2021 Gulf of Mexico Hypoxia Forecast

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This model has been transferred to operations at the National Oceanic and Atmospheric Administration where it is combined with other models to produce an official ensemble forecast. We will continue to provide our forecast updates here. Our Chesapeake Bay and Lake Erie forcasts can be found here.

The Gulf of Mexico annual summer hypoxia forecasts are based on average May total nitrogen loads from the Mississippi River basin. This year's load estimate, recently released by USGS, is 4,365 metric tons per day. Based on that estimate, we predict the area of this summer's hypoxic zone to be 13,006 square kilometers (95% credible interval, 5,427 to 20,585), almost 3 times the goal of 5000 square kilometers.

Our forecast hypoxic volume is 48 km^3 (95% credible interval, 19 to 74 km^3).

The measured hypoxic area for 2021 was 16,418 km^2.

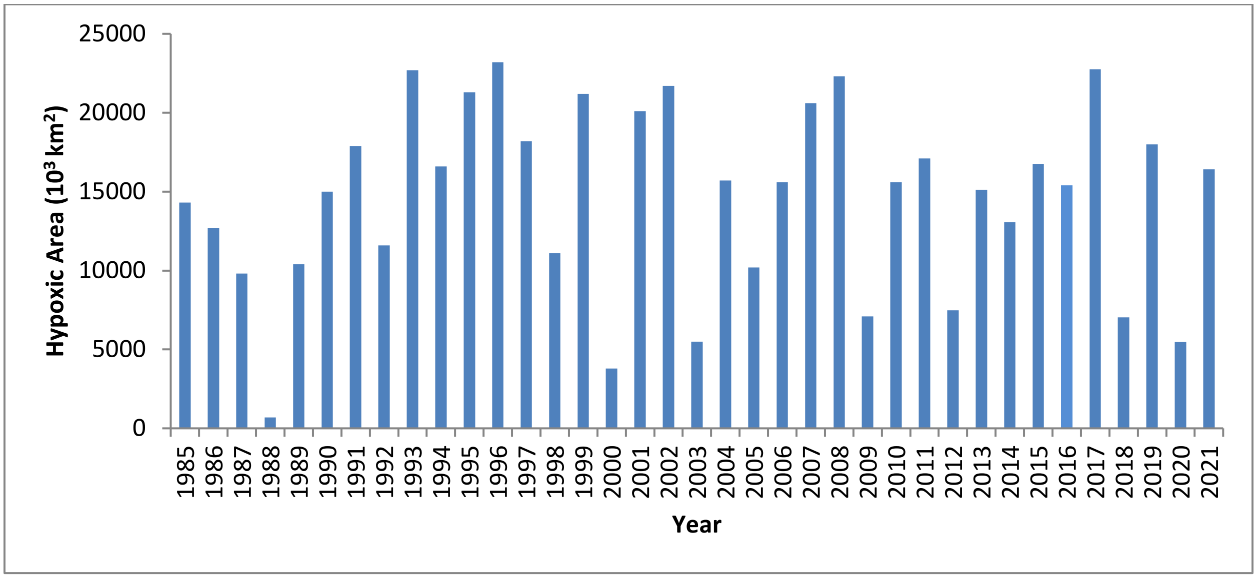

Figure 1: Mid-summer hypoxic area (Obenour et al. 2013 and Rabalais and Turner, LUMCON, 2019). The 2016 value is the average of two 3D ecological model reanalysis project from A. Lewitus, NOAA.

Hypoxia in the Gulf of Mexico – The Gulf of Mexico hypoxic zone (i.e., the area of bottom water with oxygen concentrations below 2 mg/l) is the second largest human-caused zone of hypoxia in the world's coastal waters, second only to that in the Baltic. Important fisheries are impacted at these low oxygen levels because fish, shrimp, and crabs are forced to move from their preferred habitats and animals that cannot move away die. Above (Figure 1) is a graph showing the annual changes in hypoxic area derived from geospatial analysis (Obenour et al 2013) of observations from the Louisiana Universities Marine Consortium shelfwide cruises (Rabalais et al. 2002). Support for this monitoring effort has been provided by NOAA's Center for Sponsored Coastal Ocean Research since 1990 (http://www.cop.noaa.gov/).

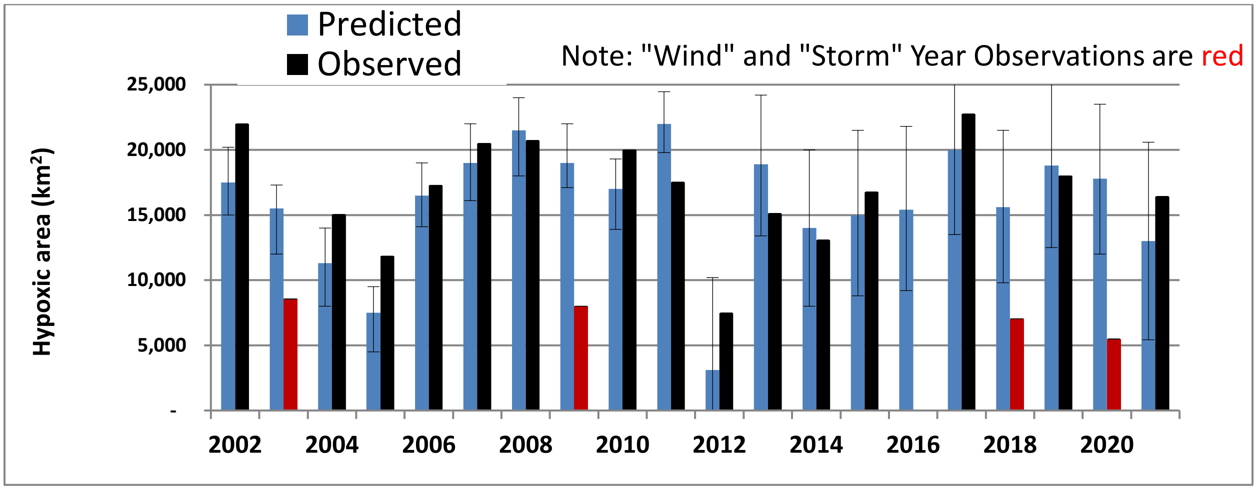

Figure 2: Forecast track record showing model forecast and observed hypoxic area for each year since 2002. "Wind" and "Storm" year observations (years when atypical weather interrupted measurement cruises) are indicated in red. Model calibration procedures have varied through time as more has been learned about the drivers of hypoxia in the Gulf.

Model track record – Hypoxic area forecasts have been generated each spring since 2002 and compared to the area measured later that summer (Figure 2). The model predicts mid-summer hypoxic area based on nitrogen load from the Mississippi River basin (Evans and Scavia, 2011). Model calibration has varied over the years as more has been learned about hypoxia in the Gulf. This year's forecast uses an updated model that corrects for some of the differences observed in the historical track record. In general, forecasts have performed well. Removing the year 2009 (see below) and four years when tropical storms impeded measurement of the hypoxic area (2003, 2005, 2018, and 2020), these forecasts explained 70% of the variation in observed hypoxic area. The hypoxic area was unusually small in 2009 due to unusual weather patterns that re-oxygenated the waters and persistent winds from the west and southwest likely pushed low oxygen water mass to the east, 'piling' it up along the southeastern Louisiana shelf (see www.gulfhypoxia.net).

Updated Hypoxia Model – This year we are using the model calibration described in Scavia et al (2013). This calibration was conducted, in part, to account for deviations in the relationship of hypoxia to nutrient loads caused by weather events such as tropical storms and winds that compress hypoxia to the eastern shelf (as in 2009, Figure 2). This calibration uses the model developed originally to relate Gulf of Mexico hypoxic area to loads from the Mississippi and Atchafalaya Rivers (Scavia et al. 2003). This model has been used in comparisons to other models (Scavia et al. 2004), for exploration of nitrogen vs. phosphorus control (Scavia and

Donnelly 2007), to provide guidance for the 2001 and 2008 Gulf Action Plans (Task Force, 2001, 2008), and to explore potential impacts of climate-induced changes in nutrient delivery (Donner and Scavia 2007). It is an adaptation of the Streeter-Phelps river model that simulates oxygen concentration downstream from point sources of organic matter loads using mass balance equations for oxygen-consuming organic matter, in oxygen equivalents (i.e., BOD), and dissolved oxygen concentration (DO). Assuming no upstream oxygen deficit, and ignoring longitudinal dispersion, the model's steady state solution for DO is

$$DO_y(x) = DO_s - \left(\frac{k_d\, BOD_{m,y}}{k_r - k_d}\right)\left(e^{(-k_d x/v)} - e^{(-k_r x/v)}\right), \text{for } x < 220 \text{ km}$$

$$\begin{aligned} DO_y(x) = DO_s &- \left(\frac{k_d\, BOD_{m,y}}{k_r - k_d}\right)\left(e^{(-k_d x/v)} - e^{(-k_r x/v)}\right) \\ &- \left(\frac{k_d\, BOD_{a,y}}{k_r - k_d}\right)\left(e^{(-k_d (x-220)/v)} - e^{(-k_r (x-220)/v)}\right), \text{for } x \geq 220 \text{ km} \end{aligned}$$

Where: y = year index, x = distance from the Mississippi River mouth (km), DO = DO (mg L^{-1}), DO_s = DO saturation concentration (mg L^{-1}), k_d = first order organic matter decay rate (d^{-1}), k_r = first order reaeration rate of the lower layer (d^{-1}), and BOD = BOD load for the Mississippi (m) and Atchafalaya (a) rivers. In the original Streeter-Phelps model for rivers, v represents the downstream velocity in km d^{-1}. However, in this application, its interpretation is more complicated because it represents a combination of the net effect of surface and bottom layer flow and sinking of organic matter into the bottom layer.

Organic matter load and associated oxygen demand (BOD) was approximated by multiplying May TN loads by the Redfield ratio to convert nitrogen to algal carbon (5.67 gCgN^{-1}), and by assuming an oxygen equivalent (e.g. respiratory ratio) of 3.47 gO$_2$gC $^{-1}$. We assumed 50% of the Mississippi River load moved east or offshore and did not contribute to hypoxia development (Dinnel and Wiseman, 1986), and that all of the surface algal production settled into the bottom waters.

The model produces a DO concentration profile stretching from the mouth of the Mississippi River toward the Louisiana-Texas border. From that profile, we determined the total length for which DO < 3 mg L^{-1}. A value of 3 mg L^{-1} was used because that average sub-pycnocline DO concentration roughly corresponds in time to a bottom water DO concentration of 2 mg L^{-1} and hypoxic conditions (Scavia et al. 2003). Hypoxic length is then converted to area ($area_y$) using an empirical formula determined from geospatial model output: $area_y = 57.8\ length_y$. Hypoxic volume (vol_y), when estimated, was calculated as: $vol_y = area_y$*thickness + $area_y^2 * \tau$ (Scavia et al. 2013)

This revised model calibration allows categorical parameter estimates for k_2 and v, based on the presence or absence of storms and strong westerly winds (Scavia et al. 2013), and is calibrated to new area and volume estimates for 1985-2020. Estimates for 1985-2011 are based on geostatistical estimation proceedures (Obenour et al. 2013). Estimates for 2012-2015 and 2017-2020 are from Rabalais and Turner 2018). Because there was no shelf-wide cruise in 2016, the estimate is the average of two 3D ecological model reanalyses (A. Lewitus, NOAA, personal communication). The current forecast uses this model calibration as applied to years without strong storms or winds and is drawn from the response curve of hypoxia vs. nutrient load in Scavia et al (2013).

Bayesian calibration - Calibration was conducted using Markov Chain Monte Carlo (MCMC) implementation of Bayes Theorem using WinBUGS (version 1.4.3) called from R (version 4.5.0, R2WinBUGS, version 2.1-21). The use of Bayesian calibration allows all parameters and predictions to be represented as probability distributions, thus ensuring propagation and quantification of uncertainty. All MCMC calibrations were run until full mixing was achieved between three independent chains. Mixing was monitored using the ratio of among chain to within chain variance (r^), and chains were considered mixed when r^ < 1.01 for all parameters.

Nutrient Loads - A substantial body of scientific evidence links long-term changes of this hypoxic region to loads of nitrogen from the Mississippi River system (e.g., Scavia and Donnelly 2007, Justić et al. 2002; Turner et al. 2007, 2012). Previous forecasts have been based on various loads (e.g. NO_3 vs. TN; May-June, vs. May; etc). This version has been calibrated with May TN loads. The graph below (Figure 3) represents those loads from the Mississippi basin between 1985 and 2021 from the USGS LOADEST AMLE method (http://toxics.usgs.gov/hypoxia/mississippi/oct_jun/index.html).

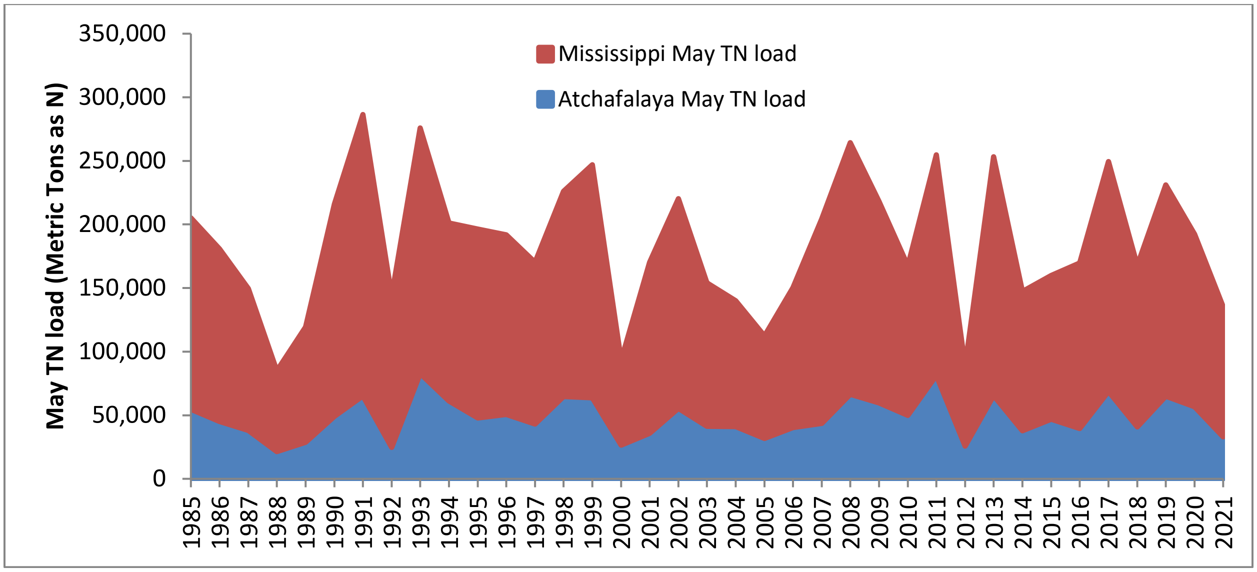

Figure 3: May total nitrogen loads from the Mississippi and Atchafalaya Rivers since 1985. The Mississippi load is the red area and the Atchafalaya load is the blue area such that the height of the combined shaded areas is the total load.

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