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Links between saltwater intrusion and subtidal circulation in the Changjiang Estuary: A model-guided study

Hui Wu [a,*], Jianrong Zhu [a], Byung Ho Choi [b]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, 3663 North Zhongshan Road, Shanghai 200062, PR China
[b] Department of Civil and Environmental Engineering, Sungkyunkwan University, Chunchun-dong 300, Jangan-gu, Suwon 440-746, Republic of Korea

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ABSTRACT

In this paper we discuss the links between saltwater intrusion and subtidal circulation in the Changjiang Estuary based on a 3D numerical model. We restricted our study mainly to the three major outlets of the estuary: the South Passage, the North Passage, and the North Channel. Subtidal transport is landward in the South Passage and NNW- or NW-ward on the shoals, whereas it is mainly seaward in the North Passage and North Channel. Such a residual characteristic is caused by the interaction between tide and shallow water depth. Decomposing analysis indicated that Stokes transport is the major mechanism causing this particular residual transport pattern. Under its influence, the South Passage is the most saline outlet and the North Channel is the major route discharging the Changjiang runoff. Results of a tracer experiment indicated that active water mass exchange occurs from the South Passage to the North Passage and finally to the North Channel. Thus, the salinity in each outlet is determined not only by the tidal-averaged diversion ratio around the bifurcation of the South and North Channels but also by the subtidal circulation in the waterways and on the shoals. The northerly wind produces a horizontal circulation around the river mouth, which flows into the estuary in the North Channel and out of the estuary in the South Channel and South Passage. This circulation increases the salinity in the North Channel and decreases it in the South Passage. Recent engineering projects have intensified the landward residual in the South Passage, thereby increasing the salinity in the South Passage and decreasing the salinity in the North Channel.

1. Introduction

The Changjiang River, also known as the Yangtze River, is the largest river leading into the western Pacific Ocean. It discharges huge amounts of freshwater (9.24×10^{11} m^3) into the East China Sea (ECS) each year (Shen et al., 2003). The runoff varies seasonally, with a maximum monthly mean of 49,500 m^3 s^{-1} in July and a minimum of 10,500 m^3 s^{-1} in January (Shen et al., 2003). Its huge estuary has a 90 km wide river mouth and a nearly 640 km tidal limit (Fig. 1). The estuary experiences multilevel bifurcations. The Chongming Island divides it into the South Branch and the North Branch. The lower South Branch is bifurcated into the South Channel and the North Channel by Changxing Island and Hengsha Island. Finally, the South Channel is bifurcated into the South Passage and the North Passage by the Jiuduan Sandbank (Fig. 1). Thus, four outlets are formed to discharge the Changjiang runoff into the East China Sea (ECS). Previous studies have focused on the interaction between saltwater and freshwater, such as saltwater intrusion (e.g., Shen et al., 1980, 2003; Kong et al., 2004) and extension of Changjiang diluted water (e.g., Beardsley et al., 1985; Zhu and Shen, 1997; Chen et al., 2008). Because the Changjiang Estuary is bifurcated, saltwater intrusion is distinct in its North Branch and South Branch (and its lower reaches). Salt is carried by the flow of water, and it plays a role in the hydrodynamics of a body of water (Pritchard, 1952, 1954, 1956). In the dry season when runoff is low, the North Branch almost always contains high salinity water, and the saltwater there can spill over into the South Branch (this spillover hereafter is denoted as the SSO) under strong tidal conditions (e.g., Shen et al., 1980, 2003; Wu et al., 2006; Wu and Zhu, 2007; Xue et al., 2009). In the lower reaches of the South Branch, saltwater intrudes landward mainly in a wedge-like manner, just like in other partially mixed estuaries (Shen et al., 2003; Kong et al., 2004).

Tides are the most energetic source of water movement in the Changjiang Estuary, where they exhibit a mesoscale tidal range. According to data from Luchaogang Station (for location see Fig. 1) collected in 2006 and 2007, the tidal range exhibits significant monthly, semi-monthly, and semi-diurnal signals. During the spring tide, the amplitude is mostly >4.5 m and is approximately

* Corresponding author. Tel.: +86 21 62238711; fax: +86 21 62546441.
E-mail address: hwu@sklec.ecnu.edu.cn (H. Wu).

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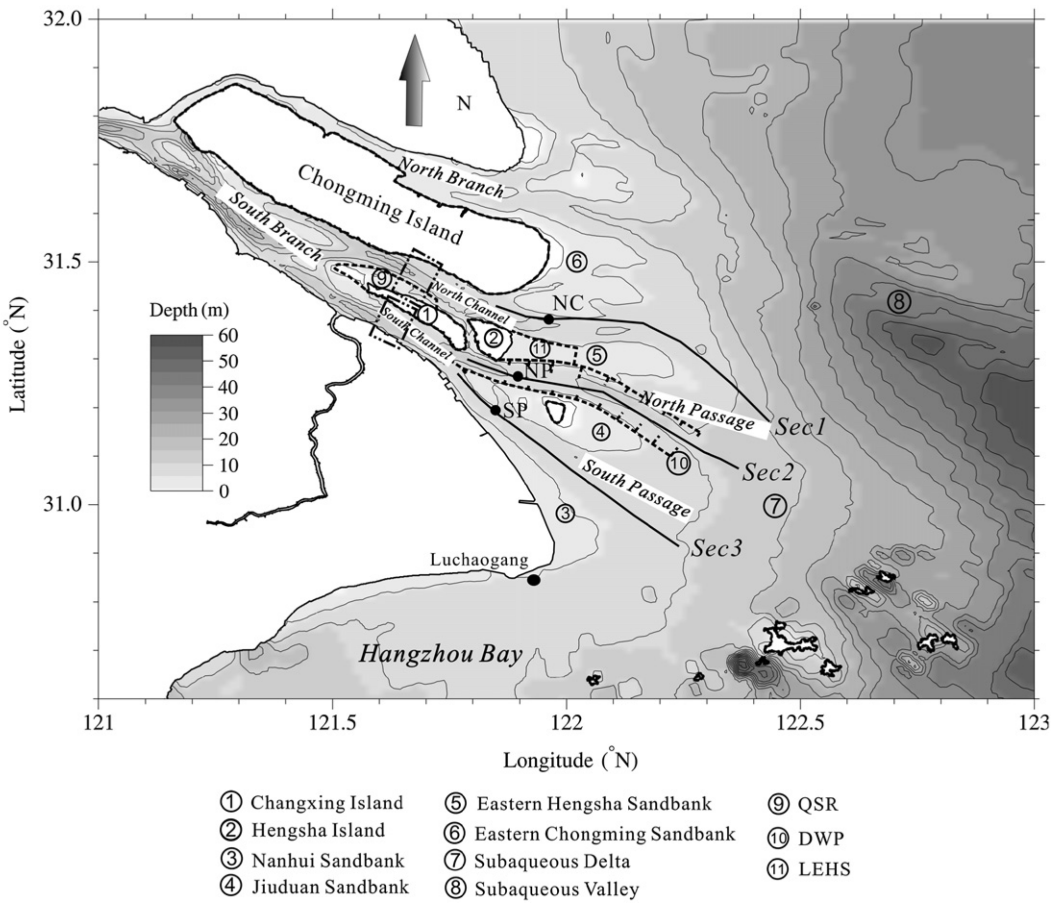

Fig. 1. Topography of the Changjiang Estuary. The engineering projects (dashed lines) are also included in this figure. SP, NP, and NC (bolded dots) are the locations selected to output the modeled salinity. Sec1, Sec2, and Sec3 are the locations of the three longitudinal profiles. Dotted boxes in the South and North Channels are the locations where tracers are initially distributed.

twice that during neap tide, which is typically <2.5 m. The strong tidal range introduces a significant tidal current, which can oscillate the estuarine fronts and mix dissolved materials.

Compared to the tidal current, subtidal circulation inherently determines the long-term transport of salt and other materials. Previous studies revealed that the tidal-averaged cross-sectional water flux at the upper North Branch essentially determined the intensity of the SSO. For example, Wu et al. (2006) used the SSO to derive a quantitative relationship between the SSO and tidal range and Changjiang runoff. In that study, the residual current in the North Branch was found to flow into the South Branch, thus linking the SSO to the subtidal circulation in the North Branch. Xue et al. (2009) further investigated the dynamics driving such an upstream net flux. They found that the up-estuary net flux is driven by tidal rectification through a subtidal momentum balance of surface elevation gradient force, horizontal advection, and vertical diffusion. They showed that particles released in the North Branch could flow upstream and into the South Branch after several tide cycles. Furthermore, they found that northerly wind tends to enhance the SSO.

Although numerous studies of the SSO have been conducted, saltwater intrusion in the lower reaches of the South Branch (the other three outlets: South Passage, North Passage, and North Channel) has not been investigated sufficiently. These three outlets are shallow (minimal channel depth is <8 m) and bounded by extensive intertidal sandbanks. Saltwater intrusion in this region has distinctly different dynamics than the SSO. The SSO is controlled by the net upstream flux from the North Branch to the South Branch (Wu et al., 2006; Xue et al., 2009), whereas saltwater intrusion around the river mouth acts just like a partially mixed estuary (Shen et al., 2003; Kong et al., 2004). Moreover, the SSO has little impact on estuarine dynamics, whereas saltwater intrusion around the river mouth can produce estuarine circulation (Pritchard, 1952, 1954, 1956) and change the stratification (Simpson et al., 1990), thereby influencing the movement of sediments and producing an estuarine turbid maximum (Geyer, 1993).

Kong et al. (2004) conducted a detailed analysis of the saltwater intrusion around the river mouth based on in situ data. They found that the South Passage is the most saline outlet (except for the North Branch) and the North Channel is the freshest during the dry season. This finding differs from the traditional view that freshwater should tend to flow into the sea on the right side outlet under the influence of the Coriolis force and thus the South Passage should be fresher. In Xue et al.'s (2009) study, the modeled salinity in the South Passage was also higher than that in the North Channel during dry season (their Fig. 4), and the fresher water in the North Channel could flow into the North Branch. However, the detailed mechanisms responsible for this pattern have not been explored. Kong et al. (2004) also found that during the dry season and spring tide, the South Passage is flood dominated. This result is also surprising and led us to wonder: Are these common situations or just occasional events?

The three outlets—the South Passage, the North Passage, and the North Channel—are separated only by shallow sandbanks, and the water mass in these outlets can be exchanged between neighboring waterways. Due to the presence of a mesoscale tide, the subtidal circulation may be different from the flow without consideration of tide (see Fig. 1 in Xue et al., 2009). As suggested by previous studies, subtidal circulation may be active in shallow