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Effects of stratification, organic matter remineralization and bathymetry on summertime oxygen distribution in the Bohai Sea, China

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ABSTRACT

The Bohai Sea, a semi-enclosed shallow coastal sea with increasing nutrient loads, is susceptible to seasonal oxygen deficiency in its bottom waters, similar to many other areas of the worlds' coastal oceans. We examined the dissolved oxygen (DO) distribution in the Bohai during August 2014. Two oxygen-deficient zones (DO < 92 μmol O_2 kg^{-1}) with a minimum DO of ~80 μmol O_2 kg^{-1} were documented. The area and volume of bottom oxygen-deficient water were ~756 km^2 and 7820×10^6 m^3, with a mean thickness of ~10 m. Thus, the Bohai is second to the Changjiang estuary in its oxygen-deficient zone size among China's coastal waters. We classified three hydrographic areas that dictated the distribution of DO: 1) the shallow well-mixed zone; 2) the laterally-open stratified zone; and 3) the isolated stratified zone. Vertical mixing dominated the shallow well-mixed zone leading to homogeneous DO in the water column. The laterally-open stratified zone was influenced by high DO and low temperature inflow through the northern Bohai Strait. The isolated stratified zones, i.e., the low DO areas, were found in depressed regions. The stoichiometric relationship between DO consumption and the corresponding enrichment of dissolved inorganic carbon suggested that the aerobic respiration of organic matter contributed to the oxygen-depletion in the isolated stratified zone. Overall, the bottom DO distribution in the Bohai system was controlled largely by lateral DO exchange modified by bathymetric features, while superimposed on that was the build-up of stratification caused by summer heating and the remineralization of organics sourced from spring phytoplankton bloom.

1. Introduction

Hypoxia, typically defined as dissolved oxygen (DO) levels less than 63 μmol O_2 kg^{-1}, affects diversity, abundance and biomass of benthic communities, and even damages ecosystem functions (Diaz and Rosenberg, 1995, 2008; Ekau et al., 2010; Levin et al., 2009). Severe hypoxia not only triggers massive benthic mortalities and creates dead zones, such as in the Gulf of Mexico (Rabalais et al., 2002) and the Baltic Sea (Conley et al., 2009), but also causes a series of reactions such as denitrification, metal oxide reduction, sulfate reduction and methanogenesis (Conley et al., 2009; Middelburg and Levin, 2009; Peña et al., 2010; Reeburgh, 1983; Santschi et al., 1990). These reactions may generate greenhouse gases, e.g., nitrous oxide and methane (Naqvi et al., 2010), as well as toxic compounds, e.g., hydrogen sulfide (Luther et al., 1991). Thus, the DO supply to aquatic environments plays a critical role in sustaining the system in terms of ecosystem and biogeochemical cycles.

Coastal hypoxia can be induced by both natural and anthropogenic processes. Coastal hypoxia due to natural processes is primarily related to upwelling in areas with an oxygen minimum zone (Helly and Levin, 2004), while human-induced coastal hypoxia is primarily caused by eutrophication associated with water column stratification (Diaz and Rosenberg, 2008; Levin et al., 2009; Rabalais et al., 2010, 2014). As a result of the increased nutrient loads caused by rapid development of human activities, coastal hypoxic sites have spread up to ~400 sites globally (Diaz and Rosenberg, 2008) with a growth rate of 5.54% $year^{-1}$ (Vaquer-Sunyer and Duarte, 2008). With the addition of 96 hypoxia sites around the Baltic Sea, the number of hypoxia sites worldwide is now reported to be 500 sites (Conley et al., 2011), underscoring the fact that coastal hypoxia is a prominent global environmental issue. In many of these systems the natural physical features are conducive to hypoxia occurrence. Considering the fact that anthropogenic influence

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will continue to increase, coastal environmental degradation is likely to be unavoidable.

The Bohai Sea is a shallow, semi-enclosed coastal sea with a water residence time of ~1.5 years (Li et al., 2015). It is located in one of the most important economic development zones in China, the Bohai Economic Rim. Since the 1990s, the concentration of dissolved inorganic nitrogen has significantly increased in the Bohai Sea (Wang et al., 2009). Coincident with excess nutrients are increased occurrence and expanse of algal blooms from 2000 to 2014 with an average size of ~2,600 km^2 (Fig. S.1). Owing to the high level of nutrient inputs and long water residence time, the Bohai Sea is susceptible to summer hypoxia. Past investigations in the Bohai Sea have not recorded hypoxia (Cui et al., 1994; Ning et al., 2010; Zhang, 1992), although DO in the bottom water of the Bohai Sea has exhibited a decreasing trend since 1979 (Zu et al., 2005). The recent report by Zhai et al. (2012) found a minimum DO of 100 μmol O_2 kg^{-1} in August 2011. Increasing harmful algal blooms, mariculture activities, and development of cities surrounding the Bohai Sea will contribute to worsening water quality in the Bohai Sea in the form of bottom-water oxygen depletion where conditions are conducive to its formation. A better understanding of the physical and biological factors leading to hypoxia may provide guidance for water quality management.

We documented the three-dimensional structure of DO conditions in the Bohai Sea during August 2014 when hypoxia is likely to occur. Our study is the first to examine the coupled effects of stratification, organic matter remineralization and the bottom exchange affected by the bathymetric features on the distribution of the bottom DO. We also identified certain regions within the Bohai Sea where hypoxia is likely to develop and quantified the area and volume of the oxygen-deficient water.

2. Materials and methods

2.1. Study Area

The Bohai Sea is connected to the northern Yellow Sea through the Bohai Strait (Fig. 1). The total area of the Bohai Sea is 77,000 km^2 and consists of four regions: the central Bohai Sea (CBS), Liaodong Bay (LDB), Bohai Bay (BHB) and Laizhou Bay (LZB). The Bohai Sea receives 1.03×10^{11} m^3 yr^{-1} in runoff from a watershed area of 1.3×10^6 km^2 from four major rivers, the Liaohe, Luanhe, Haihe and Yellow Rivers (China Water Statistical Yearbook 2013). The freshwater influence is restricted to the nearshore areas of LDB, LZB and BHB. The mean depth of the Bohai Sea is 18 m, and the deepest water is found adjacent to the northern Bohai Strait with a depth of ~80 m. Two unique bathymetric features of the Bohai Sea are 1) the deep water channel that connects with the northern Bohai Strait; and 2) a shallow central ridge (Fig. 1) near stations S64-S65 (5–10 m shallower than the surrounding water).

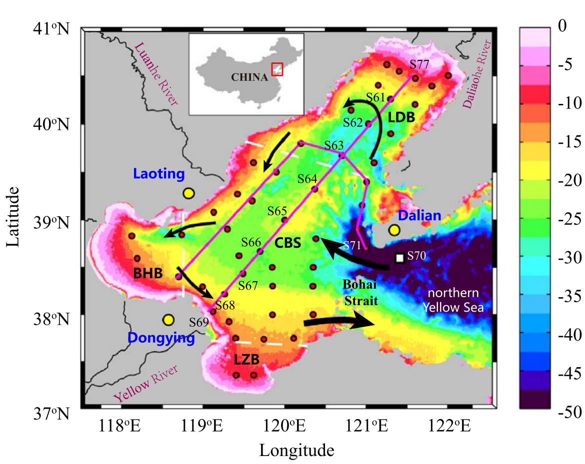

Fig. 1. Survey area and sampling sites in August 2014. The color bar represents water depth. White dashed lines are the boundaries between these sub-regions. LDB, BHB, LZB and CBS represent the Liaodong Bay, Bohai Bay, Laizhou Bay and the Central Bohai Sea. The black solid arrows indicate the circulation pattern in summer (Guan, 1994). Red circles indicate sampling stations. Magenta solid lines indicate the sections used to display the cross sectional distributions of DO. The section starting from Daliaohe Estuary (S77) southward to Yellow River Estuary (S69) was named as the DY section.

The Bohai Sea is influenced by the East Asia Monsoon, which is characterized by weak southeasterly winds in summer and strong northwesterly winds in winter. Due to the effects of seasonal solar insolation and monsoon wind-induced mixing, stratification in the Bohai Sea starts to build up in the spring and decreases in the autumn (Huang et al., 1999). Water from the northern Yellow Sea flows into the Bohai Sea through the northern Bohai Strait and returns to the northern Yellow Sea via the southern Bohai Strait (Fig. 1). In summer, the dominant circulation in the Bohai Sea is transported from the northern Bohai Strait, and moves westward along the CBS. Two surface cyclonic gyres are located to the south and north of this dominant circulation (Guan, 1994; Huang et al., 1999).

2.2. Sampling and analysis

Data were collected between 16 and 21 August 2014 at the stations indicated in Fig. 1. Field measurements of temperature, salinity and DO were taken using an SBE-19-plus Conductivity-Temperature-Depth/Pressure unit (Sea-Bird Co.) equipped with a calibrated SBE-43 DO sensor and a WET Labs ECO FLNTU sensor, the latter of which was used to analyze the turbidity and chlorophyll content. Discrete water samples for DO, dissolved inorganic carbon (DIC) and total alkalinity (TA) were taken at two to four depths depending on the total water depth and location of the thermocline, using a rosette sampler with 2.5 L Niskin bottles. DO was measured on board using the Winkler method. DIC and TA samples were collected using 60 mL borosilicate glass bottles and 140 mL high-density polyethylene bottles, respectively. Before the DIC and TA samples were sealed with screw-on caps, 50 μL saturated $HgCl_2$ was added to them. They were stored at room temperature for later analysis. DIC and TA analyses were based on the methods described in Cai et al. (2004) and Zhai et al. (2014). After a 0.5 mL DIC sample was acidified, a non-dispersive infrared detector (LI-COR 7000) was used to analyze CO_2 levels and determine the DIC concentration. TA was determined through Gran acidimetric titration of a 25 mL sample. A precision pH meter and an Orion® 8102BN Ross electrode were used for detection. Certified reference materials from A. Dickson of the Scripps Institute of Oceanography were used for quality assurance to ensure the precision was maintained at a level of ± 2 μmol kg^{-1} for the DIC and TA analyses (Cai et al., 2004; Zhai et al., 2014).

2.3. Data Processing

2.3.1. DO calibration and apparent oxygen utilization

The DO sensor was consistent with the Winkler titrations ($y=1.0455x+0.1314$, $R^2=0.9966$ in Fig. A.1a). Apparent oxygen utilization (AOU) was computed using Eq. (1) to indicate the departure of measured oxygen levels from a saturated concentration:

$$AOU = [O_2]_{eq} - [O_2] \quad (1)$$

where $[O_2]_{eq}$ is the concentration of DO in equilibrium with the atmosphere (Benson and Krause, 1984); and $[O_2]$ is the measured DO level in the field.

2.3.2. Mixed layer depth (MLD)

The mixed layer depth (MLD) was calculated using a density-based criterion (Glover and Brewer, 1988; Kara et al., 2000). The density for the MLD was determined by a 0.8 °C decrease of temperature at a reference depth of 5 m: