2021 Forecast:
Summer Hypoxic Zone Size in the 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 spring/summer. 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 so that living resources are threatened, 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 2021 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for late July 2021 is that it will cover 12,330 km^2 (4,761 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 10,397 and 14,306 km^2 (4014 and 5524 mi^2). This estimate is based on the assumption that there are no significant tropical storms or unusual wind events 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 56% of the predicted size without the storm, equivalent to 6,905 km^2 (2,666 mi^2).

The predicted hypoxic area is about three times the size of the land area of Rhode Island (4,000 km^2) and 89% of the average of 13,789 km^2 (n = 34 including years with storms). If the area of hypoxia becomes as large as predicted, then it will be 2.5 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 have occurred in the last few decades.

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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; Jarvis et al. 2021; Figure 1). 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.

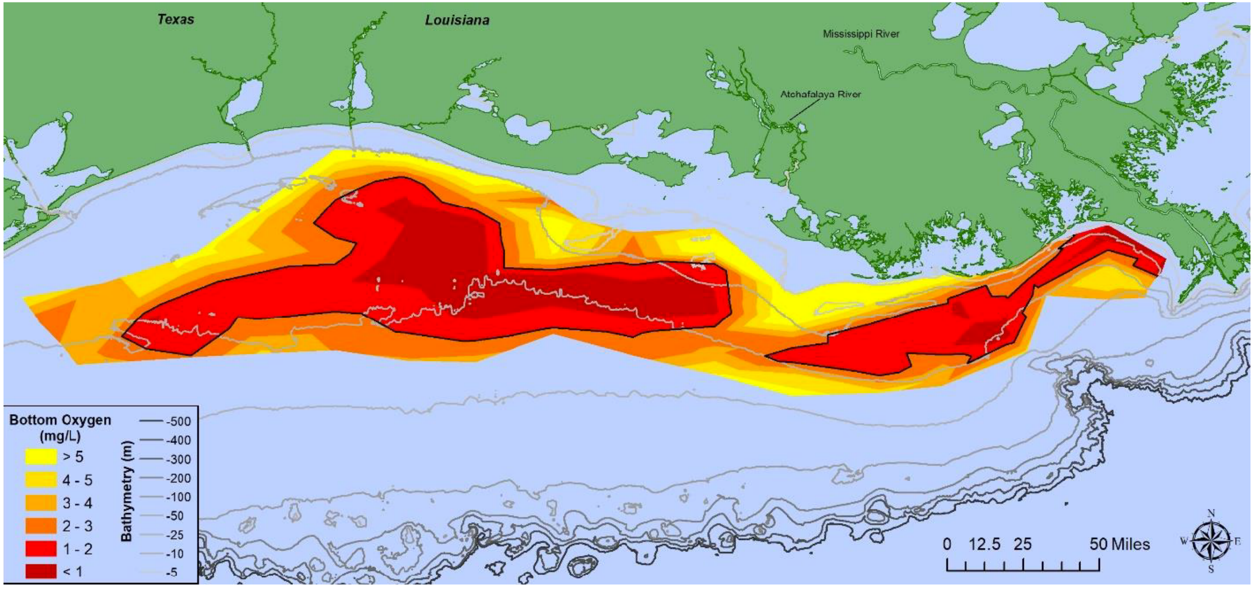


Figure 1. Oxygen concentrations in bottom water across the Louisiana shelf from July 23 – July 29, 2019. Data source: N.N. Rabalais and R.E. Turner, Louisiana State University; funded by NOAA, National Centers for Coastal Ocean Science.

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 2020 ranged between 40 to 22,720 km^2 during late July to early August and averaged 13,789 km^2 (5,526 mi^2) (Figure 2). There were no shelfwide 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 (Appendix Figure 2).

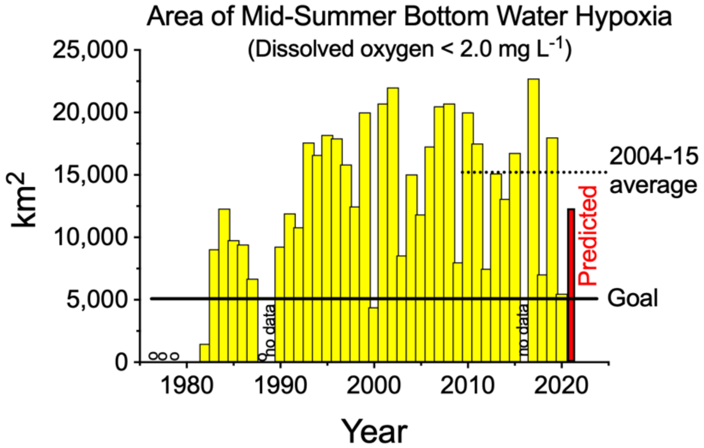


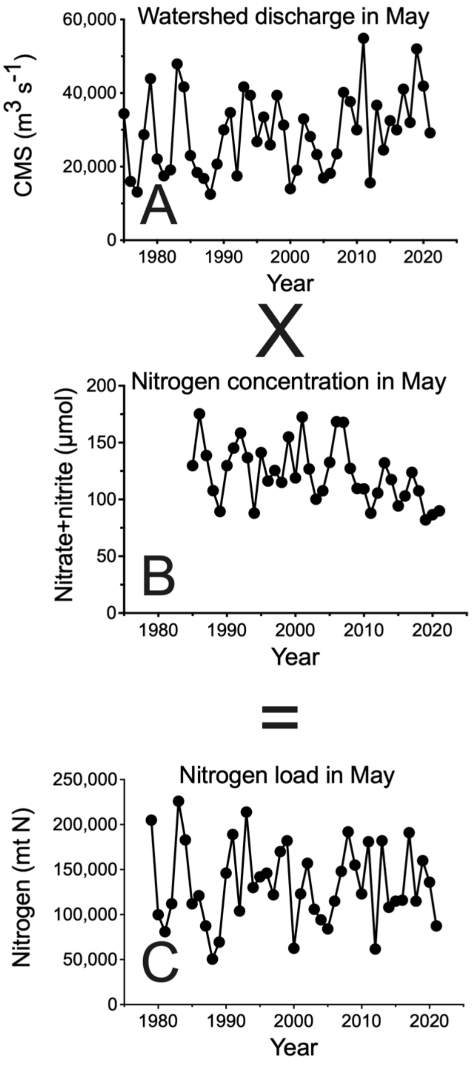
Figure 2. Area of the hypoxic zone from 1979 to 2020. The predicted value for 2021 is the red bar. The Hypoxia Action Plan restoration 'goal' is 5,000 km^2.

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 phosphorus 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 coastal 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 is based 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 nutrient controlling the hypoxia zone size in our models is nitrate, which is about 70% of the total nitrogen delivered to the northern Gulf of Mexico by the Mississippi River. The nutrient loading in May is a good predictor of the size of the hypoxic zone during the summer cruise in late July.

Mississippi River Discharge and Nitrogen Loading



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 nutrients delivered to the coastal zone. The US Geological Survey (USGS) provides monthly estimates of river discharge, nitrogen concentration (http://toxics.usgs.gov/hypoxia/mississippi/), which are used to calculate the nitrogen loading for the Mississippi River watershed into the Gulf of Mexico. The nutrient load is dependent on the: 1) discharge volume, and 2) the concentration of nutrients, primarily nitrogen.

The discharge from the Mississippi River watershed in May 2021 was 25,900 $m^3 s^{-1}$ (cms), which is the 16th largest in 37 years from 1985 to 2021, and equal to about 47% of the average May discharge (29,168 cms). The concentration of nitrate has been declining over the last 20 years, but the increase in river discharge means that the total loading has remained the same in recent decades or is increasing (Sprague et al. 2011; Crawford et al. 2019).

Figure 3. The discharge of the Mississippi River (A), the concentration of nitrate (B) and the resultant nitrogen load (C) in May. The estimates are from the United States Geological Survey.

The primary driver of the increased nutrient loading is agricultural land use (Alexander et al. 2008; Broussard et al. 2009; Robertson and Saad 2021; Figures 4 and 5), which is strongly influenced by farm subsidies controlling crop choices and farming methods (Broussard et al. 2012). Reducing nutrient loads, therefore, is intimately tied to changing the landuses, i.e., agricultural practices embedded in national policies.

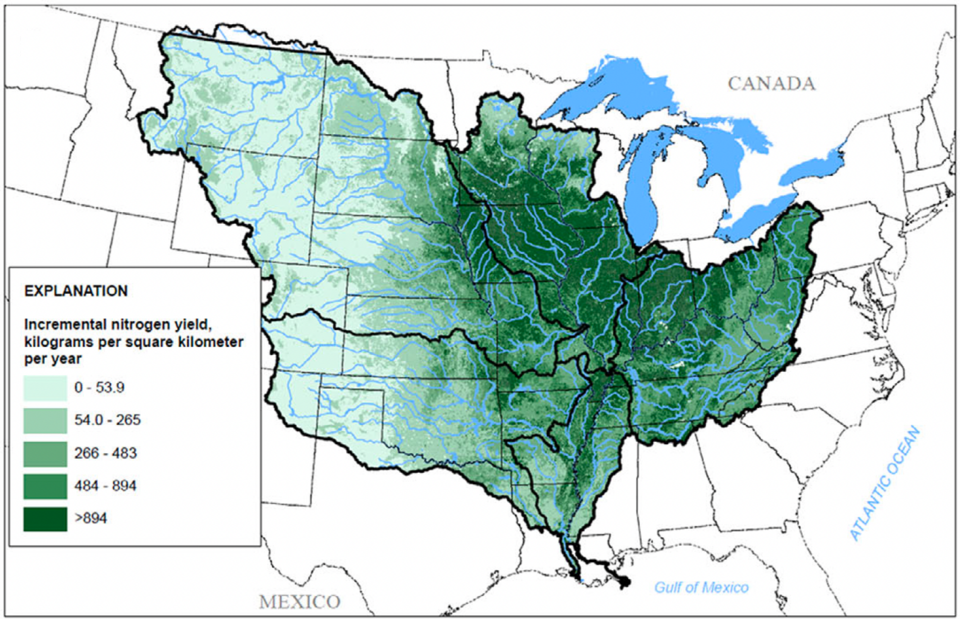


Figure 4. The yield of nitrogen (kg km^{-1}) from land in the Mississippi River watershed and the percent sourced to wastewater treatment plants (WWTP), fertilizers, atmospheric deposition and manure in 2012 and 2002 (from Robertson and Saad 2021).

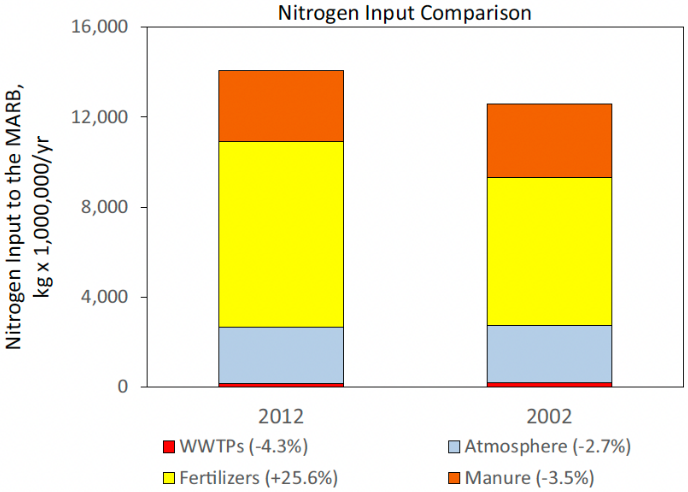


Figure 5. The percent of nitrogen loading in the watershed that is sourced to wastewater treatment plants (WWTP), fertilizers, atmospheric deposition and manure in 2012 and 2002 (from Robertson and Saad 2021).

Some consequences of water quality degradation with nitrate contamination include higher sewage treatment costs (Dearmont et al. 1998), seafood price increases (e.g., Smith et al. 2017), compromises to fish reproduction (Tuckey and Fabrizio 2016) and increased frequency and duration of harmful algae events inshore and offshore (Lopez et al. 2008). There are 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).

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 2020 are based on annual field measurements (data available at http://www.gulfhypoxia.net). 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 some transects; 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 10 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, 2018 - 2020). 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 56%. Storm frequency has been increasing to happen on more than half of the cruises in recent years (Figure 6).

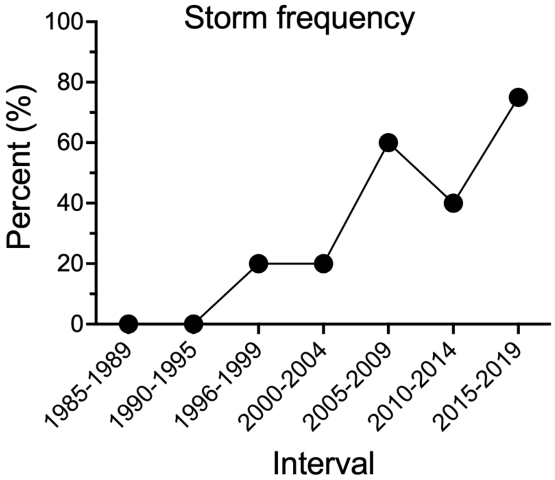


Figure 6. Storm frequency on cruises binned into 5 year increments from 1985 to 2019.

Prediction for 2021

We use several models to forecast the hypoxic zone in the northern Gulf of Mexico in July 2021. The most accurate model prediction, we think, is that it will cover 12,330 km^2 (4,761 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 10,397 and 14,306 km^2 (4014 and 5524 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 56% of the predicted size without the storm, equivalent to 6,905 km^2 (2,666 mi^2). This 'non-storm' estimate is 89% of the average of 13,789 km^2 measured for all years from 1985 to 2020, and the 15th largest measured (n=35) since systematic sampling began in 1985.

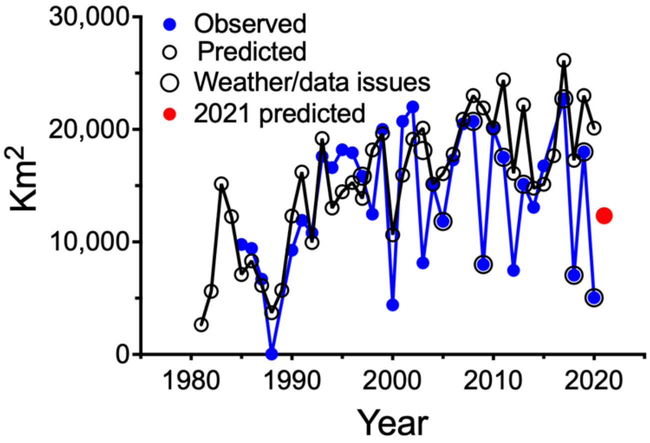


Figure 7. The measured and estimated size of the hypoxic zone from 1981 to 2020 and the predicted size for 2021.

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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 at about three times higher over the last 40 years (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 geographic 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.

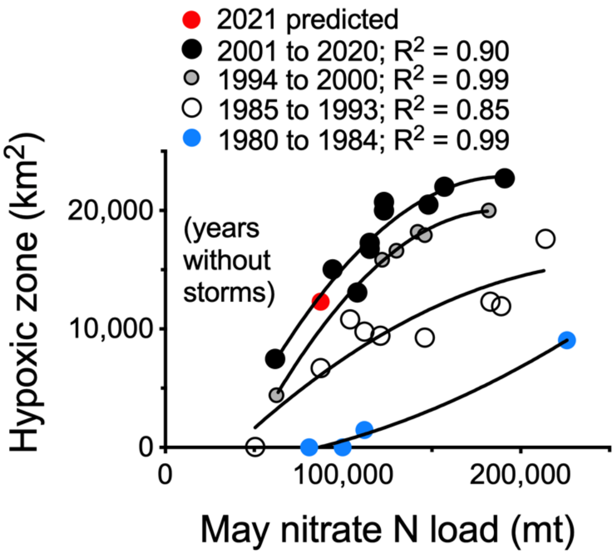

Figure 8. The relationship between nitrate+nitrate loading in May and the predicted size of the hypoxic zone in July. The predicted size of the hypoxic zone for 2021 is indicated with the red dot.

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 estimate for 2021 in Figure 8 uses nitrate data that 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.

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, or by long-term increases in bottom-water temperature (Turner et al. 2017).

Our statistical models, and their predecessors, are fairly accurate models based on past performance (Turner et al. 2008, 2012). The model used here describes 90% of the variation since 2000 (non-storm years). 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 comparisons 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. 2012).

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 7040 km^2. The post-cruise model of the hypoxic zone size revealed a strong change in wind patterns at the time of the cruise. This wind field change 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.

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), 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).

A recent more detailed description of hypoxia development in the northern Gulf of Mexico is in Rabalais and Turner (2019). We review the past, present, and possible future conditions of hypoxia in the northern Gulf of Mexico and provide some insight into possible management actions. Kirchman (2021) is a well-written and recent overview of low oxygen zones in rivers, lakes, estuaries and oceans.

Post-cruise Assessment

The 2021 mapping cruise is scheduled for July 25 to August 1. The data will be posted as close to daily as possible at http://www.gulfhypoxia.net. 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. The 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.

Acknowledgments

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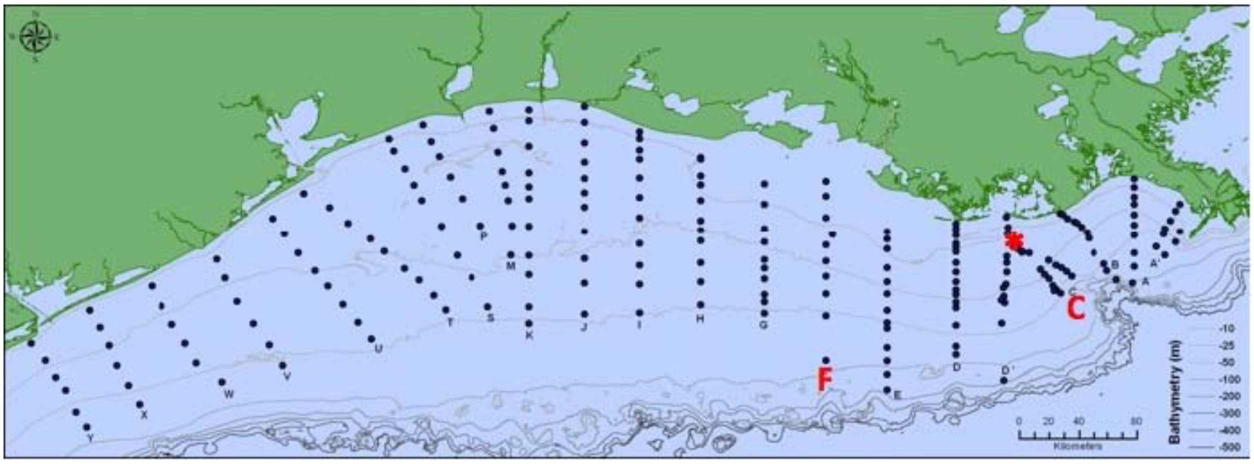
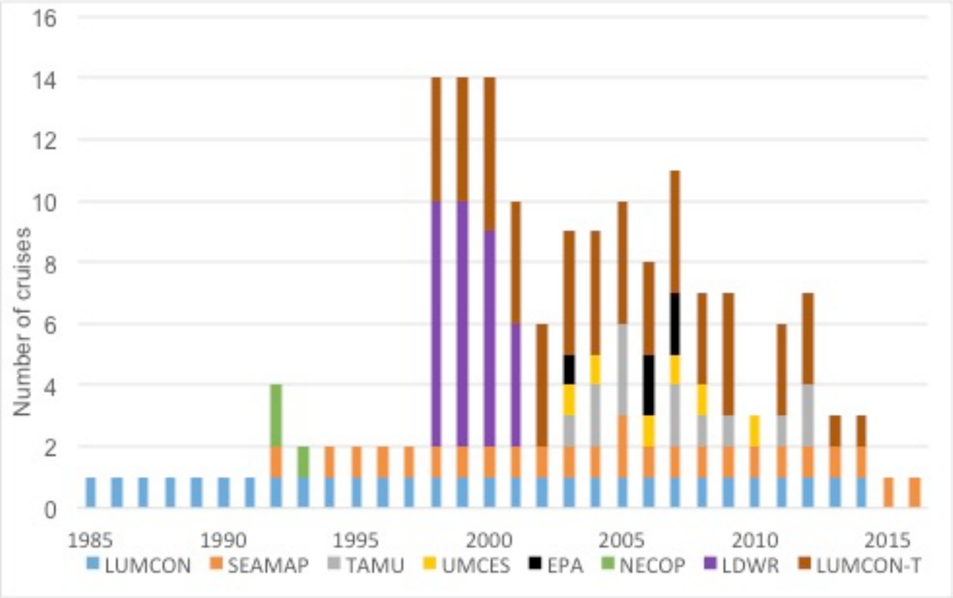
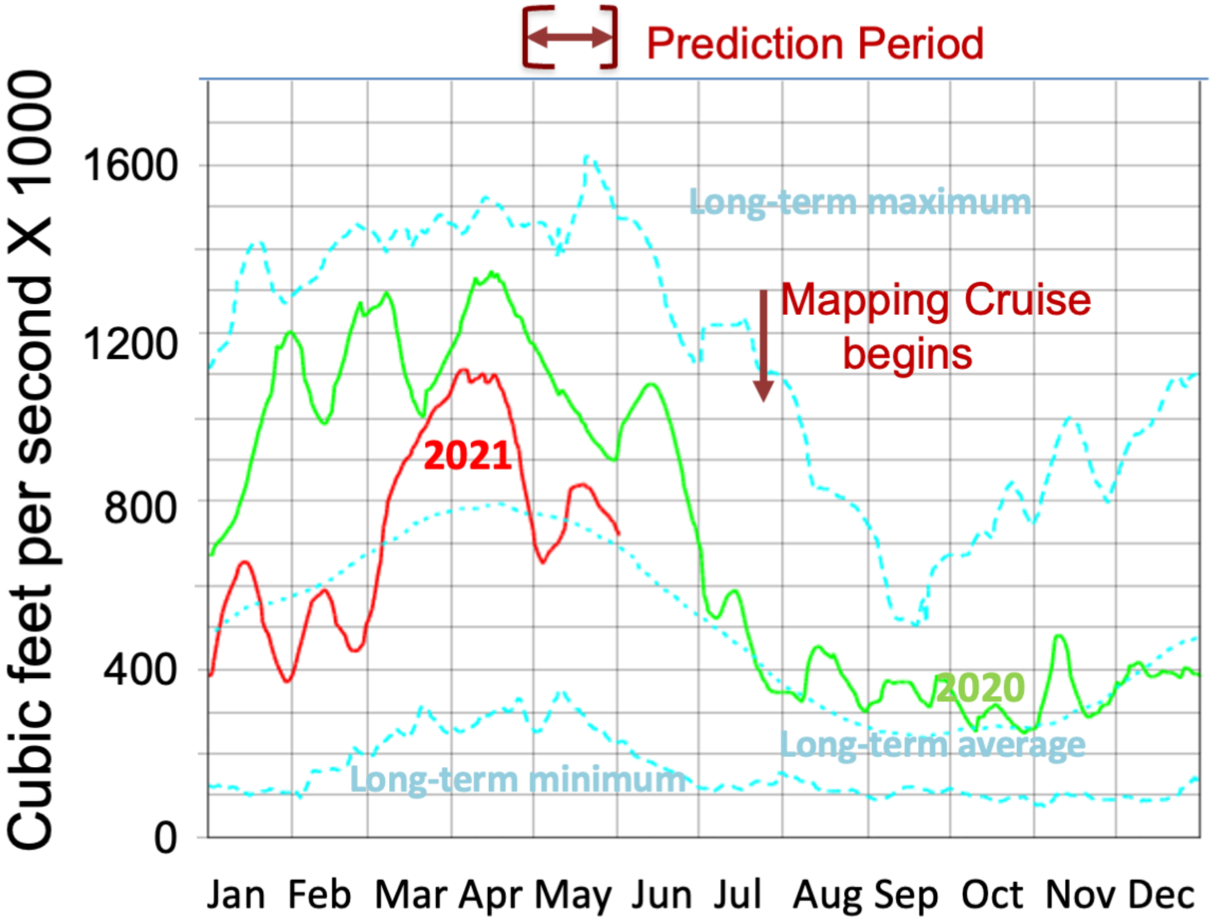
Appendix



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 (no longer in operation).



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 2021. Units are cubic feet per second × 1000. Figure modified from http://rivergages.mvr.usace.army.mil/WaterControl/Districts/MVN/tar.gif.