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Worsened physical condition due to climate change contributes to the increasing hypoxia in Chesapeake Bay

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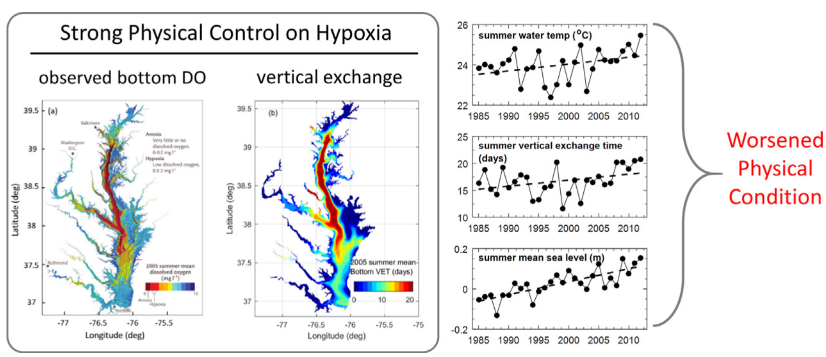
HIGHLIGHTS

- Analysis of observed data and numerical simulations reveal the great control from physical processes on bottom DO
- Physical processes determine the seasonality and spatial distribution of bottom low DO in Chesapeake Bay
- Physical and biological processes contribute equally on the interannual variability of summer hypoxic volume
- Worsened physical condition (temperature + vertical exchange) in the past decades contributed to the increase of hypoxia

GRAPHICAL ABSTRACT



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ABSTRACT

There are increasing concerns about the impact of worsened physical condition on hypoxia in a variety of coastal systems, especially considering the influence of changing climate. In this study, an EOF analysis of the DO data for 1985–2012, a long-term numerical simulation of vertical exchange, and statistical analysis were applied to understand the underlying mechanisms for the variation of DO condition in Chesapeake Bay. Three types of analysis consistently demonstrated that both biological and physical conditions contribute equally to seasonal and interannual variations of the hypoxic condition in Chesapeake Bay. We found the physical condition (vertical exchange + temperature) determines the spatial and seasonal pattern of the hypoxia in Chesapeake Bay. The EOF analysis showed that the first mode, which was highly related to the physical forcings and correlated with the summer hypoxia volume, can be well explained by seasonal and interannual variations of physical variables and biological activities, while the second mode is significantly correlated with the estuarine circulation and river discharge. The weakened vertical exchange and increased water temperature since the 1980s demonstrated a worsened physical condition over the past few decades. Under changing climate (e.g., warming, accelerated sea-level rise, altered precipitation and wind patterns), Chesapeake Bay is likely to experience a worsened physical condition, which will amplify the negative impact of anthropogenic inputs on eutrophication and consequently require more efforts for nutrient reduction to improve the water quality condition in Chesapeake Bay.

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1. Introduction

Hypoxia occurs in a variety of coastal environments when dissolved oxygen (DO) is depleted to a certain low level, where aquatic organisms, especially benthic fauna, become stressed or die due to the lack of oxygen (Diaz and Rosenberg, 1995; Levin et al., 2009; Ekau et al., 2010). The threshold of hypoxia is commonly set to 2 mg O_2/L, but some researchers (e.g., Vaquer-Sunyer and Duarte, 2008) discussed that this value was not conservative enough and suggested higher values. Hypoxia degrades an ecosystem by damaging the bottom fauna habitats, altering the food web, changing the nitrogen and phosphate cycling, decreasing fishery catch, and enhancing the water acidification (Kemp et al., 1990; Breitburg, 2002; Conley et al., 2009; Melzner et al., 2013). Permanent, seasonal, periodical or episodic hypoxia has been found in >500 coastal systems over the globe, and there is mounting evidence suggesting the duration, intensity, and extent of hypoxia have increased over the past half-century (Boesch et al., 2001; Diaz and Rosenberg, 2008; Rabalais et al., 2010; Breitburg et al., 2018). Hypoxia can occur naturally in bottom waters with restricted vertical mixing and in coastal upwelling regions where low oxygen waters are transported onto continental shelves (Pena et al., 2010). Examples of the systems susceptible to hypoxia include Baltic Sea, Black Sea, northern Gulf of Mexico, Chesapeake Bay, Yangtze River Estuary, Mobile Bay, and oxygen minimum zone in the East Pacific, Atlantic and North Indian Ocean (Hagy et al., 2004; Helly and Levin, 2004; Park et al., 2007; Conley et al., 2009; Rabalais et al., 2010; Chen et al., 2015; Wang et al., 2017).

Although hypoxia has been present throughout geologic time, the occurrence of coastal hypoxia has been accelerated by human activities. The increase of hypoxia over the past half-century is widely attributed to the excessive anthropogenic nutrient loads that stimulate intensified eutrophication (Kemp et al., 2005). To reduce the hypoxic volume, remediation measurements on nutrient loads have been carried out in coastal systems (Boesch et al., 2001; Conley et al., 2009). However, hypoxia in many systems responses to the reduction of nutrient loads in a non-linear way and there is little evidence for simple and straightforward response of hypoxia to remediation actions in both US and European coastal systems, due to various reasons including the changing physical condition and altered ecosystem (Conley et al., 2009; Kemp et al., 2009). There is increasing evidence suggesting the climate change, particularly the global warming, has contributed to the increase of hypoxia in coastal and freshwater systems (Bendtsen and Hansen, 2013; Carstensen et al., 2014; Jenny et al., 2014; Altieri and Gedan, 2015). The climate change has altered the physical condition that determines the sensitivity of the ecosystem to external nutrient and organic matter inputs (Howarth et al., 2011). Understanding the physical control is therefore essential to accurately predict the response of a system to the potential change of physical condition and biological condition, and to manage the water quality and ensure the sustainability of the ecosystem.

Hypoxia primarily results from the imbalance of oxygen replenishment and oxygen consumption. The oxygen consumption comes from two components, the water column microbial decomposition of organic matter and sediment oxygen demand, both of which are related to various biogeochemical processes (Bianchi et al., 2010). In most estuarine systems where seasonal hypoxia occurs, hypoxia usually starts with the enhanced oxygen consumption following the spring algal bloom and the strengthened haline and/or thermal stratification with the increase of freshwater discharge and/or temperature (Boesch et al., 2001). Evaluating the relative contribution of biological and physical control on the seasonal and interannual variation of hypoxia is always challenged by the complex coupling between the physical and biological processes (Caballero-Alfonso et al., 2015). For example, with a large river discharge, both the enhanced stratification and possibly intensified algal bloom stimulated by large nutrient loads contribute to the development of a more serious hypoxia. By setting a constant biological environment (e.g., using a constant DO consumption rate), multiple studies have successfully isolated and investigated the physical impact on hypoxia (e.g., Scully, 2013; Chen et al., 2015; Yu et al., 2015; Du and Shen, 2015; Xia and Jiang, 2015; Scully, 2016a). Several important physical processes in estuaries, such as longitudinal circulation, lateral circulation, and stratification, are found to have strong influence on hypoxia (e.g., Scully, 2010a; Xia et al., 2010; Murphy et al., 2011; Li et al., 2016).

Chesapeake Bay, located on the East Coast of US, is the largest estuary in US with a length of about 300 km, a total area of tidal waters of about 11,000 km^2, and a drainage watershed covering 6 states and accommodating 15 million people (Boesch et al., 2001). The hypoxia in Chesapeake Bay was first documented in the 1930s, and it has worsened over the past half century (Newcombe and Horne, 1938; Hagy et al., 2004). The persistent seasonal hypoxia is generally believed to be caused by the intensive organic carbon decomposition following the spring algal bloom and the isolation of bottom water due to strong stratification during the late spring and the summer (Officer et al., 1984). The hypoxic water volume has remained high since the 1980s, despite intense remediation on the land-based nutrient loading (Boesch et al., 2001). It is generally believed the ecosystem has been strongly disturbed and there was a regime shift around the 1980s, with the fact that hypoxic volume per unit nutrient loading was two or more times greater than that during the period of 1949–1984 (Boesch et al., 2001; Kemp et al., 2009; Liu and Scavia, 2010; Testa and Kemp, 2012).

Many studies have been conducted to understand the mechanisms that control the interannual variation of hypoxia, using monitoring data, empirical models, and sophisticated ecosystem models (e.g., Hagy et al., 2004; Murphy et al., 2011; Testa et al., 2014). It is widely agreed that both the biological processes (e.g., nutrient cycling, algal bloom, and decomposition of organic matters) and physical processes (e.g., stratification, longitudinal circulation, and lateral circulations) contribute to the seasonal and interannual variability of bottom DO condition in Chesapeake Bay. In particular, hypoxic volume has been found very sensitive to nutrient loads, wind-induced mixing, and estuarine circulations, all of which are subject to rapidly changing climate (Hagy et al., 2004; Kemp et al., 2005; Scully, 2010a; Najjar et al., 2010; Jiang and Xia, 2017). Hagy et al. (2004) related the interannual variation of hypoxia to the nutrient loads and river discharge. Scully (2010a) found the interannual variation of hypoxic volume can be much better explained when including the physical forcing, particularly the wind forcing. The physical condition is highly regulated by the large-scale climate variation, such as the North Atlantic Oscillation (Scully, 2010b; Du and Shen, 2015). However, there is still a knowledge gap on the contribution of overall physical condition on the seasonal or interannual variation of DO.

The primary goal of the present study is to investigate the physical control on the bottom DO condition and to examine the long-term trend of physical forcings over the past few decades. To this end, we utilized the long-term observation data (1985–2012) and numerical model simulations of the vertical exchange processes. We applied EOF analysis to the raw observational data to decompose the temporal-spatial variation of the DO in the mainstem of Chesapeake Bay, and explained the primary modes. We scaled the vertical exchange to quantify the overall impact of various physical transport processes (e.g., horizontal advection, vertical diffusion, and vertical advection) and examined its influence on the interannual variability of hypoxic volume in Chesapeake Bay.

2. Methods

2.1. Data collection

We collected monitoring data from the Chesapeake Bay Program (CBP) for 1985–2012 at 16 stations (Fig. 1), whose locations are approximately evenly distributed along the mainstem of Chesapeake Bay (http://www.chesapeakebay.net). The monthly or semimonthly observation