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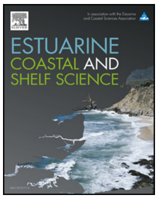

The sinking of the phytoplankton community and its contribution to seasonal hypoxia in the Changjiang (Yangtze River) estuary and its adjacent waters

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ABSTRACT

The phytoplankton sinking rates and the annual variations of dissolved oxygen (DO) were studied as part of a multi-disciplinary investigation in the Changjiang (Yangtze River) Estuary (CE) and its adjacent waters from February 2015 to January 2016. The sinking rates of phytoplankton ranged from 0.02 to 3.49 $m\ d^{-1}$, determined with the homogeneous sample method SETCOL. There was clear correlation between sinking rate and the phytoplankton composition. The diatom-dominated community had higher sinking rates than the dinoflagellate-dominated community, and the variation in DO concentration indicated a close relationship with the blooming and senescence of phytoplankton. Low DO ($< 3\ mg\ L^{-1}$) or hypoxic ($< 2\ mg\ L^{-1}$) zones were observed in near-bottom waters between July and October. Hypoxia reached its maximum in October, with a low DO zone covering approximately 4500 km^2 of the survey area. The zones of lowest DO in near-bottom water were closely associated with zones of the highest chlorophyll *a* (Chl *a*) and the highest phytoplankton sinking rates in the upper layer. The present study presents straightforward evidence on the formation of low DO and hypoxia in near-bottom waters and its correlation with sinking of the phytoplankton community, and provides useful insight to reveal the formation mechanism of seasonal hypoxia in the CE and its adjacent waters.

1. Introduction

Large estuaries and adjacent coastal ocean represent a transition zone between rivers and oceans, which are particularly vulnerable to adverse environmental impacts. Eutrophication and hypoxia are among the major coastal stresses associated with complex natural processes and anthropogenic activities (Feely et al., 2010; Cai et al., 2011). Hypoxia has furthermore been widely observed in various estuarine, coastal and gulf regions, including the Gulf of Mexico, the Black Sea, the Baltic Sea and the CE (Rabalais et al., 2002; Mee, 1992; Conley et al., 2011; Chen et al., 2007). Its intensity, duration and frequency has increased dramatically in the past decades, and has resulted in deterioration of biodiversity and fishery resources in various ecosystems (Diaz, 2001; Chen et al., 2007; Conley et al., 2011). Hypoxia can also alter the biogeochemical cycles of major elements (Turner et al., 2008). Besides, hypoxia has been found primarily associated with marine-sourced organic carbon production, which is stimulated by coastal eutrophication resulting from excessive terrestrial nutrient runoff (Zhou et al., 2008; Zhang et al., 2010; Bianchi and Allison, 2009).

The CE has a complicated hydrological system, and is mainly affected by Changjiang Diluted Water, the coastal currents along Mainland China, the Taiwan Warm Current from Taiwan Strait, and a branch of the Kuroshio Current from northeast Taiwan (Su, 1998). Similarly to other typical estuaries that are severely impacted by anthropogenic activities, the CE and its adjacent waters have been suffering from serious eutrophication and seasonal hypoxia (Chai et al., 2006; Li et al., 2007; Zhang et al., 2007b). Previous investigations indicated that the hypoxia in the CE started in late spring and early summer, became most serious in August, lessened in autumn and finally disappeared in winter (Wang et al., 2012). In summer 2006, hypoxia in the CE and adjacent waters covered an area of up to 15,400 km^2 (Zhu et al., 2011). It was closely associated with stratification of the water column and the decomposition of organic matter produced mainly by surface phytoplankton (Li et al., 2002; Wei et al., 2007).

Water column stratification influences the replenishment of oxygen by restricting exchanges between near-bottom waters and surface waters. And the elevated primary production sinking below the pycnocline leaded to more oxygen depletion in near-bottom waters (Wang, 2009;

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Li et al., 2011; Chen et al., 2015; Wei et al., 2015; Zhu et al., 2016). Phytoplankton are the most important primary producers of the marine food chain, playing a key role in the elemental cycles and energy flow. Marine phytoplankton take up CO_2 in surface waters through photosynthesis, leading to oxygen oversaturation. When massive amounts of phytoplankton sink and decompose near the bottom, oxygen is consumed. Coupled with strong water column stratification, the bottom water becomes hypoxic. It is generally considered that rapidly sinking phytoplankton cells are the major contributors to carbon export from surface layers, while slowly sinking cells contribute less (Boyd and Newton, 1999). Diatom-dominated community show higher sinking rates than dinoflagellate-dominated community, thus favouring consumption of dissolved oxygen in the bottom waters (Guo et al., 2016). Comprehensive study on the sinking of phytoplankton is therefore important to reveal the sedimentation mechanisms of carbon as well as the formation of hypoxia.

To date, there has been no complete monthly record of sinking in the phytoplankton community and thus no record of its correlation with DO in the hypoxic zone of the CE and its adjacent waters, despite various snapshots, annual or seasonal observations (Wang et al., 2012). Thus, from February 2015 to January 2016, ten multi-disciplinary investigations in the CE and its adjacent waters was conducted, to study the sinking of the phytoplankton community and the distribution and seasonal variations of DO. Furthermore, the inherent relationship among environmental parameters, phytoplankton sinking rates, and the formation of hypoxia in the CE and its adjacent waters were comprehensively assessed. The underlying hypothesis is that hypoxia in the near-bottom waters was correlated to the sinking of phytoplankton community dominated by diatoms in the upper layer of the study area.

2. Methods

2.1. Study area and cruise

The CE, one of the largest estuaries in the world, is a highly productive aquatic ecosystem (Ning et al., 2004). The Changjiang River is the world's third longest river, strongly influencing the CE and the adjacent area, forming stratified and turbid plumes, especially during summer, with a basin area of $1.8 \times 10^6\,km^2$ (Fig. 1). Maximum river discharge typically occurs in July and August and carries a large load of terrestrial materials (nutrients and organic matter) from the drainage basin into the study area (Zhang et al., 2007a). Due to the high nutrient supply, algal blooms and hypoxia frequently occur during flooding seasons (Tang et al., 2006). The study area is controlled by the East Asian Monsoon climate, which produces a homogeneous vertical distribution of temperature and salinity in the winter and early spring.

Ten cruises were conducted aboard the R/V Kexue 3 and R/V Beidou from February 2015 to January 2016 in the CE and its adjacent waters (28.0°～33.0° N, 122.0°～124.5° E). The sampling sites and stations are presented in Fig. 1 and Table 1. A typical transect (transect 12,300) has been selected to further study and illustrate vertical distributions.

2.2. Field sampling and sample processing

The profiles of temperature, salinity and density were recorded by CTD device (SBE 917, Sea-Bird Scientific, USA). Discrete water samples were collected at the surface, at depths of 5 m, 10 m, 20 m, 30 m, and 50 m, and at the bottom (2 m above the sediment) using 12-L Niskin bottles (KC-Denmark Ltd., Denmark) at each station.

DO was analyzed onboard according to Strickland and Parsons (1972). Water samples were filtered through acetate fibre membranes (0.45 μm) for analysis of inorganic nutrients (nitrate, nitrite, ammonium, phosphate and silicate), which were analyzed by a SKALAR Flow Analyzer. The Chl *a* was collected by filtering 250–500 ml of seawater through 200 μm nylon mesh and GF/F filters in turn under low vacuum pressure (< 0.04 MPa) and stored at −20 °C in the dark. After extraction with 90% acetone, Chl *a* concentration was measured with the fluorometric technique using a Turner Design fluorometer (Strickland and Parsons, 1972). Water samples for phytoplankton analysis were preserved with buffered formalin (2% final concentration). For quantitative analysis, 10–25 ml of the subsamples were settled in a Hydrobios chamber for 24 h, then identification and enumeration of taxa were carried out using an inverted light microscope (IX71, Olympus, Japan) at × 200 or × 400 magnification as described by Utermöhl (1958). The lower size limit of resolution for this analysis was ~ 5 μm.

Phytoplankton sinking rates were measured at surface layer by the SETCOL method (Bienfang, 1981). For each station, three Plexiglas columns were replicated. For analysis, a Plexiglas column with a height of 0.348 m and a volume of 460 ml was filled with a homogeneous seawater sample and capped. The SETCOL apparatus was then kept in the dark undisturbed for 1 h. The incubation was terminated by successively draining the upper, middle and bottom layers of the SETCOL compartments by taps through the wall. The phytoplankton biomass before and after incubation in all three compartments were combined to calculate the sinking rates. The water samples were collected for Chl *a* measurement, which was used to determine the whole phytoplankton community sinking rates according to the formula:

$$\psi = (Bs / Bt) \times L / t.$$

Here, ψ is sinking rate; Bs is the biomass settled into the bottom compartment; Bt is the total biomass in the column; L is the length of the column; t is settling interval.

2.3. Data analysis

The dominant species of phytoplankton were determined by the McNaughton index (Y), according to the following formula:

$$Y = (n_i / N) \times f_i$$

where n_i is the sum of cell abundance for species i in all samples; N is the sum of cell abundance for all species, and f_i is the frequency of occurrence for species i in all samples.

The phytoplankton sinking rates and the environmental parameters were normally distributed, thus Pearson correlation analysis between phytoplankton sinking rates and environmental parameters was conducted using the commercial software package SPSS20.0 (SPSS Inc., USA). While the five zonal positions of low DO and high Chl *a* were not normally distributed, thereby the Spearman's rho correlation analysis between the zonal positions of low DO and high Chl *a* was conducted using the commercial software package SPSS20.0.

The intensity of stratification was determined by the $\Delta\delta/\Delta Z$ ($\Delta\delta$ is the density difference between the upper and lower layers of the pycnocline, and ΔZ is the thickness of the pycnocline). The boundary of the pycnocline was determined according to the density gradient in the vertical direction (Liu et al., 2001; Hao et al., 2010).

3. Results

3.1. Variation of the major environmental factors

The surface temperature increased from February (average = 11.17 ± 3.22 °C) to July (average = 27.09 ± 0.70 °C) of 2015 and then decreased gradually until January 2016 (average = 14.10 ± 3.43 °C) (Fig. 2). In the summer and fall of 2015, the temperature was within the range 17.72–28.15 °C, with the maximum at station Zb12c. The southeast of the study area were influenced by the Taiwan Warm Current, which led to the relative high temperature and salinity in summer and autumn.

The surface salinity of the CE and its adjacent waters was primarily impacted by the freshwater input from the Changjiang River. It showed