NOTES AND CORRESPONDENCE

The Importance of Climate Variability to Wind-Driven Modulation of Hypoxia in Chesapeake Bay

MALCOLM E. SCULLY

Center for Coastal Physical Oceanography, Old Dominion University, Norfolk, Virginia

(Manuscript received 24 July 2009, in final form 1 February 2010)

ABSTRACT

Extensive hypoxia remains a problem in Chesapeake Bay, despite some reductions in estimated nutrient inputs. An analysis of a 58-yr time series of summer hypoxia reveals that a significant fraction of the interannual variability observed in Chesapeake Bay is correlated to changes in summertime wind direction that are the result of large-scale climate variability. Beginning around 1980, the surface pressure associated with the summer Bermuda high has weakened, favoring winds from a more westerly direction, the direction most correlated with observed hypoxia. Regression analysis suggests that the long-term increase in hypoxic volume observed in this dataset is only accounted for when both changes in wind direction and nitrogen loading are considered.

1. Introduction

It is generally believed that anthropogenic nutrient loading has increased the frequency and severity of hypoxia in coastal waters (Rabalais and Turner 2001; Diaz and Rosenberg 2008). However, in some systems, estimated nutrient loading is a poor predictor of interannual variations in hypoxia (Wilson et al. 2008). In Chesapeake Bay, estimates of nitrogen loading explain a relatively small portion of the variance in the observed hypoxic volume (Hagy et al. 2004; Kemp et al. 2005). 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 (Seliger et al. 1985).

It is generally assumed that hypoxic conditions develop when oxygen utilization rates below the pycnocline exceed the supply of oxygen across the pycnocline by vertical mixing (Taft et al. 1980; Officer et al. 1984). 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 subpycnocline waters (Malone et al. 1986; Sanford et al. 1990). The importance of lateral exchange is supported by a recent numerical modeling study that demonstrates that the extent of hypoxia in Chesapeake Bay is strongly influenced by wind direction (Scully 2010). The numerical simulations demonstrate that the interactions between vertical mixing over the shoal areas and lateral flows driven by winds from the south are the most effective at supplying oxygen to hypoxic regions, whereas winds from the west are the least effective. The purpose of this study is to test the hypothesis that summer wind direction explains a significant fraction of the observed interannual variability in summer hypoxia in Chesapeake Bay.

2. Data and methods

The time series of hypoxic volume used in this study was initially presented by Hagy et al. (2004). Estimates of hypoxic volume are based on surveys that were conducted each summer, generally in early July, and the data are spatially interpolated to give estimates of hypoxic volume based on three different oxygen concentrations: <2, <1, and <0.2 mg L^{-1}. The surveys that this dataset is based on have continued since first publication, providing an extension of the time series through the summer of 2007. Estimates of hypoxic volumes are compared with wind data from the Naval Air Station (NAS) in Patuxent, Maryland. The NAS wind data are

---

Corresponding author address: Malcolm E. Scully, Center for Coastal Physical Oceanography, Old Dominion University, 4111 Monarch Way, 3rd Floor, Norfolk, VA 23507.
E-mail: mscully@odu.edu

DOI: 10.1175/2010JPO4321.1

TABLE 1. Correlations with hypoxic volume: Correlation coefficient *r* between observed hypoxic volume and duration of summer winds, estimated January–May nitrogen loading, January–May Susquehanna River discharge, mean summer wind speed, modified BHI, and winter NAO index. Wind duration is calculated as the total time that wind with a velocity greater than 2 m s^{-1} was observed from eight equally spaced compass directions over the period 1 May–31 Jul.

Hypoxic vol	Duration of summer wind								Nitrogen loading	River discharge	Wind speed	BHI	Wind NAO index
	North	Northeast	East	Southeast	South	Southwest	West	Northwest					
<2 mg L^{-1}	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*
<1 mg L^{-1}	−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^{-1}	−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 Bonferroni adjusted 95% confidence interval (i.e., $\alpha = 0.05/n = 0.0038$).

used because they provide the most centrally located wind observations over the main stem of the bay and are continuous over the entire 58-yr period. Similar data are available from both the Baltimore–Washington International Airport (BWI) and the Norfolk International Airport (ORF). Missing data from NAS are estimated from ORF using least squares regression. The wind direction is calculated from the hourly north and east wind components after the data are filtered with a 24-h low-pass filter. For each summer, the duration of time that wind blew with a speed greater than 2 m s^{-1} from eight compass directions is calculated for the period from 1 May to 31 July. This period is selected to be most representative of the forcing contributing to the hypoxia observed in early July (when surveys were typically taken).

Hypoxic volumes also are compared with the mean summer wind speed, Susquehanna River discharge, and estimated nitrogen loading. River discharge is calculated as the average daily value between 1 January and 31 May for each year recorded at the U.S. Geological Survey (USGS) gauging station on the Susquehanna River at Conowingo, Maryland. Prior to 1981, the January–May average total nitrogen loading at Conowingo 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 1981–2007.

3. Wind direction and observed summer hypoxic volume

All three levels of hypoxia (<2, <1, and <0.2 mg L^{-1}) exhibit a significant (at the Bonferroni adjusted 95% confidence interval; i.e., $p = 0.05/n = 0.0038$) positive correlation to the summertime duration of westerly winds.

TABLE 2. Linear regression analysis: Comparison of linear regression models. Model coefficients (β_0, β_1, β_2), r^2 values, and *p* value for each model are reported. Also given is the slope of the linear fit to the residual model error and *p* value of the residual fit. To normalize the coefficients in the regression model, the nitrogen loading (NL) and duration of west winds (W) were divided by their standard deviation.

	Nitrogen loading only $y = \beta_0 + \beta_1\mathrm{NL}$					
	Model				Residual	
Hypoxic vol	β_0 (km^3)	β_1 (km^3)	r^2	*p* value	Slope (km^3 yr^{-1})	*p* value
<2 mg L^{-1}	3.22	1.03	0.13	0.021	0.072	<0.01
<1 mg L^{-1}	1.12	1.03	0.20	<0.01	0.053	<0.01
<0.2 mg L^{-1}	−1.30	1.03	0.39	<0.01	0.029	0.011

	Duration of west winds only $y = \beta_0 + \beta_1\mathrm{W}$					
	Model				Residual	
Hypoxic vol	β_0 (km^3)	β_1 (km^3)	r^2	*p* value	Slope (km^3 yr^{-1})	*p* value
<2 mg L^{-1}	0.68	2.00	0.47	<0.01	0.041	0.035
<1 mg L^{-1}	−0.40	1.64	0.50	<0.01	0.031	0.039
<0.2 mg L^{-1}	−0.68	0.90	0.30	<0.01	0.021	0.021

	Nitrogen loading and duration of west winds $y = \beta_0 + \beta_1\mathrm{NL} + \beta_2\mathrm{W}$						
	Model					Residual	
Hypoxic vol	β_0 (km^3)	β_1 (km^3)	β_2 (km^3)	r^2	*p* value	Slope (km^3 yr^{-1})	*p* value
<2 mg L^{-1}	−1.35	0.75	1.89	0.54	<0.01	0.025	0.16
<1 mg L^{-1}	−2.57	0.80	1.52	0.62	<0.01	0.015	0.27
<0.2 mg L^{-1}	−3.14	0.91	0.76	0.60	<0.01	0.011	0.28

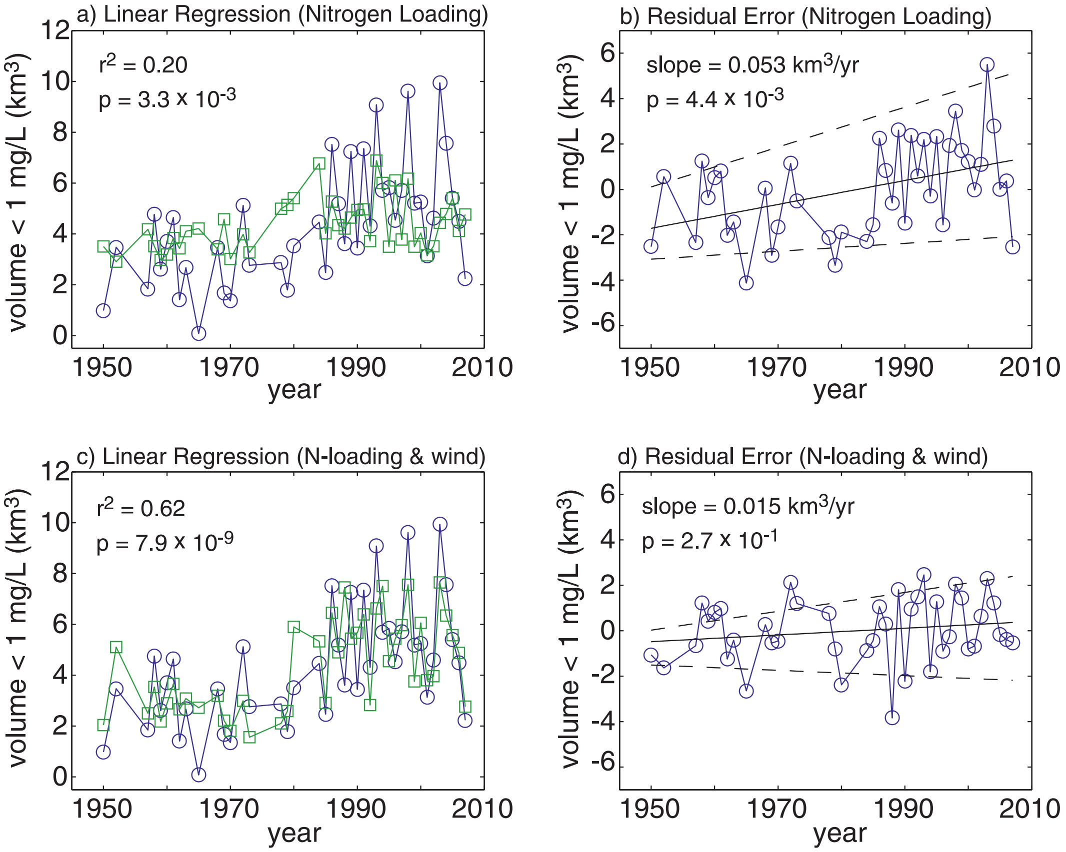

FIG. 1. (a) Comparison of time series of observed hypoxic volume <1 mg L^{-1} (circles) with linear regression model based on the average spring nitrogen loading from the Susquehanna River (squares); (b) residual error and linear fit from nitrogen loading regression; (c) comparison of time series of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

Two of the three levels of hypoxia exhibit a significant negative correlation with the duration of southeasterly winds (Table 1). 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 generally varies from southeast to southwest. These results indicate that shifts toward a more southeasterly wind direction will help moderate hypoxia, whereas shifts toward a more westerly direction will favor more severe hypoxia. The correlation between hypoxia and the duration of westerly winds is greater than the correlation between hypoxia and estimated nitrogen loading for two of the three levels of hypoxia considered (<2 and <1 mg L^{-1}). The difference between these correlation values is statistically significant at the 95% confidence level using Fisher's Z transform (Fisher 1921). The difference between the correlation coefficients for hypoxic volume and nitrogen loading and for hypoxic volume and duration of westerly winds is not significant for the third level considered (<0.2 mg L^{-1}). Thus, for two of the three levels of hypoxia considered here, the duration of westerly winds explains more of the variance in the observed hypoxic volume than the nitrogen loading.

A linear regression analysis is performed on the time series of the observed hypoxic volumes to examine the long-term trends in the data (Table 2). To normalize the results, each variable considered in the regression is first divided by its standard deviation. Consistent with previous findings (Hagy et al. 2004), estimated nitrogen loading explains a relatively small fraction of the observed variance in hypoxic volume (Fig. 1a). Moreover, when only nitrogen loading is considered, there is a statistically significant ($p < 0.05$) linear trend in the residuals (Fig. 1b). A multiple regression that includes estimated nitrogen loading and the summertime duration

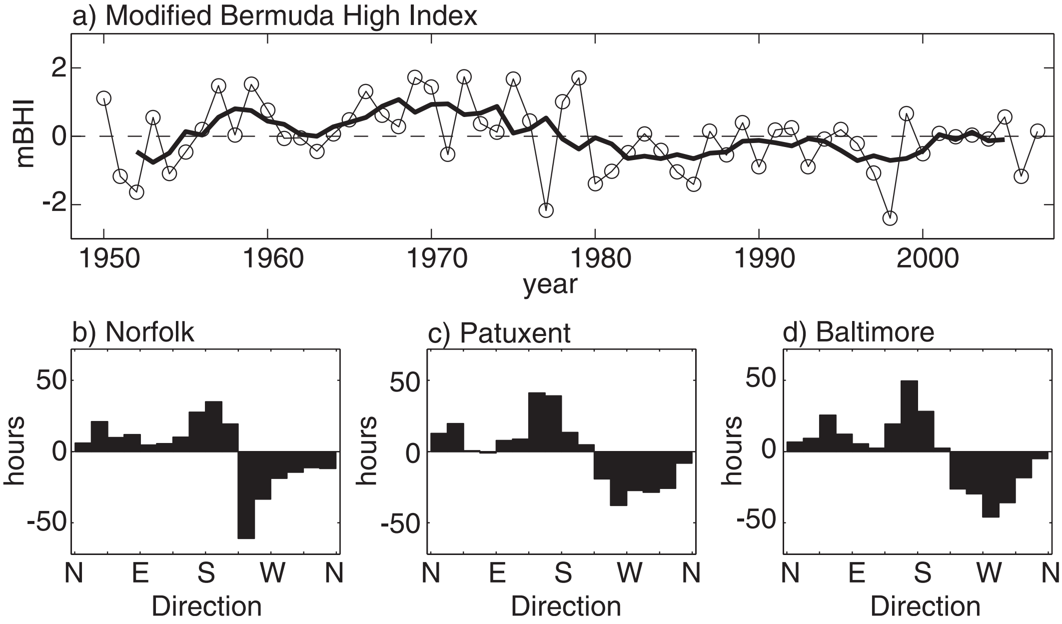

FIG. 2. (a) Time series of the modified BHI defined as the normalized pressure difference between George's Bank (40°N, 67.5°W) and New Orleans (30°N, 90°W), using NCEP–NCAR surface pressure data. Data were averaged over the period from 1 May to 31 Jul each year. Solid line denotes 5-yr running mean. Histograms presenting the difference in wind duration between average positive and negative modified BHI conditions as a function of wind direction from (b) ORF, (c) NAS, and (d) BWI. 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.

of westerly winds explains roughly 60% of the variance (Fig. 1c). More significantly, when both nitrogen loading and wind direction are accounted for, the linear trend in the residuals is no longer significant at the 95% confidence interval (Fig. 1d). This is true regardless of which definition of hypoxia is considered. If the estimated nitrogen loading is excluded from the regression and only the duration of westerly winds is considered, a significant trend in the residuals is still observed (Table 2). This suggests that the long-term variability of both nitrogen loading and wind direction play an important role in modulating hypoxia in the bay, and both must be considered when examining temporal trends in hypoxia.

4. Decadal-scale climate variability

These results imply that there have been decadal-scale variations in the summer wind climate over Chesapeake Bay. The mean wind direction over Chesapeake Bay during the summer months is generally from the south, driven by anticyclonic flow around the Bermuda high. The Bermuda high index (BHI), which is defined as the normalized pressure difference between Bermuda and New Orleans, Louisiana, has been used to estimate the western edge of the Atlantic subtropical high (Katz et al. 2003). Here, a modified form of the BHI is used, which is instead based on the normalized pressure difference between Georges Bank and New Orleans, using the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) surface pressure reanalysis data (Kalnay et al. 1996). 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 the past 25 yr. Although 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 is demonstrated by examining the wind data collected at three locations spanning the bay watershed. Figures 2b–d show the mean difference in wind duration from a given direction for positive and negative values of the modified BHI. In the histograms in Fig. 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 south–southeasterly winds for positive values of the modified BHI to more westerly winds for negative values.

The position of the Bermuda high impacts the wind climate over Chesapeake Bay by modifying the mean surface pressure gradients. Figure 3 shows the difference in surface pressure for conditions with modified

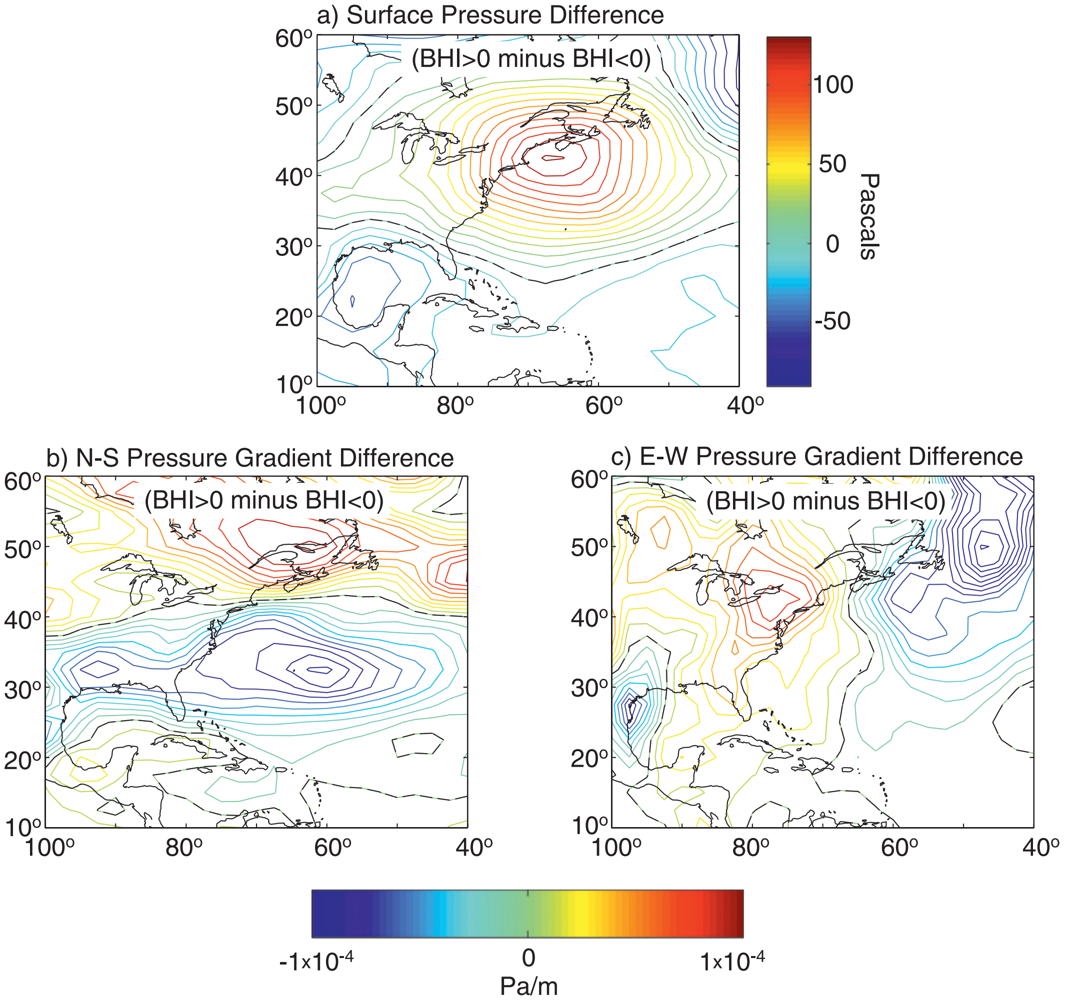

FIG. 3. Average differences (a) in summertime surface pressure, (b) in the north–south pressure gradient, and (c) in the east–west pressure gradient between years with modified BHI > 0 and BHI < 0. Positive values indicate greater pressure or pressure gradient for BHI > 0, and negative values indicate greater pressure or pressure gradient for BHI < 0. Contour intervals are (a) 10 Pa and (b),(c) 1×10^{-5} Pa m^{-1}.

BHI > 0 (indicating an intensified Bermuda high) and modified BHI < 0 (indicating a weakened Bermuda high). The average differences between the north–south and east–west pressure gradients also are shown. During summers when the Bermuda high is intensified and shifts farther 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 three decades has had the opposite effect, favoring more westerly winds. It should be noted that the mean pressure field does not necessarily reflect the atmospheric conditions that drive event-scale winds. However, it has been demonstrated that the oxygen dynamics in Chesapeake Bay are not in steady state at the time scales associated with individual wind events but are strongly influenced by the mean wind direction over longer time scales (Scully 2010). Thus, the changes in the pressure field shown in Fig. 3 are expected to impact the statistical likelihood of winds from a given direction that ultimately determines the mean wind direction over longer time scales.

It is well established that the North Atlantic surface pressure field is linked to the North Atlantic Oscillation (NAO; Wallace and Gutzler 1981). 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 between both the duration of summertime westerly winds and southeasterly winds with the mean NAO index from the previous winter. Although 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 (Ogi et al. 2003). The wintertime NAO index, which has largely been in a positive phase since 1980 (Hurrell 1995), 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.

5. Conclusions

The fact that summertime hypoxia has remained above historical levels despite some reductions in estimated nutrient loading has been suggested to indicate that Chesapeake Bay has become more susceptible to hypoxia because of the overall degradation of the ecosystem. Although profound ecological changes have certainly taken place in Chesapeake Bay, the role of physical forcing in influencing biological processes and ecosystem function needs to be better understood. As this study demonstrates, variations in physical forcing may play a key role in modulating hypoxia in Chesapeake Bay, and even slight changes in wind direction can have significant impacts on water quality. In fact, only when both nitrogen loading and wind direction are accounted for is the statistically significant long-term linear increase in hypoxia removed from this dataset. These findings highlight the importance of understanding the variability of physical forcing when assessing the effectiveness of efforts to restore water quality in Chesapeake Bay and other estuarine systems.

Acknowledgments. The author thanks James Hagy for providing the updated time series of hypoxic volume used in this study. Carl Friedrichs and two anonymous reviewers provided insightful comments that significantly improved this manuscript.

REFERENCES

Diaz, R. J., and R. Rosenberg, 2008: Spreading dead zones and consequences for marine ecosystems. *Science,* **321,** 926–929.

Fisher, R. A., 1921: On the probable error of a coefficient of correlation deduced from a small sample. *Metron,* **1,** 3–32.

Hagy, J. D., W. R. Boyton, C. W. Keefe, and K. V. Wood, 2004: Hypoxia in Chesapeake Bay, 1950-2001: Long-term changes in relation to nutrient loading and river flow. *Estuaries,* **27,** 634–658.

Hurrell, J. W., 1995: Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science,* **269,** 676–679.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Katz, R. W., M. B. Parlange, and C. Tebaldi, 2003: Stochastic modeling of the effects of large-scale circulation on daily weather in the southeastern U.S. *Climatic Change,* **60,** 189–216.

Kemp, W. M., and Coauthors, 2005: Eutrophication of Chesapeake Bay: Historical trends and ecological interactions. *Mar. Ecol.,* **303,** 1–29.

Malone, T. C., W. M. Kemp, H. W. Ducklow, W. R. Boynton, and J. H. Tuttle, 1986: Lateral variation in the production and fate of phytoplankton in a partially stratified estuary. *Mar. Ecol.,* **32,** 149–160.

Officer, C. B., R. B. Biggs, J. L. Taft, L. E. Cronin, M. A. Tyler, and W. R. Boynton, 1984: Chesapeake Bay anoxia: Origin, development, and significance. *Science,* **223,** 22–27.

Ogi, M., Y. Tachibana, and K. Yamazaki, 2003: Impact of the wintertime North Atlantic Oscillation (NAO) on the summertime atmospheric circulation. *Geophys. Res. Lett.,* **30,** 1704, doi:10.1029/2003GL017280.

Rabalais, N. N., and R. E. Turner, 2001: Hypoxia in the northern Gulf of Mexico: Description, causes and change. *Coastal Hypoxia: Consequences for Living Resources and Ecosystems,* N. N. Rabalais and R. E. Turner, Eds., Coastal and Estuarine Studies Series, Vol. 58, Amer. Geophys. Union, 1–36.

Sanford, L. P., K. G. Sellner, and D. L. Breitburg, 1990: Covariability of dissolved oxygen with physical processes in the summertime Chesapeake Bay. *J. Mar. Res.,* **48,** 567–590.

Scully, M. E., 2010: Wind modulation of dissolved oxygen in Chesapeake Bay. *Estuaries Coasts,* in press.

Seliger, H. H., J. A. Boggs, and W. H. Biggley, 1985: Catastrophic anoxia in the Chesapeake Bay in 1984. *Science,* **228,** 70–73.

Taft, J. L., E. O. Hartwig, and R. Loftus, 1980: Seasonal oxygen depletion in Chesapeake Bay. *Estuaries,* **3,** 242–247.

Wallace, J. M., and D. S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.,* **109,** 784–812.

Wilson, R. E., R. L. Swanson, and H. A. Crowley, 2008: Perspectives on long-term variations in hypoxic conditions in western Long Island Sound. *J. Geophys. Res.,* **113,** C12011, doi:10.1029/2007JC004693.