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Distribution of suspended particulate matter in the northern Bohai Bay in summer and its relation with thermocline

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ABSTRACT

Field observations of suspended particulate matter (SPM) in the Bohai Bay, China have not been widely reported. The aim of this paper is to describe the horizontal and vertical distribution of mass and volume concentrations of SPM, respectively, based on observed data at 312 stations in the northern Bohai Bay during summer of 2006. A numerical model ECOMSED coupled with a sediment transport module was also established to further discuss the mechanism of the thermocline effect on the vertical distribution of SPM. The mass concentrations of SPM exhibited high inshore values and low offshore values in the horizontal distribution; while in the vertical direction, characteristics of the volume concentration of SPM can be divided into two types: one with a sharp peak at depth of 10–15 m and another without. The peak value at the depth of the thermocline was resulted from concentrated phytoplankton. A numerical experiment further displayed that the thermocline can also prevent particles from being resuspended upward.

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1. Introduction

River discharge, winds, waves and currents are recognized as important factors affecting the distribution of suspended particulate matter (SPM) in water (Wu, 1995; Ogston et al., 1999; Guo et al., 2002; Liu et al., 2006; Song et al., 2006). In addition, some seasonal factors such as thermocline can also affect SPM distribution. During the summertime, water exhibits thermal stratification. The layer where temperature decreases rapidly with depth is called thermocline, which plays a key role in the distribution, especially in the vertical direction, of nutrients and productivity (Bao and Chai, 1995; Zhang et al., 2001; Byun et al., 2005; Yin et al., 2006; Li et al., 2008; Dueri et al., 2009). Based on the transmittance and temperature data in the south Yellow Sea, thermocline can be regarded as an invisible unidirectional valve which can keep the SPM in the bottom water (Zheng et al., 1990) from being diffused to the surface (Bai et al., 2002). Field observation data in Lake Michigan during summer stratification also showed that suspended materials were concentrated at the base of the thermocline (Harrsch and Rea, 1982).

Bohai Bay is one of the three bays forming the Bohai Sea, located in northeastern China (Fig. 1). According to Jiang et al. (2002), tidal currents are the major hydrodynamic factor control the SPM distribution in the Bohai Sea. However, waves can lift much more particles from seabed during wind days. Rare studies of the SPM in the Bohai Bay showed that sediment discharged from the Yellow River could be transported into southern Bohai Bay (Wen and Zhang, 1989). The developing projects Caofeidian Harbor could have the effect on the SPM distribution, because of sediment overflow from the inning inlets (Lu et al., 2007). However, field observations and detailed analysis of SPM in the Bohai Bay in summer have not been widely reported.

Thus, in this paper, based on the field observation data described in Section 2, we aim to display the horizontal and vertical distribution of SPM in the middle and northern Bohai Bay in Section 3, and we further discuss the mechanism of the thermocline effect on the distribution of SPM in Section 4 by field data analysis and numerical simulation.

2. Observations

Bohai Bay is a semi-closed shallow water system with an area of 15,900 km^2 and an average depth of 12 m (Fig. 1). The Lagrangian

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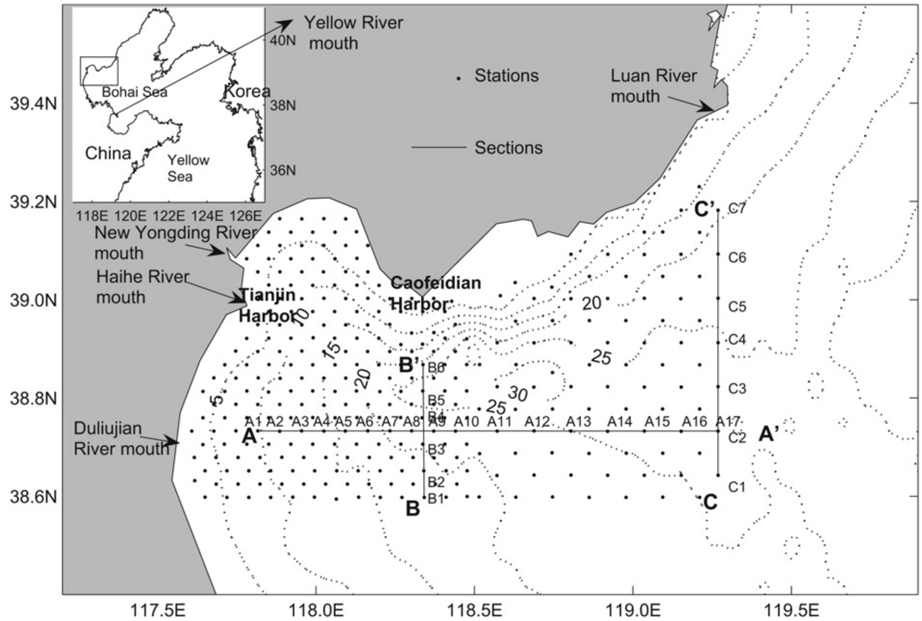

Fig. 1. Distribution of observation stations in the northern Bohai Bay. Black dots denoted stations, dashed lines indicated water depth in meter and thick lines showed sections.

residual current in the Bohai Bay is clockwise (Jiang et al., 1997) and waves are mainly caused by easterly wind (Wang et al., 2004). M_2 is the dominant tidal constituent with tidal amplitude of 0.6 m near the bay entrance and 1 m in the eastern reaches of the bay (Wang and Lin, 2006). Besides the Yellow River, situated near the southeast entrance of Bohai Bay, the Haihe, New Yongding and Duliujian Rivers flow into the northern Bohai Bay. However, the freshwater inflow and sediment discharge of these rivers are limited and intermittent after 1980s, though the total annual values of the Haihe, New Yongding and Duliujian Rivers can reach 9.23 billion m^3 and 0.3 million tons during local heavy periods of rain (Lei et al., 2007). Furthermore, Caofeidian and Tianjin Harbor are two developing projects in the Bohai Bay, their collective effect on the aquatic environment will not only be relevant to water quality (e.g., Shen et al., 2005; Gao and Yang, 2006; Wang et al., 2007; Lu et al., 2007) but also the SPM distribution, because of sediment overflow from the inning inlets.

During the summer of 2006, we conducted an extensive observation of 312 stations in the middle and northern sections of the Bohai Bay (Fig. 1) from 24 August to 22 September. Water temperature, water salinity, volume concentration (VC) and mass concentration (MC) of SPM, *in situ* particle size, chlorophyll-*a* and turbidity were measured. The observation can be considered to be quasi-synchronous though the duration is nearly one month, because of absent of heavy wind thus high wave and lack of hard rain thus large sediment discharge in the study area during the observation (Yang and Zhou, 2007). Distance between each pair of stations is no farther than 5 km.

Vertical distributions of temperature, salinity, turbidity and chlorophyll-*a* were measured by CTD (made by AAQ1183, ALEC Electronics, Japan) at the grid of stations shown in Fig. 1. During each survey, the instrument was released using a winch with a uniform speed. The vertical resolution was less than 0.1 m.

A Laser In-Situ Scattering and Transmissometry 100B (LISST 100B, made by SEQUOIA, America) particle size analyzer was attached to the CTD in order to obtain profiles of *in situ* particle size and VC of SPM at the same depth of temperature, salinity, turbidity and chlorophyll-*a*. Here, the VC is defined as the volume of suspended matter per unit volume.

In addition to the CTD and LISST surveys, water samples were also taken by Reversing Water Sampler at each station in 1 m, 5 m, 10 m, 15 m, 20 m water depths and from the bottom layer. Then, the MC of suspended particles for each sample was collected by membrane filtering, drying and weighing in the laboratory. Differently from VC, MC is defined as the mass or weight of suspended matter per unit volume.

3. Distribution of SPM

3.1. Horizontal and vertical distributions of SPM

In summer, the horizontal distribution of SPM displayed a high MC inshore and a low value offshore (Fig. 2). For the same site, the MC is generally higher at the bottom than at the surface. The average concentration of SPM at the surface layer was found to be 13 mg l^{-1}, while it rose to 36 mg l^{-1} at the bottom, and the maximum value near the Caofeidian project reached 603 mg l^{-1}.

Horizontal distribution of the MC indicates that sediment discharge of the river and the developing projects of Caofeidian and Tianjin Port were important sources of SPM in the northern Bohai Bay. The high value found off the Caofeidian Port may also be caused by strong hydrodynamic conditions resulting from cape coastline, where the maximum tidal current can reach 1.24 m s^{-1} during the spring tide (Lu et al., 2007).

Since the vertical resolution of MC at standard levels was not fine enough, VC was used to evaluate the vertical distribution of SPM. As shown in Fig. 3, during summertime, the characteristics of VC in the vertical direction can be divided into two types: one with a sharp peak of 5×10^{-3} at a depth of 10–15 m and another without. Furthermore, larger particles existed near the depth where a sharp peak of VC, which suggested a different sediment source from that in the other layers (Fig. 3d). The stations where VC exhibited peak values are located near the entrance of the Bohai Bay.

As shown in Fig. 4, thermal stratification can be found in profile C and eastern area of profile A, where the chlorophyll-*a* exhibited a maximum value. Water was well mixed in profile B, and no maximum chlorophyll-*a* can be found in the middle layer. The independent relationship between VC and salinity (Figure not shown),

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