

# Chapter 3

## Interannual Variation in Stratification over the Texas–Louisiana Continental Shelf and Effects on Seasonal Hypoxia

Robert D. Hetland and Xiaoqian Zhang

**Abstract** A numerical dye is used to track freshwater released in May and June from the Mississippi and Atchafalaya rivers using a hydrodynamic model. These months are chosen because discharge and nutrient load in May and June is significantly correlated with an area of the Texas–Louisiana continental shelf affected by seasonal bottom low dissolved oxygen. Results show that the two different river sources influence different parts of the region affected by hypoxia, so that both rivers appear to contribute to forming the hypoxic region. Analysis shows that both nutrient loading and stratification caused by freshwater fluxes from the rivers are consistent with the distribution of dyed freshwater in late July.

**Keywords** Freshwater discharge · Stratification · Hypoxia · Modeling · Mississippi River · Texas–Louisiana shelf · Gulf of Mexico

### 3.1 Introduction

The Mississippi–Atchafalaya river system drains 41% of the continental USA, supplying the northern Gulf of Mexico annually with 530 km<sup>3</sup> of freshwater, 210 million tons of sediments, and 1.5 million tons of nitrogen (Milliman and Meade 1983; Goolsby et al. 2001). This large flux of carbon and nitrogen, combined with the stratifying effects of the freshwater, create a large region of near-bottom hypoxia south of the Louisiana coast. This layer is typically a few meters thick, with the lowest oxygen concentrations most commonly observed in the benthic nepheloid layer. The affected area is generally confined between the 10 and 50 m isobaths and may extend into Texas waters during years with a very large hypoxic area. In years with a small hypoxic area, low oxygen conditions are typically found in the vicinity of the two large river mouths, west of the Mississippi Delta and south of Atchafalaya Bay.

Many previous studies have found significant statistical relationships between either the freshwater discharge from the Mississippi and Atchafalaya rivers (Wise-

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man et al. 1997; Bianchi et al. 2010) or the nitrogen load carried by these rivers (Scavia et al. 2003; Turner et al. 2005; Greene et al. 2009; Forrest et al. 2011). The highest correlations are found between the May–June average nitrogen load and the hypoxic area in late July. However, questions remain about the processes that drive these correlations.

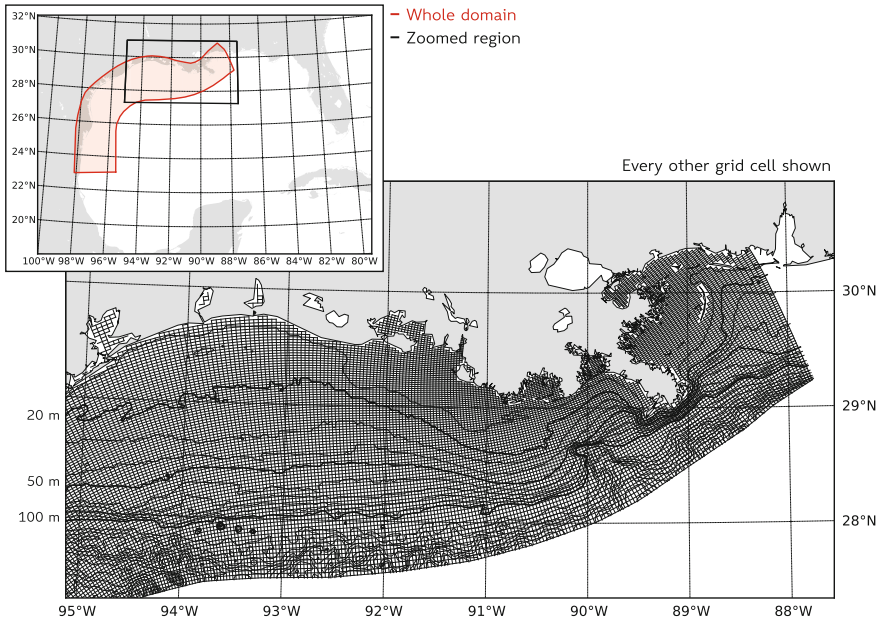
Nutrient loads and freshwater discharge are significantly correlated ( $r^2 = 0.71$ ,  $p = 2.2 \times 10^{-7}$ ); that is, the *concentration* of riverine nitrogen is roughly constant between years and is uncorrelated to the larger relative variations in freshwater discharge and load. Because of this, the causal relationships between both nutrient load and freshwater flux that create interannual variations in hypoxic area are confounded. It is not clear if observed interannual changes in hypoxic area are caused by the stratifying effects of the freshwater, or the eutroifying effects of the increased nitrogen load.

The goal of this paper is to trace the river water released onto the shelf during May and June in a number of different years, to examine the relationships between the fate of this water on the shelf and hypoxic area. May and June are chosen because of the significant statistical relationship between freshwater flux and nutrient load in these months with the subsequent extent of hypoxia in July. The numerical simulations are accomplished by adding a numerical dye to each large river source during each month. This results in four separate dyes, one for both the Mississippi and Atchafalaya rivers during both May and June. Distributions of these dyes are then compared to the extent of hypoxia in late summer.

## 3.2 Model Setup

We use the Regional Ocean Modeling System (ROMS, Shchepetkin and McWilliams 2005; Haidvogel et al. 2008) configured for the Texas–Louisiana shelf for this study. This model has been described in previous studies of circulation and freshwater budgets by Zhang et al. (2012a, b). Briefly, the model extends roughly from Laguna Madre in Mexico to Mobile Bay in Alabama. The model has 30 vertical layers, and  $\sim 1$  km horizontal resolution over the Louisiana shelf. The model domain is shown in Fig. 3.1. The model is forced with inputs from the six major rivers in Louisiana and Texas, with the Mississippi and Atchafalaya rivers contributing the most to the riverine freshwater inputs. The model is nudged to results from the GOM-HYCOM operational model to include the effects of deep ocean currents on shelf circulation. The North American Regional Reanalysis (NARR) model is used for surface momentum, heat, and freshwater fluxes; heat fluxes are calculated through a bulk formulation with a Q-correction of  $50 \text{ W m}^2$ .

The primary addition to the present set of simulations is that the freshwater from the Atchafalaya and Mississippi rivers is dyed for each river in both May and June of each simulation year. Freshwater entering the domain from the rivers is tagged with a concentration of  $1 \text{ m}^{-3}$ , so that the dye concentration represents the fraction of dyed freshwater at a particular point in the domain. The manner in which the dyes are

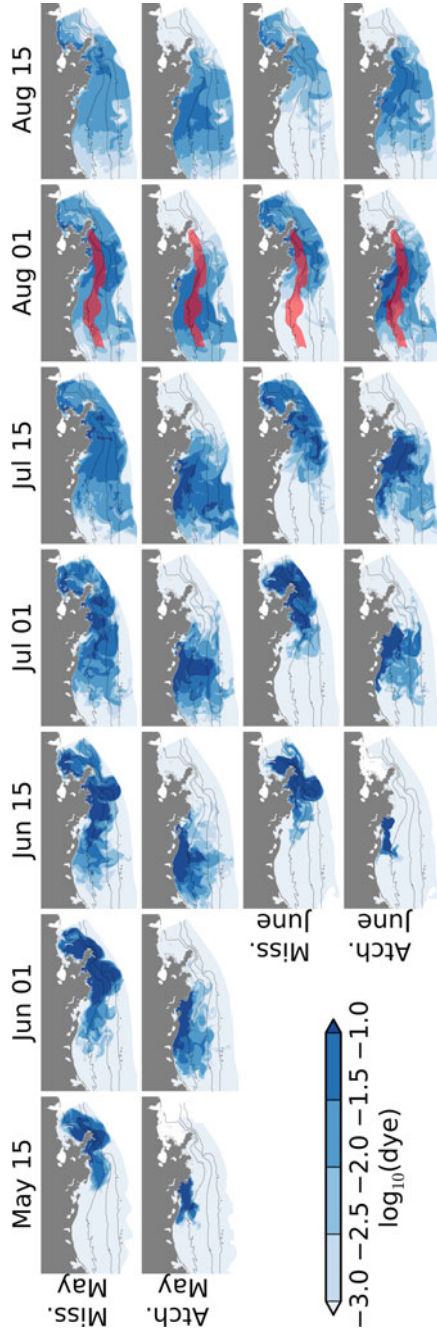


**Fig. 3.1** The model domain and grid are shown in the two maps. The model domain covers the entire Texas and Louisiana shelves from the coast past the shelf break. The grid resolution in the region just west of the Mississippi River delta is less than 1 km

added to the freshwater inputs is similar to the method used in Zhang et al. (2012b), the primary difference being that only water released in either May or June is dyed.

### 3.3 Results

The year 2008 is presented here as an example of the distribution of the dye from the Mississippi and Atchafalaya rivers in the months of May and June. The year 2008 is chosen as an example because it had a very high discharge, relatively typical summertime winds, and was the second largest hypoxic area recorded during the late July annual survey (see <http://gulfhypoxia.net>). Figure 3.2 shows the surface concentration of dye from each river, released during each of May and June over the summer. As the dye is introduced at a concentration of one, the dye may be considered as a proxy for dilution of freshwater over the shelf. Thus, the dye represents the fraction of river water in a given model cell and is thus unitless. The dye is plotted on a logarithmic scale, so that each gradation indicates an order of magnitude dilution. For this year, where the discharge was above average, by the end of summer essentially the entire Louisiana shelf is covered with fresh river water that has been diluted less



**Fig. 3.2** Surface dye concentrations are shown every 2 weeks during summer, 2008. The dye is separated into the river source, either Mississippi or Atchafalaya, and the month of the dye release, either May or June. Concentrations are plotted on a logarithmic scale. The observed area of hypoxia is shown in the four August frames

than one thousand times, with significant regions near the source that have dilution factors of less than ten.

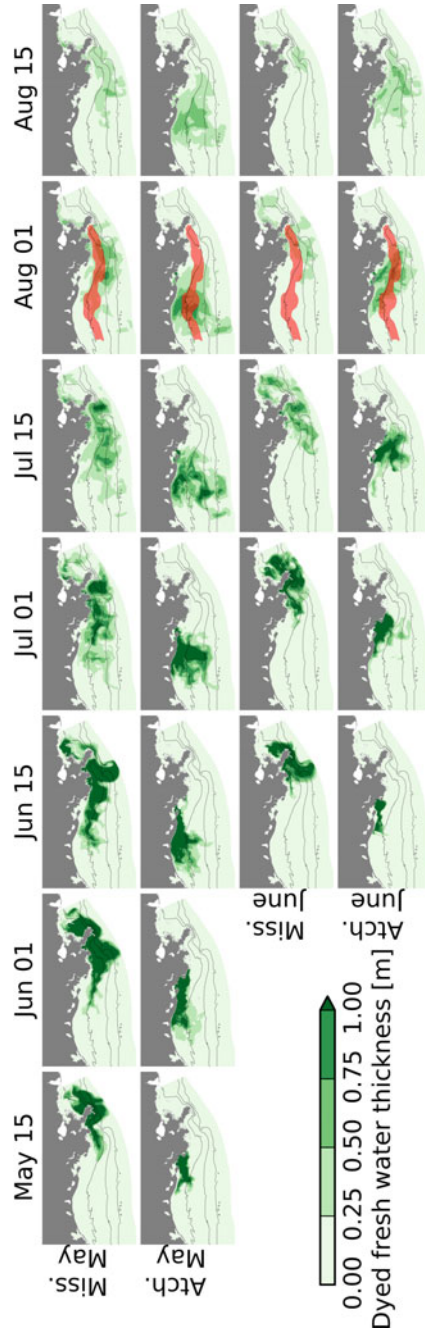
As the undiluted dyed freshwater has a concentration of one, the dye may be considered as a proxy for volume of freshwater per unit volume ocean water. Thus, the integral

$$h_f = \int_{-H}^n d_i dz \quad (3.1)$$

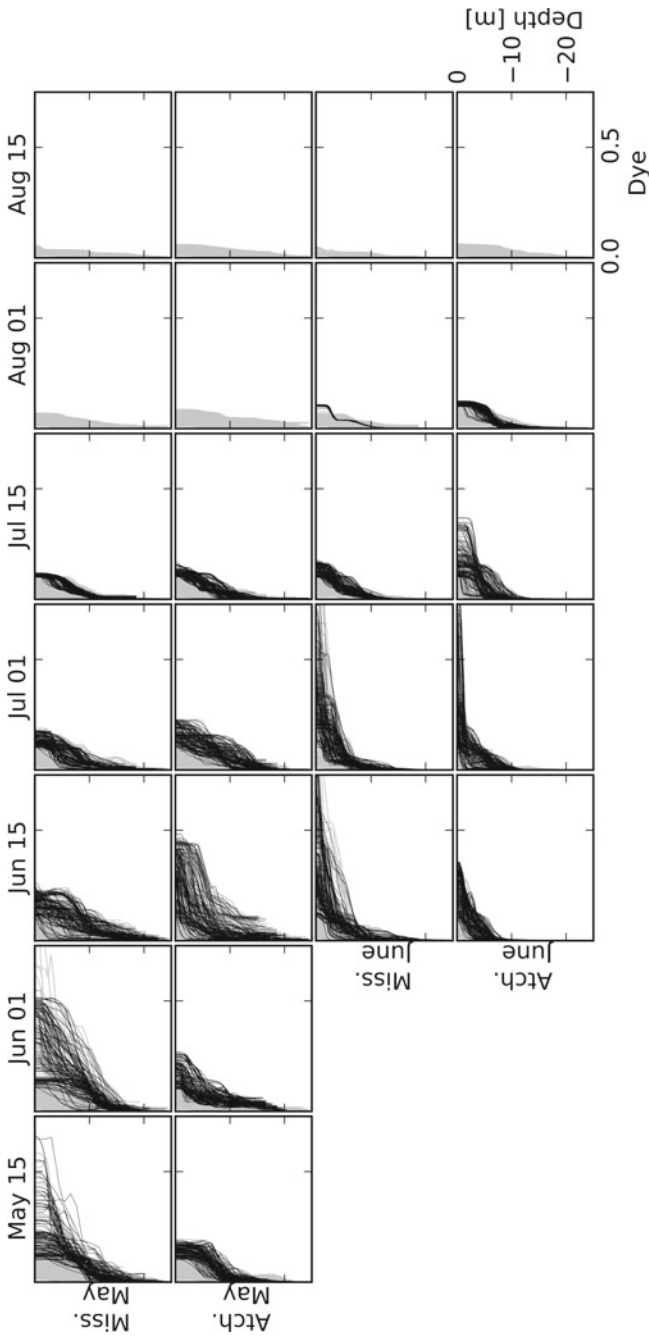
represents the freshwater thickness,  $h_f$ , associated with a particular dye,  $d_i$ . The freshwater thickness is the thickness of the dyed freshwater, if the water column “unmixed” into purely dyed freshwater with a dye concentration of one and completely undyed water. The remaining undyed water may contain some freshwater, but this freshwater was introduced at times when dye was not included in the discharge of freshwater to the ocean. Distributions of vertically integrated dye show similar patterns (Fig. 3.3); the highest concentrations of integrated dye show that some regions of the shelf have over three meters of riverine freshwater mixed through the water column.

Figure 3.4 shows vertical profiles of dye centered about the 20 m isobath in locations where surface concentrations are high, diluted by less than a factor of 100. Profiles indicate that the dye is typically concentrated at the surface and has the strongest concentrations in the upper half of the water column. The dye released in June has a particularly strong surface signature that persists throughout the month. However, all the dye profiles indicate that by the end of July, all of the dye has been significantly diluted, with concentrations in the upper water column about double those in the lower water column. Thus, while surface dye concentrations are stronger in the upper half of the water column through the entire summer, there is a relatively significant fraction of the dye that penetrates into the lower layer.

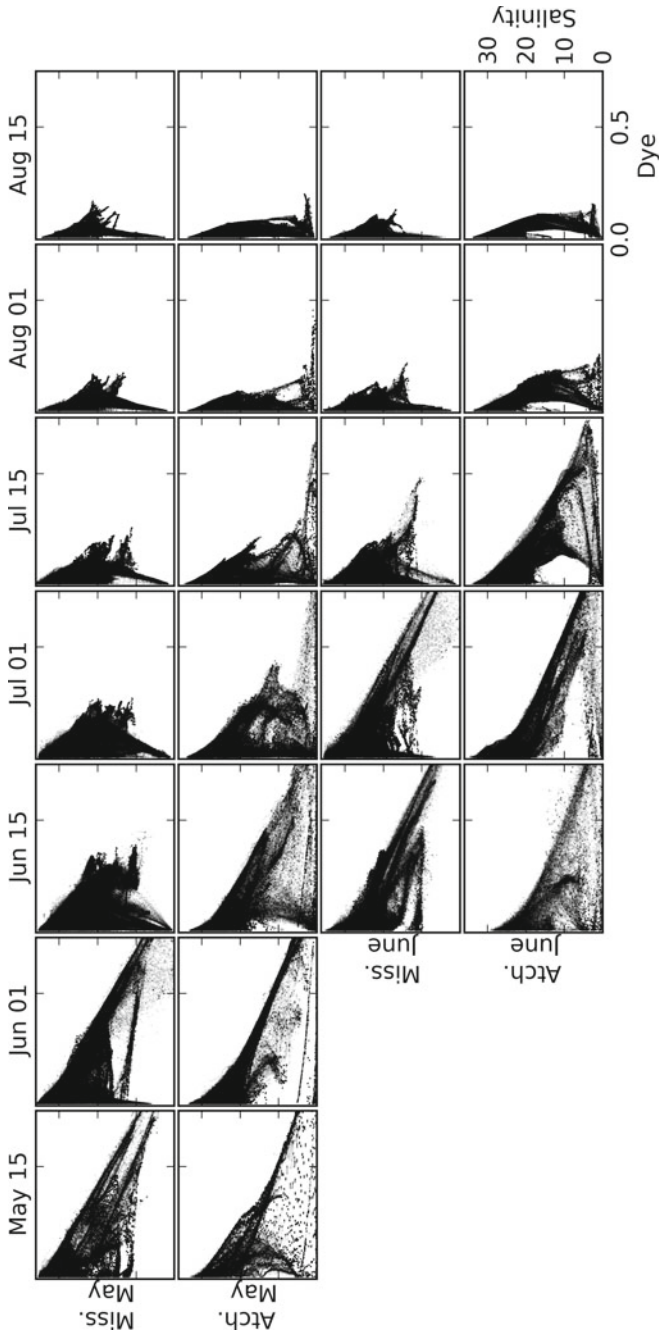
The differences in the character of each source can be found by examining the relationship between the dye and other oceanic tracers. The relationship between dye and salinity, shown in Fig. 3.5, shows that the highest dye concentrations are found at intermediate salinity ranges, between fresh riverine water ( $S = 0.0$ ) and ambient Gulf water ( $S \approx 36.0$ ). The relationship between dye and salinity is controlled primarily by the dye source; the two river sources appear distinct, regardless of the month in which the dye was released. There are some common patterns in each dye release. Initially, a mixing line is formed between the freshwater in which the dye is introduced into the domain, and the ambient Gulf water that initially contains no dye. Points below this line are filled in as the dye mixes with freshwater that was introduced earlier, and that contains no dye. Since the freshwater released from the Mississippi Delta mixes quickly, dye concentrations are not found at salinities much fresher than about  $10 \text{ g kg}^{-1}$ . As this dye interacts with the Atchafalaya plume, dye is found at even lower salinities. The Atchafalaya discharge, on the other hand, is released at the edge of a broad, shallow shelf. As such, there is a pool of freshwater that separates the Atchafalaya plume water at the beginning of each dye release from the ambient Gulf water. Because this dye is present at very freshwaters, even early in the Atchafalaya



**Fig. 3.3** Integrated dye, equivalent to the freshwater thickness associated with each source and month, is shown every 2 weeks during summer, 2008. The observed area of hypoxia is shown in the four August 1 frames



**Fig. 3.4** Random profiles of dye concentration are shown in locations between 15 and 25 m deep, where the dye is diluted by a factor of 10 (*black lines*) and 100 (*gray lines*). Profiles are shown for dye from each source and month every 2 weeks during summer, 2008



**Fig. 3.5** The relationship between dye and salinity is shown for all the model points for each source and month every 2 weeks during summer, 2008



dye releases, the mixing line at dye concentrations higher than about 0.2 indicates mixing with waters that have a salinity fresher than 30 g kg<sup>-1</sup>.

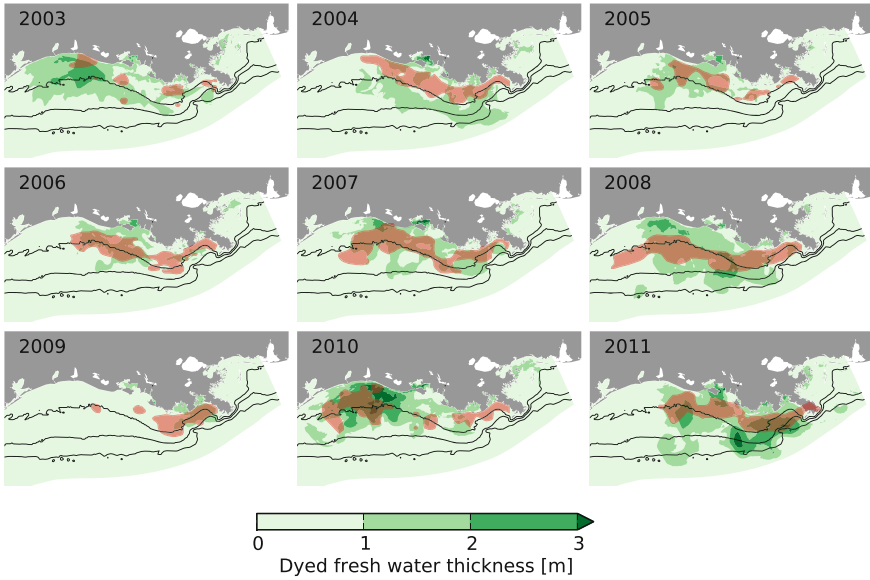
### 3.4 Discussion

In both the surface dye concentrations (Fig. 3.2) and the dyed freshwater thickness (Fig. 3.3), the Mississippi and Atchafalaya plumes cover distinct regions on the shelf. The Atchafalaya plume is generally westward and inshore of the Mississippi plume water. However, it is clear from the overlays of hypoxic area that the region of the shelf that is affected by hypoxia is associated with neither plume in particular. In Table 3.1, the cubic kilometers of dyed freshwater is integrated in the regions of the shelf that are affected by hypoxia in a given year. Generally, it is clear from this table, as well as from Figs. 3.2 and 3.3, that no one, particularly freshwater source—Mississippi or Atchafalaya—or month of dye release—May or June—is the primary contributor to stratification or nutrients in the regions associated with low dissolved bottom oxygen.

Figure 3.6 shows the dye thickness from years 2003 to 2011, with the observed hypoxic area overlaid. On average, there is about 1 m of freshwater over the hypoxic zone in each year, ranging from about 0.7 m in years with smaller areas (2003 and 2009), and about 1.2 in years with large areas (2007, 2008, and 2010). A stoichiometric analysis suggests that 1 m of freshwater could supply enough organic material to fuel hypoxia in these regions. Assuming that the nitrogen to oxygen ratio is 1:130,

**Table 3.1** Integrated freshwater (km<sup>3</sup>) in the regions associated with bottom hypoxia on July 28 of each year. The final column shows the observed hypoxic area for each year. The correlations between each integrated dye and associated *p*-values are found in the bottom rows. The correlation between the sum of all the integrated dyes is *r* = 0.90, *p* = 0.0011

Year	May Miss (km <sup>3</sup> )	May Atch (km <sup>3</sup> )	June Miss (km <sup>3</sup> )	June Atch (km <sup>3</sup> )	Hypoxic area (km <sup>3</sup> )
2003	1.34	0.91	1.90	1.76	8,560
2004	1.94	3.09	2.31	4.75	15,040
2005	1.90	1.40	2.74	2.62	11,840
2006	2.59	3.90	4.17	3.08	17,280
2007	10.24	4.37	3.69	4.64	20,500
2008	8.18	8.20	3.95	6.30	20,720
2009	1.23	2.16	0.38	2.33	8,000
2010	5.43	6.88	5.95	7.71	20,000
2011	7.05	10.39	2.85	7.99	17,520
	<i>r</i> = 0.83	<i>r</i> = 0.73	<i>r</i> = 0.83	<i>r</i> = 0.77	
	<i>p</i> = 0.0061	<i>p</i> = 0.024	<i>p</i> = 0.0059	<i>p</i> = 0.015	



**Fig. 3.6** Dye thickness, summing together all four dyes associated with the two sources and months are shown in late July for nine different years, corresponding to the period when the annual hypoxia survey occurs. The observed area of hypoxia is shown as a *red shaded region*

that the nitrogen concentration of river water is  $120 \mu\text{M}$ , that the apparent oxygen utilization in hypoxic waters is  $250 \mu\text{M}$ , and that the efficiency of converting nitrogen into oxygen utilization is 0.2, 1 m of freshwater would convert roughly to 6 m of hypoxic water. This is of course assuming (1) that there are no other mechanisms that reduce efficiency such as lags in oxygen utilization, (2) that the organic matter is delivered roughly evenly over the hypoxic area, and (3) that there is no ventilation of the bottom waters. Also, it is not clear what the timescales and processes of organic matter creation and conversion are using this simple conceptual model. For this, one would need to use a full model of biological processes, such as the NPZD model described by Fennel et al. (2011). Even so, this model suggests that it is plausible that a significant fraction of organic matter required to form hypoxia may be delivered by the two river systems during May and June.

However, each dye is not spread evenly over the hypoxic area, rather different rivers contribute differently to different regions. For example, the Mississippi is concentrated more to the east, the Atchafalaya more to the west. This may have important consequences for the formation of hypoxia in different region of the shelf, because the character of the water introduced to the shelf is very different between the Mississippi and Atchafalaya. For example, The Atchafalaya River Basin may be a small source for inorganic nitrogen, but a sink for organic nitrogen (for a total 14% reduction in total nitrogen) (Xu 2006; Scaroni et al. 2010). Other properties, such as sediments, phosphorous, and organic carbon, may be similarly altered as river water

passes through the swampy region that defines the Atchafalaya River Basin. Thus, the Mississippi and Atchafalaya form water masses with very different properties, and freshwater distributions over the shelf (Hetland and DiMarco 2008).

The dye experiments also suggest that the freshwater delivered to the shelf during May and June from both river sources may create stratification in the regions affected by hypoxia. The vertical structure of the dye in August suggests that the dye is stratified (see Fig. 3.4). The dye is associated with freshwater, and freshwater is the primary determinant of density over the Texas–Louisiana shelf. Also, the horizontal distribution of freshwater is roughly co-located with the westward termination of the hypoxic zone. This implies that it is indeed freshwater in the months of May and June that are primarily associated with determining the areal extent of hypoxia.

### 3.5 Conclusions

The water released from the Mississippi and Atchafalaya rivers during May and June appears to roughly correlate with the regions of the Texas–Louisiana shelf affected by seasonal bottom hypoxia. Different regions of the area affected by hypoxia are influenced by different rivers and different release times; the sum total of water released during May and June from the two sources extends roughly across the entire hypoxic area, and the along-shore extent of this water appears to be roughly correlated with the along-shore extent of hypoxia.

However, this analysis is not able to differentiate between the organic material flux to the benthos due to nitrogen inputs from the river, and the stratifying effects of the fresh river water. Both interpretations are consistent with the model results.

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### References

- Bianchi TS, DiMarco SF, Cowan JH Jr, Hetland RD, Chapman P, Day JW, Allison MA (2010) The science of hypoxia in the Northern Gulf of Mexico: a review. *Sci Total Environ* 408(7):1471–1484. doi:[10.1016/j.scitotenv.2009.11.047](https://doi.org/10.1016/j.scitotenv.2009.11.047)
- Fennel K, Hetland R, Feng Y, DiMarco SF (2011) A coupled physical-biological model of the Northern Gulf of Mexico shelf: model description, validation and analysis of phytoplankton variability. *Biogeosciences* 8:1881–1899. doi:[10.5194/bg-8-1881-2011](https://doi.org/10.5194/bg-8-1881-2011)
- Forrest DR, Hetland RD, DiMarco SF (2011) Multivariable statistical regression models of the areal extent of hypoxia over the Texas–Louisiana continental shelf. *Environ Res Lett* 6:045002
- Goolsby DA, Battaglin WA, Aulenbach BT, Hooper RP (2001) Nitrogen input into the Gulf of Mexico. *Environ Qual* 30(2):329–336
- Greene RM, Lehrter JC, III JDH (2009) Multiple regression models for hindcasting and forecasting midsummer hypoxia in the Gulf of Mexico. *Ecol Appl* 19(5):1161–1175

- Haidvogel DB, Arango H, Budgell WP, Cornuelle BD, Curchitser E, Di Lorenzo E, Fennel K, Geyer WR, Herman AJ, Lanerolle L, Levin J, MacWilliams JC, Miller AJ, Moore AM, Powell TM, Shchepetkin AF, Sherwood CR, Signell RP, Warner JC, Wilkin J (2008) Ocean forecasting in terrain-following coordinates: formulation and skill assessment of the regional ocean modeling system. *J Comput Phys* 227:3595–3624
- Hetland RD, DiMarco SF (2008) How does the character of oxygen demand control the structure of hypoxia on the Texas–Louisiana continental shelf? *J Marine Syst* doi:[10.1016/j.marsys.2007.03.002](https://doi.org/10.1016/j.marsys.2007.03.002)
- Milliman JD, Meade RH (1983) World-wide delivery of river sediment to the ocean. *J Geol* 91(1):1–21
- Scaroni AE, Lindau CW, Nyman JA (2010) Spatial variability of sediment denitrification across the Atchafalaya River Basin, Louisiana, USA. *Wetlands* 30(5):949–955
- Scavia D, Rabalais NN, Eugene Turner R, Justić D, Wiseman WJ Jr (2003) Predicting the response of Gulf of Mexico hypoxia to variations in Mississippi River nitrogen load. *Limnol Oceanogr* 48(3):951–956
- Shchepetkin AF, McWilliams JC (2005) The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topographically-following-coordinate oceanic model. *Ocean Model* 9:347–404
- Turner RE, Rabalais NN, Swenson EM, Kasprzak M, Romaine T (2005) Summer hypoxia in the northern Gulf of Mexico and its prediction from 1978 to 1995. *Marine Environ Res* 59:65–77
- Wiseman WJ Jr, Rabalais NN, Turner RE, Dinnel SP, MacNaughton A (1997) Seasonal and inter-annual variability within the Louisiana coastal current: stratification and hypoxia. *J Marine Syst* 12:237–248
- Xu JY (2006) Total nitrogen inflow and outflow from a large river swamp basin to the gulf of mexico. *Hydrol Sci J* 51(3):531–542
- Zhang X, Marta-Almeida M, Hetland RD (2012a) A high-resolution pre-operational fore cast model of circulation on the Texas–Louisiana continental shelf and slope. *J Oper Oceanogr* 5(1):19–34
- Zhang X, Hetland RD, Marta-Almeida M, DiMarco SF (2012b) A numerical investigation of the Mississippi and Atchafalaya freshwater transport, filling and flushing times on the Texas–Louisiana shelf. *J Geophys Res* 117:C11009, 21 pp. doi:[10.1029/2012JC008108](https://doi.org/10.1029/2012JC008108)