Marine Pollution Bulletin 97 (2015) 349–364

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Physical controls of hypoxia in waters adjacent to the Yangtze Estuary: A numerical modeling study

Xiaofeng Chen [a], Zhenyao Shen [a,*], Yangyang Li [b], Ye Yang [a]

[a] State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, PR China
[b] Chinese Academy for Environmental Planning, #8 Dayangfang, Beiyuan Rd., Chaoyang District, Beijing 100012, PR China

ARTICLE INFO

Article history:
Received 2 March 2015
Revised 28 May 2015
Accepted 29 May 2015
Available online 6 June 2015

Keywords:
Hypoxia
Simulation
Discharge
Wind speed
Wind direction
Yangtze Estuary

ABSTRACT

A three-dimensional circulation model (the Environmental Fluid Dynamic Code) was used to examine the role that physical forcing (river discharge, wind speed and direction) plays in controlling hypoxia in waters adjacent to the Yangtze Estuary. The model assumes that the biological consumption of oxygen is constant in both time and space, which allows the role of physical forcing in modulating the oxygen dynamics to be isolated. Despite of the simplicity of this model, the simulation results showed that it can reproduce the observed variability of dissolved oxygen in waters adjacent to the Yangtze Estuary, thereby highlighting the important role of changes in physical forcing in the variation of hypoxia. The scenarios tested revealed appreciable changes in the areal extent of hypoxia as a function of wind speed and wind direction. Interestingly, well-developed hypoxia was insensitive to river discharge.

1. Introduction

The concentration of dissolved oxygen (DO) in marine waters depends on the physical processes of mass transport, mixing, and air–sea exchange as well as photosynthesis, chemolithotrophic production, and metabolism in the water column and sediment. When the rate of oxygen diffusion from the sea surface is outpaced by oxygen-consuming decomposition, the oxygen concentration decreases and hypoxia can occur. Hypoxia is usually defined as an oxygen level < 30% saturation (62.5 μmol L^{-1} or 2 mg L^{-1}). Hypoxic conditions can cause suffocation and aberrant behavior of benthic fauna and can negatively impact fishery production. Moreover, low DO levels in coastal waters are a widespread phenomenon that appears to be growing globally (Diaz and Rosenberg, 2008). As a result, hypoxia has received extensive scientific and management interest (Shen et al., 2008; Zhang and Li, 2010; Le et al., 2014). Hypoxia occurs in a variety of coastal environments around the world (Diaz, 2001). The coastal areas of the Baltic Sea, northern Gulf of Mexico, northwestern shelf of the Black Sea, and the Yangtze Estuary are the largest hypoxic zones in the world (Chen et al., 2007; Bianchi et al., 2010; Väli et al., 2013; Capet et al., 2013). The hypoxic zone adjacent to the Yangtze Estuary geographically overlaps with the habitat and fishing grounds of commercially important fish and shrimp species, thus it has been the focus of considerable scientific and public attention since it was first detected.

Direct observations of hypoxic and anoxic bottom waters adjacent to the Yangtze Estuary were first made in 1959 (Gu, 1980). Continued water quality sampling demonstrated that low oxygen levels in bottom waters is a recurring seasonal phenomenon in this area (Chen et al., 2007; Li et al., 2011; Wei et al., 2007; Zhu et al., 2011). Most centers of hypoxia observed in the past 50 years (1959–2006) were situated around 123°E, 30°50′N, but the spatial extent and duration varied considerably from year to year (Wang, 2009). Jiang (2009) reported that the areal extent of hypoxia and the lowest DO concentration had increased and decreased, respectively, since the first measurements were made in the 1950s.

It is generally accepted that the increased nutrient loads that have been delivered to the system have increased the extent and severity of oxygen conditions adjacent to the Yangtze Estuary (Ning et al., 2011; Zhu et al., 2011; Wang et al., 2014). In addition, physical factors can generate stratification patterns that prevent transfer and mixing between oxygen-depleted bottom waters and oxygen-enriched surface water. Chen et al. (2014) reported that stratification of the water column and oxygen consumption through organic decomposition were two factors essential for the formation of hypoxia off the Yangtze River. Thus, nutrient loading may fail to explain the majority of the variability in hypoxia, and many studies have focused on investigating the dominant factors

* Corresponding author.
E-mail address: zyshen@bnu.edu.cn (Z. Shen).

http://dx.doi.org/10.1016/j.marpolbul.2015.05.067
0025-326X/

that modulate the DO concentration in bottom waters. For example, Wilson et al. (2008) analyzed bottom DO and density stratification in western Long Island sound and found that wind-induced current shear plays an important role in controlling stratification and vertical mixing. Interannual variations in both the direction and directional constancy of summertime winds over western Long Island were shown to control the ventilation of bottom waters and thereby the seasonal development of hypoxia. Scully (2010) conducted numerical studies in Chesapeake Bay and reported that the interaction between wind-driven lateral circulation and enhanced vertical mixing over shoal regions was the dominant mechanism for providing oxygen to hypoxic subpycnocline waters.

Other studies demonstrated that the formation and evolution of hypoxia in the Yangtze Estuary were closely related to complicated physical processes from the interaction of the Changjiang Diluted Water, Taiwan Warm Current, and wind forcing in addition to chemical and biological processes and bottom topography (Ning et al., 2011; Wang, 2009; Wei et al., 2007; Zhou et al., 2010). Through continuous observation at a stationary station adjacent to the Yangtze Estuary, Ni et al. (2014) found that the bottom DO concentration is correlated with wind magnitude. Wind direction also plays a key role in modulating the oxygen dynamics in hypoxic zones (Feng et al., 2014; Scully, 2013), including the Yangtze Estuary (Jiang et al., 2014; Wei et al., 2007). Field observations indicated that Yangtze River freshwater is the main buoyancy input to the East China Sea, thus it is the most important factor contributing to the stratification that leads to hypoxia (Chen et al., 2007; Rabouille et al., 2008). However, to date there is no direct evidence to quantify the effect of the Yangtze River discharge (independent from the associated biological response to higher nutrient delivery) on hypoxia. Moreover, how changes in wind speed and direction impact the spatial extent of hypoxia in the Yangtze Estuary is poorly understood.

Continuous monitoring of the occurrence and expansion of seasonal hypoxia events over a large domain is a challenging task because the events happen at the bottom of the water column and are highly variable due to the influences of ocean currents, typhoons, and fluctuations of freshwater and nutrient loads from the land. It is difficult to examine the effects of physical and biological factors on hypoxia based on measurements alone. Determining how physical and biological processes control hypoxia is important because if hypoxia is strongly affected by variability in physical factors, then different nutrient control end-points may be required to reach the same hypoxic condition under different physical forcing scenarios. Numerical simulation is a valuable tool because it allows a single factor to be isolated from other factors. In this study, we used the widely accepted Environmental Fluid Dynamic Code (EFDC) model to investigate the effects of river discharge, wind speed, and wind direction on the areal extent of hypoxia in summer adjacent to the Yangtze Estuary (Tetra Tech, 2007; Jia et al., 2011; Guo and Jia, 2012).

2. Model configuration

2.1. Study area

The Yangtze Estuary is situated in the eastern part of China (3 0°40′N–31°40′N, 120°55′E–123°00′E) and extends from the non-flood tidal current upstream boundary at Datong to the subaqueous delta, where the interaction of saline and fresh water occurs (Fig. 1). The Yangtze Estuary is a branching estuary that is characterized by a three-tier bifurcation with four openings to the East China Sea that are separated by Chongming Island, Changxing Island, and Jiuduansha Shoal from Xuliujing to the outer sea. It is a mesotidal estuary with a symmetric semi-diurnal tide offshore and irregular asymmetric semi-diurnal tides inside the mouth due to the variation in topography (Chen et al., 1988).

Freshwater discharge of the Yangtze River is the fifth largest in the world (Chen et al., 1988). Discharge varies widely from year to year and exhibits a pronounced seasonal cycle, with high discharge occurring in summer and autumn and low discharge from winter to spring. The annual mean freshwater discharge to the estuary is 29,300 $m^3\ s^{-1}$. The period from May to October is the flood season, which accounts for 70% of the total annual runoff. The maximum discharge occurs in July and August. The dry season is from November to April and accounts for < 30% of the total annual discharge. The minimum discharge occurs in February.

A large quantity of pollutants is discharged into the sea in China every year. Fifty percent of this amount empties into the China East Sea and directly impacts the water quality in the Yangtze Estuary (Chai, 2006). Nitrogen concentration is high, about 80.6 μmol/L, due to the annual river discharge is up to $9.0 \times 10^{11}\ m^3$ (Zhang, 2002; Zhou et al., 2008), and it affects phytoplankton growth, which exhibit obvious seasonal variation with a bimodal pattern, and the peak value always occurs in later winter and early autumn. The nitrogen concentration decreases with increasing distance away from the river mouth. Similarly, a bimodal peak of phosphorous concentration, about 1 μmol/L, occurs in late winter and autumn (Wang, 2006; Zhang, 2008; Zhou et al., 2008), and the concentration is higher near shore than offshore (Tang, 2009).

2.2. EFDC characteristics

The EFDC, which was originally developed by Hamrick (1992), is a public-domain modeling package for simulating three-dimensional flow, transport, and biogeochemical processes in surface water systems, including rivers, lakes, estuaries, reservoirs, wetlands, and coastal regions (Zhao et al., 2011; Jia et al., 2011; Guo and Jia, 2012; Hong and Shen, 2013; Shen et al., 2014). It was previously applied to the Yangtze Estuary to explore its hydrodynamics (Wang et al., 2010). The EFDC can simulate hydrodynamics, salinity and temperature transport, sediment transport, oxygen dynamics, the eutrophication process, and the transport and fate of dissolved and particulate toxic contaminants. The hydrodynamic module of the EFDC is based on the Princeton Ocean Model (Blumberg and Mellor, 1987), and the physics and computational scheme used in both models are the same. Dynamically coupled transport equations for turbulent kinetic energy and the turbulent length scale are solved using the Mellor–Yamada level 2.5 turbulence closure scheme (Mellor and Yamada, 1982). A sigma vertical coordinate and curvilinear and orthogonal horizontal coordinates are used in this model. The governing hydrodynamic equations can be found in Tetra Tech (2007).

In this study, the water quality module embodied in EFDC was applied to simulate the oxygen dynamics in the Yangtze Estuary. This module was combined with the hydrodynamic model internally and with the same spatial resolution, so the flow or current generated by the hydrodynamic component directly passed to the water quality component to drive the transport of materials internally. This model was used to explore the hypoxia dynamics in the Chesapeake Bay, and it was found to embody the main processes influencing the hypoxia dynamics (Hong and Shen, 2013). The kinetic processes included in the EFDC are equivalent to those in the Chesapeake Bay three-dimensional water quality model (CE-QUAL-ICM) (Cerco and Cole, 1994). The water quality module embodied in the EFDC model system includes 22 state variables. The equation representing the oxygen dynamics is as follows: