2013 Forecast:
Summer Hypoxic Zone Size,
Northern Gulf of Mexico

Abstract

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

The June 2013 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for July 2013 is that it will cover 22,172 km^2 (8,561 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The 95% confidence interval is that it will be between 19,771 and 24,649 km^2 (7,634 to 9,517 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 15,521 km^2 (13,840 to 17,254 km^2, or 5,995 to 6,664 mi^2).

The predicted hypoxic area is about the area of New Jersey. If the area of hypoxia becomes this large, then it will equal the largest since systematic mapping of the hypoxic zone began in 1985.

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; 4) Unusual weather patterns affecting coastal winds, as experienced in 2009 and 2011, may skew the prediction to be lower.

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 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' because of the absence of commercial quantities of shrimp and fish in the bottom layer. The number of Dead Zones throughout the world has been increasing in the last several decades and currently totals over 500 (Díaz and Rosenberg 2008; Rabalais et al. 2010; Díaz unpubl. data; Conley et al. 2011). The Dead Zone off the Louisiana coast is the second largest human-caused coastal hypoxic area in the global ocean.

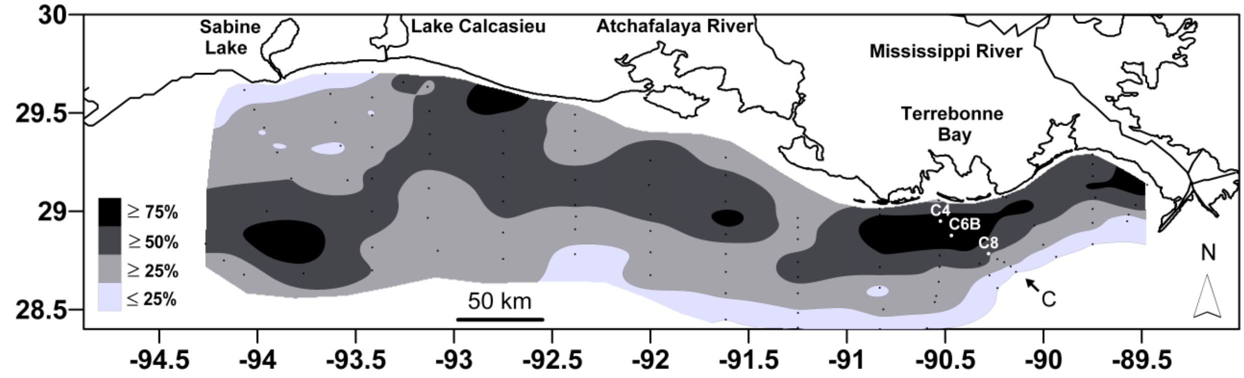


Figure 1. The frequency of mid-summer hypoxia (oxygen ≤ 2 mg l^{-1}) over the 60 to 80 station grid on the Louisiana and Texas shelf during the summer from 1985 to 2008. Stations C4, C6B and C8 are labeled on the C transect. Modified from Rabalais et al. (2007).

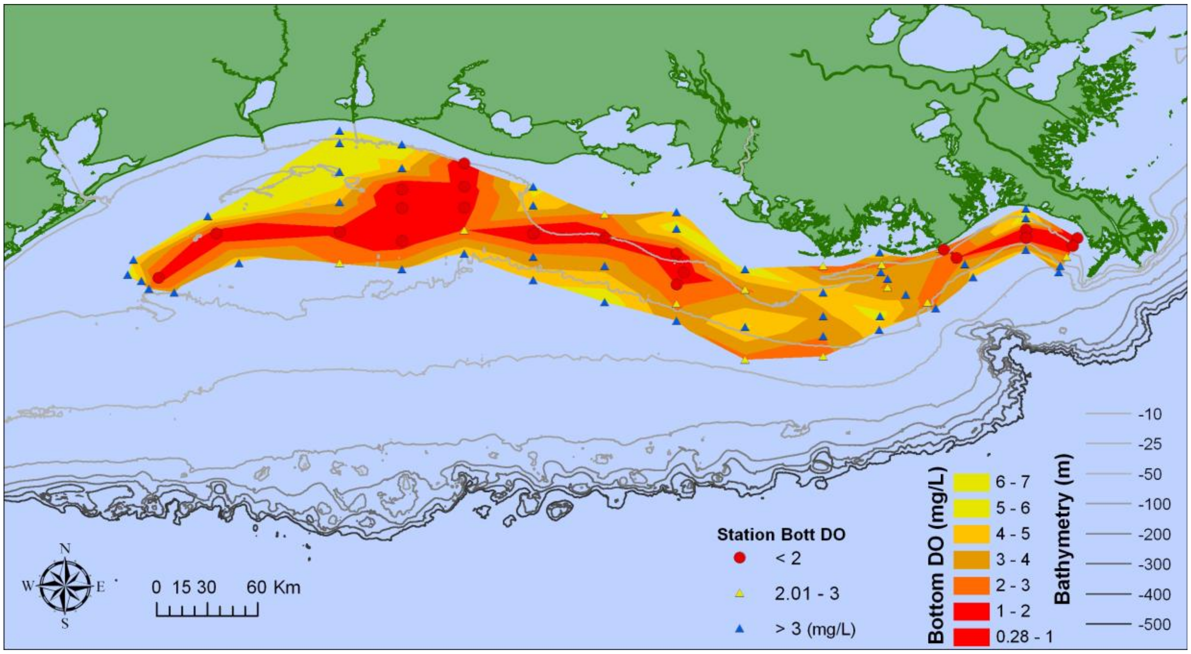


Figure 2. Oxygen concentrations in bottom-water across the Louisiana-Texas shelf from July 22-27, 2012. Data source: N.N. Rabalais, Louisiana Universities Marine Consortium, and R.E. Turner, Louisiana State University; funded by NOAA, Center for Sponsored Coastal Ocean Research.

Systematic mapping of the area of hypoxia in bottom waters of the northern Gulf began in 1985. Its size has ranged between 40 to 22,000 km^2 during July and averaged 13,727 km^2 from 1985-2012 (5,302 mi^2). It was 7,480 km^2 (5302 mi^2) in 2012 (Figure 2). There are few comparable coastwide data for other months, but monthly monitoring was conducted along two transects off Terrebonne Bay, LA, and the Atchafalaya delta, LA, until NOAA budget cuts in 2013. In addition, two coastal ocean observing stations off Terrebonne Bay and Caminada Pass (125 and 75 km west of the Mississippi River delta, respectively) record continuous bottom-water oxygen conditions. The data from them usually indicate that hypoxia occurs by April. [See Appendix Figure 1 for a map of the study area.]

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 (Turner and Rabalais 2013, Scavia and Donnelly 2007). The evidence for this conclusion is that the supply, or loading, of nitrogen (primarily in the form of nitrate-N) from the Mississippi River watershed to the continental shelf within the last few decades is positively related to chlorophyll *a* concentration (chl *a*; Walker and Rabalais 2006; R^2 0.30 – 0.42), the rate of primary production (Lohrenz et al. 1997; $R^2 > 0.77$; Lohrenz et al. 2008), and the spatial extent of the hypoxic area in summer (Turner et al. 2012; $R^2 > 0.9$). The size of the shelfwide hypoxic zone has increased since it began occurring in the 1970s, simultaneously with the rise in carbon sequestration in sediments, indicators of increased diatom production, and shifts in 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, to bottom water oxygen demand, and to the formation and maintenance of the largest hypoxic zone in the western Atlantic Ocean.

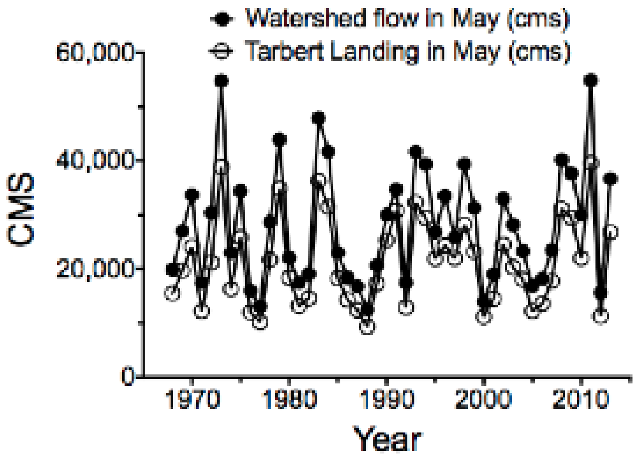
The oxygen consumption creates a zone of hypoxia that is constrained by the geomorphology of the shelf, horizontal water movement, stratification and vertical mixing (Obenour et al. 2012; Justić and Wang, submitted). The significance of reducing nutrient loads to these coastal waters rests on the coupling between the organic matter produced in response to these nutrients and its respiration in the bottom layer (MRGOM WNTF 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).

2013 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 discharge in May 2013 averaged 36,700 $m^3 s^{-1}$ (cms) (Appendix Figure 2), which is the 13th highest from 1968 to 2013. This is above average, but not particularly high (Figure 3). The May discharge in 2011 was, in contrast, 54,900 cms and the highest since 1973, whereas the 2012 May discharge was low due to a drought.

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



2013 Nitrogen Loading

The US Geological Survey 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 web site has a variety of information on these 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 nitrite+nitrate in the Mississippi River at Baton Rouge, LA, is in Figure 5.

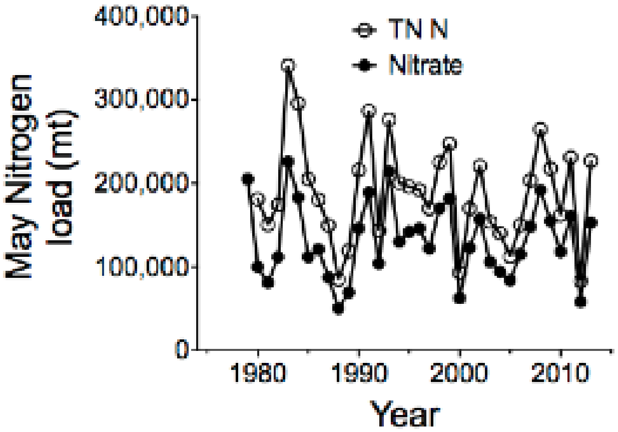
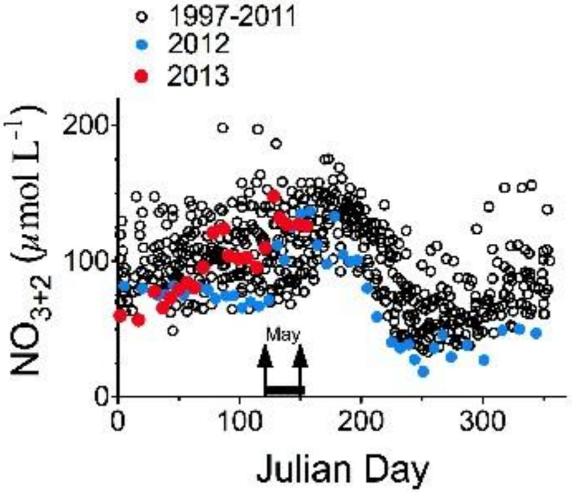


Figure 4. The annual nitrite+nitrate (NO_{2+3}) and total nitrogen (TN) load for the Mississippi River watershed for May. The estimates are from the USGS.

Figure 5. The concentration of nitrite+nitrate (NO_{2+3}) at Baton Rouge, La from 1997 to 2013. The data for 2012 and 2013 are shown separately. Unpublished data from Turner et al.



The concentration of nitrite+nitrate at Baton Rouge was relatively low in the drought year of 2012, and into January and February 2013, which was near the lowest values measured since 1997. The concentration rose at the beginning of May and dropped so that the average value for May was 128 μ mol L^{-1} (1.8 mg NO_{2+3} N l^{-1}). The river discharge was a rather moderate level, however, to result in a May nitrite+nitrate loading that was only 22% above the average value from 2000 to 2013 (Figure 5). The total nitrogen load in May is increasingly dominated by the nitrite+nitrate load (Figure 6).

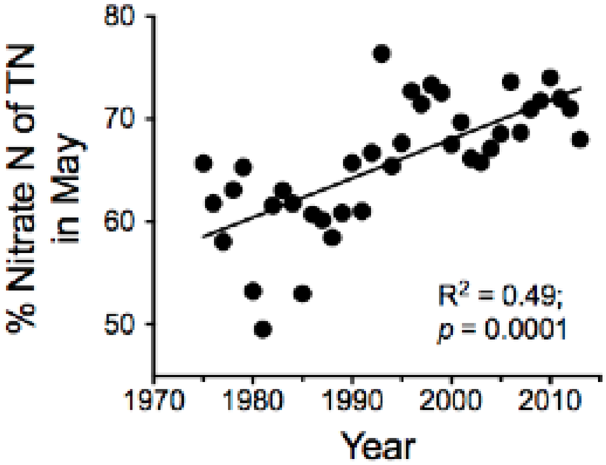


Figure 6. The % nitrite+nitrate load of the total nitrogen load for May in the main channel of the Mississippi River. The estimates are from the USGS.

Hypoxic Zone Size

Models for predicting hypoxic zone size use data from May to predict the size of the hypoxic zone in July because no comparable shelfwide data exist for other months. Data on the size of the hypoxic zone in late July from 1985 to 2012 are based on annual field measurements (data available at http://www.gulfhypoxia.net). The 2013 mapping cruise is 21-29 July; the data will be posted daily at the same web site. The values for 1989 (no funding available) and 1978-1984 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. Data for five years were not included in the analysis because there were strong storms just before or during the cruise (1998, 2003, 2005, 2008, 2010 and 2011). These storms, by comparison of pre-cruise and post-cruise sampling to data collected during the cruise, disrupted the 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 2013

There are two models to forecast the June 2013 size of the hypoxic zone in the northern Gulf of Mexico for July 2013. The most accurate one, we think, is that it will cover 22,172 km^2 (8,561 mi^2) of the bottom of the continental shelf off Louisiana and Texas (Figure 7). The 95% confidence interval is that it will be between 19,771 and 24,649 km^2 (7,634 to 9,517 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 15,521 km^2 (13,840 to 17,254 km^2, or 5,995 to 6,664 mi^2).

The prediction of a second model is that the size of the hypoxic zone will be 23,176 km^2, and the 95% confidence interval will be between 21,230 to 25,184 km^2 (8,948 mi^2; 8,197 to 9,724 mi^2). This second model prediction is slightly larger than the primary model. Both models are discussed in the next section.

The predicted hypoxic area is about the size of New Jersey (8,722 mi^2). If the area of hypoxia becomes this large, then it will equal the largest since systematic mapping of the hypoxic zone began in 1985. The maximum area before this year was 22,000 km^2 (8,497 mi^2) in 2002. It would be three times larger than the Hypoxia Action Plan goal of reducing the 5 year average size of the hypoxic zone to 5,000 km^2 by 2015.

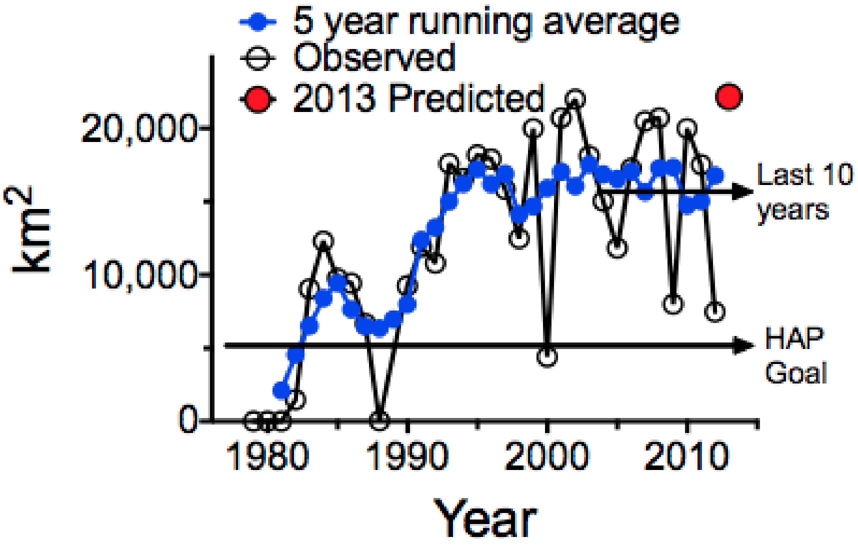


Figure 7. The measured and estimated size of the hypoxic zone from 1979 to 2012 and the predicted size for 2013.

Hypoxia Models and Model Accuracy

Models are used to summarize information, to test assumptions and to make predictions that may be useful for other purposes, including management. There are multiple models of the size of the hypoxic zone that are useful in evaluating the influence of nitrogen load and variations in ocean currents, climate, etc. These models do not always produce similar results, and model improvement is one focus of ongoing research efforts supported by the NOAA Center for Sponsored Coastal Ocean Research.

The two statistical models used here to predict the size of the hypoxic zone in July 2013 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 2-3 month lag between the loading rate calculated in May and the size of the hypoxic zone in July. The ecosystem, however, is evolving. For example, the size of the hypoxic zone for the same amount of nitrogen loading (as nitrite+nitrate) increases each year (Turner et al. 2008; 2012). The models will eventually be adjusted to account for the limited space on the shelf (a physiographic constraint).

There are two models that we use to predict the size of the hypoxic zone. Both models use the nutrient loading from the Mississippi River in May, 2 to 3 months before the annual summer hypoxia cruise that maps its areal extent (note: concentration × discharge equals the nitrite-nitrate load). The unstated hypothesis implied by these two 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 inspired 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.

Model #1

One model type assumes that the size of the zone is driven mostly by what happens this 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 or freshwater volume. This 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 3–5 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 our model does with the year term. The year term in this model is, in other words, descriptive, but not explanatory beyond the simple nitrogen loading = oxygen deficit relationship.

The results of this first model are in Figure 8. The data years were divided into three 7-year periods between 1985 and 2012. The estimated hypoxic zone size estimated from studies without an explicit systematic summer survey are also included (1980 to 1984). The nitrate data were transformed into their log10 equivalents. We did this 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 upward) without this transformation, then both the lower and upper ends of the data field are overestimated. This effect is more dramatic when

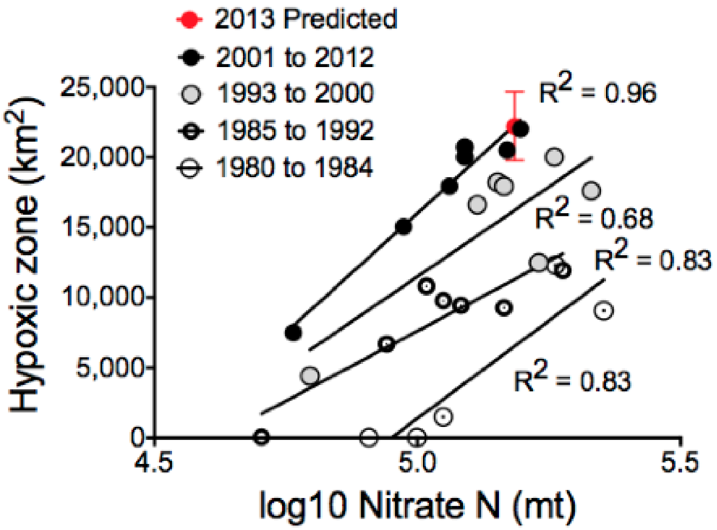


Figure 8. The measured and modeled size (Model #1) from 1976 to 2010, and the predicted size of the hypoxic zone for 2013.

the relationship is being extended into a sparse data field at the extremes of nitrogen loading, as happened during 2012, which was a drought (and low nitrate loading). The estimate for 2013 exactly overlaps the calibration curve ($R^2 = 0.98$; Figure 8). The 95% Confidence Interval is based on the uncertainty in the USGS nitrite+nitrate load estimate.

Model #2

The second model incorporates a term to include changes that might be carried over or sustained from one year to the next over the entire record (1985 to 2012). 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 % nitrate of the total nitrogen pool (e.g., Figure 6), or long-term climate change.

The results from this second model (Figure 9) describes the size of measured hypoxic zone (without storms that year) with good fidelity ($R^2 = 0.78$), but less success than the first model. It is also based on the log10 of the May nitrate load.

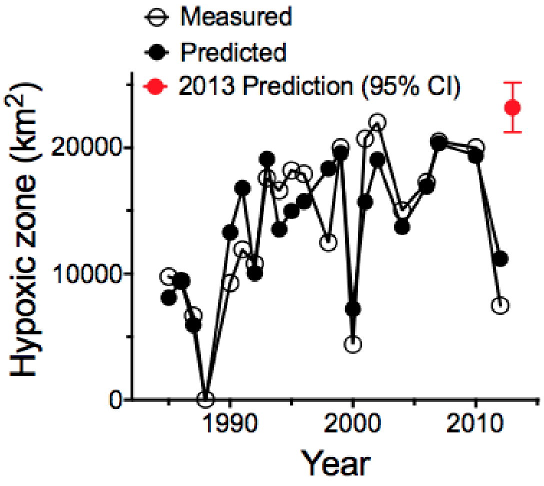


Figure 9. The measured and modeled size from 1976 to 2012, and the predicted size of the hypoxic zone for 2013 for Model #2.

Relative Accuracy

The statistical models used here, 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 second model describes 78% of the total variance in size since 1985 (27 years) and the first model 96% of the variation since 2000 (inclusive; Figure 8). The equivalent model for the Baltic Sea low oxygen conditions explains 49 to 52% of the variation in the inerannnual variation in bottom water oxygen concentration (Conley et al. 2007).

The size of the hypoxic zone this year is expected to follow the relationship with nitrogen loading best as described by Model #1 – as long as there is no 'wildcard' in the form of a tropical storm at the time of the annual summer cruise. 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. Some of the variation in the size of the Gulf hypoxic zone size, for example, is due to re-aeration of the water column during storms. The size of the summer hypoxic zone in 2008, for example, was less than predicted because of the influence of Hurricane Dolly. Tropical Storm Don was a similar complication in 2011. The long-term trend, however, is that the area of hypoxia is larger for the same amount of nitrogen loading (Turner et al. 2008, 2012; Figure 8).

Other models that also predict oxygen dynamics on this shelf are discussed in Bierman et al. (1994), Justić et al. (2003), Scavia and Donnelly (2007), and Scavia et al. (2003, 2004). The University of Michigan forecast site is: http://www.sitemaker.umich.edu/scavia.

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

Post-cruise Assessment

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

Acknowledgments

Support was received from the NOAA Center for Sponsored Coastal Ocean Research Grants No. NA09NOS4780204 to Louisiana Universities Marine Consortium and NA09NOS4780230 to Louisiana State University. Charlie Milan analyzed the nutrient samples for the Mississippi River at Baton Rouge. Louisiana hypoxia data are from Rabalais et al., LUMCON. We thank Brent T. Aulenbach and colleagues at the USGS for providing the nitrogen loading data for the Mississippi River.

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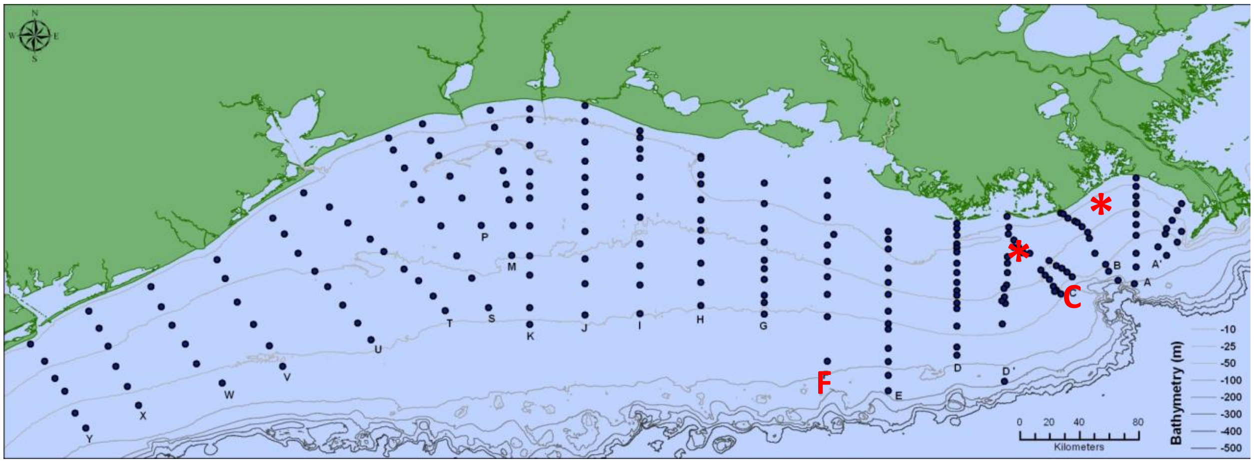
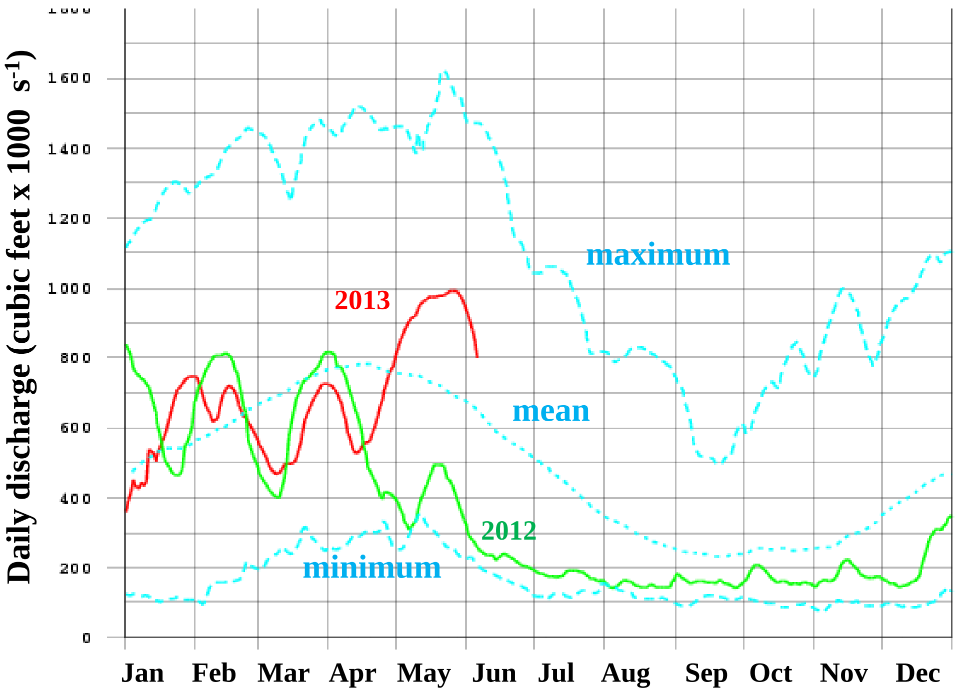
Appendices



Appendix Figure 1. Location of hypoxia monitoring stations sampled in summer, the transects off Terrebonne Bay (transect C) and Atchafalaya Bay (transect F), and the ocean observing systems (asterisks) off Caminada Pass and Terrebonne Bay.



Appendix Figure 2. The daily river discharge at Tarbert Landing from 1935 through 6 Jun 2013. Units are cubic feet per second. Figure modified from http://www2.mvn.usace.army.mil/eng/edhd/tar.gif.