2012 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. The freshwater discharge and nitrogen load of the river in May 2012 are at historic lows, which contrasts sharply with the historic high discharge and relatively high nitrogen load in May 2011.

The June 2012 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for July 2012 is that it will cover 16,092 km^2 (6,213 mi^2) of the bottom of the continental shelf off Louisiana and Texas. The predicted hypoxic area is slightly larger than the area of Connecticut. The estimate is based on the May nitrogen loading (as nitrite+nitrate) from the Mississippi watershed to the Gulf of Mexico estimated by the U.S. Geological Survey. If the area of hypoxia becomes this large, then it will be the 15th largest since systematic mapping of the hypoxic zone began in 1985.

The size of the hypoxic zone this year will tell us a lot about how the ecosystem ‘works’ – as long as there is no ‘wildcard’ in the form of a tropical storm at the time of the annual summer cruise. There are two views, and different model types that go with them, which are used to predict the size of the hypoxic zone. Both model types 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. One model type assumes that the size of the zone is driven mostly by what happens this year and that secondary 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 recent years. The other model type incorporates a term to include changes that might be carried over or sustained from one year 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 climate or increased organic matter accumulated in the sediments one year, and metabolized in later years. Simple models based on *only* the nutrient load from the Mississippi River in May suggest that the hypoxic zone size will be between 2,827 and 4,433 km^2 (1,092 and 1,712 mi^2) when it is measured in late July, 2012. The second model type, the one that incorporates a changing environment from year-to-year, suggests that the hypoxic zone will be 16,092 km^2 (6,213 mi^2) large this summer. If this larger size occurs, then it may represent another shift in the ecosystem’s sensitivity to nitrogen loading. If it does not occur, then this may indicate that system is reaching the upper limit of the

area of hypoxic water that can cover this shelf. The data from this year's cruise, therefore, can be used to quantify the relative merits of the two 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.

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 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 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. There was also a large area of hypoxia east of the river in July 2011 resulting from the record high discharge and nutrient loads from the 2011 flood and diversions of river water to the east of the river done to avoid potential flooding of the city of New Orleans. 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 400 (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.

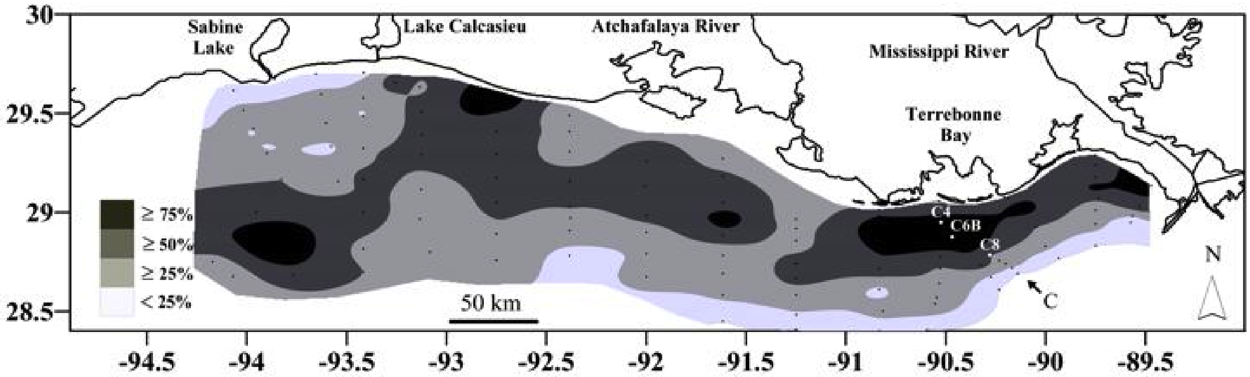


Figure 1. The frequency of mid-summer hypoxia (oxygen ≤ 2 mg l^{-1}) over the 60 to 80 station grid on the Louisiana and text shelf during the summer from 1985 to 2008. Stations C4, C6B and C8 are labeled on the C transect. The frequency distribution is updated and modified from 1985 to 2008. Modified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

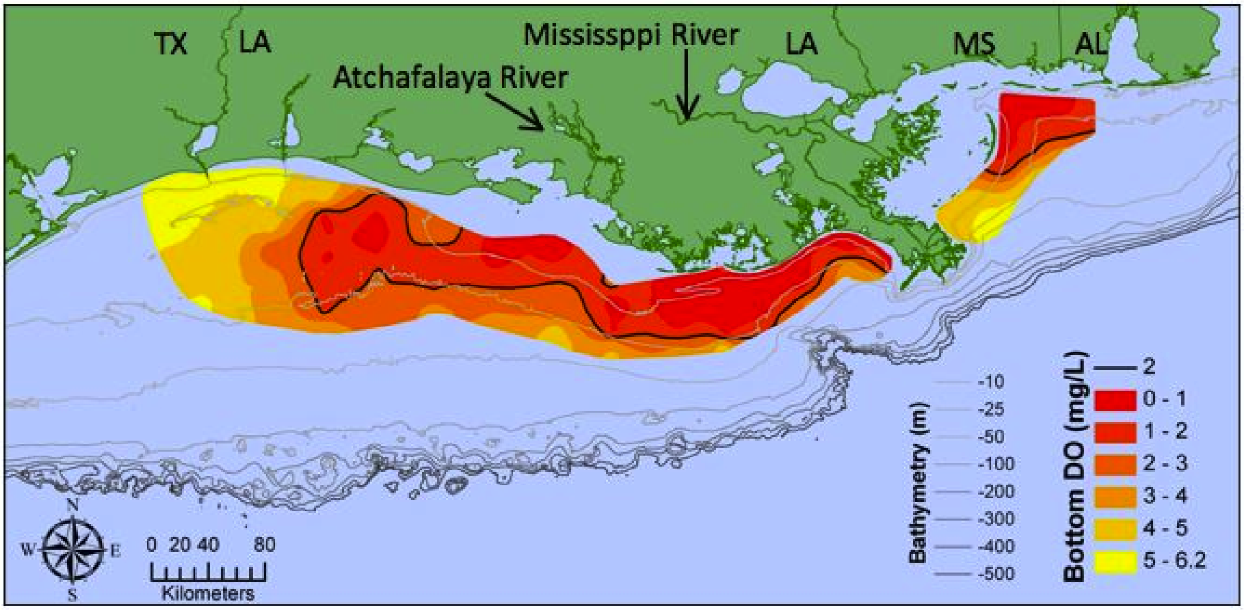


Figure 2. Oxygen concentrations in bottom-water across the Louisiana-Texas shelf from July 18-30, 2011. The black line outlines values less than ≤ 2 mg L^{-1}, which is the definition of hypoxia. Data source: N.N. Rabalais, Louisiana Universities Marine Consortium, and R.E. Turner, Louisiana State University; funded by NOAA, Center for Sponsored Coastal Ocean Research. Only the area to the west of the delta is used to make the predictions of the hypoxic zone each year.

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 14,046 km^2 from 1985-2011 (5,425 mi^2). It was 17,520 km^2 in 2011 (Figure 2). There are few comparable coastwide data for other months, but monthly monitoring is conducted along two transects off Terrebonne Bay, LA, and the Atchafalaya delta, LA. 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. These data indicate that hypoxia has been present on the two transects since April. [See Appendix Figure 1 for a map of the study area.]

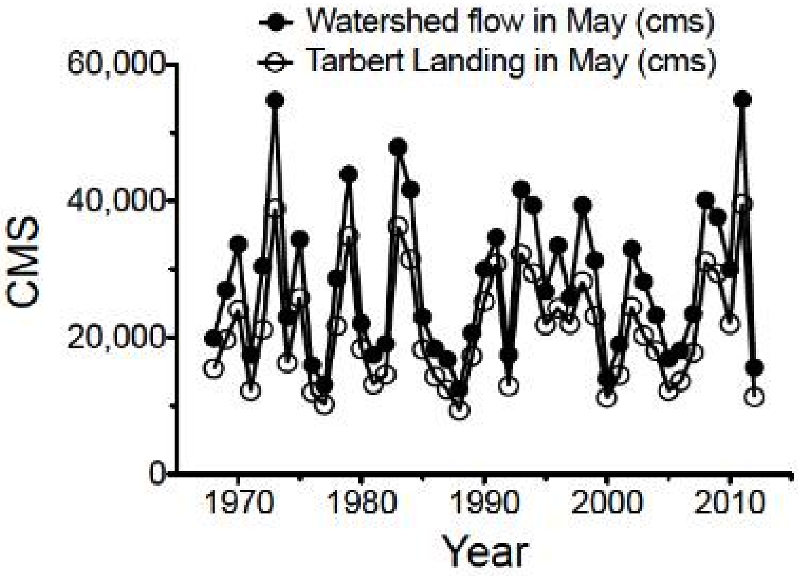
Hypoxic water masses form from spring to fall on this coast because the consumption of oxygen in bottom water layers exceeds the re-supply of oxygen from the atmosphere. The re-aeration rate is negatively influenced by stratification of the water column, which is primarily dependent on the river's freshwater 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 organic matter production rate is directly related to the nitrogen supply rate from the Mississippi River watershed. 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), and the descent rate is rapid enough so that respiration occurs mostly in the bottom layer and sediments. The oxygen consumption creates a zone of hypoxia that is constrained by the geomorphology of the shelf, water movement and vertical mixing (Obenour et al. 2012). The significance of reducing nutrient loads to these coastal waters rests on this 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 amount of nutrient loading from the river has remained the same in recent decades, or is increasing (Sprague et al. 2011). The primary driver of the increased nutrient loading is agricultural land use (Broussard et al. 2009), which is strongly influenced by farm subsidies (Broussard et al. 2012).

2012 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 2012 averaged 15,600 m^3 sec^{-1} (cms), which is the fourth lowest from 1968 to 2012 (Appendix Figure 2), and was the lowest since 2000 when it was 14,000 cms (Figure 3). The May discharge in 2011 was, in contrast, 54,900 cms and the highest since 1973. The 2011 and 2012 flows are very different (Figure 4).

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, $m^3 s^{-1}$.



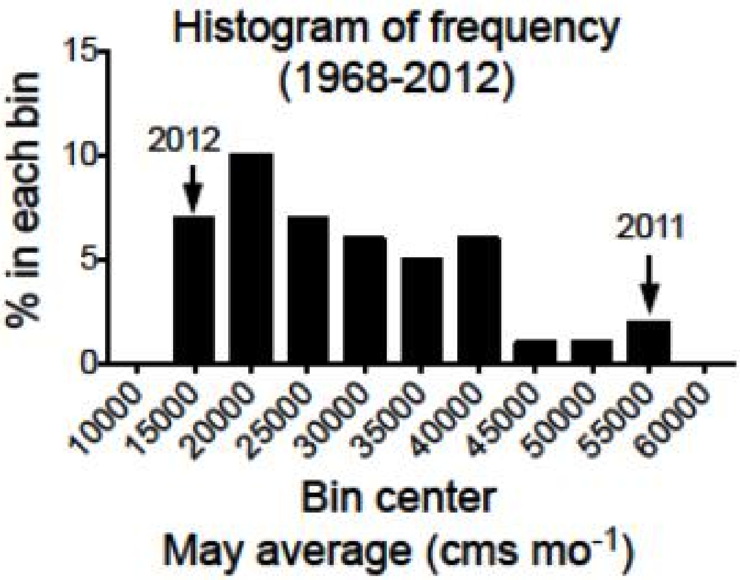


Figure 4. A frequency plot of the occurrence of various discharge amounts from the Mississippi River watershed for May. The low values in May 2012 occurred in about 7% of all years from 1968 to 2012. The relatively higher values in May 2011

2012 Nitrogen Loading

The estimate of nitrite-nitrate loading from the Mississippi River into the Gulf of Mexico is made by the US Geological Survey (USGS; http://toxics.usgs.gov/hypoxia/mississippi/). The USGS web site has more information on the data calculation. The USGS includes 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 5. The estimates used in this prediction exclude water flowing into the Bonnet Carré spillway that delivers water to the east bank of the Mississippi River. Comparative information on the seasonal concentration of dissolved nitrite+nitrate in the Mississippi River at Baton Rouge, LA, is in the Appendix Figure 3.

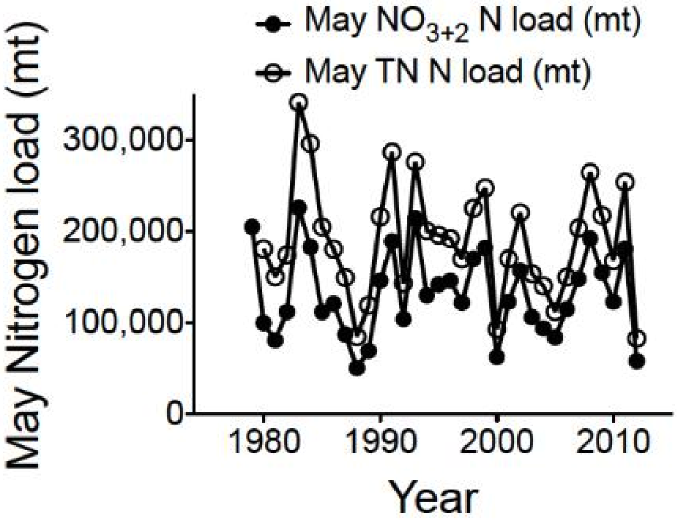
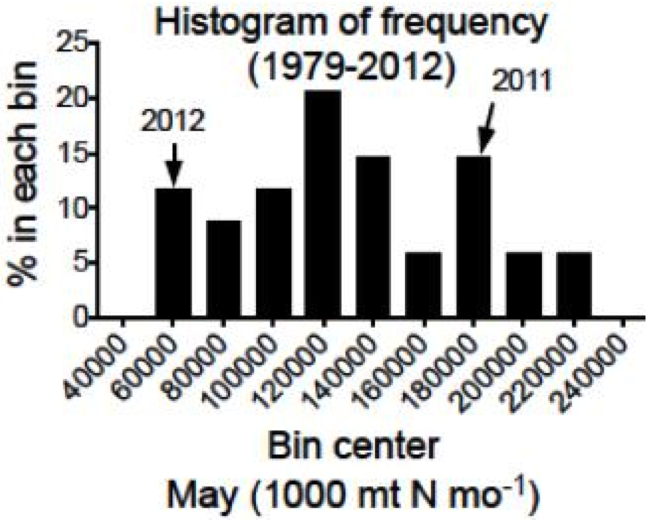


Figure 5. The annual nitrite+nitrate (NO_{3+2}) and total nitrogen (TN) load for the Mississippi River watershed for May. The estimates are from the USGS and exclude water flowing into the Bonnet Carré spillway that delivers water to the east

Figure 6. A frequency plot of the occurrence of various nutrient loads from the Mississippi River watershed for May. The low values in May 2012 occurred about 12.5% of all years from 1979 to 2012. The relatively higher values in May 2011 occurred about 15% for the same



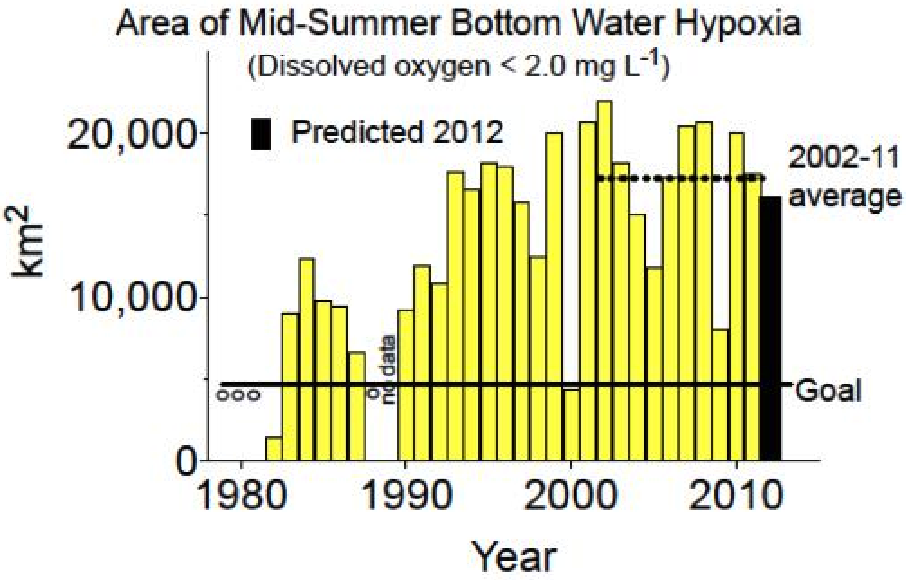
The concentration of nitrate at Baton Rouge was low in the beginning of May, and near the lowest values measured since 1997. The concentration rose sharply at the end of May. The river discharge was low enough, however, to result in the lowest May nitrite+nitrate loading since 2000 (Figure 5). The low value observed in 2012 is unusual, but the higher value in 2011 was not that unusual (Figure 6).

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 2011 are based on annual field measurements (data available at http://www.gulfhypoxia.net). The 2012 mapping cruise is scheduled to be conducted from 22-31 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 values 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.

Prediction for 2012

The June 2012 forecast of the size of the hypoxic zone in the northern Gulf of Mexico for July 2012 is that it will cover 16,092 km^2 (6,213 mi^2) of the bottom of the continental shelf off Louisiana and Texas (Figure 7). The predicted hypoxic area is about the size of the land area of Connecticut (5,543 mi^2). If the area of hypoxia becomes this large, then it will be the 16th largest since systematic mapping of the hypoxic zone began in 1985. The maximum area was 22,000 km^2 (8,900 mi^2) in 2002.



Data source: N.N. Rabalais, Louisiana Universities Marine Consortium, R.E. Turner, Louisiana State University. Funded by NOAA, Center for Sponsored Coastal Ocean Research

Figure 7. The measured and modeled size of the hypoxic zone from 1979 to 2011 and the predicted size for 2012.

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.

There are two views and two model types that we use to predict the size of the hypoxic zone. Both model types 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). One model type assumes that the size of the zone is driven mostly by what happens this year and that secondary 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 other model type incorporates a term to include changes that might be carried over or sustained from one year 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 climate or increased organic matter accumulated in the sediments one year, and metabolized in later years (Turner and Rabalais 1994).

The statistical model used here to predict the size of the hypoxic zone in July 2012 is 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 model will eventually be adjusted to account for the limited space on the shelf (a physiographic constraint).

The statistical model used here is the most accurate model 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. This model describes 73% of the total variance in size since 1987 (20 years) and 87% 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).

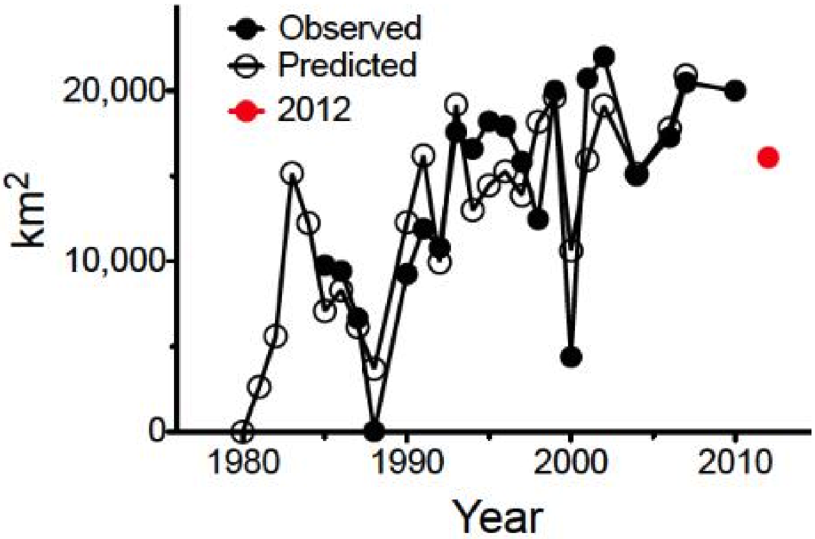


Figure 8. The measured and modeled size from 1976 to 2010, and the predicted size of the hypoxic zone for 2011. Years with unusual weather events (e.g., hurricanes and the anomalous 2009 weather patterns) are excluded.

We also use other models to test hypotheses about how this system works. One of these other model types assumes that the size of the zone is driven mostly by what happens in the current year and that secondary 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. We have two of these simpler models, and both are based on the nitrate load of recent years. The results of two simple models based on *only* the nutrient load from the Mississippi River in May suggest that the hypoxic zone size will be between 2,827 and 4,433 km^2 (1,092 and 1,712 mi^2) when it is measured in late July, 2012.

The size of the hypoxic zone this year will tell us a lot about how the ecosystem 'works' – 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). Other models that also predict or describe 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

We are working on the assumption that the 'legacy' model that predicts a hypoxic zone size of 16,092 km^2 is the most accurate model. If this model accurately predicts the size of the hypoxic zone, then it may represent another shift in the ecosystem's sensitivity to nitrogen loading. If it does not occur and the size is much smaller, this may indicate that the system is reaching the upper limit of the area of hypoxic water that can cover this shelf. The data from this year's cruise, therefore, can be used to quantify the relative merits of the assumptions of the two 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.

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 (www.gulfhypoxia.net).

Acknowledgments

Support was received from the NOAA Center for Sponsored Coastal Ocean Research, Coastal Ocean Program 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 and from offshore waters. 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.

References

Bierman, V.J., Jr., S.C. Hinz, D. Zhu, W.J. Wiseman, Jr., N.N. Rabalais, and 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.

Broussard, W. and 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, and J. Westra 2012. Do federal farm policies and agricultural landscapes influence surface water quality? **Agriculture, Ecosystems & Environment** in press 10.1016/j.agee.2012.05.022

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

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

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

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

MRGOM WNTF (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force) 2001 A*ction 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.

MRGOM WNTF (Mississippi River/Gulf of Mexico Watershed Nutrient 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.

Obenour, D.R., A.M. Michalak, Y. Zhou, and D. Scavia 2012. Quantifying the impacts of stratification and nutrient loading on hypoxia in the northern Gulf of Mexico. **Environ. Sci. Technol**. in press.

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

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

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

Scavia, D. and K.A. Donnelly 2007. Reassessing hypoxia forecasts for the Gulf of Mexico. **Environ. Sci. Technol**. 41: 8111-8117.

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/$File/EPA-SAB-08-003complete.unsigned.pdf

Sprague, L.A., R.M. Hirsch, and B.T. Aulenbach 2011. Nitrate in the Mississippi River and its tributaries, 1980 to 2008: Are we making progress? **Environmental Science and Technology** 45:7209-16. dx.doi.org/10.1021/es201221s

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

Turner, R.E. and 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, and T. Romaire 2005. Summer hypoxia, Northern Gulf of Mexico: 1978 to 1995. **Marine Environmental Research** 59: 65-77.

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

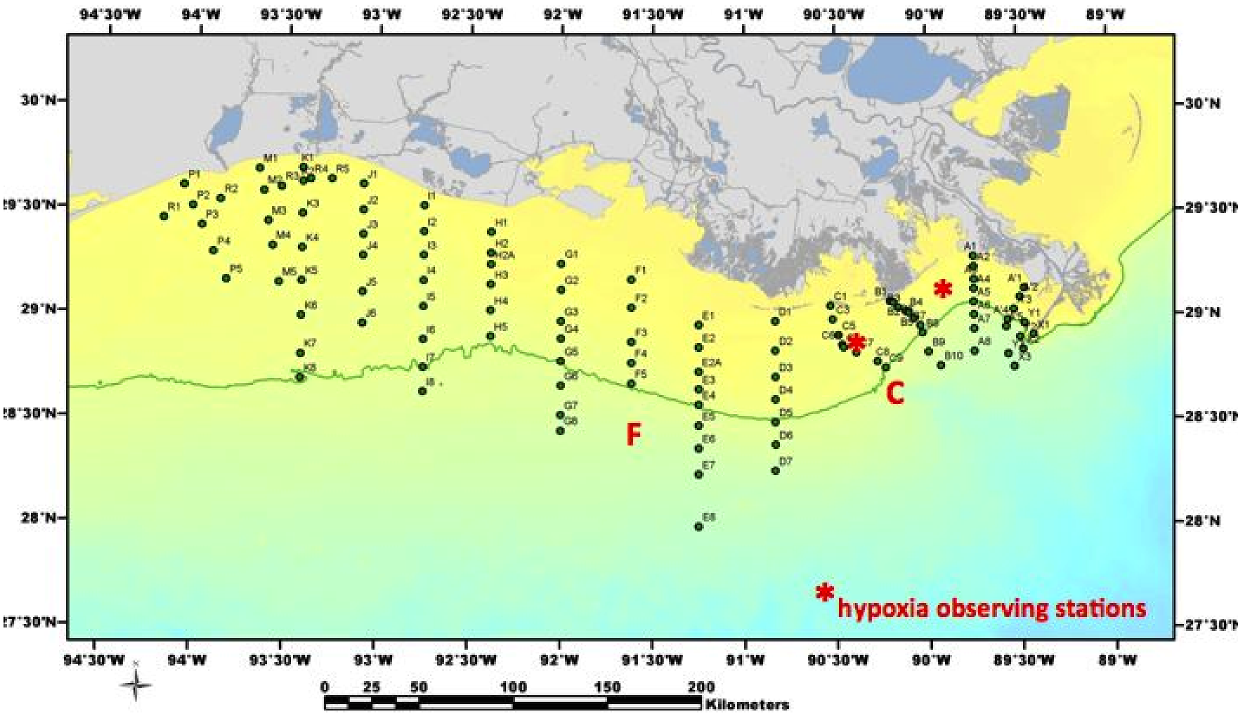
Turner, R.E., N.N. Rabalais and D. Justic 2012. Predicting summer hypoxia in the northern Gulf of Mexico: Redux. **Marine Pollution Bulletin** 64: 318-323. DOI: 10.1016/j.marpolbul.2011.11.008

Contacts for Further Information

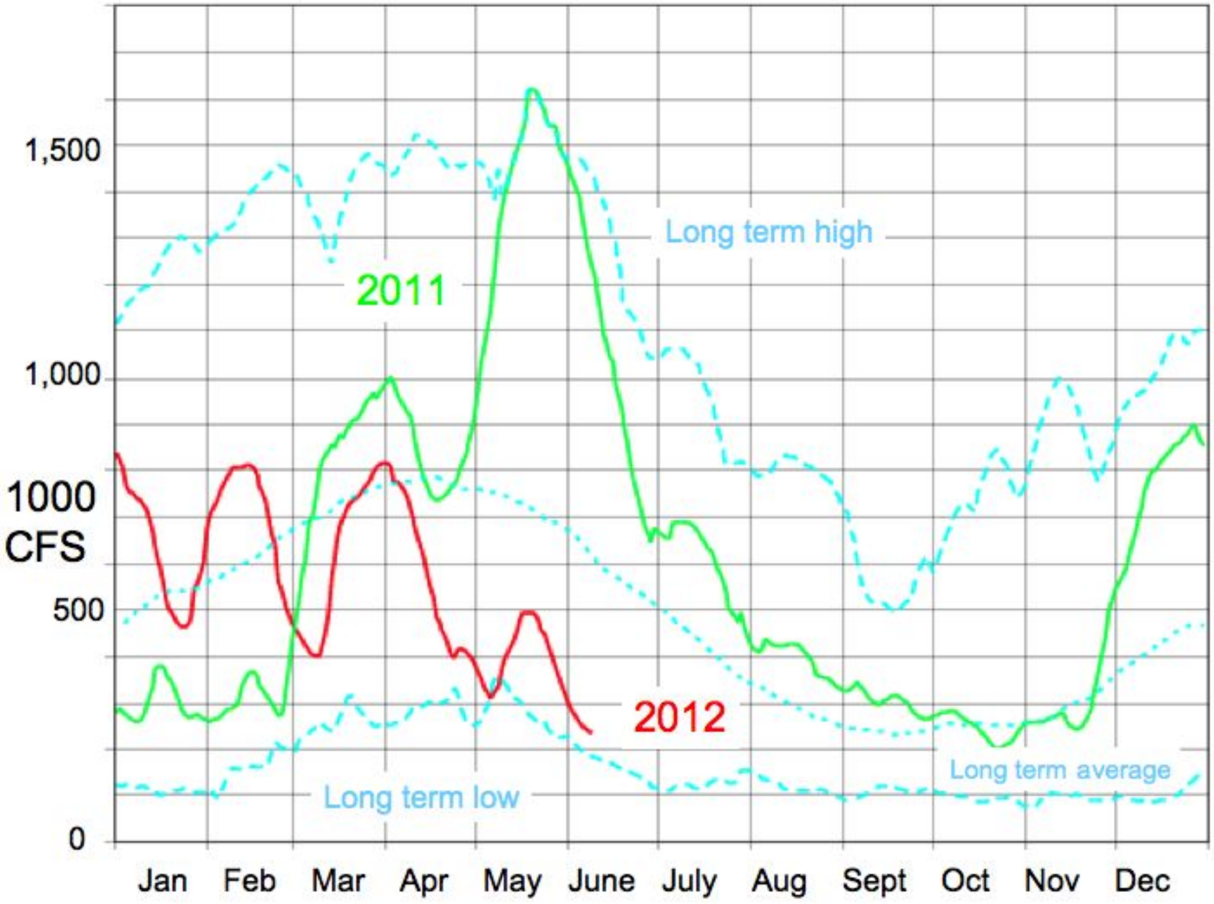
Nancy N. Rabalais (LUMCON, nrabalais@lumcon.edu)
R. Eugene Turner (LSU, euturne@lsu.edu)

Appendices

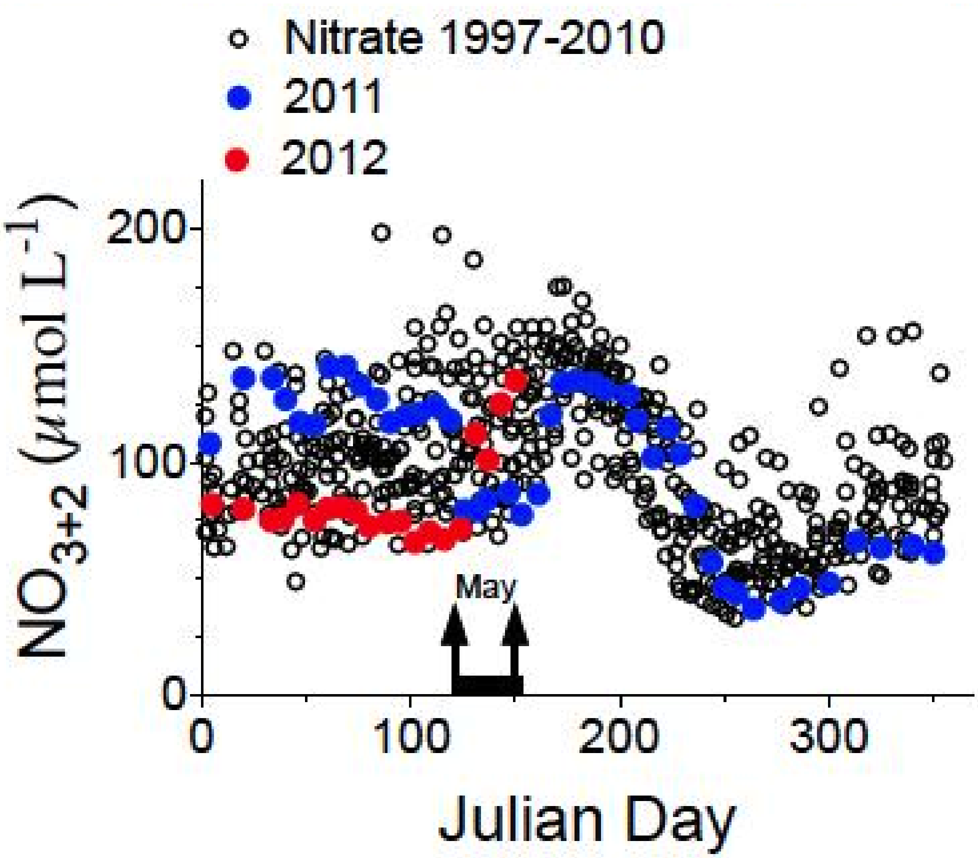
Appendix Figure 1. The study area.
Appendix Figure 2. The daily river discharge at Tarbert Landing through May 2012.
Appendix Figure 3. Dissolved nitrite+nitrate concentration in the Mississippi River at Baton Rouge, LA.



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 1930 through 9 June 2012. Units are cubic feet per second. Figure modified from http://www.mvn.usace.army.mil/eng/edhd/tar.gif.



Appendix Figure 3. Nitrate concentration at Baton Rouge from 1997 through 29 May 2012.