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Seasonal variations of transport time of freshwater exchanges between Changjiang Estuary and its adjacent regions

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ABSTRACT

Seasonal variations of transport time of freshwater between the Changjiang Estuary (CJE) and its adjacent regions, Hangzhou Bay (HZB) and Jiangsu Coast (JSC), are investigated. The freshwater exchange between the CJE and HZB is controlled by the strength of the secondary plume, which initiates from the South Passage of the southernmost waterway of CJE. The transport time varies seasonally and is modulated by spring-neap tides. The water exchange between CJE and HZB exhibits a high spatial variation. A large water age is observed in the region near the southern coast of the HZB, which corresponds to high pollutant deposition and low water quality conditions observed in the field. A large exchange occurs in summer between CJE and HZB. The freshwater transported into the HZB is accumulated in the deep channel near the western shoreline of the HZB and weak horizontal exchange occurs in the southern region near the southern shoreline, resulting in an increase of water age in the southern region. Due to the increase of northerly and northwesterly winds in winter and fall, more horizontal exchange occurs, resulting in a decrease of water age. The transport time from Xuliujing to the Hangzhou Bay ranges from 30 to 60 days near Jinshanwei, and ranges from 100 to 140 days in the southern region. The advective transport is the dominant transport mechanism to move water out of the HZB, while shear-induced exchange flow transports freshwater into the HZB. Net flux is out of HZB in winter and fall, but into the HZB in summer when Changjiang discharge is high. A weak transport of freshwater between the CJE and Subei Coast exists. A portion of a freshwater plume transports freshwater northward during summer and fall. It takes approximately 60–140 days for the freshwater from Xuliujing to be transported to the Subei Coast.

1. Introduction

Changjiang River, with a drainage area of about 1.8×10^6 km^2, is the third longest river in the world. It discharges a large amount of freshwater (~9.24×10^{11} m^3/yr, (Shen et al., 2003)), sediment (~390×10^6 ton/yr, (Yang et al., 2005)), inorganic nitrogen (~6.1×10^{10} mol/yr), particulate organic carbon (~4.4×10^6 ton/yr (Tian et al., 1993; Liu et al., 2003; Dagg et al., 2004)) into the East China Seas. These anthropogenic outputs have been attributed as one of the major sources causing the formation of one of the largest hypoxia areas along the inner shelf off the Changjiang Estuary (CJE) (Li et al., 2002; Chen et al., 2007).

An excessive amount of nutrients is transported to the shelf through the Changjiang plume (Zhu, 2005). The dynamics of the plume and its variations have been studied extensively for decades (e.g., Chen et al., 2008; Moon et al., 2010; Wu et al., 2011; Li and Rong, 2012). However, the regions immediately adjacent to the estuary have also experienced large changes as human activities increase. Increases of nutrient and pollutant substances have been observed in the Hangzhou Bay (HZB), which is situated immediately south of the mouth of the CJE (Gao et al., 1993; Che et al., 2003). Previous study shows that the secondary Changjiang plume plays an important role in both the circulation, and water and sediment transport inside the HZB (Su and Wang, 1989). A large deposition area of suspended sediment located between 122° and 123° E along the coast is attributed to the southward pathway of water and suspended sediments from the Changjiang (Liu et al., 2010). The large deposition of sediment on the tidal flat of the western coast of HZB provides clear evidence of exchanges

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of water and sediment between the Changjiang and HZB (Xie et al., 2009). It is found that the distribution of nutrients and high concentrations of heavy metals all correlate with the frontal system (Gao et al., 1993; Che et al., 2003), indicating the influence from the discharge of Changjiang. Because the discharge from Qiantang River (QTR) located at the upper portion of the HZB is much lower compared to the Changjiang River, it is debatable if high concentrations of nutrients and pollutant materials are transported through the secondary plume of the Changjiang Estuary.

Recent studies and observations also suggest that the Changjiang diluted water could drift northwards along the Subei Coast, which is in a direction different from the diluted Changjiang water that moves northeastward in summer and southward in winter (Wu et al., 2014). The existence of this plume branch is further supported by the findings of several ecological and hydrological surveys, and model studies (Tang et al., 2006; Wu et al., 2014). However, it is unclear what amount of water and pollutants could possibly be transported to the Subei Coast and how long it will take for the Changjiang water to reach there.

For an estuarine system, both the amount of the nutrients discharged into the estuary and the nutrient retention time contribute to conditions for developing eutrophication (Nixon et al., 1996; Kemp et al., 2005). The retention of nutrients is correlated with the residence time of the estuary (Nixon et al., 1996), which can be quantified by the transport timescale of the freshwater (Shen and Wang, 2007). The seasonal variation of water quality condition and potential development of estuary hypoxia are highly controlled by the transport timescales (Shen et al., 2013; Hong and Shen, 2013). Because of an increase of human activities, both dynamics and transport processes have been altered in the CJE (Wang et al., 2010). Although the Changjiang plume has been studied for decades, most studies focus on the coastal region and off the continental shelf. The transport processes and the exchanges of freshwater between CJE and HZB and the Subei Coast have not been fully investigated. Questions as to what amounts of water are transported from the Changjiang into the HZB and the Subei Coast have not been fully addressed. Although there is a consensus that a large portion of freshwater in the HZB is mainly from the Changjiang (Liu et al., 2006), it is unknown as to what amount of freshwater enters into the HZB, and how this diluted water affects the residence time of the HZB. Because the hydrodynamics of the CJE experience a high seasonal variation due to changes of buoyancy and wind conditions, it is vital to know the seasonal variation of the transport timescale and the dominant physical processes that control the transport.

The purpose of this study is to investigate the freshwater exchange between the Changjiang and HZB and the Subei Coast. This study focuses on 1) quantifying the amounts of freshwater in the HZB and the Subei Coast that are transported from the Changjiang, 2) estimating how long it will take to transport these waters to these regions, and 3) understanding the dominant mechanisms for these transport processes. Numerical modeling is used to conduct the study. The conservative tracer was used to study both the transport time and the amount of freshwater to be transported to these regions. The seasonal variations of the transport timescale with respect to freshwater and wind forces are discussed. A particular advantage of the present modeling approach is that the freshwater is tagged with a dye so that we can identify riverine water precisely and estimate the change of transport of the timescale associated with the movement of the freshwater in and out of HZB. The results will provide important information and the timescale for understanding the transport of dissolved substances in the estuary and for coastal management.

2. Description of study area

The CJE is located along the central eastern coast of China (Fig. 1), with a latitude ranging from 30°40′ to 31°11′ N and a longitude ranging from 120°55′ to 123°00′ E. Downstream from the Xuliujing, the estuary is characterized by regular channel bifurcations. The main channel downstream of the Xuliujing is divided into the North Branch (NB) and the South Branch (SB) by the Chongming Island. The SB downstream from the Liuhe River mouth branches into the North Channel (NC) and the South Channel (SC) by the Changxing and Hengsha Islands, and finally the SC branches into the NP and SP downstream of the JDS (Chen et al., 1988). The average tidal range at the Zhongjun Station located near the mouth is 2.66 m and the maximum tidal range is 4.62 m. The depth of waterways ranges from 8 to 12 m. The discharge ranges from 12,000 to 50,000 $m^3\ s^{-1}$. Fig. 2 shows a typical distribution of freshwater discharge. The majority of freshwater is discharged to the coast through NC (50%). The discharge through SP and NP is about 40%. The channel of the NB is a funnel-shaped branch and has the largest tidal range in the estuary. Discharge through the NB is less than 5% (Chen et al., 1988). The Subei Coast is located immediately northwest of the mouth of the NB. This study will only focus on the near coastal region of the Subei Coast.

Hangzhou Bay is located immediately south of the mouth of the CJE. The HZB is the outer reach of Qiantang Estuary. It is a typically funnel-shaped bay. The width is about 100 km at the mouth and narrows to around 20 km approximately 100 km to the west. It is a meso-tidal estuary near the mouth. The tidal range increases rapidly to a macro-tide scale along the Bay. The amplification produces the famous Qiantang Tidal Bore at the Qiantang River (QTR) mouth with an average tidal range of 5.45 m and a maximum range of 8.87 m (Gao et al., 1993). The average discharge is about 43 $km^3\ yr^{-1}$ (1364 $m^3\ s^{-1}$) (Su and Wang, 1989), which is about 5% of the mean discharge of Changjiang River and about 18% of the mean discharge from SP. The HZB has an average depth of 10 m. Its bottom is relatively flat, except for a 25-km stretch of deep channel along the northern shore near the Jinshanwei and Zhapu.

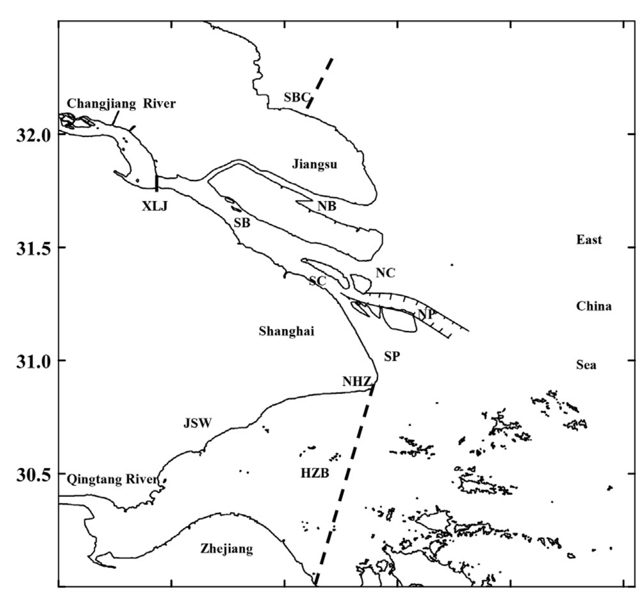

Fig. 1. A map of Changjiang Estuary and its adjacent areas.