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Jiabi Du  
Virginia Institute of Marine Science, jiabi@vims.edu

Jian Shen  
Virginia Institute of Marine Science, shen@vims.edu

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Decoupling the influence of biological and physical processes on the dissolved oxygen in the Chesapeake Bay

Jiabi Du and Jian Shen

1Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA

Abstract It is instructive and essential to decouple the effects of biological and physical processes on the dissolved oxygen condition, in order to understand their contribution to the interannual variability of hypoxia in Chesapeake Bay since the 1980s. A conceptual bottom DO budget model is applied, using the vertical exchange time scale (VET) to quantify the physical condition and net oxygen consumption rate to quantify biological activities. By combining observed DO data and modeled VET values along the main stem of the Chesapeake Bay, the monthly net bottom DO consumption rate was estimated for 1985–2012. The DO budget model results show that the interannual variations of physical conditions accounts for 88.8% of the interannual variations of observed DO. The high similarity between the VET spatial pattern and the observed DO suggests that physical processes play a key role in regulating the DO condition. Model results also show that long-term VET has a slight increase in summer, but no statistically significant trend is found. Correlations among southerly wind strength, North Atlantic Oscillation index, and VET demonstrate that the physical condition in the Chesapeake Bay is highly controlled by the large-scale climate variation. The relationship is most significant during the summer, when the southerly wind dominates throughout the Chesapeake Bay. The seasonal pattern of the averaged net bottom DO consumption rate ($\bar{B}_{20}$) along the main stem coincides with that of the chlorophyll-a concentration. A significant correlation between nutrient loading and $\bar{B}_{20}$ suggests that the biological processes in April–May are most sensitive to the nutrient loading.

1. Introduction

Dissolved oxygen (DO) is essential for the survival of almost all aquatic organisms and is the one commonly measured state variable that can integrate physical, chemical, and biological dynamics with ecosystem effects in natural waters. A seasonally hypoxic condition (DO < 2 mg L$^{-1}$) in subpycnocline waters is often observed in estuaries, lakes, and coastal waters, such as Chesapeake Bay [Taft et al., 1980; Officer et al., 1984; Kuo and Neilson, 1987; Kemp et al., 2005], the Gulf of Mexico [Rabalais et al., 2001; Justić et al., 2003], Lake Erie [Hawley et al., 2006], and Long Island Sound [Anderson and Taylor, 2001; Lee and Lwiza, 2008]. Hypoxia in coastal waters is a widespread phenomenon that appears to have been growing globally for at least 50 years [Gilbert, 2001; Diaz and Rosenberg, 2008; Rabalais et al., 2010]. Much of the recent increased extent and severity of hypoxia is believed to be caused by excessive anthropogenic inputs of nutrients and eutrophication [Cloern and Jassby, 2010; Diaz and Rosenberg, 2008].

Hypoxia was initially observed in the main stem of the Chesapeake Bay in the 1930s [Newcombe and Home, 1938], and severe anoxia (DO < 0.2 mg L$^{-1}$) was observed as early as 1984 [Seliger et al., 1984]. Hypoxia and anoxia usually develop in the Chesapeake Bay from the middle to upper Bay in summer [Kemp et al., 2005]. Generally, large amounts of organic matter are released from the euphotic zone and settle to the bottom water after the spring diatom bloom, which usually begins in March and declines in April [Harding, 1994; Marshall and Nesius, 1996; Hagy et al., 2005]. As bottom water is isolated from oxygenated surface water due to strong stratification [Taft et al., 1980], the decomposition of organic matter by microbes in the bottom water depletes the DO, leading to hypoxia [Taft et al., 1980; Officer et al., 1984; Malone et al., 1986]. Net oxygen demand in bottom water is exacerbated by decreased aeration due to increased stratification and lower solubility of DO in summertime [Sanford et al., 1990]. Besides the impact of various biological processes, the variation of estuarine dynamics is one of the key factors controlling the development of hypoxia in the Chesapeake Bay [Malone et al., 1986; Kuo and Neilson, 1987; Kuo et al., 1991; Boicourt, 1992; Scully, 2001; Officer et al., 2001; Officer et al., 2003; Officer et al., 2008; Rabalais et al., 2010].
2010a, 2010b). It is largely believed that freshwater, usually associated with nutrient loading, is a major factor in regulating both interannual stratification and bottom DO variation, and is an important predictor of summertime hypoxia volume [Boicourt, 1992; Hagy et al., 2004]. Two major nontidal circulations that contribute to oxygen transport are gravitational circulation and lateral circulation. The strength of the gravitational circulation is responsible for determining hypoxia conditions of the bottom waters in Virginia tributaries [Kuo and Neilson, 1987]. Lateral circulation, caused by wind-driven Ekman transport, replenishes the low DO bottom water in deep channels with oxygenated shallow water [Sanford et al., 1990; Scully, 2010b], and also transports oxygen-depleted bottom waters over adjacent shallow areas [Tuttle et al., 1987].

In general, both the extent and duration of hypoxia are positively correlated with the nutrient loading [Hagy et al., 2004; Kemp et al., 2009]. One interesting question that remains unanswered for the Chesapeake Bay is the inconsistent relationship between the rates of increase of hypoxia volume and nutrient inputs since the 1980s. The nutrient loading has shown a slightly decreasing trend or has remained at the same level since the early 1980s [Murphy et al., 2011], while summertime hypoxia volume in the Chesapeake Bay has increased over time [Hagy et al., 2004]. Hypoxia is the result of both biological and physical processes. However, they are highly coupled as the biological process can be highly modulated by the physical process due to changes of transport and residence time [Nixon et al., 1996; Lucas et al., 2009]. To address this problem, a quantitative evaluation of the relative contributions of the biological effect and the physical effect is needed.

Previous studies show that the development of hypoxia in the bottom layer of estuaries results from the competition between DO consumption and DO supply and is highly correlated to the external physical forcings [Kuo and Neilson, 1987; Sanford et al., 1990; Scully, 2010a, 2010b; Lee et al., 2013]. To diagnose the influence of physical processes and biological processes on DO, complex three-dimensional eutrophication models have been successfully applied to Chesapeake Bay [Cerco, 1995a, 1995b; Cerco and Noel, 2004; Linker et al., 2000; Testa et al., 2014]. On the other hand, the statistical approaches and simplified models provide important correlations between hypoxia volume and external forcings, such as freshwater, nutrient loading, and wind strength [Hagy et al., 2004; Scavia et al., 2006; Lee et al., 2013]. Shen et al. [2013] proposed a conceptual bottom DO budget model, which is applicable to separate physical and biological processes based on time scales that quantify both physical and biological processes. This approach will be used to investigate the long-term variation of physical and biological conditions in the Chesapeake Bay in this study. By decoupling the effects of physical and biological processes, the variation of biological processes and its correlation with nutrient loading can be evaluated.

The purpose of this study is (1) to understand the inconsistent relationship between variation of hypoxia volume and nutrient loading in Chesapeake Bay since the 1980s, (2) to assess the effect of interannual variation of physical and biological processes on the bottom DO condition, and (3) to discern the causes of the interannual variation of physical and biological conditions. A three-dimensional numerical model was used to compute the time scale of vertical exchange time that quantifies the interannual variation of the influences of physical processes. Using the bottom DO budget model and sufficient observation data along the deep channel of the Chesapeake Bay, we are able to estimate the monthly variation of the net consumption rate of dissolved oxygen, which can be used to evaluate the biological effect on hypoxia.

2. Methods

2.1. Conceptual Bottom DO Budget Model

A conceptual model based on time scales for describing the bottom DO for an estuary was developed by Shen et al. [2013] and has been applied to estimate the bottom DO in the Chesapeake Bay [Hong and Shen, 2013]. For a partially mixed estuary, the gravitational circulation can be described by a two-layer model [Pritchard, 1952; Kuo and Neilson, 1987; MacCready, 2004]. Assuming steady state for tidally averaged flow, the lower layer oxygen for a uniform estuary is governed by the following equation [Kuo and Neilson, 1987]:

\[
\frac{dO}{dx} = \frac{k_z}{H} \left( O_s - O \right) - \frac{B}{d}
\]

(1)

where \( u \) is the mean bottom inflow velocity due to estuarine circulation and is assumed to be constant, \( O_s \) and \( O \) are the DO concentrations (mg L\(^{-1}\)) in the surface and bottom layers, \( k_z \) is the vertical exchange rate.
(m² s⁻¹) between the surface and bottom layers that parameterizes the overall exchange between surface and bottom layers and is not limited to turbulent mixing. \( H \) is the bottom layer thickness, \( d \) is the distance between the middle of two layers, and \( B \) is the total DO consumption rate (g O₂ m⁻³ d⁻¹) including both that from water column and SOD. Letting \( D = O_s - O \) as DO deficit, and applying boundary condition \( D = D_0 \) at \( x = 0 \), equation (1) can be solved as:

\[
\frac{D}{O_s} = \frac{BHD}{K_d O_s} (1 - e^{-\frac{K_s x}{Hd}}) + \frac{D_0}{O_s} e^{-\frac{K_s x}{Hd}}, \quad \text{and} \quad D \geq 0
\]  

(2)

An approach similar to that of Lucas et al. [2009] is used by letting (1) \( \tau_x = x/u \) be the longitudinal transport time scale indicating the travel time of gravitational circulation; (2) \( \tau_v = H_d/k_s \) be the vertical exchange time scale; and (3) \( \tau_b = O_s/B \) be the time scale of the biological oxygen consumption. Substituting into equation (2) gives:

\[
\frac{O}{O_s} = 1 - \frac{\tau_x}{\tau_b} \left(1 - e^{-\frac{\tau_x}{\tau_b}}\right) - \frac{D_0}{O_s} e^{-\frac{\tau_x}{\tau_b}}
\]  

(3)

The equation is a function of time scales and gives a Lagrangian perspective of the DO budget in the sub-pycnocline. The third term on the right-hand side of equation (3) accounts for the effect of the boundary condition, which diminishes as \( x \) increases. Because the Chesapeake Bay has a persistent stratification, the bottom layer is referred to the layer below the pycnocline in this study. The boundary of the conceptual model is set to coincide with the open boundary of the 3-D hydrodynamic model and \( x \) is the distance from the open boundary (≈60 km from the mouth of Chesapeake Bay). The effect of the boundary condition can be neglected due to the minor variability of oxygen conditions for the open ocean and the long distance from the main stem of the Bay to the open boundary.

The longitudinal transport time scale \( \tau_x \) usually ranges from 100 to 150 days in the mid to upper Bay [Shen et al., 2013]. Even if DO at the open ocean is well oxygenated, it will be consumed by biological processes after 100–150 days while transported upstream by the gravitational circulation. \( \tau_x \) usually ranges from 0 to 40 days in the Chesapeake Bay [Shen et al., 2013]. \( \tau_x / \tau_v \) is larger than 2, and the term \( \exp (-\tau_x / \tau_v) \ll 1 \). Thus, DO is mainly controlled by biological consumption and vertical exchanges, and the effect of longitudinal circulation that transport oxygenated water at the mouth to the middle and upper Bay can be neglected. Consequently, the bottom DO in the mid-to-upper Bay can be simplified as:

\[
O = O_s - B \times \tau_v
\]  

(4)

### 2.2. Vertical Exchange Time Calculation

One essential variable required in the bottom DO budget model is the vertical exchange time scale \( (\tau_v) \). We use this vertical exchange time scale (VET) to parameterize the overall exchange between the surface and bottom layers, which includes effects due to lateral circulation, gravitational circulation, and other processes, and is not limited to turbulent mixing.

The time scale can be computed using the concept of water age [Delhez et al., 1999; Huang et al., 2010; Liu et al., 2012; Shen et al., 2013]. The vertical exchange time is the elapsed time since the water parcel was last in contact with the surface. The age is the mean time required for the parcel to be transported from the surface to the bottom, regardless of its pathway. The age clock will be reset to zero if the water parcel travels back to the surface before reaching the bottom.

Delhez et al. [1999] provided a way to use a numerical model to compute the water age. Assuming there is only one tracer released to a system without internal sources and sinks, the transport equations for computing the tracer and the age concentration can be written as [Deleersnijder et al., 2001]:

\[
\frac{\partial C(t, \bar{x})}{\partial t} + \nabla (\bar{u} C(t, \bar{x}) - K \nabla C(t, \bar{x})) = 0
\]  

(5)

\[
\frac{\partial x(t, \bar{x})}{\partial t} + \nabla (\bar{u} x(t, \bar{x}) - K \nabla C(t, \bar{x})) = C(t, \bar{x})
\]  

(6)

The mean age can be calculated as follows:
where $r = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z}$, $C$ is the tracer concentration, $x$ is age concentration, and $K$ is the diffusively tensor.

Following equations (5–7), we use Environmental Fluid Dynamics Code (EFDC) [Hamrick, 1992] to compute the vertical age by continuously releasing tracers at the surface and applying a zero-flux boundary condition at the bottom [Gustafsson and Bendtsen, 2007]. EFDC uses a boundary fitted curvilinear grid model in the horizontal and sigma grids in the vertical. This model has been calibrated for surface elevation, current, and salinity for the Chesapeake Bay and is suitable for hydrodynamic simulations in the Chesapeake Bay [Hong and Shen, 2012, 2013]. The model produces reliable stratification and destratification response temporally and spatially in both wet and dry year [Hong and Shen, 2012]. The same model configuration and boundary condition are used for computing the age in this study as were used in Hong and Shen [2012]. The bathymetry and grid are shown in Figure 1. The simulation of vertical age ($\tau_v$) starts in 1984 and continues until 2012. The first year is for model spin-up. The model is forced by interpolated observed tide at the open boundary (http://tidesandcurrents.noaa.gov), freshwater discharges of eight main tributaries (http://waterdata.usgs.gov/nwis/), and wind obtained from the North America Regional Reanalysis (NARR) produced at the National Center for Environmental Prediction (http://www.esrl.noaa.gov/psd/thredds/catalog/Datasets/NARR/pressure/catalog.html).

### 2.3. Estimation of the Influence of Physical Processes on DO Variation

By assuming a constant biological condition (or mean condition), we can examine the DO variation induced by the physical condition via the conceptual bottom DO budget model. As shown in equation (4), bottom DO is mainly controlled by two variables, $B$ representing the biological processes and $\tau_v$ representing the physical process. In this study, we use an averaged net bottom DO consumption rate of 0.3 g O$_2$ m$^{-3}$ d$^{-1}$ at a temperature of 20°C based on observations. The observed net DO consumption rate varies temporally and spatially with a range of 0.1–0.9 g O$_2$ m$^{-3}$ d$^{-1}$ [Boynton and Kemp, 1985; Kemp and Boynton, 1992; Smith and Kemp, 1995]. The temperature effect is considered as follows [Thomann and Mueller, 1987]:

$$
\tau_v(t, \vec{x}) = \frac{x(t, \vec{x})}{C(t, \vec{x})}
$$

Figure 1. (a) Bathymetry of the Chesapeake Bay; (b) curvilinear orthogonal grid for the Chesapeake Bay model. The selected section along the deep channel (red solid line) and observation stations (green diamond symbols) are marked.
\[ B = 0.3 \times 1.06^{(T-20)} \]  

Saturation DO is assumed at the surface layer and saturation DO is calculated as a function of temperature and salinity. The temperature and salinity is based on the observation data collected from Chesapeake Bay Program (http://www.chesapeakebay.net/data/).

### 2.4. Estimation of Net Bottom DO Consumption Rate

By combining observed DO data and modeled time scale, the estimated net bottom DO consumption rate, designed by \( \dot{B} \), can be computed based on equation (4) as follows:

\[ \dot{B} = \frac{O_{s,obs} - O_{s,obs}}{\tau_{v, bottom}} \]  
\[ \dot{B}_{20} = \frac{\dot{B}}{1.06^{(T-20)}} \]

where \( O_{s,obs} \) is observed surface layer DO concentration, \( O_{s,obs} \) is observed bottom layer DO concentration, and \( \tau_{v, bottom} \) is the modeled bottom layer \( \tau_v \). The surface and bottom values are the vertically averaged values to represent the mean values above and below pycnocline water. The pycnocline depth is determined by the observed salinity profile. Observed DO data for 20 stations (shown in Figure 1b) along the deep channel section from 1985 to 2012 are collected through Chesapeake Bay Program. DO data are first averaged monthly and interpolated vertically for each station and then interpolated into the model grid along the main channel section (207 horizontal grids, 20 layers). In this way, \( \dot{B} \) can be estimated monthly for every grid along the deep channel section. \( \dot{B}_{20} \) is the estimated net bottom DO consumption rate at a temperature of \( 20^\circ C \). \( \dot{B}_{20} \) represents the rate of bottom water net ecosystem metabolism that quantifies the effect of all possible biological processes that regulate bottom DO, including sediment oxygen demand, decay of organic matter, and other respirations.

### 3. Results

#### 3.1. Variation of Vertical Exchange Time

Figure 2 shows the spatial distribution of the VET averaged over 28 years (1985–2012) (Figures 2a and 2e), conceptual model-predicted DO (Figures 2b, 2c, 2f, and 2g), and observed DO (Figures 2d and 2h) along the main channel in spring (left) and summer (right). There is a remarkably similar spatial pattern of VET and observed DO. Both VET and observed DO show a vertical gradient and horizontal gradient in the bottom layer with a relatively high VET and low DO in the middle Bay (38°N–39°N). During the spring, the observed DO can be as low as 4 mg L\(^{-1}\), and the averaged VET reaches 21 days near 39°N. During the summer, the averaged VET can be as large as 27 days, and hypoxia (DO < 2 mg L\(^{-1}\)) appears in the bottom waters at location from 37.8°N–39.2°N. The region with VET values larger than 24 days is consistent with that having DO values less than 1 mg L\(^{-1}\) in summer, while VET values of 18 days corresponds to DO value of 2 mg L\(^{-1}\).

A qualitative comparison of variation of DO due to the spatial variation of the physical condition can also be inferred by applying the simple budget model at each layer using a constant net DO consumption rate (equation (4)). Figures 2b and 2f show the model-predicted DO using a constant net DO consumption rate of 0.3 g O\(_2\) m\(^{-3}\) d\(^{-1}\) at 20°C with a correction of temperature (equation (8)). Compared to the observed DO, it appears that the predicted DO over and underestimates the bottom DO condition in spring and summer, respectively. The difference suggests that \( \dot{B}_{20} \) is of high temporal variability, and a higher \( \dot{B}_{20} \) and a lower \( \dot{B}_{20} \) should be applied in spring and summer, respectively. Figure 2c shows the estimated DO in spring with a higher \( \dot{B}_{20} \) of 0.4 g O\(_2\) m\(^{-3}\) d\(^{-1}\), and Figure 2g shows the estimated DO in summer with a lower \( \dot{B}_{20} \) of 0.2 g O\(_2\) m\(^{-3}\) d\(^{-1}\). The great similarity of estimated DO (Figures 2c and 2g) and observed DO (Figures 2d and 2h) indicates that both temporal and spatial variations of the physical condition play an important role in the distribution of bottom DO. Despite the great similarity, the difference between predicted DO and observed DO suggests that the spatial and temporal variations of the biological condition are equally important. A 0.1 g O\(_2\) m\(^{-3}\) d\(^{-1}\) difference of \( \dot{B}_{20} \), which accounts for 30% of the mean value, can make a significant difference on the distribution of DO, especially for the hypoxic condition in summer.

The seasonal variation of VET is examined. Figure 3 shows the monthly sectionally averaged bottom layer VET along the main channel (Figure 1b) for every month over 1985–2012. The bottom layer is the layer below the multiyear averaged pycnocline depth based on the observed salinity profile. A significant
 seasonal pattern of the VET is revealed and a peak VET occurs in the summer. The VET (solid line), averaged over 28 years, shows the bottom layer VET is about 10 days in the winter, and 16 days in the summer. Besides the seasonal pattern, the VET varies greatly in any specific month over the 28 years, with an averaged range of about 10 days. For example, the VET of July ranges from 8 to 23 days, which indicates that the average bottom DO concentration ranges from 5.5 to 1.4 mg L\(^{-1}\), respectively, given an average temperature of 26.3 \(^\circ\)C and a \(B_{20}\) value of 0.2 g O\(_2\) m\(^{-3}\) d\(^{-1}\) for spring/March–May and summer (June–August) along the deep channel of the Bay (the location of the section is marked in Figure 1b). The VET contour line of 21 days and the DO contour line of 2 mg L\(^{-1}\) are shown in bold. The contour intervals are 3 days and 1 mg L\(^{-1}\) for VET and DO, respectively. Different net DO consumption rates at a temperature of 20 \(^\circ\)C (i.e., \(B_{20}\)) are used for the model-predicted DO, 0.3 g O\(_2\) m\(^{-3}\) d\(^{-1}\) (Figure 2b) and 0.4 g O\(_2\) m\(^{-3}\) d\(^{-1}\) (Figure 2c) for spring, 0.3 g O\(_2\) m\(^{-3}\) d\(^{-1}\) (Figure 2f) and 0.2 g O\(_2\) m\(^{-3}\) d\(^{-1}\) (Figure 2g) for summer, respectively. The interannual variation of the sectionally monthly averaged VET from April to July is shown in Figure 4. Statistically, no consistent trend of VET is found for any of these 4 months, and the decadal variation of VET is different for each month. For April, VET shows a slightly decreasing trend from 1985 to 2002 and a rapidly increasing trend from 2002 to 2012. An extremely high VET occurred in 2010 while an extremely low VET occurred in 2002. For May, rapid decreases of the VET occurred during 1989–1996 and 1998–2004, with an extremely low value in 2004. Both June and July shows an increasing trend from 1999 to 2012. The slightly increasing trend of VET over the recent 10 years may contribute to an earlier shift of the maximum hypoxia
in the Chesapeake Bay [Murphy et al., 2011; Zhou et al., 2014]. However, this does not necessarily result in an increase of hypoxia volume, as hypoxia is also highly controlled by the biological condition.

3.2. Physically Induced Bottom DO Variation

Physically induced bottom DO variation is estimated based on equation (4), where a net constant bottom DO consumption rate is assumed, but modulated by temperature (equation (8)). Therefore, the variation of
modeled DO represents the contribution of the interannual and seasonal variations of estuarine dynamics and temperature. The seasonal patterns of observed and modeled DO averaged over the entire longitudinal section (shown in Figure 1b) are consistently matched (Figure 5). The estimated low value of DO in summer and its high value in winter correspond to the high value of VET in summer and its low value in winter, and the seasonal variation of temperature. A linear regression between observed and estimated DO for subpycnocline waters of the main stem shows that the physically induced bottom DO variation accounts for 88.8% of the observed DO variation (Figure 6), suggesting that the variability of the physical condition, including seasonal and interannual variations of both the VET and temperature, plays an important role in modulating the bottom DO.

The difference between observed and modeled DO cannot be neglected, although the simple model has a good predictive skill. As shown in Figure 6, modeled DO is usually less than observed DO for a relatively low DO condition (DO < 6 mg L\(^{-1}\), usually in summer), indicating that the DO consumption rate is less than the average value (i.e., 0.3 g O\(_2\) m\(^{-3}\) d\(^{-1}\)) in summer, which is probably due to the O\(_2\)-limitation of aerobic respiration. This is consistent with the fact that the observed bottom DO consumption rate is smaller in the summer in the middle Bay (Kemp et al., 1997). The bias is randomly distributed when DO is high. Nevertheless, the bias can be as large as 2 mg L\(^{-1}\) for a high DO condition and 3 mg L\(^{-1}\) for a low DO condition (Figure 6). The bias of modeled DO is largely contributed from the variation of the biological condition besides the model uncertainty, which will be presented in the following section.

3.3. Net Bottom DO Consumption Rate

The net bottom DO consumption rate can serve as an important indicator of
the biological condition, including the effect of plankton respiration, decay of organic matter, and sediment oxygen demand, i.e., a net ecosystem metabolism. The net bottom DO consumption rate \(B'\) can be calculated by combining the modeled time scale and observed DO data at each observation station (equation (9)). The sectionally averaged \(B_0\) has a mean value of 0.24 g O\(_2\) m\(^{-3}\) d\(^{-1}\), a standard deviation of 0.10 g O\(_2\) m\(^{-3}\) d\(^{-1}\), and a maximum value of 0.8 g O\(_2\) m\(^{-3}\) d\(^{-1}\) (Figure 7a), which is consistent with the range of observed and modeled results [Boynton and Kemp, 1985; Kemp and Boynton, 1992; Smith and Kemp, 1995; Scavia et al., 2006; Testa et al., 2014]. The result also shows a significant seasonal pattern with a peak in May and a trough in October. After removing the temperature effect (equation (10)), the DO consumption rate at a temperature of 20°C \(B'_{20}\) is calculated and can serve as an indicator quantifying dissolved organic matter in the water column, as well as the strength of biological processes. It shows a similar seasonal pattern, with a peak in April and a mean value of 0.33 g O\(_2\) m\(^{-3}\) d\(^{-1}\), a standard deviation of 0.16 g O\(_2\) m\(^{-3}\) d\(^{-1}\), and a maximum value of 0.78 g O\(_2\) m\(^{-3}\) d\(^{-1}\) (Figure 7b). Different from \(B'\), \(B'_{20}\) has a larger range from December to May, but has a much smaller range from June to November.

The seasonal pattern of \(B'_{20}\) coincides with that of the chlorophyll-a concentration in Chesapeake Bay. The observed chlorophyll-a concentration data were collected by the Chesapeake Bay Program from 1985 to 2012 and interpolated along the deep channel section for every month. The sectionally averaged chlorophyll-a concentration shows a similar pattern as that of \(B'\). However, the peak concentration occurs in March and decreases from March to June (Figure 7c). The seasonal pattern of \(B'_{20}\) is associated with the variation of phytoplankton biomass from two aspects. First, the peak of multiple years of monthly mean values of \(B'_{20}\) shows a 1 month delay to the peak of plankton biomass. Following the peak of algal bloom (usually in March), a large amount of organic matter is released to the subpycnocline waters, which cause the peak of \(B'_{20}\) (usually in April). Besides, the range of different months has similar patterns for \(B'_{20}\) and chlorophyll-a concentration, both of which have a larger range for the months of December to May and a much smaller range for the months of June to November.

Besides the temporal variation, the spatial variation of estimated net DO consumption rate (\(B'\)) is also important in regulating the DO. The spatial variation of \(B'\) for April–July is shown in Figure 8. A 28 year average of \(B'\) (solid line) usually has its smallest value at the mouth of the Bay, increasing from the mouth to the lower Bay (37°N–38°N). Averaged \(B'\) maintains the same level or decreases slightly in the middle Bay, with a mean value of about 0.3 g O\(_2\) m\(^{-3}\) d\(^{-1}\). A smaller standard deviation is found in the middle Bay rather than the lower Bay, suggesting a more stable biological condition in the middle Bay. A larger mean standard deviation is found in April and May, rather than that in June and July. However, the spatial distribution of standard deviation is quite different between April and May. Compared to June and July, the spatial pattern of

![Figure 7](https://example.com/figure7.png)

**Figure 7.** Seasonal distribution of estimated monthly sectionally averaged (a) net bottom DO consumption rate \(B'\), (b) temperature corrected net bottom DO consumption rate \(B'_{20}\), and (c) chlorophyll-a concentration. Solid line represents the mean of 28 years for each month.
the standard deviation in April is characterized with a larger standard deviation in the lower Bay and a relatively smaller deviation in the middle Bay, while the deviation in May is larger in both the lower Bay and the middle Bay. The larger maximum $B'$ of April is found in the lower Bay ($37^\circ$–$38^\circ$ N), while the maximum $B'$ of May has a similar magnitude in both the lower Bay and the middle Bay. This indicates that the high variability of $B'$ occurs in the lower Bay, while low variability of $B'$ occurs in the middle and upper Bay regions.

4. Discussion

4.1. Effect of Large-Scale Climate Variability

The physical condition is controlled by external forcing, including wind, precipitation, solar radiation, and river discharge. The variability of the local physical condition is likely to relate to the change of the large-scale climate pattern. There is growing evidence that climate forcing plays a role in recent changes in the Chesapeake Bay [e.g., Najjar et al., 2010; Scully, 2010a; Varnell, 2014]. We hypothesize that the physical condition of the Bay is highly controlled by the large-scale climate variation. North Atlantic Oscillation (NAO) index has been used as an indicator of the variability of the large-scale climate pattern, as it is a major source of the interannual variability in the atmospheric circulation, dominating the climate pattern in North America and Europe [Loon and Rogers, 1978; Barnston and Livezey, 1987; Kushnir and Wallace, 1989; Hurrell, 1995; Hurrell and Loon, 1997]. Correlation analysis between sectionally averaged bottom VET and NAO index (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml) is conducted over the 1985–2012 period. The results show that they are negatively correlated in June–July (Figure 9a, $R = 0.58$, $P = 0.001$).

Two of the most important external forcings are wind and freshwater discharge. We found a significant correlation between southerly wind and VET in June–July (Figure 9b), while no significant correlation is found between freshwater discharge and VET for the same corresponding period. Regressions between bottom VET of different regions (lower Bay, middle Bay, and upper Bay) in June–July and spring river discharge show that spring river discharge only accounts for 4–13% of the variation of the summer VET. The effect of river discharge on the VET has been discussed by Hong and Shen [2013], which shows that the pulse of river...
discharge has a weak impact on the summer VET because the Bay is buffered by the large amount of the freshwater inside the Bay. Therefore, the effect of the spring river discharge pulse tends to diminish after several months. In addition, the impact of the spring river discharge is confounded by the profound impact of the interannual variation of the wind field. Compared to freshwater discharge, wind forcing modulates the vertical mixing more directly and rapidly, as responses to stratification and the VET of the main stem Bay have a much longer time lags to the variation of freshwater [Boicourt, 1992; Scully, 2010a; Lee et al., 2013; Hong and Shen, 2013].

We use wind strength, which is computed as the summation of the product of wind duration and wind speed, to quantify the overall wind effect. The southerly wind strength is found to be positively correlated with VET in June–July (Figure 9b, R = 0.70, P < 0.001). Scully [2010b] demonstrates that southerly winds, compared to winds from other directions, are the most effective at replenishing DO in subpycnocline waters via the enhancement of lateral circulation. The reason that a significant correlation is found only during June–July is probably because southerly winds are dominant during the summer in Chesapeake Bay [Scully, 2010a]. Southerly wind in eastern U.S. has been found associated with the NAO in winter [Hurrell, 1995], and also shows a high correlation with NAO in summer (Figure 9c, R = 0.82, P < 0.001). Therefore, the relationship among southerly wind strength, NAO, and VET suggests that interannual variability of the physical condition in Chesapeake Bay is highly controlled by the large-scale climate variation.

The key linkage among the large-scale climate variation and VET is wind forcing. Wind forcing has been generally believed to play an important role in modulating hydrodynamics in Chesapeake Bay [Wang, 1979; Sanford et al., 1990; Guo and Valle-Levinson, 2008; Chen and Sanford, 2009; Scully, 2010a, 2010b; Li and Li, 2012; Hong and Shen, 2013; Lee et al., 2013]. Hong and Shen [2013] indicate that VET is highly correlated with total discharge and wind forcing. Southerly wind is believed to not only enhance the lateral circulation,
but also enhance the vertical mixing, and horizontal transport time [Shen and Wang, 2007; Scully, 2010a, 2010b]. Stratification, related with freshwater discharge and wind, has been proven to have a dramatic effect on the DO condition in Chesapeake Bay [Taft et al., 1980; Murphy et al., 2011]. Increased freshwater will enhance stratification as well as gravitational circulation. However, the short-term variation of freshwater discharge will not necessarily result in a quick response of the VET [Hong and Shen, 2013], as it may take several months for the freshwater being transported from the heads of rivers to reach to the middle Bay and the lower Bay. In contrast, a variation of wind forcing will cause the change of stratification in hours or days [Wang, 1979; Chen and Sanford, 2009; Scully, 2010b; Li and Li, 2012]. Stratification is always reduced by an up-estuary wind, i.e., southerly wind, and shows an increase-then-decrease transition when the down-estuary wind increases [Chen and Sanford, 2009]. The enhanced stratification weakens the vertical mixing and causes the increase of VET. Another important mechanism regulating VET is the lateral circulation, which serves to replace the aging bottom water in the deep main channel with younger water from the shallow region where vertical mixing is able to bring surface water to the bottom. Lateral circulation, caused by the Ekman transport driven by surface wind forcing, is believed to have a significant effect on the replenishment of low DO bottom water in the main stem of the Bay with oxygenated water in shallow water [Sanford et al., 1990]. Scully [2010b] suggested that both southerly wind and northerly wind can enhance the lateral circulation, and yet the southerly wind can reduce the hypoxia condition more. This is confirmed by the correlation between southerly wind strength and VET (Figure 9b).

Varnell [2014] studied the long-term (1948–2010) wind in the Chesapeake Bay, based on hourly wind velocity data collected at Norfolk International Airport. A noted decreasing trend of southeasterly and southerly wind since 1948 is observed. Southerly wind hours decreased from 1948 to year 2000 and increased from 2000 to 2008. Southeasterly wind decreased from 1948 to 2010, while southwesterly wind has no significant trend [Varnell, 2014]. A slight increase of bay stratification in June is evident [Murphy et al., 2011]. Our model results show that the long-term VET has a slight increase in summer, but no statistically significant trend was found, suggesting that the VET variation is modulated by interannual variability (Figures 4 and 9). The result agrees with results from Zhou et al. [2014], which concludes that there is no trend in the seasonal-maximum hypoxic volume itself and yet the end time and maximum hypoxia time move earlier.

4.2. Effect of Nutrient Loading on Biological Condition

Nutrient input is largely agreed to be the dominant factor regulating the hypoxia condition in Chesapeake Bay [Malone et al., 1996; Hagy et al., 2004; Scavia et al., 2006]. In general, a large amount of organic matter is released after a diatom bloom, which starts as early as midwinter and continues until late spring with a maximum concentration between March and May [Marshall et al., 2005]. This organic material is subsequently decomposed by the bacteria or other microorganisms [Taft et al., 1980; Officer et al., 1984]. Seasonal O₂ depletion in Chesapeake Bay is generally driven primarily by planktonic respiration in the bottom layer rather than benthic respiration [Taft et al., 1980; Kemp and Boynton, 1992]. Therefore, water-column oxygen consumption is assumed to be sensitive to the intensity of an algal bloom, which is usually positively correlated with nutrient loading [Cerco, 1995a; Boesch, 2002; Anderson et al., 2002]. The $B_{20}$ value obtained from equation (10) represents the level of net ecosystem metabolism, or the biochemical activities, in the bottom water. The use of $B_{20}$ instead of $B^*$ is to remove the temperature effect on biological activities. Therefore, we hypothesize that the $B_{20}$ is positively correlated with the nutrient loading during the months after the spring bloom.

A correlation analysis between the monthly value of $B_{20}$ (from April to September) and the January–May averaged nutrient loading from the Susquehanna and Potomac Rivers based on USGS data (http://cbrim.er.usgs.gov/) is conducted. The Susquehanna and Potomac Rivers are selected because the nutrient loadings of these two largest rivers are much larger than those of other small tributaries. The results show a significantly positive correlation between $B_{20}$ and nutrient loading in the months of April and May (Figure 10) ($R = 0.69, P = 0.001$). If extreme years of 2010 (second minimum $B_{20}$), 2004 (maximum $B_{20}$), and 1989 (minimum $B_{20}$) are excluded, the R value becomes 0.82. The anomalously estimated $B_{20}$ in these 3 years is not well understood. The possible reasons include the effect of extreme events, model uncertainty of estimation of $c_v$, and measurement uncertainty. Absence of a relationship between $B_{20}$ and nutrients in summer suggests that DO consumption is more sensitive to the winter-spring nutrient loading in the months following an algal bloom. There are two possible reasons for the different sensitivity of $B_{20}$ to the nutrient loading in different months. First, the peak of the decomposition usually occurs in April and May, following the peak
chlorophyll-a concentration in March (Figure 7c). The decline of dissolved oxygen of bottom water during spring is primarily caused by respiration of spring deposition events \cite{Boynton and Kemp, 2000} and there is a 1–2 month lag between the spring phytoplankton bloom and significant deep water oxygen depletion \cite{Boynton and Kemp, 2000; Cowan and Boynton, 1996; Hagy et al., 2005}. Therefore, it is reasoned that the DO consumption rate in the month following an algal bloom is directly related and highly sensitive to the intensity of the algal bloom. Second, an oxygen limitation of aerobic respiration in summer causes less sensitivity of the bottom DO consumption rate to nutrient loading.

5. Conclusions

A bottom DO budget model is applied to decouple the effect of physical and biological processes on the dissolved oxygen in Chesapeake Bay for the period from 1985 to 2012. Vertical exchange time (VET) that serves as an important indicator of the physical condition is computed by the 3-D numerical model and its monthly average value along the main stem of the Chesapeake Bay is analyzed. The VET shows a significant seasonal pattern, and usually peaks in the summer. Physical conditions (vertical exchange and temperature) induced bottom DO variation, assuming a constant net DO consumption rate (0.3 g O2 m\(^{-3}\) d\(^{-1}\), at \(T = 20\) °C), predicted DO matched well with the observed DO in the main stem. The correlation between estimated and observed DO indicates that interannual variability of the physical condition can account for 88.8% of the variation of observed DO. Because temperature has a much lower interannual variation, the high similarity of spatial patterns of VET and observed DO suggests that hydrodynamic processes play a key role.
role in regulating the hypoxic condition. The region with VET larger than 24 days is consistent with that of the distribution of DO less than 1 mg L$^{-1}$ in the summer. Our model results also show that long-term VET has a slight increase in summer although no statistically significant trend is found.

The relations among southerly wind strength, NAO (North Atlantic Oscillation) index, and VET suggest that the hydrodynamic condition in Chesapeake Bay is highly controlled by the large-scale climate variation. The correlation is significant in the summer (June–July), when the southerly wind dominates. A negative correlation between NAO and VET is found for June–July ($R = 0.58, P = 0.001$), which can be well explained by the negative relationship between VET and southerly wind strength ($R = 0.70, P < 0.001$) and the positive relationship between NAO and southerly wind strength ($R = 0.82, P < 0.001$).

The net bottom DO consumption rate ($B'$), indicating the strength of biochemical processes and the biological condition, is estimated by combining the observed DO data and modeled VET along the main stem of the Chesapeake Bay. A significant seasonal pattern of $B_{20}$ (temperature corrected $B'$) is found, with a peak in April and a mean value of $0.33$ g O$_2$ m$^{-2}$ d$^{-1}$. The seasonal pattern coincides with that of plankton biomass indicated by the observed chlorophyll-a concentration, which usually has a peak in March and rapidly decreases subsequently. The relationship between nutrient loading and $B_{20}$ suggests that the biological processes are most sensitive to the nutrient loading in April–May and contribute highly toward interannual DO variation.

References


