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Dynamic mechanism of extremely severe saltwater intrusion in the Changjiang Estuary occurred in February 2014

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Abstract. Estuarine saltwater intrusion is mainly controlled by river discharge and tide. Unexpectedly, an extremely severe saltwater intrusion event in February 2014 occurred in the Changjiang Estuary under normal river discharge conditions. It cut off the freshwater input for 23 days into the Qingcaosha Reservoir, which is the largest estuarine reservoir in the world, creating a severe threat to water safety in Shanghai. Such catastrophic saltwater intrusion has not occurred since recorded salinity in the estuary. During the event, a persistent and strong northerly wind existed, with a maximum speed of 16 m s^{-1}, lasting ten days and coinciding with a distinct water level rise. Our study demonstrates that this extremely severe saltwater intrusion was caused by a persistent and strong northerly wind, which drove substantial landward Ekman transport to form a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel. This process surpassed seaward runoff and brought very large amounts of highly saline water into the upper reaches in the North Channel. An ordinary cold front passing over the estuary cannot produce strong saltwater intrusion; only a strong northerly wind lasting 8 days can produce a severe saltwater intrusion in the Changjiang Estuary. The revealed dynamic mechanism is important to ensure safety of freshwater resource utilization in estuaries.

1 Introduction

Saltwater intrusion is a common phenomenon in estuaries where fresh water and saltwater converge, and is mainly controlled by tide and river discharge (Prandle, 1985; Simpson et al., 1990; Geyer, 1993), but it can also be affected by wind stress (Aristizábal et al., 2015; Giddings and Maccready, 2017) and vertical mixing (Simpson and Hunter, 1974; Prandle and Lane, 2015). Saltwater intrusion can produce estuarine circulation (Pritchard, 1956) and affect stratification (Simpson et al., 1990), thereby influencing sediment transport, producing peak estuarine turbidities (Geyer, 1993), and degrading the freshwater quality (Zhu et al, 2013). Therefore, study of estuarine saltwater intrusion has scientific significance for circulation, sediment, environment and ecology, and application value for utilization of estuarine freshwater resources.

Changjiang, also known as the Yangtze River, is one of the largest rivers in the world and discharges large amounts of freshwater (9.24×10^{11} m^3) into the East China Sea each year (Shen et al., 2003), with seasonal variations in river discharge ranging from a maximum monthly mean of 49,850 m^3 s^{-1} in July to a minimum of 11,180 m^3 s^{-1} in January (Zhu et al., 2015). The Changjiang Estuary is characterized by multiple bifurcations (Fig. 1). The tides in the Changjiang Estuary are semidiurnal,

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have biweekly spring-neap signals and are the most energetic sources of water movement. The maximum spring tide reaches 3.38 m, and the minimum neap tide reaches 0.64 m at the Baozhen hydrological station (Zhu et al., 2015). The maximum tidal current amplitude reaches approximately 2.0 m s^{-1} at the river mouth during the spring tide. The prevailing monsoon climate results in a stronger northerly wind of 5.5 m s^{-1} during winter and a southeasterly wind of 5.0 m s^{-1} during summer (Zhu et al., 2015). Saltwater intrusion in the Changjiang Estuary is also mainly determined by river discharge and tides (Song and Mao, 2002; Gu et al, 2003; Shen et al., 2003; Luo and Chen, 2005; Qiu et al. 2012; Chen et al, 2019a) but is also influenced by wind (Xue et al., 2009; Li et al., 2012), and topography (Li et al., 2014; Chen et al., 2019b). The impact of wind on saltwater intrusion has been studied, but only with a climatological wind (Xue et al., 2009), and a strong northerly wind induced by ordinary cold fronts in winter lasting 1-2 days, which could cause a change in the observed salinity (Li et al., 2012).

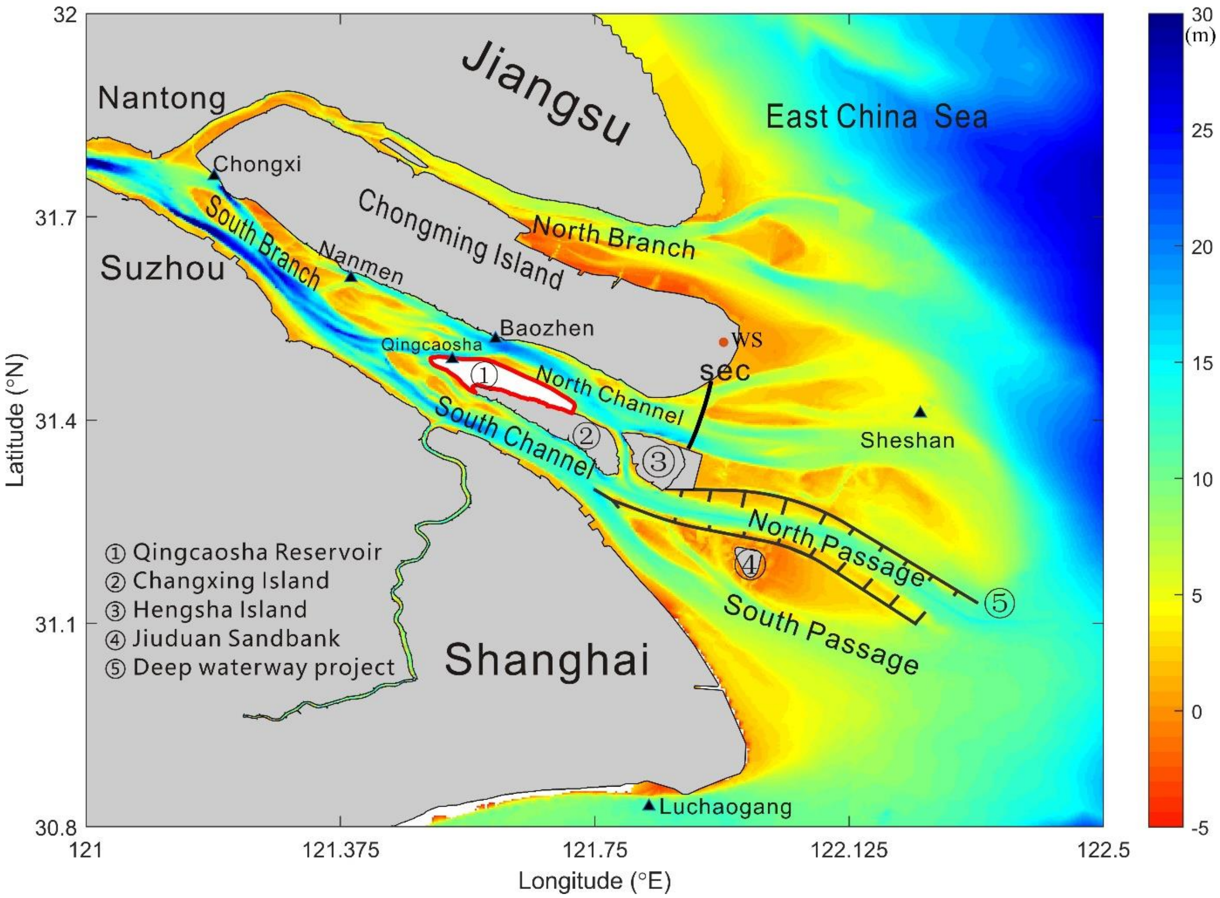

Figure 1: Topography of the Changjiang Estuary. The black triangles indicate the locations of hydrologic stations Chongxi, Nanmen, Baozhen, Qingcaosha, Sheshan and Luchaogang. WS is the location of the weather station at the Chongming eastern shoal, and Sec is a transect at the river mouth of the North Channel.

The estuaries of large rivers are often associated with growing populations and developing economics, leading to complex challenges when supporting environmental conditions. Among these, freshwater supplementation is of vital importance for industrial and civilized usage, but it is often violated by seawater intrusion. The Changjiang Estuary, which is surrounded by

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fast-developing cities, such as Shanghai, Suzhou and Nantong city, is threatened by saltwater intrusion in the winter season. Numerous efforts have been made in the past decades to secure the astronomic freshwater demands of the megacity Shanghai, which has a population over 24 million people. The water resources in Shanghai were strategically transferred from the Huangpu River to the Changjiang Estuary in 2010, which was the largest estuarine reservoir in the world, the Qingcaosha Reservoir, was built (shown in Fig. 1). This reservoir has an effective capacity of 4.35×10^{8} m^3 and a daily water supply amount of 7.19×10^{6} m^3 for the 13 million people in the main districts of Shanghai, accounting for 70% of the total freshwater in the city. However, the Qingcaosha Reservoir is frequently influenced by saltwater intrusion, particularly during the dry season. Limited by reservoir capacity, long-lasting saltwater intrusion is extremely harmful (Chen et al, 2019a).

An extremely severe saltwater intrusion event in February 2014 occurred in the Changjiang Estuary under normal river discharge conditions, and seriously influenced the water intake of the Qingcaosha Reservoir and threated water safety in Shanghai. Historically, there have been two severe saltwater intrusion events in the Changjiang Estuary in the dry seasons of 1979 and 1999, which were caused by very low river discharge of approximately 7000 and 8000 m^3 s^{-1} lasting three mouths, respectively (Zhu et al., 2013). However, the mean monthly river discharge in February 2014 was 10,800 m^3 s^{-1}, which approached the annual climatic mean value of 11,500 m^3 s^{-1} in February from 1950 to 2019. Such a catastrophic saltwater intrusion event in February 2014 has not occurred since recorded salinity data, even when there was a much lower river discharge in the estuary, such as in the dry seasons of 1979 and 1999. Because the river discharge in February 2014 approached the monthly mean discharge since 1950, it was not the cause of the extremely severe saltwater intrusion event. The tides in February in different years should be similar, as should the estuarine topography over the last ten years. What was the reason for the extremely severe saltwater intrusion event in the Changjiang Estuary in February 2014? In this paper, the dynamic mechanism of the event was studied with observed data and a numerical model.

2 Methods

2.1 Observed data

The observed data of salinity, water level and wind were used to study the extremely severe saltwater intrusion event in February 2014. The observed data was conducted by State Key Laboratory of Estuarine and Coastal Research, East China Normal University. At the Baozhen hydrologic station, the salinity was normal before February 8, 2014 (referencing other years in January and February), but rose to a very high value with a peak of 20.1 from February 9 to 20, which was beyond expectations and had never occurred (Fig. 2a). At Nanmen station, the salinity was also abnormally high, with a peak salinity of 12.4. At Chongxi station, the salinity was higher with a peak salinity of 6.5, where the saltwater mainly spilled over from the North Branch into the South Branch during the dry season. At the Qingcaosha, the salinity was greater than 0.45 (the salinity standard for drinking water hereafter) from February 4 to 26 with a peak salinity of 8.6, resulting in the continuous period of unsuitable drinking water reaching 23 days and resulting in serious threat to the water intake of the Qingcaosha

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Reservoir and water safety in Shanghai. The observed salinities at hydrologic stations indicated that there was an extremely severe saltwater intrusion event in February 2014.

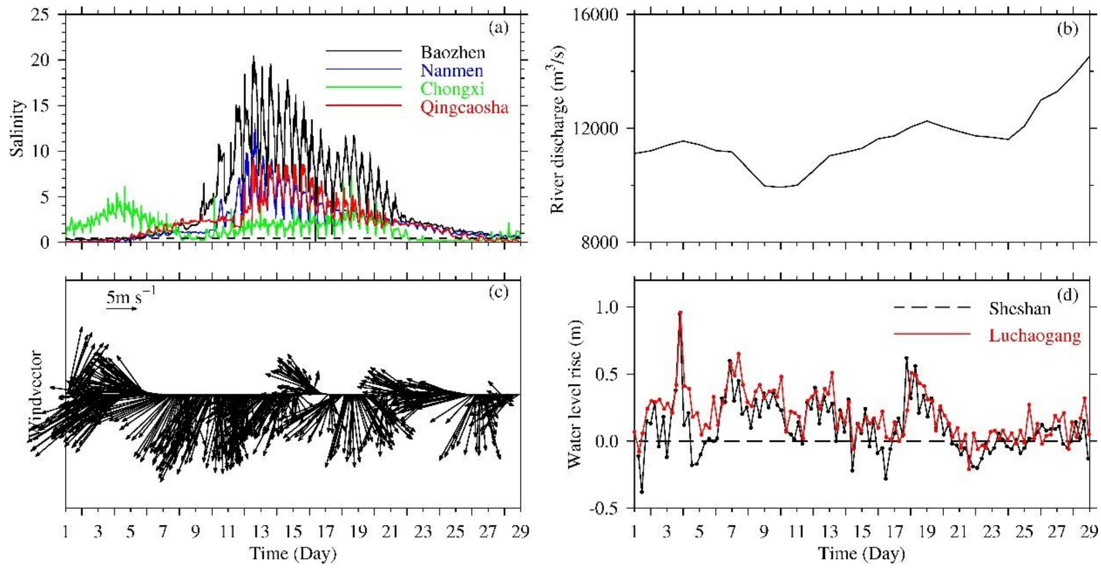

Figure 2: Temporal variations in the measured data in February. a: salinity at hydrologic stations Baozhen (black line), Nanmen (blue line), Chongxi (green line) and Qingcaosha (red line), the dashed line represents a salinity of 0.45, which is the standard for drinking water; b: river discharge at Datong station; (c): wind vector at WS; (d): water level rise at hydrologic stations Sheshan (black line) and Luchaogang (red line).

The mean monthly river discharge recorded at Datong hydrologic station (Changjiang Water Resources Commission, 2014) in February 2014 was 10,800 m^3 s^{-1} (Fig. 2b), which approached the annual climatic mean value of 11,500 m^3 s^{-1} in February from 1950 to 2019. Seen in river discharge, it was not the cause of the extremely severe saltwater intrusion event.

The weather station at the Chongming eastern shoal (location shown in Fig. 1, WS) recorded a persistent and strong northerly wind from February 5 to 14, 2014, lasting ten days with an average wind speed of 9.1 m s^{-1} and a maximum wind speed of 16 m s^{-1} on February 10 (Fig. 2c). After a two-day southerly wind existed from February 15 to 16, there was a four-day strong northerly wind from February 17 to 20, 2014. At the same time, the hydrologic stations Sheshan and Luchaogang recorded a distinct water level rise simultaneous with a peak value of more than 0.5 m during the strong northerly wind (Fig. 2d).

The observed data indicated that an extremely severe saltwater in the Changjiang Estuary occurred in February 2014, meanwhile, the river discharge was normal, and a persistent and strong northerly wind happened.

2.2 Numerical model

The numerical model used in this study was based on ECOM-si (Blumberg, 1994) and later improved for better studying hydrodynamics and substance transport (Chen et al., 2000; Wu and Zhu, 2010). The model used a sigma coordinate system in

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the vertical direction and a curvilinear nonorthogonal grid in the horizontal direction (Chen et al., 2004). The model domain for saltwater intrusion covers the Changjiang Estuary and its adjacent sea region (Fig. 3a).

The model simulations in this study covered the period from January 1 to February 28, 2014. The daily river discharge recorded at the Datong hydrologic station was used in the model as the river boundary condition (Fig. 2b). At the open sea boundaries of the model, the momentum open boundaries were driven by total water levels, which are composed of the residual water level and tidal level:

$$\zeta = \bar{\zeta} + \sum_{i}^{16} a_i \cos(\omega_i + g_i) \qquad (1)$$

where ζ is the total water level and $\bar{\zeta}$ is the residual (mean) water level reflecting the shelf current. The tidal level is calculated by combining the 16 main tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, MU_2, NU_2, T_2, L_2, $2N_2$, J_1, M_1, and OO_1) with harmonic constants, a and g, which are the amplitude and phase of the tidal constituent, respectively, derived from the NaoTide dataset (NaoTide, 2004), and ω is the frequency. How to determine the mean water level in Eq. (1) is a critical issue for correctly simulating saltwater intrusion in the Changjiang Estuary under a strong northerly wind. In this study, the mean water level was simulated by a large domain model encompassing the Bohai Sea, Yellow Sea and East China Sea (Fig. 3b, the model grids and domain), which is driven by ocean circulation, tide, river discharge and sea surface wind to simulate the water level, current and salinity (Wu et al., 2011).

The saltwater intrusion model in the Changjiang Estuary has been extensively calibrated, validated and applied in a number of previous studies of the Changjiang Estuary, which have shown that the model can reproduce the observed water level, current and salinity with high simulation accuracy (Wu and Zhu, 2010; Qiu and Zhu, 2015; Lyu and Zhu, 2018). Detailed descriptions of the model validation process can be found in the literature mentioned above.

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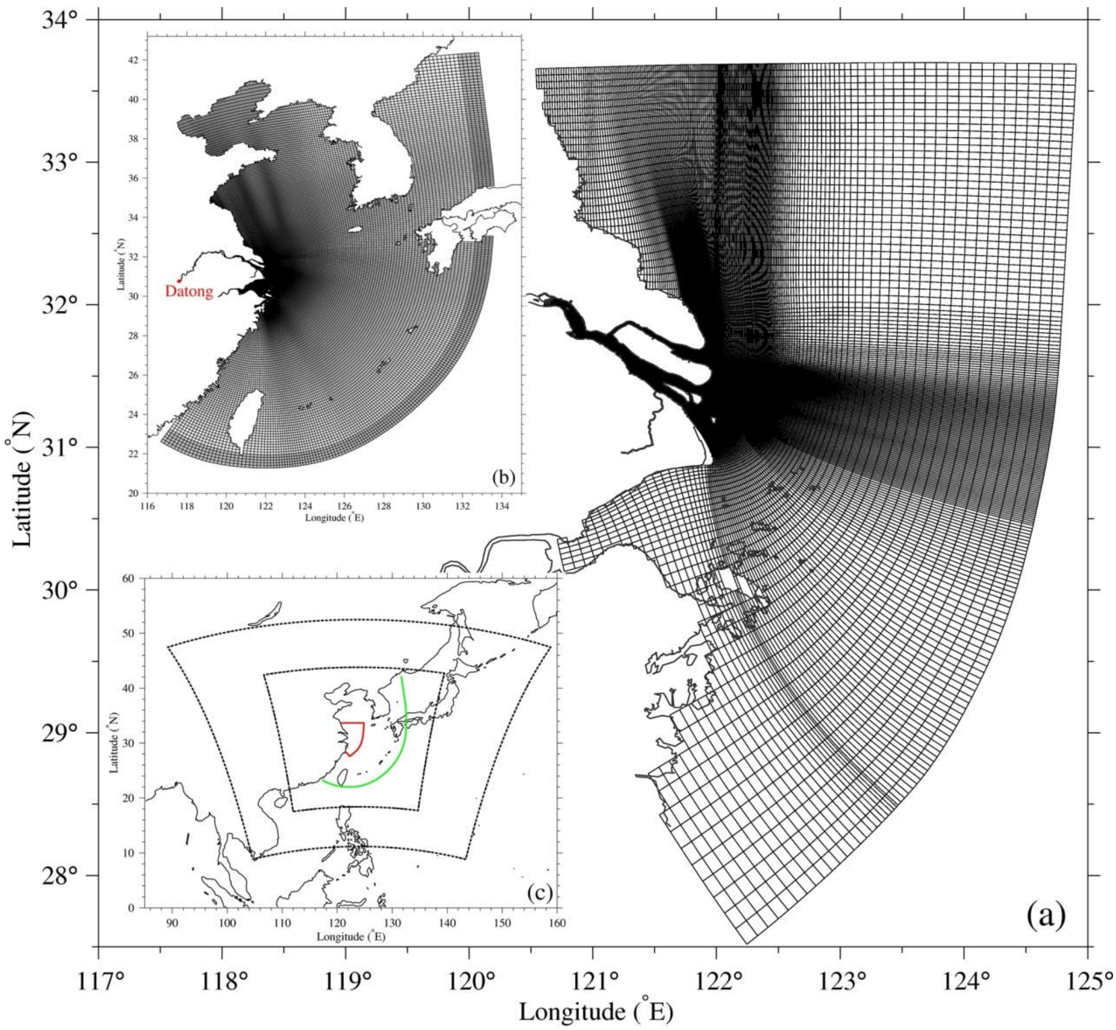

Figure 3: Model grids of the Changjiang Estuary (a); the Bohai Sea, Yellow Sea and East China Sea (b); and the model domains (c), in which the red line is the Changjiang Estuary, the green line is the Bohai Sea, Yellow Sea and East China Sea, and the black dashed lines are the two-fold nested WRF model.

3 Results

3.1 Climatic wind and residual water level conditions at open sea boundaries

Under climatic wind conditions at the sea surface and residual water levels at open sea boundaries, the performance of the saltwater intrusion in February 2014 was numerically investigated. The monthly mean wind field dataset, with a spatial resolution of 0.25 °×0.25 ° and a temporal resolution of 6 h from the National Centers for Environmental Prediction/Quick Scatterometer (NCEP/QSCAT, 2014), was used. The climatic wind field in February is a northerly wind with a speed of approximately 8 m s^{-1} over the Yellow Sea and East China Sea (Fig. 4a). The residual water level simulated by the model,

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including the Bohai Sea, Yellow Sea and East China Sea, was 10~20 cm away from the Changjiang River mouth and was mainly induced by river discharge and a climatic northerly wind (Fig. 4b). The residual water level was interpolated into the open sea boundary of the saltwater intrusion model as an external forcing condition.

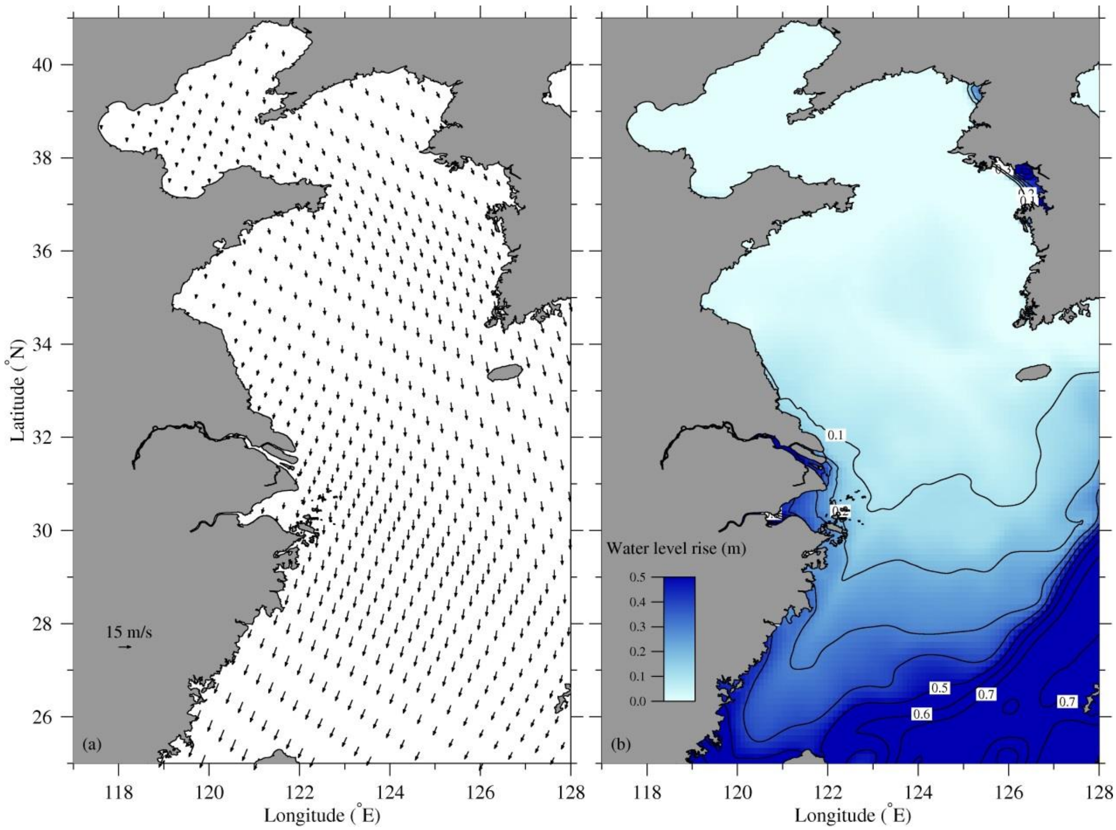

Figure 4: Distributions of the climatic wind field (a) and residual water level (b) in February.

The modeled water level at Baozhen station is fairly consistent with the observed level (Fig. 5a), meaning that the water level is mainly determined by tide and river discharge inside the river mouth. However, during the neap tide from February 7 to 11, 2014, the modeled water level was approximately 15 cm lower than the observed level because the wind was not a realistically strong northerly wind. The modeled salinity at Baozhen station was significantly lower than the observed salinity (Fig. 5b), which is similar to the normal saltwater intrusion regularly occurring under monthly mean river discharge and wind in the dry season.

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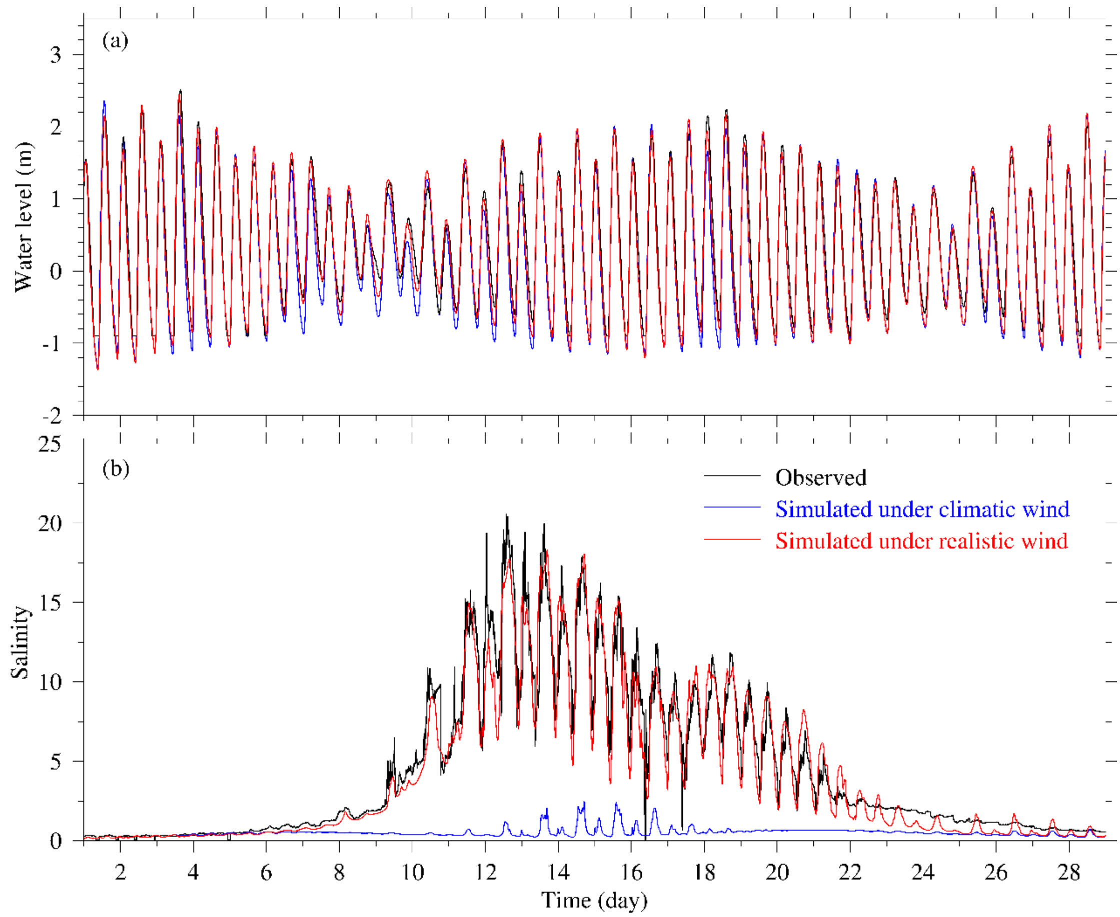

Figure 5: Temporal variations in the observed and modeled data. Water level (a) and salinity (b) at hydrologic station Baozhen in February 2014. Black line: observed; blue line: simulated under climatic wind and residual water level at open sea boundaries; red line: simulated under realistic wind and residual water level at open sea boundaries.

The residual unit width water flux at the surface from February 10 to 13, 2014, flowed seaward into the South Branch, North Channel, North Passage and South Passage but flowed landward into the North Branch due to its funnel shape and tidal Stokes transport (Qiu and Zhu, 2015), which means that the South Branch, North Channel and South Channel are the main channels for discharging river water into the sea (Fig. 6a). The distribution of time-averaged surface salinity indicated that there was a strong salinity front near the river mouth, which was caused by the confluence and mixing of fresh river water with sea water (Fig. 6b). The North Branch was occupied by highly saline water due to its funnel shape, which amplifies the tide in its upper reaches and lowers the amount of river discharge inflow caused by a wider tidal flat in its upper reaches (Wu et al., 2006; Lyu and Zhu, 2018). Salinity in the South Branch was less than 0.45, meaning that there was a wide area of fresh water near the water intake of the Qingcaosha Reservoir. Among the South Passage, North Passage and North Channel, saltwater intrusion was the strongest in the South Passage and weakest in the North Channel, which is consistent with previous studies (Li et al., 2014; Lyu and Zhu, 2018).

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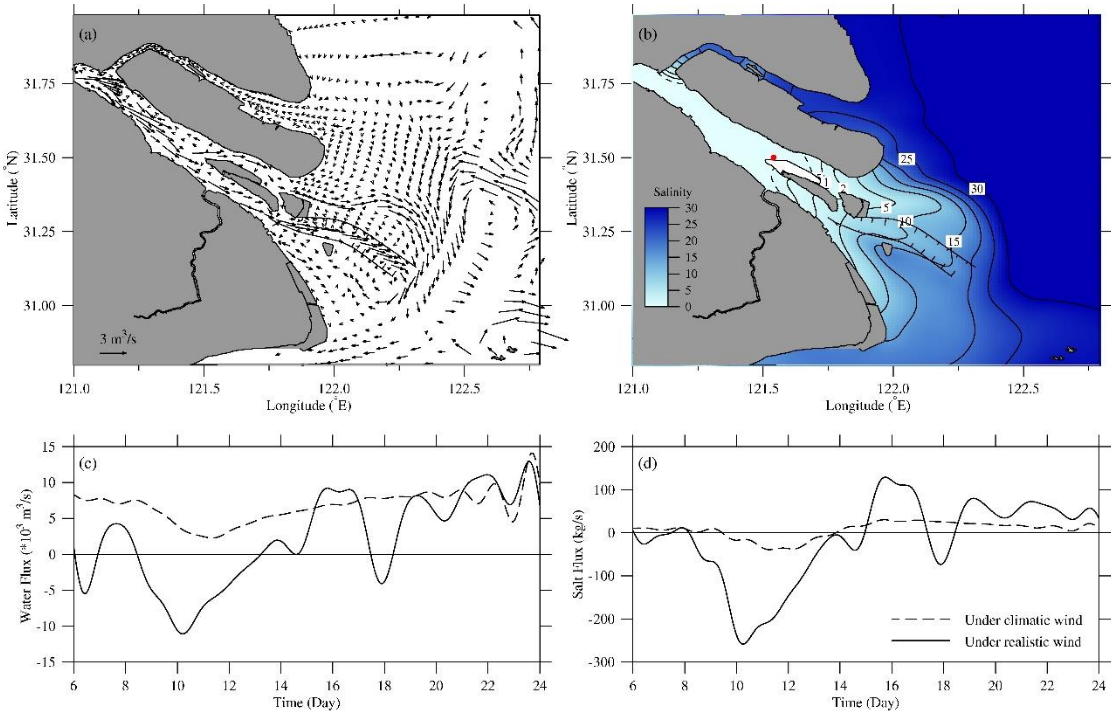

Figure 6: Modeled results. Distributions of residual unit width water flux at the surface (a) and time-averaged surface salinity (b) from February 10 to 13, 2014 under climatic wind and residual water level at open sea boundaries. The dashed isohaline represents a salinity of 0.45; the red dot denotes the location of water intake for Qingcaosha Reservoir. Temporal variations in residual water flux (c) and salt flux (d) across Sec in the North Channel from February 6 to 24, 2014. Dashed line: under climatic wind and residual water level at open sea boundaries; solid line: under realistic wind and residual water level at the open sea boundaries in February 2014. A positive value represents seaward flux, and a negative value represents landward flux.

The residual water flux across the transverse section in the North Channel (location labeled in Fig. 1) from February 6 to 24, 2014, flowed seaward and decreased during neap tide from February 9 to 11 due to runoff force (Fig. 6c). For the bifurcated Changjiang Estuary, more river discharge flowed into the North Channel during spring tide and into the South Channel during neap tide (Li et al., 2010; Lyu and Zhu, 2018). The residual salt flux across this section flowed landward from February 10 to 13, 2014, during the later neap tide and the subsequent early-middle tide due to weaker tidal mixing and the saltwater wedge and flowed seaward during other tidal conditions (Fig. 6d).

3.2 Under a realistic wind in February 2014 and residual water levels at the open sea boundaries

Under a climatic northerly wind, realistic river discharge and tide, the extremely severe saltwater intrusion event in February 2014 cannot be repeated. In this section, the performance of saltwater intrusion was simulated under realistic wind in February 2014, as well as the residual water level at open sea boundaries. The realistic wind was simulated by a mesoscale atmospheric model: the Weather Research Forecasting (WRF) model. Two nested domains were used (Fig. 3c). The NCEP reanalysis dataset was used to establish the initial and boundary conditions of the WRF model. A comparison between the

WRF modeled wind vector and the measured one showed that the persistent and strong northerly wind at the weather station located along the Chongming eastern shoal in February 2014 was well simulated by the WRF model (Figure omitted).

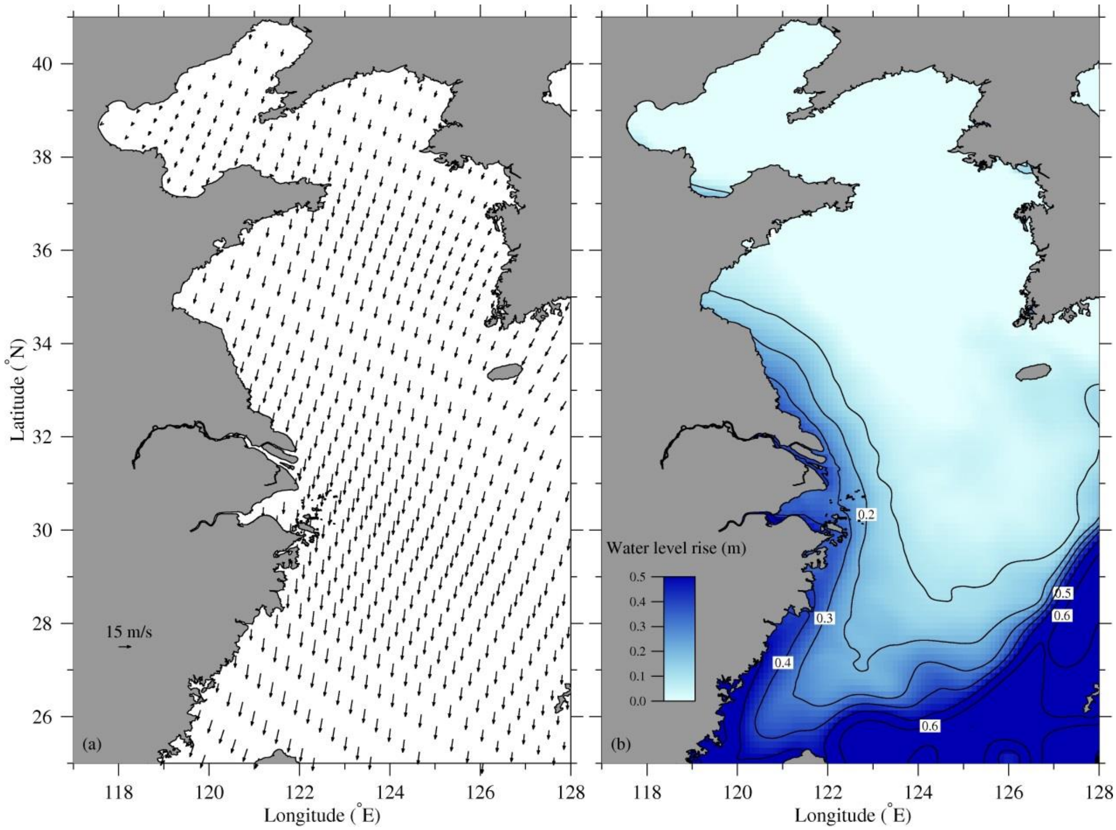

Figure 7: Distributions of the temporally averaged wind field from February 7 to 14, 2014, as simulated by the WRF model (a) and the time-averaged water level from February 10 to 13, 2014, as simulated by the model encompassing the Bohai Sea, Yellow Sea and East China Sea (b).

The simulated temporally averaged wind field over the Yellow Sea and East China Sea from February 7 to 14, 2014, indicated that the northerly wind speed reached approximately 18 m s^{-1} (Fig. 7a), which was much larger than that observed at the weather station along the Chongming eastern shoal (Fig. 2c). The residual water level simulated by the model of the Bohai Sea, Yellow Sea and East China Sea showed that the strong northerly wind induced a significant water level rise along the coast of China during the extremely severe saltwater intrusion event from February 10 to 13, 2014 (Fig. 7b). The residual water level was interpolated into the open sea boundaries of the saltwater intrusion model.

The simulated water level at Baozhen station was close to the observed level, especially during neap tide from February 7 to 11, 2014 (Fig. 5a). Comparing the result with that under climatic wind and residual water level at the open sea boundaries, the simulated salinity at Baozhen station was significantly improved and was very consistent with the observed salinity in terms of both magnitude and phase (Fig. 5b). The long-lasting persistent and strong northerly wind produced a strong southward current with a speed of 40-60 cm s^{-1} and landward Ekman water transport under the Coriolis force, resulting in a water level rise of more than 30 cm along the coast of China (Fig. 8a), which was confirmed by the observed water level rise at the Sheshan and Luchaogang stations (Fig. 2d). Because the North Branch is very shallow, the landward Ekman water transport was weaker, flowing along the north side and flowing out along the south side only near the river mouth (Fig. 8b). However, the North Channel is deeper and wider and located on the north side of the South Branch, which is in favor of producing strong landward Ekman water transport in the North Channel, surpassing the seaward runoff and forming a horizontal circulation in the estuary.

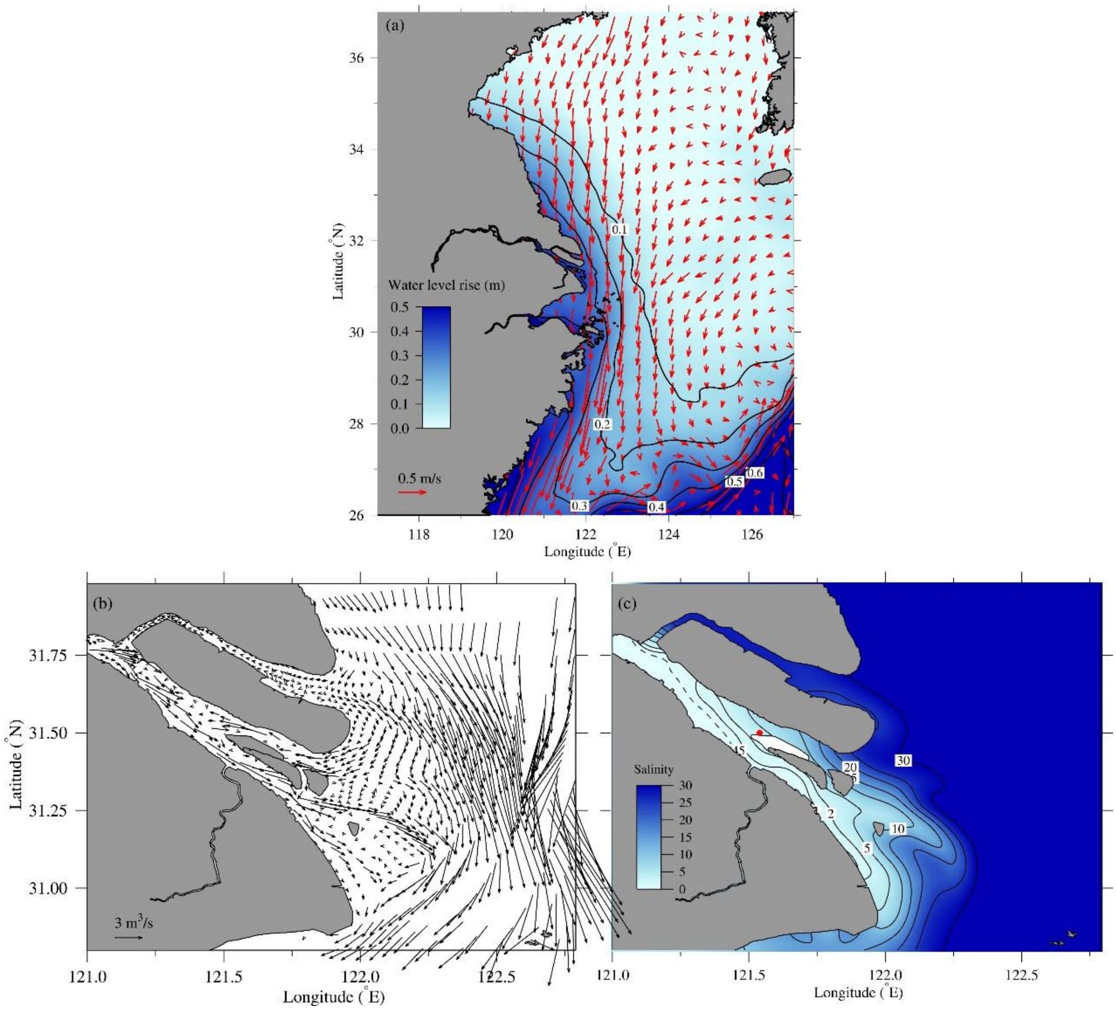

Figure 8: Modeled results. Distribution of the residual water level and surface current from February 10 to 13, 2014, as simulated by the model encompassing the Bohai Sea, Yellow Sea and East China Sea. Distributions of residual unit width water flux (b) and time-averaged salinity (c) at the surface from February 10 to 13, 2014, as modeled under the real wind and residual water level at the open sea boundaries.

The residual unit width water flux at the surface from February 10 to 13, 2014, flowed landward into the North Channel, meaning that the landward Ekman transport induced by the persistent and strong northerly wind surpassed the seaward runoff. The Changjiang River is a large river, and its river discharge is 10,800 m^3 s^{-1} in February 2014, so it is unexpected that wind-

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driven landward water transport could surpass strong seaward runoff. The current flowed into the North Channel and flowed out of the South Channel, forming a horizontal circulation and leading to highly saline sea water in the North Channel (Fig. 8c). Therefore, the extremely severe saltwater intrusion event in February 2014 was caused by this circulation induced by strong landward Ekman transport and abnormal water level rise due to the persistent and strong northerly wind.

4 Discussion

In winter, there are frequent cold fronts passing over the Changjiang Estuary and bringing strong northerly winds, enhancing saltwater intrusion (Li et al., 2012). For example, the relatively stronger saltwater intrusions that occurred from February 15 to 18, 2011, and from February 23 to 26, 2017 were caused by passing cold fronts. No extremely severe saltwater intrusion event occurred because the strong northerly wind induced by the cold front lasted only 1-2 days. We reveal how a long-lasting strong northerly wind can induce severe saltwater intrusion. Based on the persistent and strong northerly wind process in February 2014, numerical experiments were conducted, and the results indicate that if a strong northerly wind lasts 2 days, saltwater intrusion is weak (Fig. 9), which is similar to the case of an ordinary cold front passage; if a strong northerly wind lasts 4 days, saltwater intrusion is stronger than normal, similar to the case of a stronger cold front passage; if a strong northerly wind lasts 6 days, saltwater intrusion becomes severe; if a strong northerly wind lasts 8 days, the salinity is dramatically increased, the maximum salinity approaches the real salinity, and the saltwater intrusion becomes extremely severe. With more frequent persistent and strong northerly wind caused by climate change, more attention should be paid to extremely severe saltwater intrusion events and freshwater safety in the Changjiang Estuary because the Qingcaosha Reservoir takes water from the Changjiang Estuary for the 13 million people in Shanghai.

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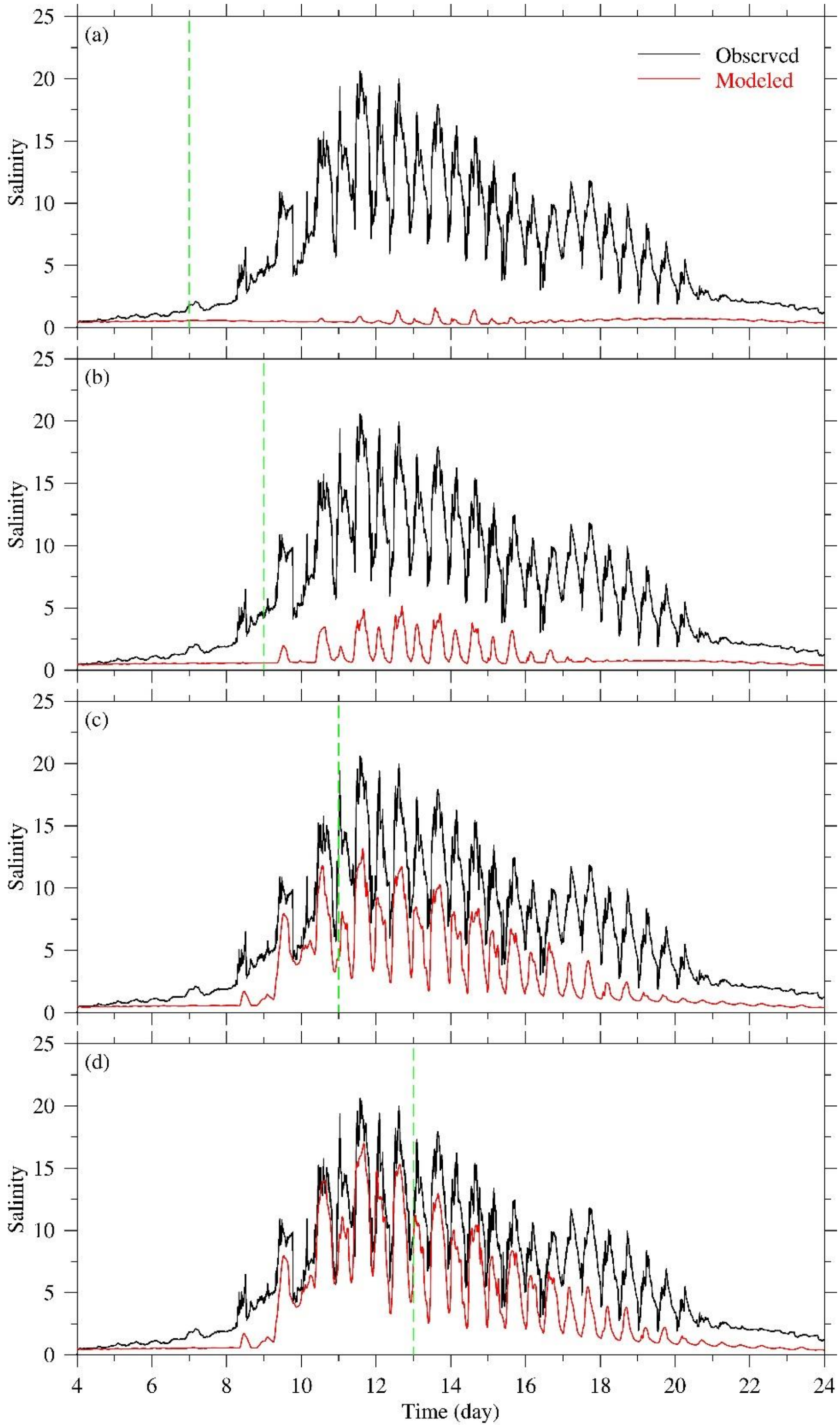

Figure 9: Temporal variation in observed (black line) and modeled (red line) salinity at hydrological station Baozhen from February 4 to 24, 2014. The green dashed lines indicate the time before it the wind was realistic and after it was set to 5 m s^{-1}.

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5 Conclusions

An extremely severe saltwater intrusion event in February 2014 occurred in the Changjiang Estuary under normal river discharge conditions and caused a severe threat to water safety in Shanghai. Such catastrophic saltwater intrusion has not occurred since recorded salinity in the estuary. Our findings are that this extremely severe saltwater intrusion event was caused by a persistent and strong northerly wind, which drove substantial landward Ekman transport to form a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel. This process surpassed seaward runoff and brought very large amounts of highly saline water into the upper reaches of the North Channel, which seriously threatened the water intake of the Qingcaosha Reservoir. Numerical experiments showed that a northerly wind lasting 8 days can produce extremely severe saltwater intrusion in the Changjiang Estuary. With more frequency persistent and strong northerly wind caused by climate change, more attention should be paid on extremely severe saltwater intrusion and freshwater safety in the Changjiang Estuary, where the Qingcaosha Reservoir takes water from the estuary for the 13 million people in Shanghai.

Data Availability. The data underlying the findings of this article can be accessed at https://doi.org/10.6084/m9.figshare.c.5011391.v1.

Author contributions. Jianrong Zhu analyzed the dynamics of the extremely severe saltwater intrusion in the Changjiang Estuary. Linjinag Li simulated the extremely severe saltwater intrusion in the Changjiang Estuary. Hui Wu simulated the residual water level with the large domain model encompassing the Bohai Sea, Yellow Sea and East China Sea. Jinghua Gu measured the water level, salinity at the hydrological station. Hanghang Lyu validated the saltwater intrusion model. Xinyue Cheng simulated the persistent and strong northerly wind with the Weather Research Forecasting (WRF) model.

Competing interests. The authors declare that they have no conflict of interest.

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