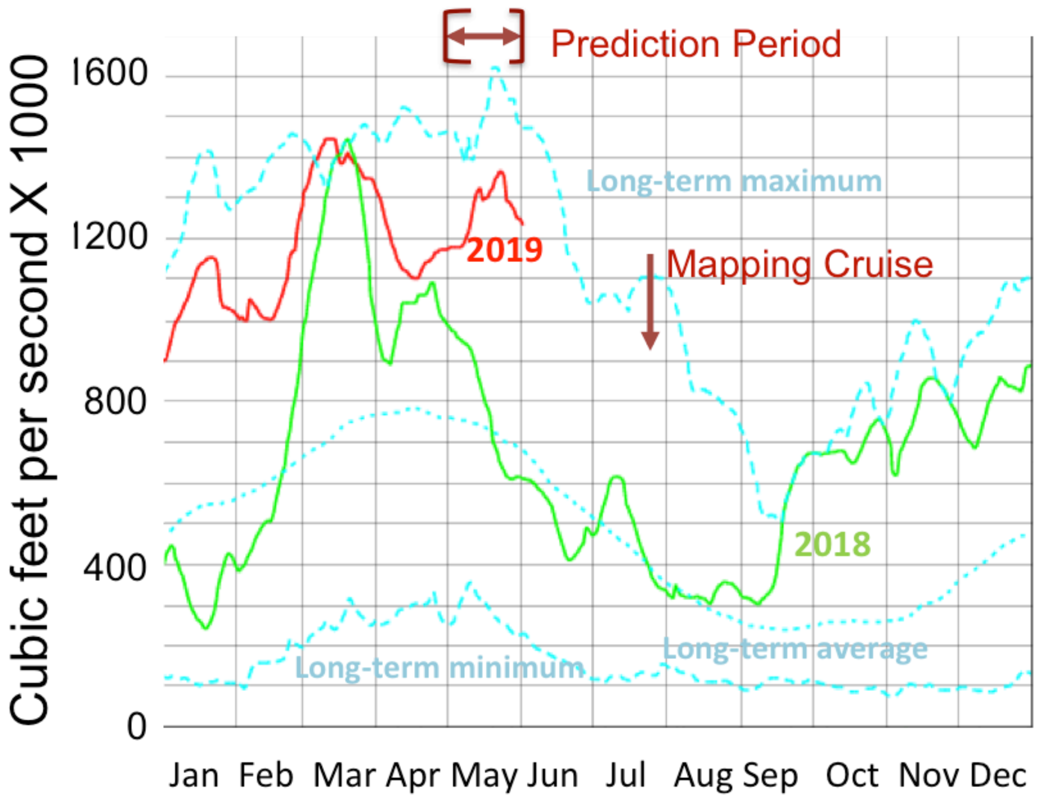
Appendix



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. Source: Maiti et al. 2018; used with permission.



Appendix Figure 3. The daily river discharge at Tarbert Landing, LA, from 1935 through 31 May 2019. Units are cubic feet per second × 1000. Figure modified from http://rivergages.mvr.usace.army.mil/WaterControl/Districts/MVN/tar.gif.