The importance of decadal-scale climate variability to wind-driven modulation of hypoxia in Chesapeake Bay.

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ABSTRACT--Millions of dollars are spent annually to reduce nutrient loading to Chesapeake Bay, with a fundamental goal of reducing the extent and severity of low dissolved oxygen (hypoxia) during the summertime months[1]. Yet despite recent reductions in nutrient loading, large volumes of the Bay continue to be impacted by hypoxia and anoxia during the summer months[2-3]. One obstacle to assessing efforts to improve water quality in the Bay and other estuarine systems is a complete understanding of the physical processes that modulate dissolved oxygen and the long-term variability of these processes. Here I analyze a 58-year data set of estimated hypoxic volume in the Bay[2] and demonstrate the importance that wind direction plays in controlling the extent and severity of summertime hypoxia. This analysis indicates that wind direction explains a greater percentage of the observed inter-annual variation in hypoxic volume than estimates of nutrient loading. The implication is that physical processes play a dominant role in modulating hypoxia and that much of the increased hypoxia observed since the early1980s can be attributed to changes in wind forcing that are the result of decadal-scale climate variability. These findings emphasize the importance of understanding the physical processes that modulate dissolved oxygen in coastal and estuarine systems and highlight the potential impact that climate change may have on water quality in Chesapeake Bay and other estuarine systems.

It is generally believed that anthropogenic nutrient loading has increased the frequency and severity of hypoxia in coastal waters[4-5]. Yet in many systems, estimated nutrient loading is a poor predictor of inter-annual variations in hypoxia[6,2]. In Chesapeake Bay, estimates of nitrogen loading explain a relatively small portion of the variance in the observed hypoxic volume[2]. One potential explanation for the lack of correlation between hypoxia and nitrogen loading is the importance of variations in the physical processes that modulate dissolved oxygen. It is generally assumed that hypoxic conditions develop when oxygen utilization rates exceed the replenishment rates across the pycnocline by turbulent mixing[7-8]. However, it has been suggested that the rotational response of the pycnocline to wind-driven forcing may provide an important mechanism for the lateral exchange of dissolved oxygen between the surface and sub-pycnocline waters[9-10]. It is hypothesized here that wind-driven lateral exchange is the dominant mechanism for providing oxygen to sub-pycnocline waters, and that the effectiveness of this mechanism will be strongly dependent on the direction of the wind forcing.

To investigate this hypothesis, I revisit the time-series of hypoxic volume in Chesapeake Bay initially presented by Hagy et al. (2004), to evaluate the role that wind direction plays in contributing to the inter-annual variability. This is a unique data set, with a nearly continuous 58-year time-series of observed summertime hypoxia. The surveys that this data set is based on have continued since first publication, providing an extension of the time series through the summer of 2007. Surveys were conducted each summer, generally in July, and the data were spatially interpolated to give estimates of hypoxic volume based on three different oxygen concentrations: > 2 mg/L, > 1 mg/L and > 0.2 mg/L. Here I examine the correlation between the observed hypoxic volumes and the duration of summertime winds from 8 equally spaced compass directions. Hourly wind speed and direction were obtained from the Naval Air Station (NAS) in Patuxent, Maryland. The NAS wind data are used because they provide the most centrally located wind observations over the main stem of the Bay and are continuous over the entire 58-year period. For each summer, the duration of time that wind blew with a speed greater than 2 m/s from eight compass directions was calculated over the period from May 1 to July 31. Hypoxic volumes also are compared with the mean summer wind speed, river discharge and total nitrogen loading. River discharge was calculated as the average daily value between January 1 and May 31 for each year recorded at the United States Geological Survey (USGS) gauging station on the Susquehanna River at Conowingo, Maryland. Prior to 1981, nitrogen loading was not measured at Conowingo so, the January through May average total nitrogen loading was estimated following Hagy et al. (2004). Measured values of total nitrogen loading at the USGS gauging station at Conowingo were used for the period of 1981 through 2007.

The correlations between hypoxic volume based on the three definitions and the wind duration from a given direction are reported in table 1. For all three definitions, there is a significant ($p < 0.05$) positive correlation between the observed hypoxic volume and the summertime duration of westerly winds and a significant negatively correlation with the duration of southeasterly winds. The estimated hypoxic volumes are not significantly correlated with the average summer wind speed. The dominant wind direction over Chesapeake Bay during the summer months is generally from the south. These results indicate that shifts towards a more easterly wind direction will help moderate hypoxia while shifts towards a more westerly direction will favor more severe hypoxia. Estimated nitrogen loading is significantly correlated with observed hypoxia, but the duration of westerly winds explains more of the variance for all but one definition of hypoxia. Average spring river runoff is only significantly correlated with hypoxic volume based on the > 0.2 mg/L definition.

Scientists and resource managers have noted that the extent of summertime hypoxia in the Bay remains above historical levels despite the fact that estimated nutrient loading has decreased over recent years[2]. It has been suggested that as a result of the overall degradation of the ecosystem the Bay has become less able to assimilate nutrient inputs and as a result is more susceptible to hypoxia than in the past[3]. While profound ecological changes have certainly taken place in Chesapeake Bay, such conclusions often neglect the inter-annual variability of the physical forcing. To examine the long-term trends in the data, a linear regression analysis is performed on the time-series of the observed hypoxic volumes (table 2). To normalize the results, each variable considered in the regression is first divided by its standard deviation. Consistent with previous findings[2], accounting only for the estimated nitrogen loading explains a relatively small fraction of the observed variance (fig. 1a). Moreover, the residuals suggest that despite recent reductions in estimated nitrogen loading, the hypoxic volume in the Bay has continued to increase over the past several decade (fig. 1b). In contrast, a multiple regression model that includes estimated nitrogen loading and both the duration of westerly and southeasterly wind explains roughly 60 percent of the variance (fig. 1c). More significantly, the linear trend in the residuals is no longer significant at the 95% confidence interval when both nitrogen loading and wind direction are accounted for (fig. 1d). This is true regardless of which definition of hypoxia is considered, and indicates that the increases in hypoxia over the past several decades are consistent with estimated nitrogen loading when the wind direction is properly accounted for (table 2).

This result suggests that there has been a long-term shift in the summer wind climate over Chesapeake Bay. The dominant atmospheric feature over the North Atlantic during the summer months is the Bermuda High subtropical anticyclone. Generally the presence of the Bermuda High favors southerly flow over the Chesapeake Bay watershed. However, the intensity and western extent of the Bermuda High determines whether more southeasterly or more westerly winds will prevail. The Bermuda High Index (BHI), which is defined as the normalized pressure difference between Bermuda and New Orleans, LA, has been used to estimate the western edge of the Atlantic subtropical high[11]. Here a modified form of the BHI is used, instead based on the normalized pressure difference between Georges Bank and New Orleans, using the NCEP/NCAR surface pressure reanalysis data[12]. From roughly 1955 through 1980, the modified BHI displays positive values (fig. 2a). A shift occurred around 1980 and the modified BHI has been largely negative over past 25 years. This coincides with when increased hypoxia was observed in Chesapeake Bay. While this index is only a proxy for wind forcing, it is significantly correlated with the observed hypoxic volumes (table 1). The impact of the position of the Bermuda High on the summertime wind climate in Chesapeake Bay can seen more clearly by examining the wind data collected at 3 locations spanning the Bay watershed. Figures 2b-d show the mean difference in wind duration for positive and negative values of the modified BHI at Norfolk International Airport, NAS, and Baltimore-Washington International airport. In the histograms in figure 2, positive values indicate a greater duration of winds from a specific direction when the modified BHI >0 and negative values indicate a greater duration of winds from that direction when the modified BHI < 0. Throughout the watershed, there is a clear shift from more southerly winds for positive values of the modified BHI to more westerly winds for negative values.

The NCEP/NCAR reanalysis data cover the entire North Atlantic with a 2.5-degree resolution from 1948 to the present[12]. For each year, the NCEP/NCAR reanalysis data were averaged over the months of May, June and July, consistent with the treatment of the wind data from NAS. Figure 3 shows the difference in surface pressure for conditions with modified BHI > 0 (indicating an intensified Bermuda High) and modified BHI < 0 (indicating a weakened Bermuda High). In addition, the average difference between the North-South and East-West pressure gradients are shown. During summers when the Bermuda High is intensified and shifts further west, the East-West pressure gradient over Chesapeake Bay is intensified and the North-South pressure gradient is weakened. The stronger Bermuda High condition, which was more prevalent during the 1960s and 1970s, generally favors a more southerly wind climate. In contrast, the weakened Bermuda High that has persistent over much of the past 3 decades has had the opposite effect favoring more westerly winds.

It is well established that the North Atlantic surface pressure field is linked to the North Atlantic Oscillation (NAO)[13]. However, the NAO is a more robust feature during the winter months, and the summertime NAO index is not significantly correlated with the wind observations presented here. However, there is a statistically significant correlation ($p < 0.05$) between both the duration of summertime westerly winds and southeasterly winds with the mean NAO index from the previous winter. While the pressure signal associated with the NAO generally does not hold through the summer months, it has been hypothesized that the wintertime NAO impacts summertime atmospheric circulation in the North Atlantic through sea-ice, sea surface temperature and snow cover anomalies[14]. The wintertime NAO index, which has largely been in a positive phase since 1980[15], may be contributing to the changes in the wind climate observed over this time period. In fact, the observed hypoxic volumes are all significantly correlated with the NAO index from the previous winter (table 1). All of this suggests that the decadal-scale variability in the climate forcing over the North Atlantic is playing a significant role in the extent and severity of hypoxia in the Chesapeake Bay.

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Figure Captions

Figure 1. a) Comparison of time-series of observed hypoxic volume < 1mg/L (circles) with linear regression model based on the average spring nitrogen loading from the Susquehanna River (squares); b) Residual error and linear fit from nitrogen loading regression. Dashed lines indicate 95% confidence interval on fit to residual error; c) Comparison of time-series of observed hypoxic volume < 1mg/L (circles) with multiple linear regression model including nitrogen loading and the summer duration of westerly and southeasterly winds (squares); d) Residual error and linear fit from multiple regression model including nitrogen loading and summer wind direction. Dashed lines indicate 95% confidence interval on fit to residual error. Model coefficients are given in table 2.

Figure 2. a) Time series of the modified Bermuda High Index defined as the normalized pressure difference between George's Bank (-67.5°W, 40°N) and New Orleans (-90°W, 30°N), using NCEP/NCAR surface pressure data. Data were averaged over the period from May 1—July 31 each year. Solid line denotes 5-year running mean. Histrograms presenting the difference in wind duration between average positive and negative modified Bermuda High Index (BHI) conditions as a function of wind direction from: b) Norfolk International Airport; c) Paxtuxent Naval Air Station; d) Baltimore-Washington International Airport. Positive values indicate a greater duration of winds from a given direction for modified BHI > 0 and negative values indicate a greater duration of wind from a given direction for modified BHI < 0.

Figure 3. a) Average difference in summertime surface pressure between years with modified BHI > 0 and BHI < 0. Positive values indicate greater pressure for BHI > 0 and negative values indicate higher pressure for BHI > 0. Contour interval is 10 Pascals. b) Average difference in the North-South pressure gradient between years with modified BHI > 0 and BHI < 0. Positive values indicate greater pressure gradient for BHI > 0 and negative values indicate greater pressure gradient for BHI < 0. Contour interval is 1×10^{-5} Pa/m. d) Average difference in the East-West pressure gradient between years with modified BHI > 0 and BHI < 0. Positive values indicate greater pressure gradient for BHI > 0 and negative values indicate greater pressure gradient for BHI < 0. Contour interval is 1×10^{-5} Pa/m.

Table 1. Correlations with Hypoxic Volume

Hypoxic Volume	Duration of Summer Wind								Nitrogen Loading	River Discharge	Wind Speed	Bermuda High Index	Wind NAO Index
	N	NE	E	SE	S	SW	W	NW					
< 2 mg/L	0.00	0.08	0.18	**-0.49***	**-0.37***	0.04	**0.69***	**0.32***	**0.36***	0.16	-0.03	**-0.42***	**0.55***
< 1mg/L	-0.02	0.04	0.15	**-0.48***	**-0.34***	0.03	**0.71***	**0.36***	**0.44***	0.24	-0.04	**-0.45***	**0.53***
< 0.2 mg/L	-0.11	-0.08	0.05	**-0.42***	-0.17	-0.10	**0.55***	0.30	**0.62***	**0.33***	-0.11	**-0.47***	**0.58***

*** indicates significance at 95% confidence interval.**

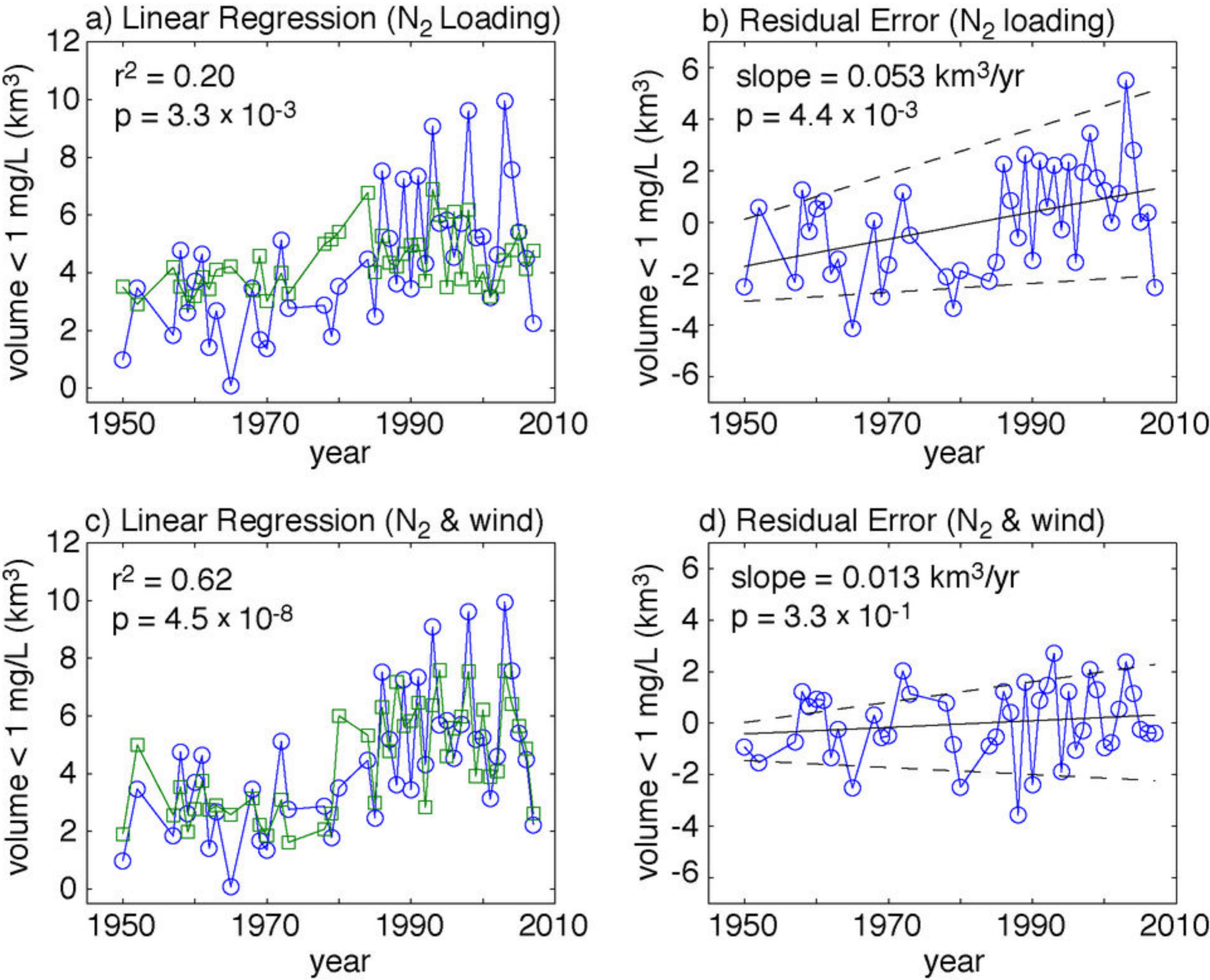
Correlation coefficient (r) between observed hypoxic volume and duration of summer winds, estimated Jan-May nitrogen loading, Jan-May Susquehanna River Discharge, mean summer wind speed, modified Bermuda High Index and Winter NAO Index. Wind duration is calculated as the total time that wind with a velocity greater than 2 m/s was observed from 8 equally space compass directions over the period May 1 through July 31.

Table 2. Linear Regression Analysis

Hypoxic Volume	$y = \beta_o+\beta_1$(N-loading)						$y = \beta_o+\beta_1$(N-loading)+ β_2(W-Winds)+β_3(SE-Winds)							
	model				residual		model						residual	
	β_o	β_1	r^2	p-value	slope (km^3/yr)	p-value	β_o	β_1	β_2	β_3	r^2	p-value	slope (km^3/yr)	p-value
< 2mg/L	3.22	1.03	0.13	2.1×10^{-2}	0.072	2.6×10^{-3}	0.01	0.74	1.71	-0.30	0.54	1.2×10^{-6}	0.022	2.3×10^{-1}
< 1mg/L	1.12	1.03	0.20	3.3×10^{-3}	0.053	4.4×10^{-3}	-1.87	0.79	1.43	-0.15	0.62	4.5×10^{-8}	0.013	3.3×10^{-1}
< 0.2mg/L	-1.30	1.03	0.39	1.0×10^{-5}	0.029	1.1×10^{-2}	-2.37	0.91	0.66	-0.17	0.60	8.6×10^{-8}	0.008	3.8×10^{-1}

Comparison of linear regression models. Model coefficients, r^2-values, and p-value for each model are reported. Also given is the slope of the linear fit to the residual error and p-value of residual fit.

Figure 1

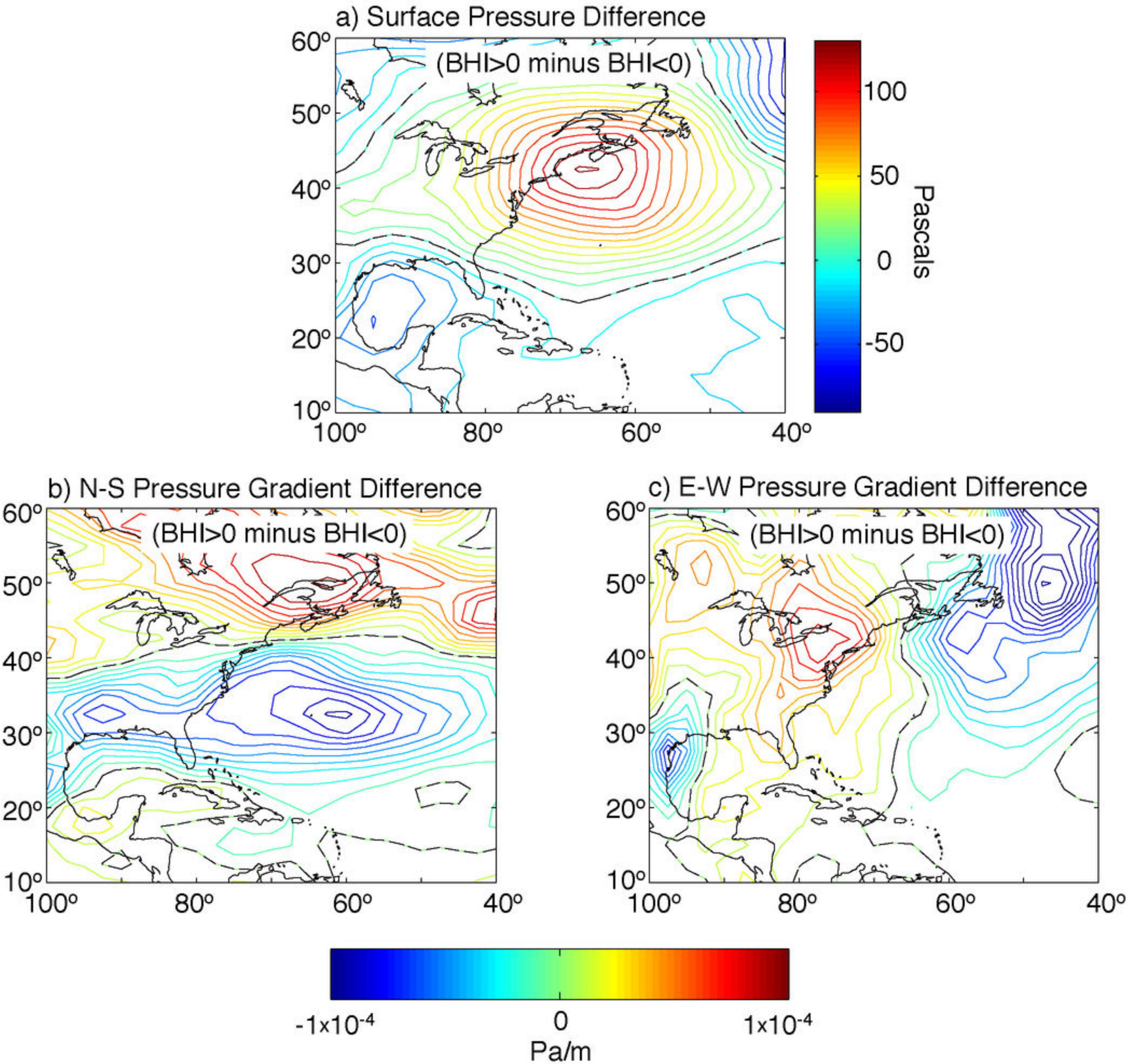


a) Linear Regression (N2 Loading)
r2 = 0.20
p = 3.3 x 10-3
b) Residual Error (N2 loading)
slope = 0.053 km3/yr
p = 4.4 x 10-3
c) Linear Regression (N2 & wind)
r2 = 0.62
p = 4.5 x 10-8
d) Residual Error (N2 & wind)
slope = 0.013 km3/yr
p = 3.3 x 10-1
volume < 1 mg/L (km3)
year

Figure 2


a) Modified Bermuda High Index
2
0
-2
mBHI
1950
1960
1970
1980
1990
2000
year
b) Norfolk
c) Patuxent
d) Baltimore
50
0
-50
hours
N
E
S
W
N
Direction

Figure 3



a) Surface Pressure Difference
(BHI>0 minus BHI<0)
60º
50º
40º
30º
20º
10º
100º
80º
60º
40º
100
50
0
-50
Pascals
b) N-S Pressure Gradient Difference
(BHI>0 minus BHI<0)
c) E-W Pressure Gradient Difference
(BHI>0 minus BHI<0)
-1x10-4
0
1x10-4
Pa/m