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Influence of sea level rise on saline water intrusion in the Yangtze River Estuary, China

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ABSTRACT

The Yangtze River Estuary (YRE) is vulnerable to the accelerated sea level rise (SLR). In this study, a three-dimensional hydrodynamic and salinity transport model, with a high resolution unstructured mesh and spatially varying bottom roughness, is applied to quantify the influences of SLR on saline water intrusion in the YRE. The model has well been validated through observation data of tidal level, flow velocity and direction, and salinity. The performances of four scenarios of the present sea level (PSL) as well as 0.5, 1 and 2 m SLR reveal that (1) the isohaline shifts upstream nonlinearly in the YRE with SLR, and non-uniform in the spatial distribution under the same SLR. The isohalines of 1, 2 and 5 psu near the north bank of the South Branch intrude farther upstream than those near the south bank, and the upstream advance distance of 0.45 psu isohaline is much longer than those of 1, 2 and 5 psu isohalines under the same SLR. (2) The spillover of saline water from the North Branch into the South Branch intensifies with SLR, while the salinity in the lower reach of the North Branch is reduced due to increased low salinity flow from the South Branch and the North Channel caused by SLR. (3) The durations of undrinkable water increase at four reservoirs with SLR, and four reservoirs cannot intake raw drinking-water in the dry season in the 2 m SLR scenario. (4) A regression analysis obtains a quantitative quadratic expression between salinity and SLR. Finally, the effects of the operation of the Three Gorges Reservoir and more SLR scenarios on the salinity, and two different approaches for SLR simulations are also discussed.

1. Introduction

The 5th IPCC report provides abundant evidences that our freshwater resources can be severely affected by sea level rise (hereafter denoted as SLR) [1]. SLR could push saline water further upstream in estuaries. Severe saline water intrusion can impair water supplies in local regions and threat the aquatic plants and animals [2]. A number of studies revealed that SLR could alter salinity stratification [3], circulation [4] and lead to oxygen depletion [5]. In the Yangtze River Estuary (YRE) in China, salinity intrusion can significantly impact on four large size drinking-water reservoirs that supply drinking-water to about 50 million people. A better understanding of saline water intrusion induced by SLR plays a vital role in the government strategies in mitigating the effects of the SLR.

A number of researches have been conducted to better understand the saline water intrusion caused by SLR in estuaries. Bhuiyan and Dutta [2] reported a 1 m SLR can produce an increase of 1.5 psu in the salinity in the Gorai river network, Bangladesh. A salinity model study due to SLR in the James River (USA) showed that salinity could intrude about 10 km farther upstream for a 1 m SLR [6]. Grabemann et al. [7] reported a 2 km upstream advance of the brackish water zone in the approximately 80 km long Weser Estuary in Germany for a 0.55 m SLR scenario. In the Chesapeake Bay, the mean salinity, salinity intrusion distance and stratification would increase with rising sea level [3]. However, SLR may also lead to salinity decrease in some special branches of estuaries. For example the isohaline of 0.45 psu was reported to move seaward in the Jiaomen and Hongqili river outlets of the Pearl River Estuary in China in response to SLR and river discharges decreasing [8].

The Yangtze River, the longest river with a length of 6380 km in China, has a catchment area of 1.8×10^6 km^2. Its annual mean freshwater discharge 28,300 m^3/s is obtained from measurements from 1950 to 2011 at Datong gauge station. The monthly mean

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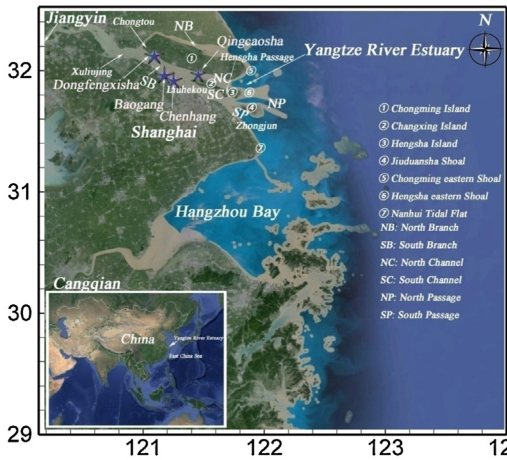
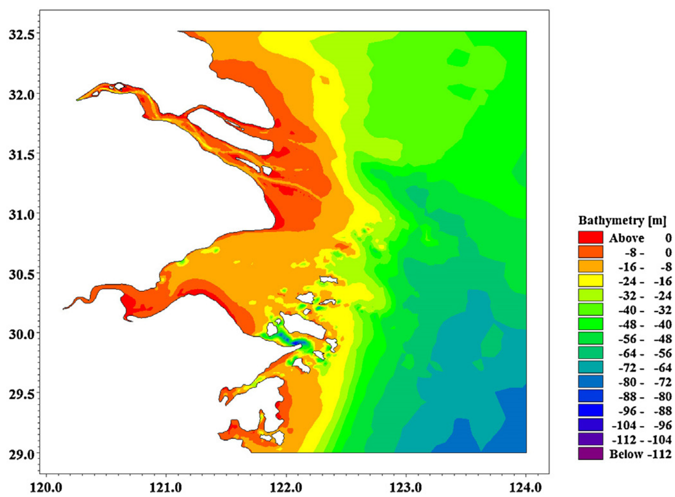


(a) Geographic location of the YRE and the four freshwater reservoirs (indicated as star symbols)



(b) Bathymetry of the YRE

Fig. 1. Geographic location and the bathmetry of the YRE.

runoff varies seasonally, with a maximum 49,500 m^3/s in July and a minimum 10,500 m^3/s in January, respectively [9]. The YRE, with a mouth at approximately 90 km wide, is characterized by three-order bifurcations, numerous islands and shoals, and deep channels. The Chongming Island divides the YRE into the North Branch (hereafter denoted as NB) and the South Branch (hereafter denoted as SB), shown in Fig. 1. The Changxing Island and Hengsha Island divide the lower South Branch into the North Channel (hereafter denoted as NC) and the South Channel (hereafter denoted as SC). Finally, the lower South Channel is divided into the North Passage (hereafter denoted as NP) and the South Passage (hereafter denoted as SP) by Jiuduansha Shoal. The semi-diurnal tide is dominated around the river mouth with the mean tidal level range at approximately 2.65 m. Due to the large river discharge of the Yangtze River; the ebb duration is longer than the flood duration. It has an irregular semi-diurnal character, with average flood and ebb durations of 5 h and 7.4 h, respectively, at Zhongjun station near the mouth [9].

Four reservoirs in the YRE (see Fig. 1), named as the Chenhang Reservoir, the Baogang Reservoir, the Qingcaosha Reservoir and the Dongfengxisha Reservoir, supply freshwater resources to Shanghai and the Jiangsu Province. The Chenhang Reservoir built in the 1980s is a side-shoal reservoir and is located in the downstream of Liuhekou with small capacity. The Baogang Reservoir is located at the south bank of the SB, and its storage volume decreases due to sedimentation in the reservoir. The Qingcaosha Reservoir, located in the north of Changxing Island, has an area of 70 km^2 and a capacity of 0.44 billion m^3. The water quality in the reservoir is very good with a Category I or II according to Chinese surface water standard, which makes the Qingcaosha Reservoir being one of the best reservoirs in China. The Dongfengxisha Reservoir is located at the north side of the upper reach of the SB with a total capacity up to 9.762 million m^3.

The estuarine circulation and its associated spring-neap stratification play an important role in salinity transport processes [10] and water quality [11] in the estuary. Saline water intrudes upstream when tide rises, and to the farthest upstream at the flood peak with the surface salinity smaller than the bottom one on the same vertical plane [12]. The salinity stratification due to SLR has been analyzed in many estuaries worldwide [3,4,13]. Rising sea levels increase the strength of the longitudinal salinity gradient and reduce the impact of bottom-generated turbulence, both of which result in an increase in the strength of the gravitational circulation and longitudinal dispersion [13]. Qiu and Zhu [4] applied the residual transport mechanism of salt to analyze the changes in transport processes and estuarine circulation pattern in the YRE. Various studies provide general insight about saline water intrusion in the YRE, which is mainly influenced by topography, river discharge, tide and wind stress. The upstream large hydraulic engineering projects, such as the Three Gorges Dam and the South-to-North Water Diversion Project, also affect the saline water intrusion in the YRE. Due to the increased river discharge provided by the Three Gorges Dam Project in the dry season, the durations of undrinkable water at locations of Dongfengxisha, Chenhang and Qingcaosha Reservoirs are all shortened [14]. However, the saline water intrusion in the YRE is strengthened by the South-to-North Water Diversion Project [15] due to transport water from the YRE to the North China in the dry season.

Previous studies assessed salinity transport and mixing in estuaries using numerical models. Kuang et al. [16] applied Delft3D to study the effect of wind on vertical mixing in Hong Kong waters. Zhang et al. [17] established a one-dimensional salinity model to study the salinity transport in the Pearl River networks. Wu et al. [18] discussed the links between salinity intrusion and subtidal circulation in the YRE using ECOM-si model. Jeong et al. [19] used EFDC model to study the extent of salinity intrusion effects at different flow rates in the downstream of Geum River (South Korea). Liu et al. [20] developed a model to investigate the influence of freshwater discharge on residual current and salinity intrusion under different freshwater inflow condition in the Danshuei River estuarine system in Taiwan. Numerical model is found to be an effective tool to study salinity transport in estuaries.

Over the past three decades, the impact of SLR on the hydrodynamic and salinity transport in the YRE has attracted significant attentions. Zhou et al. [21] applied TIMOR model to study the impact of SLR on the hydrodynamic of the YRE. Yang and Zhu [22] used an empirical correlation method to study saline water intrusion at Wusong station in 0.5–1 m SLR. Chen and Zong [23] discussed saline water intrusion owing to SLR based on measured salinity. Luo et al. [24] predicated the intrusion distance of isohaline of 1.5 psu in the NC of the YRE under SLR by using EFDC numerical model. Qiu and Zhu [4] applied residual mechanism to assess the influence of SLR on salt transport processes and estuarine circulation in the YRE using ECOM-si model with a structured and coarse grid subject to uniform bottom stress. In this study, we continue the hydrodynamic modeling of the YRE of Kuang et al. [25] by including the Hangzhou Bay, because there can be significant water exchange between the YRE and the Hangzhou Bay (see position in Fig. 1). Based on the past 30 years of the tidal level data, Yue et al.