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Effects of cross-channel bathymetry and wind direction on destratification and hypoxia reduction in the Chesapeake Bay

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ABSTRACT

A coupled estuarine hydrodynamic model and water quality model were used to analyze differences in destratification and anoxia/hypoxia reduction by wind directions in the north-south oriented Chesapeake estuary, USA. The predominant cross-channel bathymetry in the Bay's anoxic center is asymmetric with a steeper and narrower shoal on the eastern shore than on the western shore, which modifies wind-induced circulation differently for two opposite wind directions. Model experiments of winds for 2-day at 8 m/s indicated that, for a stratified water over the aforementioned asymmetric bottom topography, the easterly wind caused greater destratification and hypoxia reduction than the westerly wind. This is a result of differential modulations on the two wind-induced cross-channel circulations by the asymmetric cross channel bathymetry. The downwelling along the gentle slope in the easterly wind was characterized with stronger baroclinicity than the downwelling along the steep slope (nearly perpendicular to surfaces of constant density) in the westerly wind. On the broad slope, there undergo greater contrasting density readjustments to the vorticity changes around the bottom boundary layer (BBL) during upslope and downslope motions. During the upslope condition, the flow in BBL tends to decelerate under adverse pressure gradient which leads to a stable condition in the outer layer; whereas, during the downslope condition, the BBL tends to accelerate under favourable pressure gradient, which leads to unstable condition in the outer layer of the large scale flow. Overall, the easterly wind caused greater anoxia reduction than the westerly wind during the entire wind period. A similar case was found for northerly versus southerly winds in the early stages of the wind period; modulated by the aforementioned bathymetry on the wind-induced cross-channel circulation, the northerly wind caused greater anoxia reduction than the southerly wind. However, as wind continues, the wind-induced along-channel circulation influences a larger area of greater hypoxia in the mid-Bay, by which the southerly wind causes a greater destratification and anoxia reduction than the northerly wind. This can supersede the greater destratification and anoxia reduction by the northerly wind under the bathymetry-affected cross-channel circulation.

1. Introduction

Hypoxia is a water quality concern in the Chesapeake Bay. One challenge facing scientific and management communities is understanding the relative importance of anthropogenic and natural factors in the development of Chesapeake hypoxia. Dissolved oxygen in the water is a function of physical process (such as reaeration and stratification), biological processes (such as photosynthesis and respiration by phytoplankton), and chemical processes. The hypoxic conditions in the Chesapeake Bay vary from year to year. The nutrient-related biochemical processes leading to Chesapeake's summer anoxia/hypoxia have been studied extensively (Officer et al., 1984; Thomann et al., 1994; Hagy et al., 2004; Murphy et al., 2011; Wang et al., 2015a). However, the influence of wind on hypoxia has had less attention. Wind plays an important

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role in the temporal and spatial variation of hypoxia, which has significant implications for the Chesapeake Bay water quality management and the Chesapeake's Total Maximum Daily Load (TMDL) (USEPA, 2010). Consistent with Chesapeake Bay water quality criteria of dissolved oxygen for aquatic living resources, in this article hypoxia is defined as dissolved oxygen (DO) concentration < 1 mg/l, and anoxia as DO ≤ 0.2 mg/l. This paper mainly analyses the lower DO part of hypoxia, i.e., the anoxia.

Winds blowing along or across an elongated eutrophic water body of estuary cause different degrees of destratification and hypoxia reduction as found in the Cape Cod Bay, USA (Geyer, 1997), the Long Island Sound, USA (O'Donnell et al., 2008; Wilson et al., 2008), and the Chesapeake Bay (Malone et al., 1986; Chen and Sanford, 2009; Chen et al., 2009; Scully, 2010, 2013; Li and Li, 2012; Li et al., 2015).

The main channel of the Chesapeake Bay is principally north (N)-south (S) oriented (Fig. 1). The cross-channel bathymetry in the hypoxic/anoxic center at the mid Bay and the lower Upper Bay is dominant with a narrower and steeper slope in the eastern shore shoal, and a wider and gentler slope in the western shore shoal. The Bay is a partially mixed estuary, characterized by a two-layer circulation, with seaward (southward) average flow at the surface, and landward (northward) near the bottom (Pritchard, 1967; MacCready and Geyer, 2010). Wind energy can cause mixing on the surface water directly and generate a turbulent boundary layer that penetrates downward to erode stratification (Kato and Phillips, 1969; Chen and Sanford, 2009). Wind's longitudinal (along-channel) straining, lateral (cross-channel) straining and direct wind mixing are three mechanisms causing destratification by winds in the Chesapeake Bay (Chen and Sanford, 2009). Different wind directions can cause different degrees of destratification (Chen and Sanford, 2009; Li and Li, 2011) and hypoxia reduction (Scully, 2010). It is commonly agreed among Chesapeake researchers from model experiments with 2- or 3-day wind events, that the southerly wind causes greater destratification and anoxia reduction than the northerly wind (Chen and Sanford, 2009; Scully, 2010; Wang and Wang, 2012) because the southerly wind blows against the tidal averaged surface flow direction, while the northerly wind blows along the direction of net surface flow. Wang and Wang (2012) noticed that, in the first day of the simulated wind event, the northerly wind caused greater destratificaiton and hypoxia reduction than the southerly wind. They suggested it was related to the modulation of the asymmetric channel bathymetry on cross-channel circulation.

Bed geometries of most water bodies are asymmetric. It is of interest for scientists to understand the mechanisms leading to differences in destratification and hypoxia reduction by different wind directions and the modulation of asymmetric bathymetries. This paper focuses on the effects of asymmetric cross-channel bathymetry on destratification and hypoxia reduction by wind-induced cross-channel circulation for two opposite wind directions. Since the cross-channel component is the main component of wind-induced circulation by the easterly and westerly winds, this paper will firstly discuss easterly versus westerly winds, followed by northerly versus southerly winds.

2. Method

The coupled CH3D hydrodynamic and CE-QUAL-ICM water quality model called WQSTM – Water Quality and Sediment Transport Model was used in this study (Cerco and Cole, 1994; Cerco et al., 2010). This model and its predecessors have been extensively used in management of Chesapeake water quality (Thomann et al., 1994; Wang et al., 2001), and the model is now used in the assessment of the Chesapeake Bay TMDL (USEPA, 2010). The model was calibrated for 10 years using a 1991–2000 hydrology and loads from the watershed. Application of the coupled CH3D and ICM model framework with watershed loads provided by the HSPF watershed model (USEPA, 2010) yielded reasonable multi-year calibration. The examples of comparison with observations for surface and bottom salinity and DO are shown in Fig. 2. In the mainstem Bay, the comparison to the observed data on the same date, the mean difference (MD) and the relative difference (RD) of the model for salinity are -0.01 (in the Practical Salinity Scale) and 10%, respectively. For DO, at depth <6.7 m, the MD is -0.14 mg/l and the RD is 11%; at depths $= 6.7–12.8$ m, the MD is 0.3 mg/l and the RD is 19%; at depth >12.8 m, the MD is -0.45 mg/l and the RD is 29% (Cerco et al., 2010). Appendix A describes model specification.

An initial condition of relatively high hypoxia prior to wind events could provide a noticeable response of hypoxia to wind. Year 1996 was selected, since it had high spring nutrient loads and summer hypoxia. For all scenarios, the model was preceded by a 5-year spin-up using 1991–1995 calibration conditions (i.e., observed data) and a pre-wind period with zero wind for the first 7 months of 1996. The wind event lasted for 2 days at speed $= 8$ m/s, beginning (i.e., Hour 0 of wind event) at 4 o'clock on August 10 of 1996. Finally, a post-wind period relaxation without wind forcing was simulated for the remainder of 1996. Five types of wind conditions were simulated: no-wind, and winds from the north, south, east, and west, respectively. Model experiments on winds at other speeds and durations were also conducted, which will be briefly discussed.

Time series of anoxic volumes throughout the whole mainstem Bay were calculated. Dissolved oxygen and/or salinity at cross-sectional fields and at seven segments, CB5.2, CB5.1, CB4.4, CB4.3C, CB4.2C, CB4.1, and CB3.3C in the Bay's anoxic center, were assessed. These segments are designated around the channel monitoring stations (see Fig. 1), each extending about 10 km northward and southward. The transect PC is along the center of the main channel from the upper lower-Bay (south) to the mid upper-Bay (north) (Fig. 1). Though oxygen kinetics was important in the model simulation that generated the initial DO condition prior to the wind events, the differences of oxygen production or consumption among wind directions in the two-day wind events were negligible, therefore, oxygen respiration was excluded from the comparison of oxygen changes in the anoxic zone.

Various methods had been applied to analyze estuarine circulation, such as a momentum budget (Scully et al., 2009) and a streamwise budget (Li and Li, 2012). This study uses advection velocity, salinity distribution, eddy viscosity and diffusivity, Richardson number, oxygen budget, and anoxic volume to analyze the influence of wind and bathymetry on destratification and hypoxia. Strength of stratification was evaluated by the square of the Brunt-Vaisala frequency (Knauss, 2005): $N^2 = -\frac{g}{\rho}\frac{d\rho}{dz}$, where ρ is density, g is the acceleration of gravity, and z is depth. The vertical Richardson number, Ri, was used to estimate the potential destratification by wind stress, which is controlled by the relative strengths of stratification and flow shears (Van Gastel and Pelegri, 2004):

$$R_{\mathrm{i}} = N^2/S^2, \text{ where } S \text{ is total vertical shear; or } Ri = \frac{-g\frac{\partial\rho}{\partial z}}{\rho\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]},$$

where ∂u/∂z and ∂v/∂z are the current shears in the cross- and along-channel directions, respectively. Time-series of vertical Richardson number, eddy viscosity and diffusivity were used to analyze destratification by winds.

Salinity, DO, and current velocity along the transects were