

2021 Gulf of Mexico Hypoxia Forecast

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June 3, 2021

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 forecasts 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 km³ (95% credible interval, 19 to 74 km³).

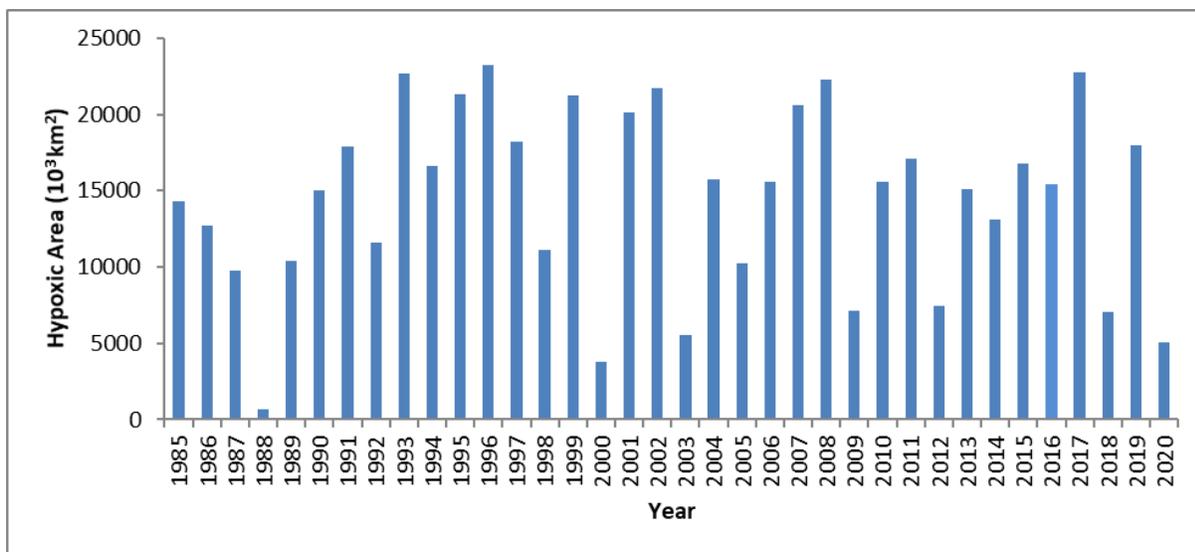


Figure 1: Mid-summer hypoxic area (Obenour et al. 2013 and Rabalais and Turner, LUMCON, 2019). The 2016 value is the average of two 3D ecological model reanalysis project from A. Lewitus, NOAA.

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/>).

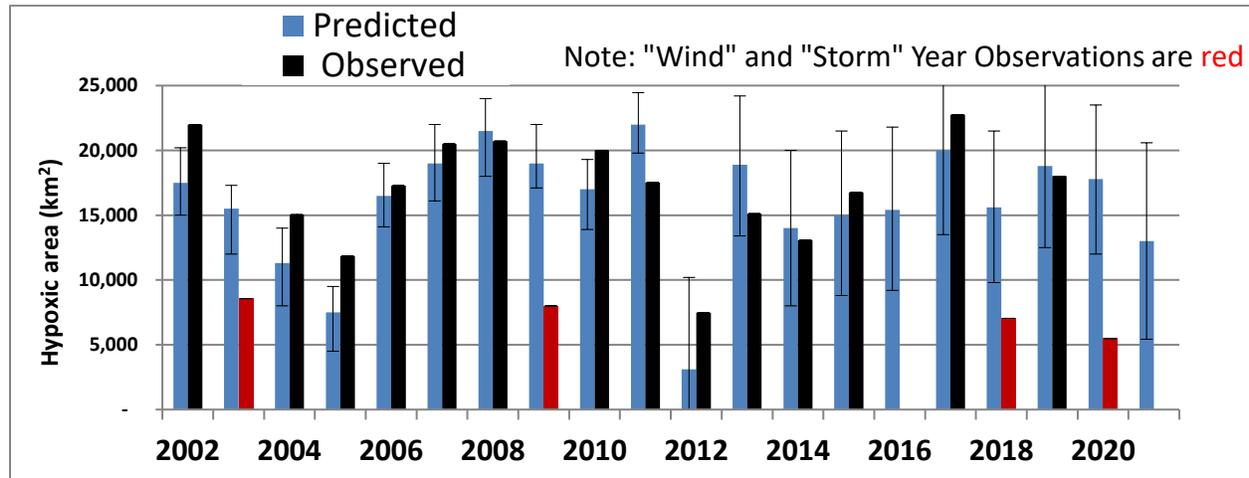


Figure 2: Forecast track record showing model forecast and observed hypoxic area for each year since 2002. “Wind” and “Storm” year observations (years when atypical weather interrupted measurement cruises) are indicated in red. Model calibration procedures have varied through time as more has been learned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

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

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

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 $3.47 \text{ gO}_2\text{gC}^{-1}$. 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 $DO < 3 \text{ mg L}^{-1}$. 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 procedures (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^{\wedge}), and chains were considered mixed when $r^{\wedge} < 1.01$ 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. NO₃ 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).

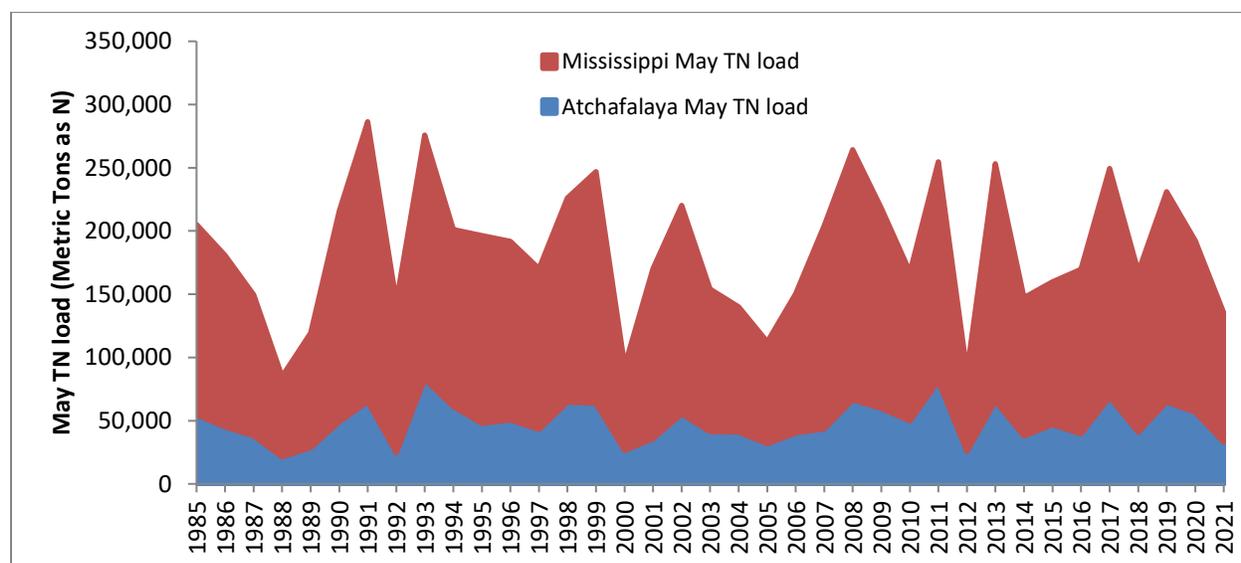


Figure 3: May total nitrogen loads from the Mississippi and Atchafalaya Rivers since 1985. The Mississippi load is the red area and the Atchafalaya load is the blue area such that the height of the combined shaded areas is the total load.

References

- Arhonditsis, G. B., S. S. Qian, C. A. Stow, C. E. Lamon, and K. H. Reckhow. 2007. Eutrophication risk assessment using Bayesian calibration of process-based models: Application to a mesotrophic lake. *Ecological Modelling*, 28: 215-229.
- Bierman, V.J., Jr., S.C. Hinz, D. Zhu, and W.J. Wiseman, Jr. 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.
- CENR 2000. Integrated Assessment of Hypoxia in the Northern Gulf of Mexico. National Science and Technology Council, Washington, D.C.

- Dinnel, S.P. and W.J. Wiseman Jr 1986. Fresh water on the Louisiana and Texas shelf. *Continental Shelf Research* 6:765–784)
- Donner, S.D and D. Scavia. 2007. [How climate controls the flux of nitrogen by the Mississippi River and the development of hypoxia in the Gulf of Mexico.](#) *Limnol. Oceanogr.* 52(2): 856-861.
- Evans. M.A. and D. Scavia. 2010. Forecasting hypoxia in the Chesapeake Bay and Gulf of Mexico: Model accuracy, precision, and sensitivity to ecosystem change. *Environmental Research Letters* 6: 015001
- Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. Nitrogen input to the Gulf of Mexico. *J. Environ. Qual.* 30: 329-336.
- Justić, D., N.N Rabalais, and R.E. Turner. 1997. Impacts of climate change on net productivity of coastal waters : implications for carbon budgets and hypoxia. *Clim. Res.* 8: 225-237.
- Justić, D., N.N Rabalais, and R.E. Turner. 2002. Modeling the impacts of decadal changes in riverine nutrient fluxes on coastal eutrophication near the Mississippi River Delta. *Ecological Modelling* 152: 22-46.
- Justić, D., N.N. Rabalais, and R.E Turner. 1996. Effects of climate change on hypoxia in coastal waters : a doubled CO₂ scenario for the northern Gulf of Mexico. *Limnol. Oceanogr.* 41: 92-1002.
- Liu, Y, M.A. Evans, D. Scavia. 2010 [Gulf of Mexico Hypoxia: Exploring Increasing Sensitivity to Nitrogen Loads.](#) *Environ. Sci. Technol.*
- Lunn, D.J., A. Thomas, N. Best, and D. Spiegelhalter. 2000. WinBUGS - a Bayesian modelling framework: concepts, structure, and extensibility. *Statistics and Computing*, 10: 325-337.
- Malve, O., and S. S. Qian. 2006. Estimating nutrients and chlorophyll a relationships in Finnish lakes. *Environmental Science and Technology*, 40 (24): 7848-7853.
- Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001. Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico. Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, Washington D.C.
- Mitsch, W.J., J.W. Day Jr., J.W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N.Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi River basin: Strategies to counter a persistent ecological problem. *BioScience* 15: 373-388.
- Qian, S. S., C. A. Stow, and M. E. Borsuk. 2003. On Monte Carlo methods for Bayesian inference. *Ecological Modelling*, 159(2-3): 269-277.
- Rabalais, N.N, R.E. Turner, and D. Scavia. 2002 a. Beyond science into policy: Gulf of Mexico Hypoxia and the Mississippi River. *BioScience* 52: 129-142.
- Rabalais, N.N., R.E. Turner, D. Justić, Q. Dortch, and W.J. Wiseman Jr. 1999. Characterization of hypoxia. NOAA Coastal Ocean Program Decision Analysis Series No. 15. Silver Spring, Maryland.
- Rabalais, N. N.; Turner, R. E.; Wiseman, W. J. Gulf of Mexico hypoxia, aka "The dead zone". *Annu. Rev. Ecol. Syst.* **2002**, 33, 235-263.

- Rabalais, N.N. and Turner, R.E., 2018, Area of bottom water hypoxia for mid-summer cruises, 1985-2017, available at <https://gulfhypoxia.net/research/shelfwide-cruises/>. Last accessed 6/5/18.
- Reckhow, K.H. 1994. Importance of scientific uncertainty in decision-making. *Environmental Management* 18: 161-166.
- Scavia, D. and K. A. Donnelly 2007 Reassessing Hypoxia Forecasts for the Gulf of Mexico *Environ. Sci. Technol.*, 41 (23), 8111–8117
- Scavia, D. N.N. Rabalais, R.E. Turner, D. Justic, and W. Wiseman Jr. 2003. Predicting the response of Gulf of Mexico Hypoxia to variations in Mississippi River Nitrogen Load. *Limnol. Oceanogr.* 48(3): 951-956.
- Scavia, D., D. Justic, and V.J. Bierman, Jr. 2004, Reducing hypoxia in the Gulf of Mexico: Advice from three models. *Estuaries* 27(3): 419-425.
- Scavia, D., E.A. Kelly, and J. D. Hagy III. 2006 A simple model for forecasting the effects of nitrogen loads on Chesapeake Bay hypoxia. *Estuaries and Coasts* 29(4): 674-684.
- Stow, C.A., and D. Scavia. 2008. Modeling hypoxia in the Chesapeake Bay: Ensemble estimation using a Bayesian hierarchical model. *J. Marine Systems*, 76:244-250.
- 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, and D. Justic 2008 Gulf of Mexico Hypoxia: Alternate States and a Legacy *Environ. Sci. Technol.*, 42 (7), 2323–2327, 2008
- Turner, R.E., Rabalais, N.N., Alexander, R.B., McIsaac, G., Howarth, R.W., 2007. Characterization of nutrient and organic carbon and sediment loads and concentrations from the Mississippi River into the northern Gulf of Mexico. *Estuaries and Coasts* 30, 773-790.
- Turner, R.E., Rabalais, N.N., Justić, D., 2012. Predicting summer hypoxia in the northern Gulf of Mexico: redux. *Marine Pollution Bulletin* 64, 319-324.
- Task Force (2001) *Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 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, DC, 2001, <http://water.epa.gov/type/watersheds/named/msbasin/history.cfm>.
- Task Force (2008) *Mississippi River/Gulf of Mexico Watershed Nutrient Task Force Gulf Hypoxia Action Plan 2008 for Reducing Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin*; U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds: Wash., D.C., 2008, <http://water.epa.gov/type/watersheds/named/msbasin/actionplan.cfm>.
- USGS 2002. The U.S. Geological Survey provided monthly nutrient loading data. Those data are available at <http://co.water.usgs.gov/midconherb/hypoxia/index.html>.