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Relative role of wind forcing and riverine nutrient input on the extent of hypoxia in the northern Gulf of Mexico

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[1] Seasonal hypoxia of the northern Gulf of Mexico has been observed for more than 25 years. It is generally accepted that the variation in the areal extent of hypoxia is determined by changes in nutrient addition from the Mississippi River. In this study, we investigate the statistical relation between the hypoxic area and a new variable, the duration of west wind, using the available measurements for the period 1985–2010. Special consideration was paid to the 1993–2010 period, a time when a large shift in the seasonal hypoxia pattern has been reported. When excluding the years in which hurricanes directly impacted the hypoxic area observation, we find that the duration of west wind is correlated with the hypoxic area at $r^2 = 0.32$ for the 1985–2010 period, and $r^2 = 0.52$ for the 1993–2010 period. Multilinear regressions using both wind duration and May-June nitrate loading improve the statistical relationships for both periods to $r^2 = 0.69$ and 0.74 for the long and short time periods, respectively. Mechanistically, the statistical relationships reflect the movement and changes in horizontal river plume position associated with the wind and the influence of stratification on the hypoxic area. **Citation:** Feng, Y., S. F. DiMarco, and G. A. Jackson (2012), Relative role of wind forcing and riverine nutrient input on the extent of hypoxia in the northern Gulf of Mexico, *Geophys. Res. Lett.*, *39*, L09601, doi:10.1029/2012GL051192.

1. Introduction

[2] The Mississippi River (MR) is the largest river system in North America. It delivers significant amounts of freshwater and nutrients to the Louisiana shelf in the spring, causing a large hypoxic area in the summer that is potentially harmful to the ecosystem. The hypoxic region of the northern Gulf of Mexico has been surveyed in late July annually since 1985. The reported hypoxic areas range from 40 km^2 to 22,000 km^2 and average more than 13,600 km^2 [*Dale et al.*, 2010].

[3] Both statistical and mechanistic models have been used to explore factors affecting the size of the hypoxic region. Results show that the variation in the hypoxic area is related primarily to the variation of nutrient supply or stream flow from the Mississippi and Atchafalaya Rivers (MAR). *Wiseman et al.* [1997] found a high correlation between hypoxic area in July and the average MR stream flow for the previous 11 months using 9 years of data. *Turner et al.* [2006] explained the change in hypoxic area using a multiple linear regression model, with the May MR N-loading and Julian year as predictors. The relationship to Julian year was interpreted as a proxy for carbon stored in the sediments [*Turner et al.*, 2008]. *Greene et al.* [2009] used a multiple linear regression model to predict the area using nitrate and phosphate concentrations and river discharge. An important conclusion of both *Turner et al.* [2008] and *Greene et al.* [2009] was that the relationship between the hypoxic area and N-loading changed in the early 1990's. *Scavia et al.* [2003] reproduced the hypoxic area by using a one-dimensional model driven by the May-June total N-loading from the MAR. *Liu et al.* [2010] improved the predictions of this model by incorporating an additional parameter to describe a system change in 1993. The above models were the basis of the hypoxia management strategy [*Mississippi River/Gulf of Mexico Watershed Nutrient Task Force*, 2001, 2008].

[4] Observations have shown large interannual changes in bottom dissolved oxygen concentrations and hypoxic area [*Rabalais et al.*, 2007; *Bianchi et al.*, 2010]. Such variability can also result from non-river factors, such as the wind-driven currents, types of water-column respiration, and topographic influences [*Hetland and DiMarco*, 2008; *DiMarco et al.*, 2010]. Furthermore, the reported hypoxic area can differ substantially from predictions that use only nutrient loading as the principal driver, as in the *Turner et al.* [2006] and *Scavia et al.* [2003] models. In 2009, the observed area was about 8,000 km^2; the predictions from these two models were 25,000 km^2 and 22,000 km^2, respectively. The nearly three-fold difference has been hypothesized to result from the long duration of the west wind preceding the observations (http://www.gulfhypoxia.net). One objective of this manuscript is to address and quantify this hypothesis.

[5] The wind is the primary driver of the low-frequency circulation on the Texas-Louisiana shelf [*Cochrane and Kelly*, 1986; *Cho et al.*, 1998]. The wind varies seasonally and is directed downcoast (from east to west) during the non-summer (defined as September through May) and is directed upcoast with a relatively weaker magnitude during the summer (June through August). The change in wind direction alters the horizontal distribution of the river plume on the continental shelf and thereby the vertical stratification. The relationship between the Gulf hypoxic area and the average east-west wind speed has been examined in a recent study [*Forrest et al.*, 2011]. The correlation was weak ($r^2 = 0.16$), but statistically significant. In this study, we use duration of westerly wind instead of east-west wind speed in statistical analysis. The wind duration excludes wind magnitude and better represents the role of wind direction instead of wind speed. We examined the relationships

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Table 1. Single and Multiple Linear Regression Analysis Result

	85-10		85-10 NH		93-10		93-10 NH	
	r^2	p	r^2	p	r^2	p	r^2	p
Single Linear Regressions								
$\bar{F}_{May}$	0.11	0.10	0.10	0.14	0.05	0.38	0.02	0.62
$\bar{F}_{spring}$	0.14	0.07	0.12	0.11	0.08	0.25	0.04	0.47
$\bar{F}_{11}$	0.13	0.08	0.13	0.09	0.09	0.22	0.09	0.25
May–June NO_{3+2}	0.39	<0.01	0.36	<0.01	0.31	0.02	0.24	0.05
May NO_{3+2}	0.33	<0.01	0.31	<0.01	0.29	0.02	0.22	0.07
t_{Uwind}	0.12	0.09	0.32	<0.01	0.18	0.08	0.52	<0.01
Multiple Linear Regressions								
$\bar{F}_{May} + t_{Uwind}$	0.33	0.01	0.53	<0.01	0.36	0.04	0.64	<0.01
$\bar{F}_{spring} + t_{Uwind}$	0.34	<0.01	0.52	<0.01	0.40	0.02	0.65	<0.01
$\bar{F}_{11} + t_{Uwind}$	0.27	0.03	0.49	<0.01	0.30	0.07	0.66	<0.01
May–June $NO_{3+2} + t_{Uwind}$	0.58	<0.01	0.69	<0.01	0.57	<0.01	0.74	<0.01
May $NO_{3+2} + t_{Uwind}$	0.50	<0.01	0.62	<0.01	0.55	<0.01	0.71	<0.01

[a] $\bar{F}_{spring}$ is the average Apr–June discharge. $\bar{F}_{11}$ is the average discharge from previous year August to current year June. NH means hurricane years (2003, 2005) excluded.

between the hypoxic area, wind direction and discharge and N-loading of MAR from historical data.

2. Methods

[6] The annual July shelfwide survey, which has occurred every year since 1985, with the exception of 1989, measures the areal extent of hypoxia on the Louisiana shelf, between the Mississippi River bird foot delta and the Texas-Louisiana border [*Rabalais et al.*, 2001]. There was no survey in 1989. We divided our correlation analysis into two periods: the longer was from 1985–2010, the shorter was from 1993–2010. The shorter period begins with 1993, i.e., the year in which the relationship between hypoxic area and riverine N-loading was reported to have changed [*Turner et al.*, 2008; *Greene et al.*, 2009; *Liu et al.*, 2010; *Forrest et al.*, 2011]. Following the results of *Greene et al.* [2009] and *Forrest et al.* [2011], we have applied the post-1992 epoch correction to the hypoxic area for all correlation analyses by adding 6450 km^2 to the area values for the years before 1993 to the longer period. We test the relationships with and without those years when strong storms passed along the Louisiana shelf within 10 days prior to the annual cruises: 2003 (Tropical Storm Bill and Hurricane Claudette) and 2005 (Hurricane Dennis).

[7] The predictors in our single and multiple regression analyses are: the new variable t_{Uwind} (defined below), the 11-month averaged MR flow ($\bar{F}_{11}$) [*Wiseman et al.*, 1997], the averaged spring flow ($\bar{F}_{spring}$; April, May and June), the averaged May flow ($\bar{F}_{May}$) [*Greene et al.*, 2009], the May NO_{3+2} loading [*Turner et al.*, 2006] and the combined May–June NO_{3+2} loading [*Donner and Scavia*, 2007]. The regional wind data are from the North America Regional Reanalysis (NARR), which is a high resolution weather data set covering our study period at 3-hr intervals and 0.3° spatial resolution. We smoothed the east-west wind over our spatial domain (87°W to 94°W, 27°N to 31°N), using a 40-hr low-pass filter to remove the influence of the relatively high-frequency diurnal sea breeze signal [*Zhang et al.*, 2009, 2010]. The duration of wind (t_{Uwind}) is the number of days with west-to-east winds before the July shelfwide cruise during a defined time interval. A 32-d interval gave the highest correlations for the years 1985–2010 (excluding 2003 and 2005) when intervals from 1 to 50-d were tested (see Figure S1 in the auxiliary material).[1] The daily discharge of MR was measured by the U. S. Army Corps of Engineers at Tarbert Landing, MS; monthly nutrient loading was estimated by the USGS at St. Francisville, LA. All the data metrics are given in Table S1 in the auxiliary material.

[8] We calculate the significance level (p) of each regression result as well as the coefficient of determination (r^2). Because normality is difficult to test using small numbers of measurements, we also determine the statistical robustness of the value of r^2 using a bootstrap technique, randomly resampling the data with replacement and repeatedly estimating r^2 for each resampled series. The median (r^2_{med}) and 95% confidence interval of r^2 for 10,000 resampled ensemble are used to characterize the results. The level of robustness is therefore based on a combination of p-value, closeness of r^2_{med} to r^2, the width (a measure of the 95% confidence interval) and peakedness of the bootstrap histogram. Correlations with highest robustness have $r^2_{med} \simeq r^2$ with a distinct histogram peak near r^2_{med}. The r^2_{med} and 95% confidence interval of the bootstraps are in Table S2 in the auxiliary material.

3. Results

3.1. Hurricane Years Included in Regression Analysis

[9] The largest correlation between a single predictor and the hypoxic area for the 1985–2010 (hurricanes years included) period was with the May–June NO_{3+2} loading ($r^2 = 0.39$, $p < 0.01$, Table 1 and Table S2 in the auxiliary material). Correlation of area with May NO_{3+2} loading is also statistically significant ($r^2 = 0.33$, $p < 0.01$). However, $\bar{F}_{May}$ ($r^2 = 0.11$, $p = 0.38$), $\bar{F}_{spring}$ ($r^2 = 0.13$, $p = 0.33$), and $\bar{F}_{11}$ ($r^2 = 0.14$, $p = 0.25$) are not significantly correlated with the hypoxic area. The single variable correlation results are similar for the 1993–2010 (hurricane included) period. The t_{Uwind} variable is not significantly correlated to area for either time period when the hurricane years are included in the calculation (Figures 1a and 1c).

[1] Auxiliary materials are available in the HTML. doi:10.1029/2012GL051192.

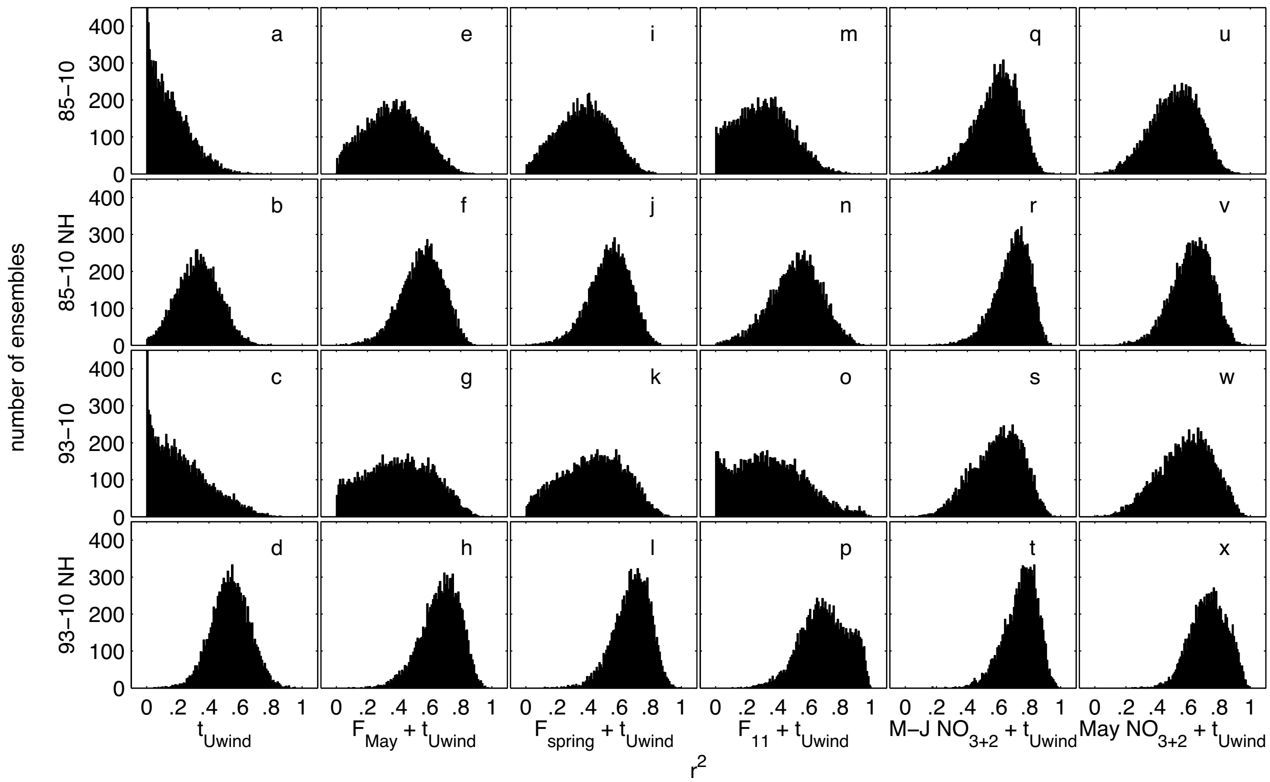

Figure 1. Histograms of r^2 from bootstrap analyses of 10,000 ensembles for (a–d) single and (e–x) multiple regressions with t_{Uwind}. From top to bottom: 1985–2010 (Figures 1a, 1e, 1i, 1m, 1q, and 1u); 1985–2010 excluding 2003 and 2005 (NH means no hurricanes, Figures 1b, 1f, 1j, 1n, 1r, and 1v); 1993–2010 (Figures 1c, 1g, 1k, 1o, 1s, and 1w); and 1993–2010 excluding 2003 and 2005 (Figures 1d, 1h, 1l, 1p, 1t, and 1x). From left to right: t_{Uwind} only (Figures 1a–1d); $\bar{F}_{May} + t_{Uwind}$ (Figures 1e–1h); $\bar{F}_{spring} + t_{Uwind}$ (Figures 1i–1l); $\bar{F}_{11} + t_{Uwind}$ (Figures 1m–1p); May–June $NO_{3+2} + t_{Uwind}$ (Figures 1q–1t); May $NO_{3+2} + t_{Uwind}$ (Figures 1u–1x).

3.2. Hurricane Years Excluded From Analysis

[10] The correlation with t_{Uwind} increases noticeably for the wind variable when excluding the hurricane years. For the period 1985–2010, t_{Uwind} is the largest single predictor r^2 for area ($r^2 = 0.32$, $r = -0.57$, $p < 0.01$, Figure 1b). The negative correlations indicate that a longer west wind duration results in a smaller hypoxic area. The correlations for discharge variables are not significant and nutrient correlations change little from the values found for the hurricane inclusive periods. For the 1993–2010 non-hurricane period, t_{Uwind} has the highest correlation ($r^2 = 0.52$, $p < 0.01$, Figure 1d). Correlations with May and May–June NO_{3+2} loading decrease slightly and have relatively large p-values. When compared to the longer time period, there is no significant correlation between the area and $\bar{F}_{May}$, $\bar{F}_{spring}$ and $\bar{F}_{11}$ ($r^2 < 0.1$, p-value > 0.22).

3.3. Multiple Variable Regression

[11] The statistical relationships further improve when using two predictors (Table 1 and Figures 1e–1x). For the 1985–2010 period (hurricanes included), the largest correlation is for t_{Uwind} and May–June NO_{3+2} ($r^2 = 0.58$, $p < 0.01$; Figure 1q). The multiple regression correlations involving discharge and t_{Uwind} increase with improved p-value relative to the single variable regressions for the same period. For the 1993–2010 hurricane inclusive period, the multiple regression results are similar to the 1985–2010 period.

[12] When hurricane years are excluded from the dataset, the multiple regressions involving wind improve and all correlations are significant (p-values < 0.01). For the 1985–2010 non-hurricane period, t_{Uwind} and May–June NO_{3+2} give the largest correlation ($r^2 = 0.69$, Table 2). Correlations for discharge variables increased to about $r^2 = 0.50$. For the 1993–2010 non-hurricane time period, the t_{Uwind} and May–June NO_{3+2} correlation increases to $r^2 = 0.74$; the t_{Uwind} and discharge correlations increase to $r^2 > 0.64$.

4. Discussion

[13] In this study, we examine the relationships between the hypoxic area, duration of westerly wind, and discharge and N-loading of MAR from 1985 to 2010. In addition to the high positive correlations between the hypoxic area, and river discharge and NO_{3+2} loading, noted in previous studies, our principal finding is that the duration of west wind is negatively and significantly correlated with the hypoxic area of the Louisiana shelf. The correlation between average east-west wind and hypoxic area was also found to be negative, i.e., wind to the east can reduce hypoxic area, by *Forrest et al.* [2011].

[14] Observations by *Wiseman et al.* [1997] show that a west wind during summer could drive the river plume eastward and offshore, strengthening the pycnocline and inhibiting the ventilation of the bottom water. Although a west wind can, at times, facilitate hypoxia development [*Forrest*

et al., 2011], a persistent west wind reduces the areal extent by ultimately moving the river plume offshore, away from the continental shelf and into deep water [*Lentz*, 2004; *Morey et al.*, 2003a, 2003b; *Schiller et al.*, 2011]. This movement removes the two factors necessary for coastal ocean hypoxia formation: nutrient supply and density stratification. Additionally, *Schaeffer et al.* [2011] report that wind driving also contributes to temporal and spatial patterns of light attenuation along the Louisiana Shelf that may influence subpycnocline hypoxia by influencing subpycnocline primary production.

[15] Wind has been known to be an important controlling factor for dissolved oxygen concentration for open upwelling systems [*Chapman and Shannon*, 1987; *Grantham et al.*, 2004; *Sobarzo et al.*, 2007]. The timing for the upwelling wind start and the intensity of the upwelling wind stress control the strength of the on-shore advection of oxygen-poor and nutrient-rich deep water, and thereby the bottom oxygen concentration on the continental shelf [*Barth et al.*, 2007; *Chan et al.*, 2008]. Duration of directional wind as a strong predictor for hypoxic volume has also been examined in closed estuaries systems [*Scully*, 2010a; *Wilson et al.*, 2008]. The persistence of directional wind controls the ventilation of bottom waters and thereby the bottom oxygen concentration through the along-channel straining mechanism [*Scully et al.*, 2005] and lateral advection [*Scully*, 2010b]. The details of how wind controls the spatial and temporal distribution of freshwater and bottom oxygen concentration on the Louisiana shelf has been addressed by *Feng* [2012]. We provide an example in the auxiliary material, in the context of a couple physical-biological circulation numerical model [*Fennel et al.*, 2011; *Hetland and DiMarco*, 2012], of the MAR plume forced by a persistent upwelling-favorable wind during 2009 summer.

[16] For both the 1985–2010 and 1993–2010 hurricane exclusive periods, there are no strongly significant statistical relationships for flow as a single predictor. However, using flow as a predictor with the wind duration yields statistically significant and robust correlations. The improvement is greater for the 1993–2010 period. The difference between one and two predictor results reflects that the model fit to hypoxic area is better conceptualized as a plane in a three-dimensional space formed with the two predictors as axes, than as a simple linear fit in a two-dimensional space (Figure S2 in the auxiliary material). The finding that the optimal window for calculating the amount of west wind is about one month may reflect the low-frequency (i.e., periods of several days) response time of subpycnocline oxygen to changes in vertical mixing as stratification on the shelf changes.

[17] The post-1993 period yields a better correlation when using t_{Uwind} as the predictor than did the post-1985 period for the hurricane inclusive and exclusive cases. There are multiple reasons for the enhanced r^2. We find strong variability in the observed east-west wind field during the hurricane years (see Figure S3 in the auxiliary material). The wind magnitude in 2003 and 2005 oscillated rapidly from -5 to 5 m s^{-1} during the 1-month window. This strong variability can lead to increased vertical mixing and mix oxygen-rich surface water with low oxygen subpycnocline water. Because of the strong vertical mixing, the horizontal hypoxic area distributions in the hurricane years differ from those in the non-hurricanes years by having a tendency to be a series of disconnected patches of low oxygen (see for example the hypoxic area images at http://www.gulfhypoxia.net/).

[18] The post-1993 shelfwide survey cruises had similar start/end dates (see Table S1 in the auxiliary material). The hypoxia cruises usually began between 15 July and 25 July, i.e., the time generally accepted as the peak in hypoxic area. However, two cruises prior to 1992 occurred in early July— 1986 (7 July) and 1987 (1 July)— and one occurred in August— 1988 (12 August). Our selected time window length is about 1-month before the cruise. For the cruises that started 15 July to 25 July, the 1-month window length covered a period in which summer wind variations are typically small. Winds in early June and August tend to have larger variability than July and may alter the statistical relationship. *Forrest et al.* [2011] shows that the year 1988, i.e., the mid-August cruise, should be considered a statistical outlier because its inclusion significantly alters the statistics of the dataset. Lastly, most pre-1992 hurricanes did not pass into Texas waters and, therefore, may have missed some of the western extent of the hypoxic region.

[19] When excluding hurricane years for 1993–2010, t_{Uwind} explains more than half ($r^2 = 0.52$) of the area variability ($p < 0.01$, $r^2_{med} = 0.54$, [0.29 0.77]). The modification of the hypoxic area by the west wind is a slow and cumulative effect. In this way, the surface river plume is forced offshore and to the east; the hypoxic area changes gradually over weeks. Strong impulsive wind events impose strong vertical mixing, leading to rapid changes in the hypoxic area.

[20] In this study, we find that including the duration of the west wind can explain a significantly larger percentage of the interannual variance of hypoxic area than any single variate predictor and significantly improve multiple variable regressions that use river nutrient load and discharge. This means incorporating the role of the wind can lead to better understanding of long-term observed system responses when nutrient reductions are in place. We envision the role of wind can be better considered in hypoxic area management and prediction in the future.

[21] The precipitation over the central U.S. is expected to increase under some global warming scenarios, resulting in an increase in the MR flow [*Justic et al.*, 2003a, 2003b; *Donner and Scavia*, 2007]. Increased flow brings both increased buoyancy and possibly increased nutrients to the shelf, thus, increasing the tendency toward a potentially larger hypoxic area. Our study reminds us that in addition to changing precipitation, global climate change may alter the extent of hypoxia by regional winds [*Scully*, 2010a]. The shift of the transition time for the seasonal wind can influence the distribution of the river plume in the mid-summer, thereby influencing the hypoxic area. Although *Bianchi et al.* [2010] speculate on how changing regional wind fields may impact hypoxia on the Louisiana Shelf under some climate change scenarios, the details of how the winds may change as a result of the evolving global system are not presently understood and are worth further investigation.

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