Author's Response to Reviewers

Reply to anonymous referee #1

Dear referee,

We appreciate your valuable questions and comments on our manuscript. The manuscript has been carefully revised according to your advice, and the questions and comments are marked with red (with blue and green for the other two reviewers). We believe your suggestions have improved our manuscript on the underlying mechanism of extremely severe saltwater intrusions and the role of the persistent and strong northerly wind. The point-by-point answers to the questions and comments are listed as follows.

Sincerely,

Jianrong Zhu, on behalves of the co-authors

Comment 1: Section 2.1: It can be seen from observed salinity (in Figure 2a) that at normal condition the salinity at the upstream Chongxi station is higher than other stations, while during the abnormal condition (i.e., the studied case) the maximum salinity concentration appears at Baozhen station. I would suggest the authors to clarify the difference between these two conditions since the underlying mechanism for saltwater intrusion may be completely different. For instance, to what extent the spilling of saltwater from the North Branch into the South Branch may impact the dynamics of saltwater concentration during this abnormal condition when compared with the normal condition.

Reply: Thanks for your good comment. Under normal conditions with climatic wind in the dry season, there exists saltwater spillover (SSO) from the North Branch into the South Branch during spring tide, which causes the salinity at Chongxi station to exceed the levels at Nanmen and Baozhen stations. During the abnormal condition with a persistent and strong northerly wind in February 2014, the maximum salinity was considerably higher at Baozhen station than at Chongxi station. To quantitatively analyze of impact of the SSO on the saltwater intrusion in the South Branch, the temporal variations in residual water flux and salt flux across sec2 (newly labeled in Figure 1) at the upper reaches of the North Branch in February 2014 were modeled under climatic wind and real wind conditions in February 2014. In addition, a numerical experiment in which the upper reaches of the North Branch is blocked was designed to determine the effect of the SSO on saltwater intrusion in the South Branch under the real wind in February 2014. The above contents have been added to the discussion section 4.1 in the revised manuscript.

In the original manuscript, we did not mention SSO. Now, we added the description of SSO at the end of the third paragraph in the introduction section on lines 69-75: "The most characteristic type of saltwater intrusion in the estuary is the saltwater spillover (SSO) from the North Branch into the South Branch (Shen et al., 2003; Wu et al., 2006; Lyu and Zhu, 2018). The shallow and funnel-shaped topography helps to prevent runoff from entering the North Branch, especially during the dry season, and produces a greater the tidal range in the North Branch than in the

South Branch. The saltwater from the SSO is transported downstream by runoff and arrives in the middle reaches of the South Branch during the subsequent neap tide, threatening the water supplies of reservoirs located in the estuary."

Comment 2: Section 2.1: With regard to this section, I would suggest to move the analysis of the observed data into "Results" section 3.

Reply: Thanks. We moved Section 2.1 into results section 3.1 in the revised manuscript. The relevant section number was changed.

Comment 3: Calibration and Validation of the numerical model: Although the saltwater intrusion model has been extensively calibrated and validated, I would suggest the authors to present the calibration for the salinity along the channel (i.e., Baozhen, Nanmen, Chongxi and Qingcaosha). For the time being, we can only see the reproduction of the salinity in Baozhen station, while the performances in other available stations are unknown. In addition, it would be better to clarify the basic calibration parameters used in the numerical model in the manuscript.

Reply: This is a very good suggestion. To preserve the length of the original manuscript, we only presented the model validation for the salinity at Baozhen station. We first calibrated the model for water level and salinity by adjusting the basic parameters of bottom drag coefficient, vertical turbulent viscosity and diffusion coefficient used in the numerical model, then validated the model. Now, we added the model validation for salinity at Baozhen, Nanmen, Chongxi and Qingcaosha stations along the channel in Figure 3 and for water level at Baozhen, Sheshan and Luchaogang stations in Figure 6 in the revised manuscript, and presented the results of model validation on lines 227-236 in the revised manuscript.

Because the model validations for salinity and water level at the hydrologic stations were added, the figures in the original manuscript were renumbered and redrawn.

Comment 4: Section 4: In principle, the discussion part should systematically discuss the potential mechanism of saltwater intrusion with regard to the persistent and strong northerly wind. How the wind affects the individual terms in the momentum equation? The relationship between residual water level rise and wind? The generation of Ekman transport and the resulted horizontal circulation etc. In current form, the discussion part is more or less the same as the conclusions part since we see an identical sentence "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" in both sections.

Reply: Thanks for your good suggestion. We added the following content to discuss the potential mechanism of saltwater intrusion with regard to the persistent and strong northerly wind in the discussion section of the revised manuscript:

1) To quantitatively analyze the impact of the SSO on the saltwater intrusion in

the South Branch, the temporal variations in residual (net) water flux and salt flux across sec2 at the upper reaches of the North Branch in February 2014 under climatic wind and real wind in February 2014 were added, and the analyses are presented in Section 4.1 in the revised manuscript.

In addition, we added a numerical experiment in which the upper reaches of the North Branch are blocked to distinguish the effect of the SSO on saltwater intrusion in the South Branch under the real wind in February 2014. The results are shown in Figure 12.

2) The individual terms in the momentum equations were output to discuss the wind effect on the saltwater intrusion.

This content was added in Section 4.2. Temporal variations in the vertically and time averaged terms in the momentum equations along the channel and across the channel from February 5 to 13, 2014, under climatic wind (Exp 1) and real wind (Exp 2) at a site in the North Channel are shown in Figure 13. How the wind affected the terms in the momentum equations is discussed.

3) Relationship between residual water level and wind

The residual (mean) water level in the Changjiang Estuary is closely correlated with the wind. The water level at Sheshan and Luchaogang stations rose during the northerly wind and dropped during the southerly wind in February 2014 (Fig. 4d). The water level rise of more than 50 cm corresponded to the strong northerly wind. The water level was approximately 20 cm (Fig. 5b) under climatic wind in February and 30 cm (Fig. 9b) under persistent and strong northerly wind in February 2014. At

Baozhen, Sheshan and Luchaogang stations in February 2014, the modeled water level under climatic wind was lower than that under strong northerly wind, especially from February 6 to 10, 2014, when the difference reached 10-30 cm (Fig. 6). Therefore, the stronger the northerly wind is, the higher the water level in the Changjiang Estuary and adjacent sea.

The above part was added in the revised manuscript in discussion section 4.3.

4) The generation of Ekman transport and the resulting horizontal circulation

This suggestion was added in discussion section 4.4. The distribution of pure wind-driven current time averaged from February 10 to 13, 2014, modeled under the real wind, and the relationship between water flux across sec1 in the North Channel and the northerly wind speed are presented in Figure 14.

5) The sentence "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" in the discussion section was removed the revised manuscript.

The contents added in the discussion section are summarized in the conclusion section and presented in the abstract.

Reply to anonymous referee #2

Dear referee,

We appreciate your valuable questions and comments on our manuscript. The manuscript has been carefully revised according to your advice, and the revisions are marked with blue (with red and green for the other two reviewers). The point-by-point answers to the questions and comments are listed as follows.

Your sincerely,

Jianrong Zhu, on behalves of the co-authors

Comment 1: According to Figure 5b, the realistic wind can be a cause. However, what is the role of the spring tide (The period from 10 Feb to 18 Feb 2014 according to the lunar calendar) for the intrusion during this issue?

Reply: As we can see from Figure 5b, the strongest saltwater intrusion occurred from February 11 to 14, 2014, in the middle tide, corresponding to lunar calendar dates 12 to 15. The tidal pattern of the middle tide is indicated by the measured tidal level at Baozhen hydrologic station in Figure 5a. The highest tidal level is on lunar calendar date 18, not 15, in the Changjiang Estuary. There are four tidal patterns in one neap-spring tide: neap tide, middle tide after neap tide, spring tide, and middle tide after spring tide. Each tidal pattern lasts approximately 4 days. Our study indicated that the saltwater intrusion event was caused by the persistent and strong northerly wind, which played a more important role in the saltwater intrusion event during neap tide than spring tide.

Comment 2: Had some issues also happened in the near Hangzhou Bay? Since the wind also causes a rise of residual water level there (Figures 4, 7, 8). If yes please add some details; if no what caused the different issues between the Changjiang Estuary (saltwater intrusion) and Hangzhou Bay (no issue) since the wind would be equal for these two.

Reply: Thanks for your good comment. Hangzhou Bay is adjacent to the Changjiang Estuary and is occupied by seawater all year round. The salinity is considerably higher than 0.45 (the standard salinity for drinking water), and there is no freshwater in Hangzhou Bay. Therefore, there is no study of saltwater intrusion there. It is true that the strong northerly wind also caused a rise in residual water level and an increased salinity in Hangzhou Bay.

The Qiantang River connects Hangzhou Bay, and saltwater intrusions often occur in the dry season. The most downstream water plant, Nanxing water plant, is located in the Qiantang River to supply water to Hangzhou (Figure R2-1, just for reply to referee, not included in the manuscript). Because the water intake of the water plant is far away from the river mouth and the river depth is only 1-2 m, the severe saltwater intrusion in the Changjiang Estuary in February 2014 did not occur there. The saltwater intrusion was not as severe in the North Branch of the Changjiang Estuary because the water depth is very shallow there, as is the case for the Qiantang River. In the North Branch of the Changjiang Estuary, the landward wind-driven Ekman water transport was weaker, flowing along the north side and flowing out along the south side only near the river mouth (Fig. 7c in the revised manuscript). However, the North Channel is deeper and wider and located on the north side of the

South Branch, which is conducive to strong landward Ekman water transport in the North Channel.

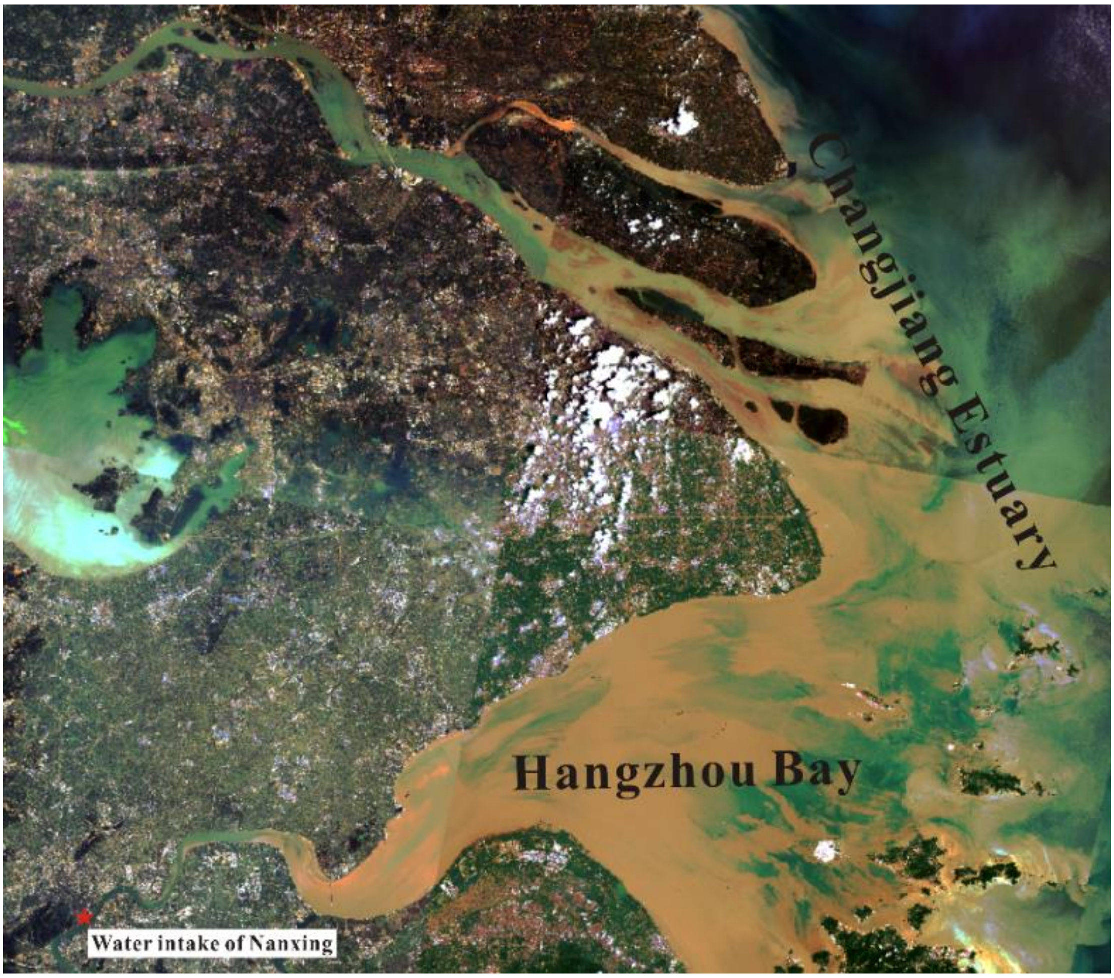


Figure R2-1 Satellite image of the Changjiang Estuary, Changjiang Bay and Qiantang River

Minor issue

1, Line 239, Page 14, Check the name.

Reply: Thanks. The name “Lijinag” has been changed to “Linjiang.”

Reply to anonymous referee #3

Dear referee,

We appreciate your valuable questions and comments on our manuscript. The manuscript has been carefully revised according to your advice, and the revisions are marked with green (with red and blue for the other two reviewers). Thank you again for your time in reviewing this manuscript. The point-by-point answers to the questions and comments are listed as follows.

Your sincerely,

Jianrong Zhu, on behalves of the co-authors

First review

Major issues:

Major issue 1: There are many studies about the influence of winds on saltwater intrusion in the estuary. But authors only mentioned two papers (Xue et al., 2009; Li et al., 2012) about the Changjiang Estuary. Even about the Changjiang Estuary, there are not only two papers.

Reply: Thanks for your good suggestion. We have cited the following papers about the influence of winds on saltwater intrusion in the estuary:

Aristizabal, M. F., and Chant, R. J. (2015): An observational study of salt fluxes in Delaware Bay, Journal of Geophysical Research-Oceans, 120, 2751-2768, 2015.

Chen, S. N., and Sanford, L. P.: Axial wind effects on stratification and longitudinal salt transport in an idealized, partially mixed estuary, Journal of Physical Oceanography, 39(8), 1905-1920, 2009.

Duran-Matute, M., Gerkema, T., and Sassi, M. G.: Quantifying the residual volume transport through a multiple-inlet system in response to wind forcing: The case of the western Dutch Wadden Sea, Journal of Geophysical Research: Oceans, 12, 8888-8903, 2016.

Regarding the Changjiang Estuary, the following papers on the influence of winds on saltwater intrusion have been cited:

Wu H., Zhu J. R., and Choi B. H.: Links between saltwater intrusion and subtidal circulation in the Changjiang Estuary: a model-guided study, Cont. Shelf Res., 30, 1891-1905, 2010.

Zhang E, Gao S, Savenije H. H. G, Sic C, and Cao S: Saline water intrusion in relation to strong winds during winter cold outbreaks: North Branch of the Yangtze Estuary, Journal of Hydrology, 574: 1099-1109, 2019.

Ding L., Dou X. P., Gao X. Y., Jiao J., and Hu J.: Response of salinity intrusion to winds in the Yangtze Estuary, Proceedings of 5th International Conference on Hydraulic Engineering, CHE2017, 241-247, 2017.

Major issue 2: About the strong wind event, it should be defined such as wind speed and duration. Authors said that from February 5 to 14, 2014 a persistent and strong northerly wind occurred lasting ten days. And they presented that only a strong northerly wind lasting 8 days can produce a severe saltwater intrusion in the Changjiang Estuary. But seen from plot c of Figure 2, on 5-6 the wind directions were southerly and easterly, and the winds seemed not strong. On 12-14, the winds were not strong as well. Authors should show what magnitude of wind event could induce severe saltwater intrusion. In plot c of Figure 2, the curve of wind speeds should be added. Thus the magnitude of winds can be seen clearly. What kind of data was used in plot c, instantaneous value, 2 minutes average, or maximum in a gust of wind? They should be presented clearly. In addition, the weather station locates inside the estuary near the mouth. The wind direction at this station may be different from the sea.

Reply: Thanks for your good question. There is really no defined strength of wind causing severe saltwater intrusions in the Changjiang Estuary. From the observed and simulated wind and results of numerical experiments on the effect of wind on saltwater intrusion in the estuary, wind with a speed greater than 10 m/s and lasting 8 days can be called a strong wind.

We checked the wind in plot c of Figure 2; the wind was northeasterly on February 3 and 4 and was southeasterly on 5 with speed of approximately 10 m/s. The mean wind speed on February 12-13 was approximately 10 m/s and was only 5 m/s on February 14. In fact, the measured wind at the weather station on the Chongming eastern shoal was only used to describe the phenomenon of persistent and strong wind and was not used to simulate the severe saltwater intrusion event. The wind used in the model was that simulated by the WRF, in which the wind speed adjacent to the sea near the Changjiang River mouth was stronger than that on the Chongming eastern shoal (Figure R3-1). Now, the sentence “a persistent and strong northerly wind from February 5 to 14, 2014, lasting ten days” was changed to “a persistent and strong northerly wind from February 6 to 14, 2014, lasting nine days”. Other relevant parts of the manuscript have also been revised.

In plot c of Figure 2, the curve of wind speeds has been added (Figure R3-2). This figure was enlarged to clearly illustrate the wind vector and wind.

The wind data used in plot c were 2 minute averages and are illustrated in the revised manuscript.

Yes, the weather station is located inside the estuary near the mouth, and the wind direction at this station was somewhat different from that over the sea (seen in Figure R3-1 and Figure R3-2). It needs to be emphasized again that the wind used in the model was that simulated by the WRF, in which the wind speed over the sea was stronger than that on the Chongming eastern shoal.

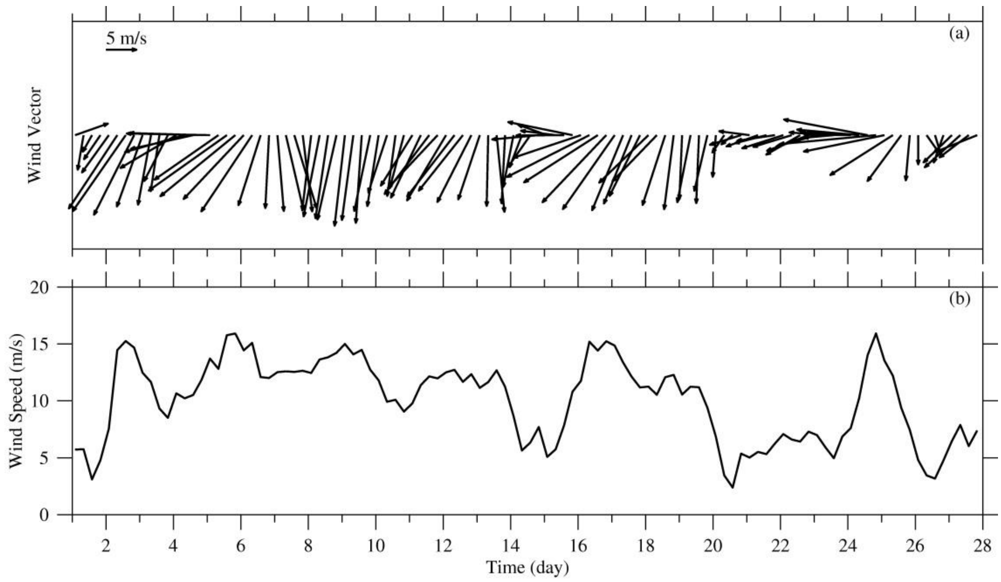


Figure R3-1: Temporal variations in wind vector (a) and wind speed (b) simulated by the WRF model off the Subei coast in February 2014.

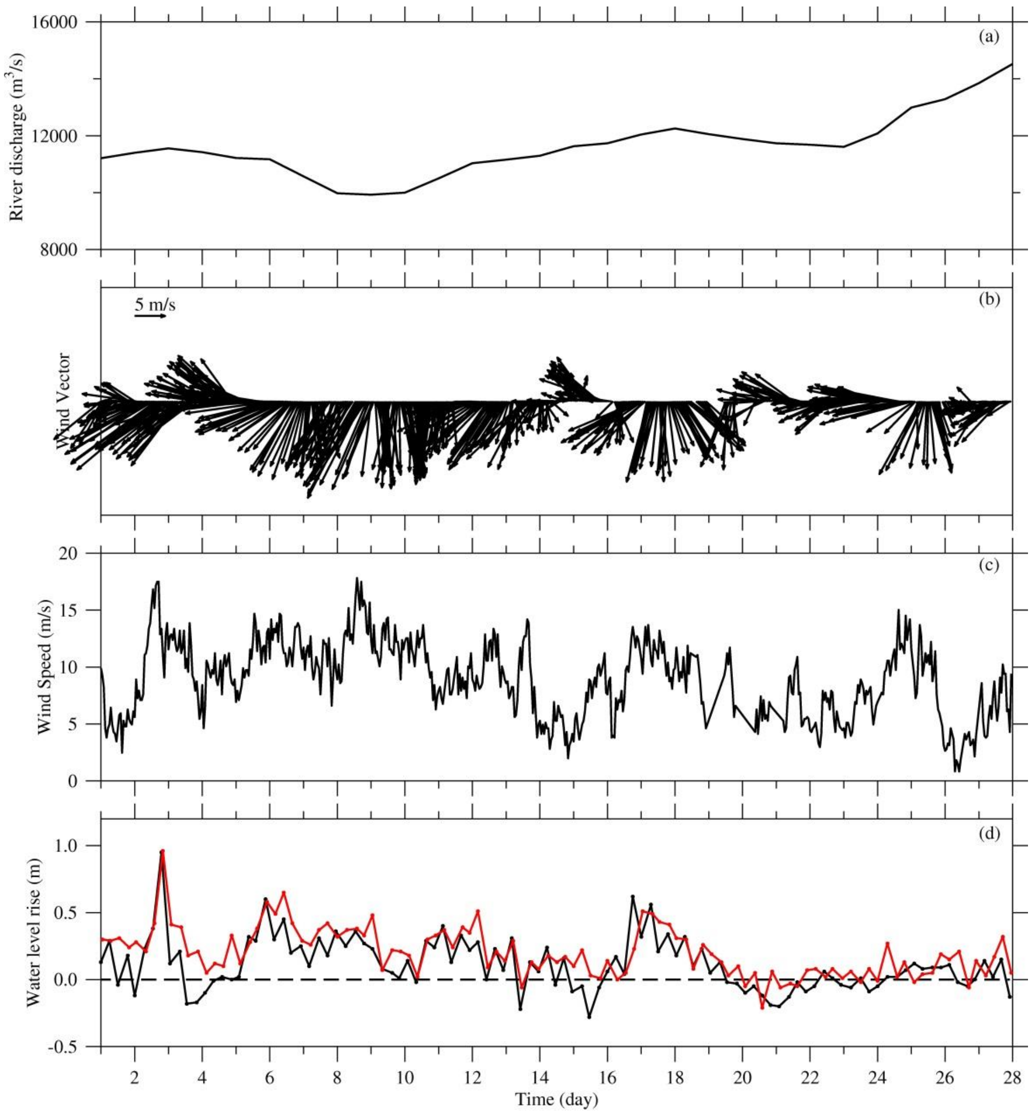


Figure R3-2: Temporal variations in the measured river discharge at Datong station (a), wind vector (b) and wind speed (c) at WS, and water level rise obtained by subtracting the data in the tide table from the measured water level at Sheshan station (black line) and Luchaogang station (red line) (d) in February 2014 in February 2014.

Major issue 3: This severe saltwater intrusion event is strange. The peak salinity at Baozhen and Nanmen stations reached 20.1 and 12.4 respectively. But why did the salinity only reach 8.6 at Qingcaosha? The location of Qingcaosha is close to Baozhen, and downstream of Nanmen. It can be seen from plot a of Figure 2 that salinity at

Qingcaosha was much lower than Baozhen. In addition, salinity at Chongxi station is from the North Branch. Before 7 February salinity was high at Chongxi, very low even close to zero at other stations. But during the severe event salinity was very high at other stations, but low at Chongxi station. These need explanation.

Reply: This is a good question and is exactly what this manuscript intends to reveal. From the longitudinal view, the extreme saltwater intrusion in February 2014 came from the downstream sea; consequently, the peak salinity at Baozhen, Nanmen and Chongxi stations was 20.1, 12.4 and 4.0 during the event, respectively.

From the transverse perspective, although the location of Qingcaosha is close to Baozhen and downstream of Nanmen, the salinity only reached 8.6 at Qingcaosha and was much lower than that at Baozhen. This was because the saltwater was brought by the flood current and moved rightward under the effect of Coriolis force, causing the salinity to be higher on the north side than on the south side of the North Channel. The simulated salinity distribution showed the same phenomenon. In both of the normal condition and the abnormal condition (i.e., the studied case), this transverse difference of salinity was same.

Under normal conditions with climatic wind in the dry season, there exists saltwater spillover (SSO) from the North Branch into the South Branch in spring tide, causing the salinity at Chongxi station to be higher than at Nanmen and Baozhen stations. This is the most obvious feature of saltwater intrusion in the Changjiang estuary and is a well-known phenomenon that increases the salinity at Chongxi station compared to those at Nanmen and Baozhen stations. During the abnormal condition with persistent and strong northerly wind in February 2014, the opposite occurred. This is the phenomenon our paper seeks to reveal.

Major issue 4: Authors presented that the water level rose distinctly at the coast during the event (Figure 2, line 91). Why did the water level inside the estuary not rise obviously (Figure 5, lines 133-135)? Authors said that the water level inside the river mouth was mainly determined by tide and river discharge. This needs explanation. Seen from plot b of Figure 4 and plot b of Figure 7, the water level rise inside the estuary was much larger than the coast. This is inconsistent with authors' expression and observations at Baozhen. The water level rises in figure 7 and figure 8 seem the same both for 10-13 February. In addition, about plot d in Figure 2, how was the water level rise obtained or how did authors calculate the water level rise? This should be presented clearly in methods section.

Reply: Thanks. The two different concepts of water level and water level rise need to be distinguished here. The water level rise at Sheshan and Luchaogang stations in Figure 2d was almost the same as the high water level along the coast which was induced by the strong northerly wind shown in Figure 5a. We note that the water level at Baozhen station inside the river mouth was mainly determined by tide and river discharge because the temporal variations in the observed and modeled water level were roughly same.

In plot b of Figure 4 and plot b of Figure 7, the time-averaged water level from February 10 to 13, 2014, is shown, not the water level rise. The mean water level was much higher inside the estuary than off the coast due to the river discharge.

The residual water level from February 10 to 13, 2014, in Figure 7b and Figure 8a is the same and was duplicated. These two figures were redrawn, plot a of Figure 8 was deleted, and the residual surface current was moved to plot b of Figure 7 (Figure R3-3).

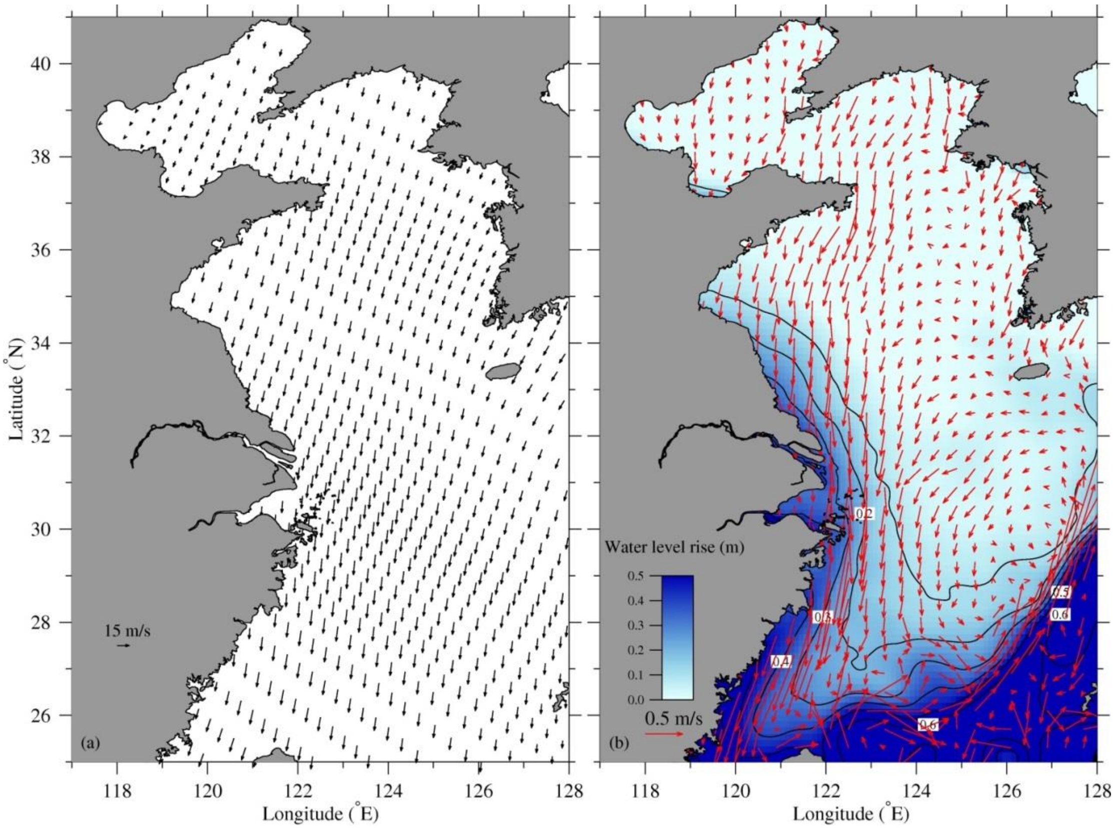


Figure R3-3: Distributions of the temporally averaged wind field from February 7 to 14, 2014, as simulated by the WRF model (a), and the time-averaged water level and surface current from February 10 to 13, 2014, as simulated by the model encompassing the Bohai Sea, Yellow Sea and East China Sea (b).

Regarding plot d in Figure 2, the water level was provided by the Shanghai Hydrology Administration, and the water level rise was obtained by subtracting the data in the tide table from the measured water level value. This information is provided in the revised manuscript.

Major issue 5: The main work of this manuscript is modeling of salinity and water level during the severe event. But authors only presented the results at Baozhen station (Figure 5). The results at other stations should be shown as well. Figures 6-8 only present the time-averaged results on10-13 February.

Reply: This is a good suggestion. Now, we present the measured results of salinity at Baozhen, Nanmen, Chongxi and Qingcaosha stations and of water level at Baozhen, Sheshan and Luchaogang stations (Figure R3-4 and Figure R3-5). The model was validated for salinity and water level (as Reviewer 1 suggested). The following contents marked with green were added in the revised manuscript:

The difference between the observed water level and modeled water level under climatic wind can be considered the water level rise by the northerly strong wind. It is seen from the Figure R3-5 that the water level rise at low water level from February 5 to 12, 2014 was approximately 0.35, 0.40, and 0.30 m at Baizhen, Sheshan and Luchaogang station, respectively.

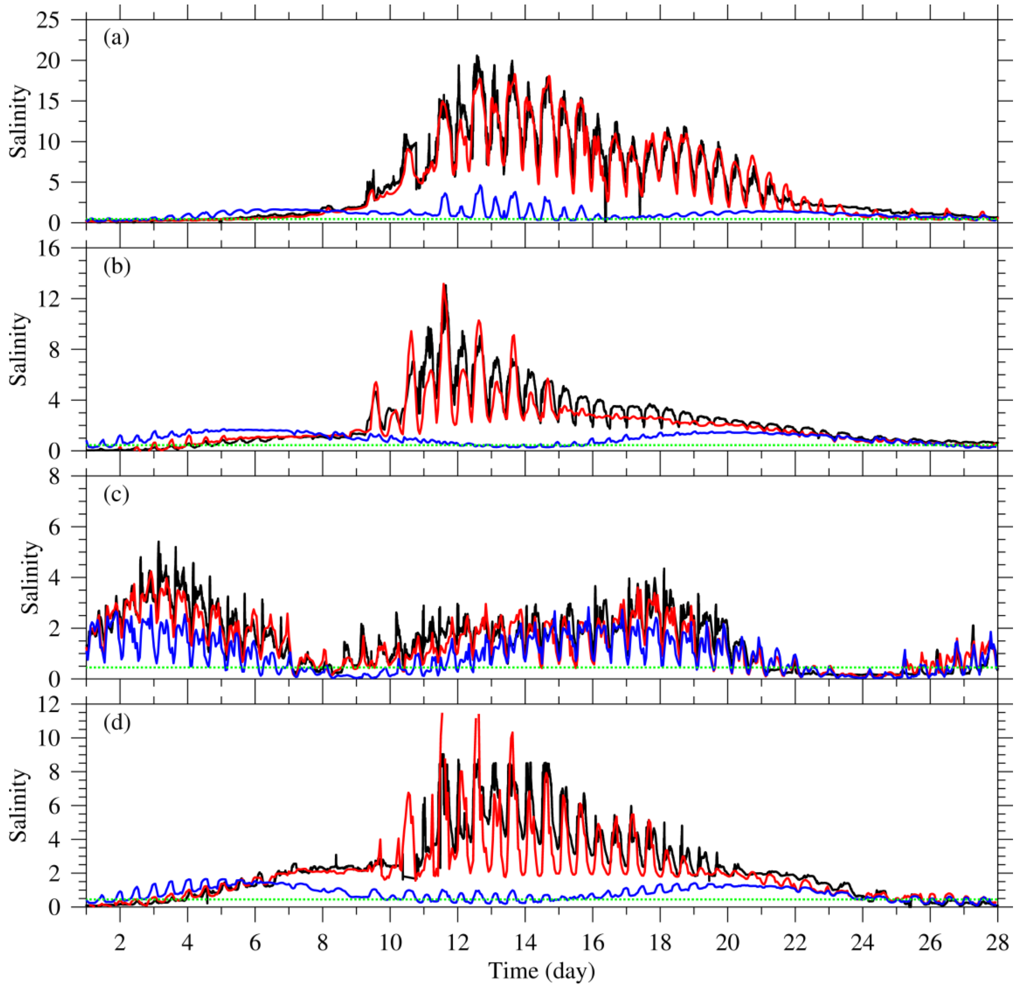


Figure R3-4: Temporal variations in salinity in February 2014 at hydrologic stations. a: Baozhen station; b: Nanmen station; c: Chongxi station; c: Qingcaosha station. Black line: measured salinity; blue line: simulated salinity under climatic wind and residual water level conditions at open sea boundaries; red line: simulated salinity under a realistic wind and residual water levels at the open sea boundaries. The dashed green line represents salinity of 0.45, which is the standard for drinking water.

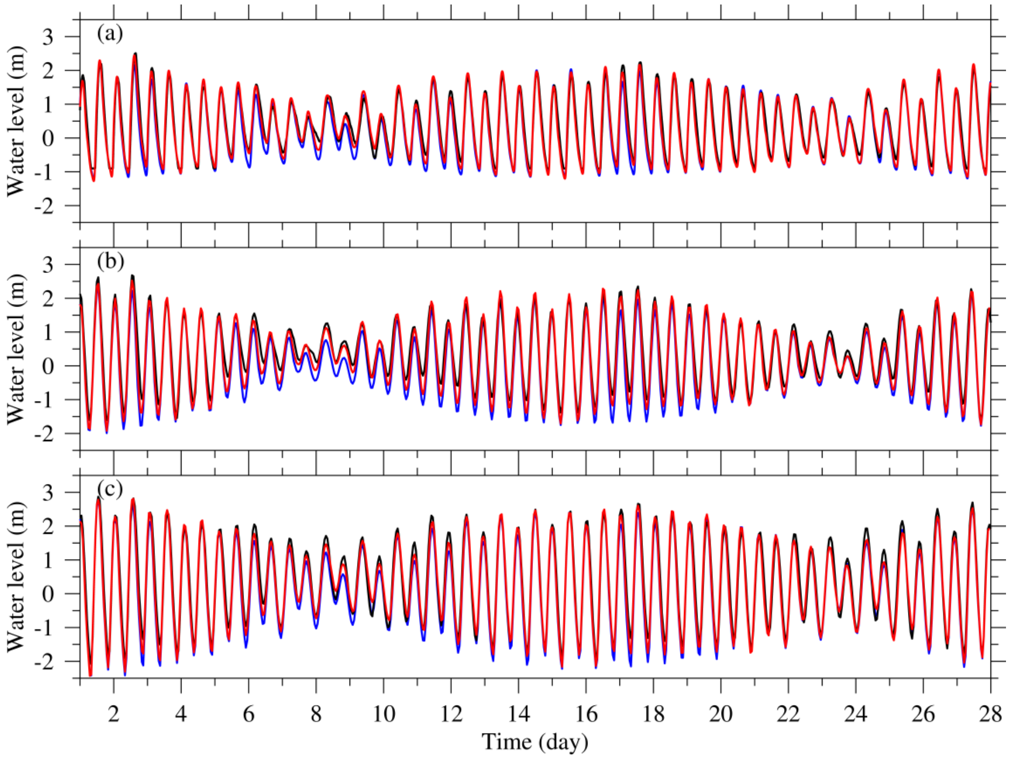


Figure R3-5: Temporal variations in water level in February 2014 at hydrologic stations. a: Baozhen station; b: Sheshan station; c: Luchaogang station. Black line: measured data; blue line: simulated data under climatic wind and residual water level conditions at open sea boundaries; red line: simulated data under a realistic wind and residual water levels at the open sea boundaries.

Major issue 6: The dynamic mechanism of the severe saltwater intrusion event is the objective of this manuscript. The manuscript proposed the mechanism: landward Ekman transport forms a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel. This mechanism or result is not new. It has been presented in authors' previous work (Wu Hui, Zhu Jianrong, Choi Byung Ho, 2010. Links between saltwater intrusion and subtidal circulation in the Changjiang Estuary: a model-guided study. Cont. Shelf Res. 30 (17): 1891–1905.).

But authors did not mention this work. This reference did not occur in the manuscript as well. The strong winds were not persistent for very long time. And the wind directions were not always northerly, even southerly in some periods. Why did the severe saltwater intrusion last 23 days? This is the question the manuscript should answer. About the results presented in discussion part and figure 9, it is doubtful. About plot b, can two-day strong winds induce the higher than normal salinity in after 8 days? About plots c and d, there are similar doubts. What is the mechanism of this? This needs detailed explanation. In addition, many studies mentioned that water withdrawal between Datong and estuary could increase saltwater intrusion in dry season. Is there possibility that during the severe event water withdrawal downstream Datong was large contributing to this event as well?

Reply: This is a misunderstanding. Wu et al. (2010) did present a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel; rather, the circulation they described was a purely wind-driven current under a northerly wind of 7 m/s (Figure 10 in their paper). Li et al. (2012) also presented a pure wind-driven current (Figure 14 in their paper). This pure wind-driven current was used to explain how the northerly wind affected the saltwater intrusion in the Changjiang Estuary. The pure wind-driven estuarine current can enhance saltwater intrusion in the North Channel and weaken it in the South Channel. In this study, the horizontal estuarine circulation was a total (net) circulation induced by the river discharge, tide and persistent and strong northerly wind and was not a pure wind-driven circulation, which surpassed the strong seaward runoff. This result was unexpected and was found for the first time. The relevant illustration was added in the revised manuscript. The paper of Wu et al. (2010) was cited in the revised manuscript.

It is rare for a northerly wind with speed of greater than 10 m/s and lasting more than 9 days to occur in the Changjiang Estuary, but it did occur (Figure R3-2) and caused the severe saltwater intrusion in February 2014, influencing the water intake of Qingcaosha reservoir for 23 days. If the wind directions were not always northerly, even southerly in some periods, the saltwater intrusion would be more severe and more serious impact on the Qingcaosha reservoir. This manuscript reveals why the extreme saltwater intrusion occurred as well as the dynamic mechanism.

In Figure 9, the strong northerly wind lasts two, four, six and eight days in plot a, b, c and d, respectively. Two-day strong winds are in plot a, not in plot b. It is true that several days of strong wind can induce the higher than normal salinity after 8 days because the strong wind Ekman transport brought the salinity front in a sandbar area upstream and closer to the Baozhen station (model output site in Figure 9) and then moved upstream and downstream with the oscillation of flood and ebb currents for 8 days when the northerly wind is 5 m/s. It will take approximately 8 days to eliminate the impact of the upstream forward salinity front on the salinity at Baozhen station. This phenomenon was also shown in Figure 2a, 2c. The relevant illustration was added in the revised manuscript.

Yes, many studies pointed out that water withdrawal between Datong and the estuary could increase saltwater intrusion in dry season, but there was no possibility that the water withdrawal downstream Datong had a large contribution to the severe saltwater intrusion event because the water withdrawal amount by the South-to-North Water Diversion Project and water diversion and drainage along the river was approximately 1000 m^3/s, and the monthly mean river discharge was 12,430 m^3/s.

Major issue 7: The structure of the manuscript is strange. In section 2.1 observed data, authors introduced the severe saltwater intrusion events, which should be moved to introduction section or results section. In section 3 results, section 3.1 is not necessary. The results under normal situations and special situations can be compared in order to show the difference. But the result under normal situation is not the important results for the objective of the manuscript. In other words, it is not necessary presented separately. In addition, the discussion part is too simple.

Reply: Thanks for your good suggestion. We moved Section 2.1 on observed data to section 3 of the results in the revised manuscript and deleted the headings of 3.1 Climatic wind and residual water level conditions at open sea boundaries and 3.2 Under a realistic wind in February 2014 and residual water levels at the open sea boundaries in the revised manuscript, and add the follow contents as the first paragraph of the section 3.2 Model results:

To reveal which dynamic factor caused the extremely severe saltwater intrusion event in February 2014, two numerical experiments were designed. The first experiment considered climatic wind conditions at the sea surface and residual water levels at open sea boundaries (Exp 1), and the second considered a realistic wind in February 2014 and residual water levels at the open sea boundaries (Exp 2). The river discharge at the upper boundary at Datong station and tide at the open sea boundary were the same in Exp 1 and Exp 2.

According to Reviewer 1 and your suggestions, the discussion part has been greatly expanded. The contribution of the SSO to the saltwater intrusion event, how the wind affects the individual terms in the momentum equations, the relationship between residual water level and wind, and the generation of Ekman transport and the resulting horizontal circulation were added and discussed in the revised manuscript.

Major issue 8: Some presentations or data in the manuscript are unreliable. Besides some mentioned above examples are as follows.

(1) About the data source, in section 2.1 (observed data), authors said that the observed data was conducted by State Key Laboratory of Estuarine and Coastal Research, East China Normal University. But in acknowledgements part authors said that the observed data was provided by Shanghai Hydrology Administration.

(2) Page 3, line 57, "... caused by very low river discharge of approximately 7000 and 8000 m^3s^{-1} lasting three mouths (mouths should be months), respectively". In this sentence, "8000 m^3s^{-1} in 1999" and "lasting three months" are not correct. In dry season of 1979, river discharges in January and February were really very low between 7000 and 8000 m^3s^{-1} at Datong station. In March the monthly mean discharge was more than 10000 m^3s^{-1} during which severe saltwater intrusion also occurred. In 1999 the monthly mean river discharges at Datong were all larger than 9000 m^3s^{-1}. In February extremely severe saltwater intrusion occurred as well

inducing continuous 25 days of unsuitable drinking water at Chenhang Reservoir upstream of Qingcaosha, during which discharge was 9110 m^3s^{-1}.

Reply: Thanks for pointing out the incorrect expressions in the original manuscript.

(1) In Section 2.1 (observed data), we modified the expression as follows: the observed salinity and wind data were from the State Key Laboratory of Estuarine and Coastal Research, East China Normal University, and the observed water level data were from the Shanghai Hydrology Administration. In the acknowledgements part, we modified the expression as follows: the authors thank the Shanghai Hydrology Administration for providing the observed water level in the Changjiang Estuary.

(2) We checked and drew the variation processes of river discharge measured at Datong station in dry seasons of 1979 and 1999 (Figure R3-6). In the dry season of 1979 from January 1 to March 15, the river discharge at Datong station was between 6000 and 9280 m^3s^{-1} with mean value of 7485 m^3s^{-1}, lasting 2.5 months. In the dry season of 1999 from January 1 to March 16, the river discharge at Datong station was between 7650 and 1,0900 m^3s^{-1} with mean value of 9246 m^3s^{-1}, lasting 2.5 months.

Therefore, we modified the sentence “Two severe saltwater intrusion events were recorded 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^3s^{-1} lasting three months” to “Two severe saltwater intrusion events were recorded in the Changjiang Estuary in the dry seasons of 1979 and 1999, which were caused by very low river discharge with a mean value of 7485 $m^3 s^{-1}$ from January 1 to March 15, 1979, and 9246 m^3s^{-1} from January 1 to March 16, 1999, both lasting 2.5 months".

The word "mouths" has been changed to "months."

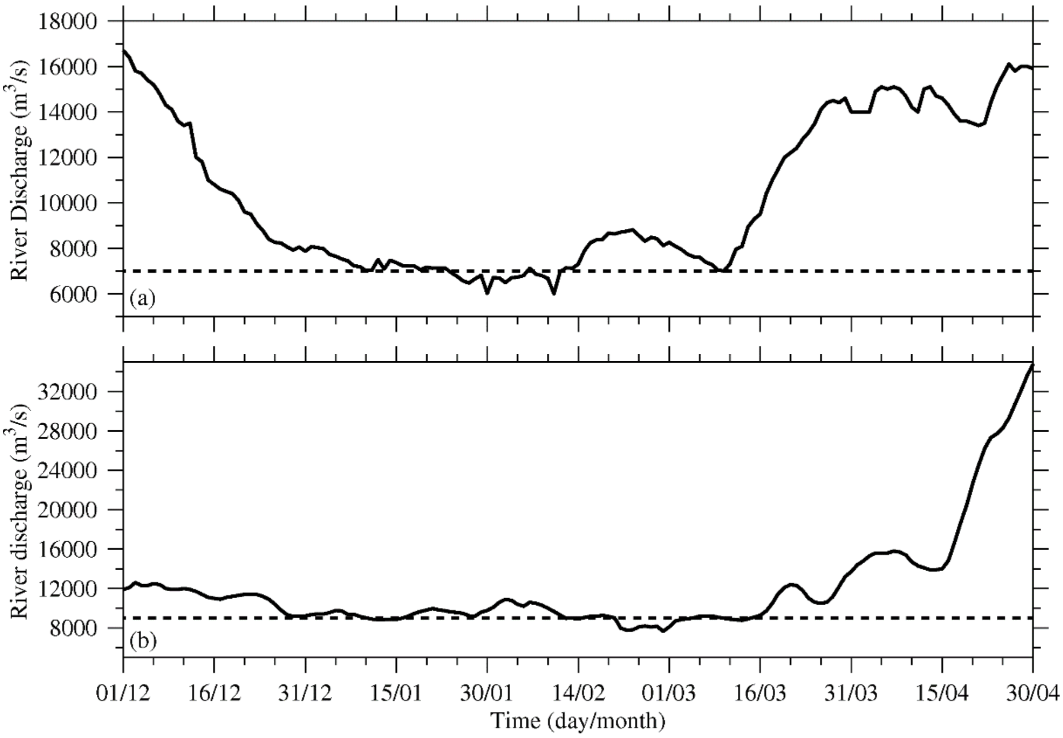


Figure R3-6: Temporal variations in river discharge measured at Datong station from December 1, 1978 to April 30, 1979 (a), and from December 1, 1998 to April 30, 1999 (b).

Minor issues:

Minor issue 1: In page 2, lines 30-31, what is the maximum spring tide and minimum neap tide? The proper expressions should be the maximum tidal range of spring tide and minimum tidal range of neap tide. Or, the maximum tidal range and minimum tidal range are enough.

Reply: Thanks. "the maximum spring tide" was changed to "the maximum tidal range", and "the minimum neap tide" was changed to "minimum tidal range".

Minor issue 2: In page 3, lines 49-50, “which was the largest estuarine reservoir in the world, the Qingcaosha Reservoir, was built”. There is syntax error in this sentence.

Reply: “which was the largest estuarine reservoir in the world, the Qingcaosha Reservoir, was built” was changed to “when the largest estuarine reservoir in the world, the Qingcaosha Reservoir, was built”.

Minor issue 3: In the last paragraph of introduction, authors said that an extremely severe saltwater intrusion event in February 2014 occurred, and this is a catastrophic event never occurred. But we did not see how severe and catastrophic. The compare between this event and historical severe events should be presented as well in order to show the severe magnitude.

Reply: The extremely severe saltwater intrusion event in February 2014 resulted in the continuous period of unsuitable drinking water reaching 23 days and caused a serious threat to the water intake of the Qingcaosha Reservoir and water safety in Shanghai. Therefore, we refer to the saltwater intrusion as a catastrophic event. Historically, there were severe saltwater intrusions, such as in dry seasons of 1979 and 1999, but there was no reservoir in the Changjiang Estuary at that time. Thus, we only called these saltwater intrusions severe events. A catastrophic event refers to water security.

Minor issue 4: About the river discharge used during modelling, did you consider the time required for water traveling from Datong to the estuary? Usually the discharges several days in advance are used because Datong station is located more than 600 km upstream of the estuary.

Reply: This is a good question. The west open boundary of the Changjiang River in the model is up to Datong station in the Changjiang River. Thus, it is not necessary to consider the time required for water traveling from Datong to the estuary. The sentence “Datong hydrological station is on the western open boundary of the Changjiang River” was added at the end of the first paragraph in section 2.1 numerical model.

Minor issue 5: Caption of Figure 2: Temporal variations in the measured data in February. Plot d does not present the measured data. The water level rises are calculated results.

Reply: Thanks. Now the caption of Figure 2 was changed to “Temporal variations in the measured river discharge at Datong station (a), wind vector (b) and wind speed (c) at WS, and water level rise obtained by subtracting the data in the tide table from the measured water level at Sheshan station (black line) and Luchaogang station (red line) (d) in February 2014. The figure number is changed to Figure 4 in the revised manuscript.

Minor issue 6: Caption of Figure 3 is not clear. And there are syntax errors.

Reply: The caption of Figure 3 was rewritten. The Figure 3 is changed to Figure 2 in the revised manuscript.

Figure 2 Model grids of the Changjiang Estuary (a), and model grids of the Bohai Sea, Yellow Sea and East China Sea (b). Domains of the models (c); within the red line: the Changjiang Estuary model domain; within the green line: model domain of the Bohai Sea, Yellow Sea and East China Sea; the black dashed lines: the two-fold nested WRF model domain.

Minor issue 7: What is the climatic wind? This expression is strange.

Reply: Climate wind means monthly mean wind for many years.

Minor issue 8: Captions of Figures 5, 6, 8 are not clear.

Reply: The captions of Figures 5, 6, 8 were rewritten. The figures were reorganized and redrawn, and the modified captions were presented in the revised manuscript.

Second review

Referee's reply to major issue 1: What authors should do is adding introduce about previous related research, instead of only adding several references.

Author's reply: Thanks your comment. We didn't make it clear about citing more references of influence of winds on saltwater intrusion in the estuary. We thought the revised manuscript will be uploaded and the referee will see the detailed modification. We cited the references and briefly described them in the introduce section besides in the inferences section.

The sentences in the original manuscript are rewritten to the following sentences in introduce section in the revised manuscript (the green parts are the added contents): 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 (Chen and Sanford, 2009; Aristizábal and Chant, 2015; Duran-Matute et al., 2016; Giddings and Maccready, 2017) and vertical mixing (Simpson and Hunter, 1974; Prandle and Lane, 2015). Along-estuary winds can strain density gradients, and the associated destruction or enhancement of stratification depending on wind direction, and the entrainment depth ratio (Chen & Sanford, 2009). Wind-driven sea-level setups at the mouth of estuaries can produce landward flows that outcompete river runoff, resulting in the net, landward advection of salt (Aristizabal & Chant, 2015). For multi-inlet coastal systems, residual (horizontal) circulation is influenced by winds, which alters salt transports in each inlet (Duran-Matute et al., 2016). The upwelling and downwelling favorable wind can significantly influence the estuarine exchange flow (Giddings, and MacCready, 2017).

For the Changjiang Estuary, the sentences in the original manuscript are modified to the following sentences in introduce section in the revised manuscript (the green parts are the added contents): 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; Wu et al., 2010; Li et al., 2012; Ding et al., 2017; Zhang et al., 2019), and topography (Li et al., 2014; Chen et al., 2019b). The impact of wind on saltwater intrusion has been studied, but only with a climatic wind (Xue et al., 2009; Qiu et al. 2012; Chen et al, 2019a), 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). Xue et al. (2009) pointed out that a northerly wind tends to enhance the saltwater intrusion in the North Branch by reducing the seaward surface elevation gradient forcing. Wu et al. (2010) and Li et al. (2012) simulated the pure wind-driven current that flows into the North Channel and out of the South Channel with climatic wind to explain that the northerly wind can enhance saltwater intrusion in the North Channel, and weaken it in the South Channel. Zhang et al. (2019) reported that the frequency of saltwater intrusion events in the Changjiang Estuary is increasing in recent years due to increasing frequency of winter storms passing East China Sea.

Referee's reply to major issue 2: Authors added the wind speed curve at weather station in figure R3-2 and said that the data used was 2 minutes average. I also have the wind observations data. At this land-based station inside estuary, it is impossible that the 2 minutes average wind speeds are so large, persistent more than 10 m/s for long time and even larger than 15 m/s. In figure R3-1, why did authors present the modeled wind directions and speeds off the Subei coast, instead of off the

Changjiang Estuary?

Author's reply: We established and managed the weather station at the Chongming eastern shoal for more than 15 years. The wind direction and speed was recorded with several forms, i.e., instantaneous, 2 minutes average, 10 minutes average, and maximum. We used the 2 minutes averaged wind direction and speed. The monthly mean wind in the Changjiang river mouth is 5.5 m/s during winter and 5.0 m/s in summer. February 2014 is a special month, occurred persistent and strong northerly wind. In Fact, the weather station is just on the river mouth (shown in Figure 1), not inside the estuary. The reviewer said he also has the wind observations data. Would you please draw a figure of the wind vector and speed curve to see how weak your wind is? And where is the weather station? This is a major issue the reviewer proposed, we will very appreciate you if the question can be figured out and what is the really wind.

We presented the figure R3-1 only to indicate the wind was much stronger on the sea than at Chongming eastern shoal for the reviewer. This picture is not used in the manuscript, only appears in the author's reply. We did not instead of the observed wind at the weather station with the modeled wind on the seas. We want to emphasize again that the observed wind data is only used to illustrate the wind status, and the wind used in the saltwater intrusion model was the simulated wind field by the WRF. The model domain is large, and wind has spatial variation. A point wind cannot represent a wind field. It can been seen from the figure 7a that the temporally averaged wind field from February 7 to 14, 2014 simulated by the WRF reached more than 15 m/s in the Yellow Sea and off the Changjiang river mouth, indicating that there did exist a long persistent and strong northerly wind in February, 2014.

Referee's reply to major issue 3: About why the water level rise inside estuary is small, authors said that I misunderstood and water level rise at Sheshan and Luchaogang stations in Figure 2d was almost same as the one in 2 Figure 5a. Authors clearly said in the manuscript that the water level rise at Sheshan and Luchaogang are distinct with a peak value more than 0.5 m (line 91), which is shown in plot d of figure 2 as well. But at Baozhen the relatively large rise during neap tide 7-11 is about 0.15 m (line 135), which can be seen from plot a of figure 5 as well. So, what is the real situation?

About the method used calculating water level rise in plot d of figure 2, authors said that they subtracted the data in the tide table from the measured water level value. The obtained water level rises based on this method could have much error because the forecasted water levels in tide table have error as well.

About much more water level rise inside the estuary in plot b of Figure 4 and Figure 7, authors said that in plot b of Figure 4 and plot b of Figure 7, the time-averaged water level was shown, not the water level rise. But it can be seen clearly that "water level rise" was labeled in the legend.

Author's reply: Thanks again. We checked the water level rise in Figure 2d and water level in in Figure 5a, and concluded that the water level rise at Sheshan and Luchaogang are distinct with a peak value more than 0.5 m (Figure 2d). At Baozhen station, the difference between the observed water level and modeled water level under climatic wind can be roughly considered the water level rise by the northerly strong wind. It is seen from the Fig. 5a that the water level rise at low water level from February 5 to 12, 2014 was approximately 0.35 m.

We agree the reviewer's opinion that the forecasted water levels in tide table have error. Because the water level can be directly measured, the water level rise cannot be obtained by direct observation, and the forecasted water levels in tide table without strong northerly wind considered, the water level rise is roughly reasonable with the method subtracted the data in the tide table from the measured water level value.

Thank you pointing out the mistake. The legend in Figure 4b and in Figure 7b should be mean water level. Now we modified it in the revised manuscript.

Referee's reply to major issue 4: About already presented in previous work and unmentioned mechanism proposed in this manuscript, authors argued that the previous work was pure wind-driven and the work in this manuscript was not only wind-driven. But the proposed mechanism is the same. There is no the new thing, such as interaction between wind, tide, and river discharge. If you thought they were different, why did you not mention the previous work? Even if they are the same, it is ok only if you introduce and discuss the work. But you did not do this.

Authors said that if the wind directions were not always northerly, even southerly in some periods, the saltwater intrusion would be more severe and more serious impact on the Qingcaosha reservoir. Why? If it is true, the mechanism should be shown as well.

In addition, it can be seen clearly from figure R3-4 that at Chongxi station the increase of salinity relative to the normal situation on 3-4 was more than the "extreme event" period. On 3-4 the strong northerly or northeasterly winds occurred as well. Why was the saltwater intrusion in the North Branch during the extreme event period is not extremely serious? During 13-17, salinity was similar to the normal situation, which means that there is no increase of saltwater intrusion. However, saltwater intrusion at other stations did not occur on 3-4, but was very serious on the "extreme event" period. What is the difference between mechanisms of winds influencing the North Branch and the North Channel?

Author's reply: Thanks your comment. Now we added the previous work of the wind impact on the saltwater intrusion in the Changjiang Estuary in introduction section. Xue et al. (2009) pointed out that a northerly wind tends to enhance the saltwater intrusion in the North Branch by reducing the seaward surface elevation gradient forcing. Wu et al. (2010) and Li et al. (2012) simulated the pure wind-driven current that flows into the North Channel and out of the South Channel with climatic wind to explain that the northerly wind can enhance saltwater intrusion in the North Channel, and weaken it in the South Channel. In the discussion section in the revised manuscript, we added the following sentences marked with green:

The wind-driven estuarine current can enhance saltwater intrusion in the North Channel, and weaken it in the South Channel. Previous studies revealed the dynamic mechanism of northerly wind on the saltwater intrusion by the pure wind-driven current in the estuary (Wu et al., 2010; Li et al, 2012). In this study, the horizontal estuarine circulation was a total (net) circulation forced by the river discharge, tide and persistent and strong northerly wind (Fig. 8a), which surpassed the strong seaward runoff.

I'm sorry we didn't make it clear of the impact of wind direction on saltwater intrusion. The correct expression is: If the wind directions were always northerly, and the southerly in some periods is northerly, the saltwater intrusion would be more severe and more serious impact on the Qingcaosha reservoir.

Thank you asking a very good question of the different performance of saltwater intrusion between at Chongxi station and at Nanmen, Baozhen station. The saltwater intrusion at Chongxi station is completely from the North Branch (SSO, saltwater-spill-over from the North Branch into the South Branch), while at Namen and Baozhen station is mainly from the SSO under normal wind condition. Because the North Branch is very shallow, the landward wind-driven Ekman water transport in it was weaker, flowing along the north side and flowing out along the south side only near the river mouth (Fig. 8b), the persistent and strong wind cloud enhance the SSO, but not so much significant as in the North Channel. The North Channel is deeper and wider and located on the north side of the South Branch, which is conducive to strong landward Ekman water transport in the North Channel, resulting in severe saltwater intrusion. Therefore, the saltwater intrusion in the North Branch during the extreme event period is not extremely serious.

At Chongxi station the increase of salinity relative to the normal situation on February 3-4 was more than the "extreme event" period, this is because the northerly wind was strong which has somewhat influence on the saltwater intrusion, but the major cause was the asymmetry of the semi lunar spring tide. This can be confirmed in Figure 5a that the high water level was higher on February 3-4 than on February 18-19 in the spring tide.

In order to better reveal the contribution of the SSO in the saltwater intrusion event in February 2014, we added contents in the discussion section 4.1 in the revised manucript. Reviewer 1 asked the same quiestion, so the contents are marked with red in the revised manuscript. The contents are as follows.

4.1 What was the contribution of the SSO to the saltwater intrusion event?

The most obvious feature of saltwater intrusion in the Changjiang Estuary is the SSO. Previous studies showed that the SSO is the main source of saltwater intrusion in the upper and middle reaches of the South Branch and the main saltwater source of the reservoirs (Shen et al. 2003; Wu et al. 2006; Zhu et al., 2013; Lyu and Zhu, 2018). What was the extent of the contribution of the SSO to the extremely severe saltwater intrusion in February 2014? A transect Sec 2 at the upper reaches of the North Branch (location labeled in Fig. 1) was set to calculate water and salt flux.

In Exp 1 (under climatic wind and residual water level conditions at open sea boundaries), the water flux from February 6 to 8, 2014, and salt flux on February 7, 2014, were transported from the South Branch into the North Branch (Figure R3-7). This phenomenon occurred during a neap tide (indicated by the water level in Figure

R3-5), while in the other tidal patterns, the water and salt flux was transported from the North Branch into the South Branch, especially during the spring tide from February 14 to 17, 2014. This is the famous SSO occurring during middle and spring tide in dry season.

In Exp 2 (under a realistic wind and residual water levels at the open sea boundaries), the seaward water flux on February 7 decreased and the landward water flux increased from February 4 to 6 and from February 8 to 14, and the salt flux from February 4 to 14 was landward, under strong northerly wind, which was distinctly greater than the result under climatic wind and residual water level conditions at open sea boundaries. Therefore, the strong northerly wind enhanced the SSO.

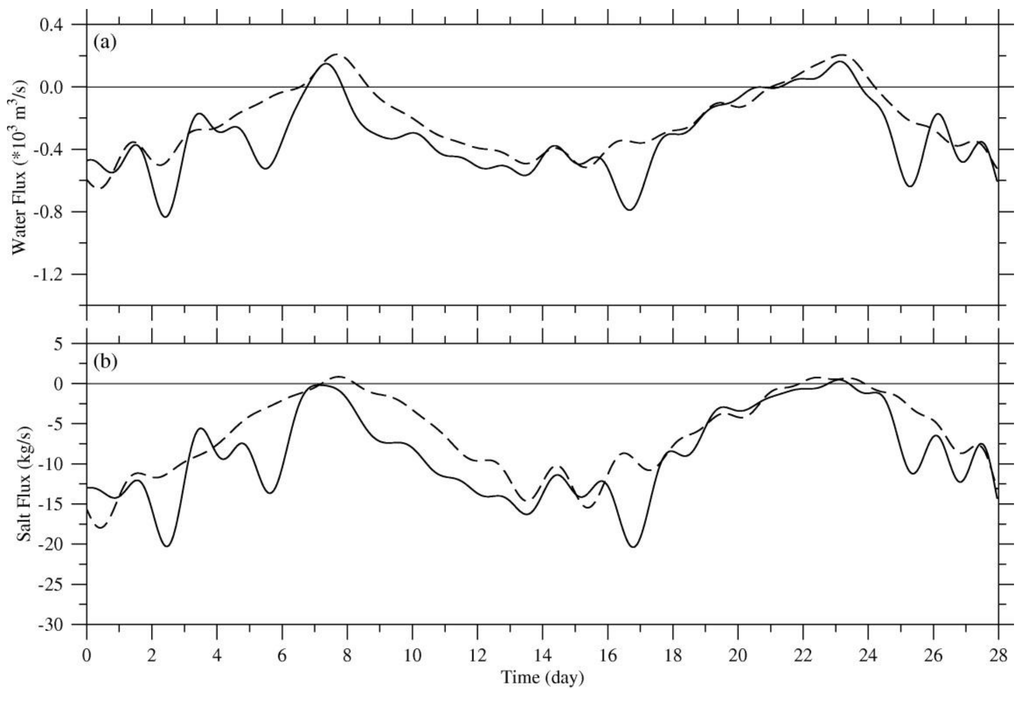


Figure R3-7: Temporal variations in residual water flux (a) and salt flux (b) across Sec 2 in the North Branch in February 2014. Dashed line: Exp 1; solid line: Exp 2. A positive value represents seaward flux, and a negative value represents landward flux.

A numerical experiment was designed in which the upper reaches of the North Branch were blocked (location labeled in Fig. 1 in the revised manuscript) to further distinguish the contribution of SSO in the saltwater intrusion event. The distribution of time-averaged surface salinity from February 10 to 13, 2014 (Fig. R3-8a) and the temporal variations in salinity from February 8 to 22, 2014 at Chongxin station (Fig. R3-8b) show that the SSO was completely absent, while the salinity in the river mouth and near the Qingcaosha reservoir and at the Baozhen, Nanmen and Qingcaosh stations was almost identical to the results from Exp 2 (Fig. 8c, Fig. R3-4), indicating that the SSO had almost no contribution to the saltwater intrusion event in February 2014.

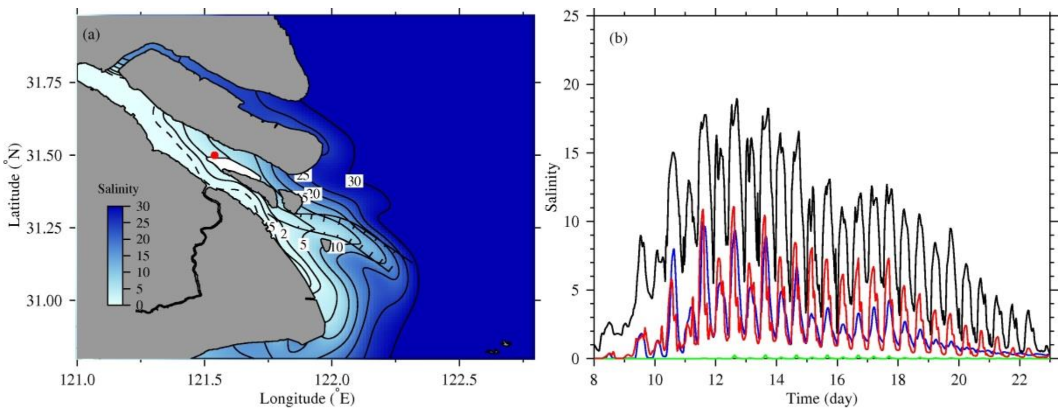
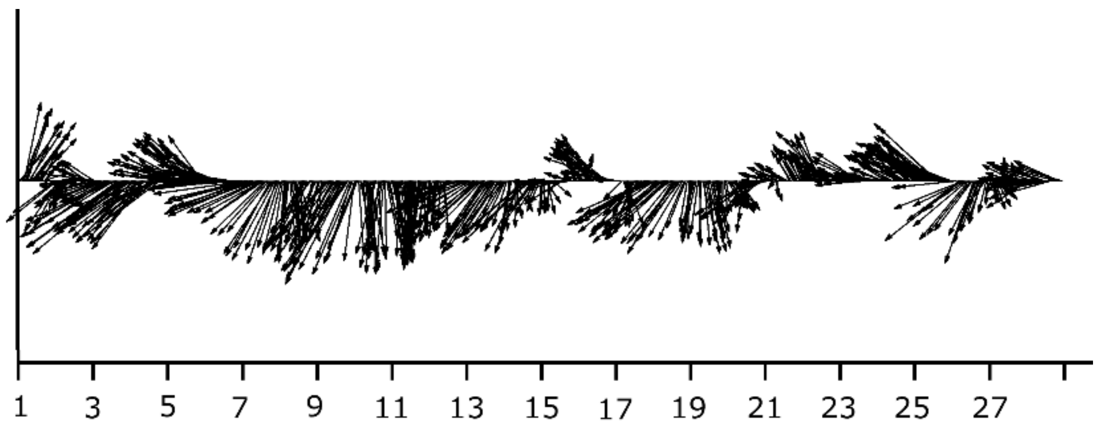
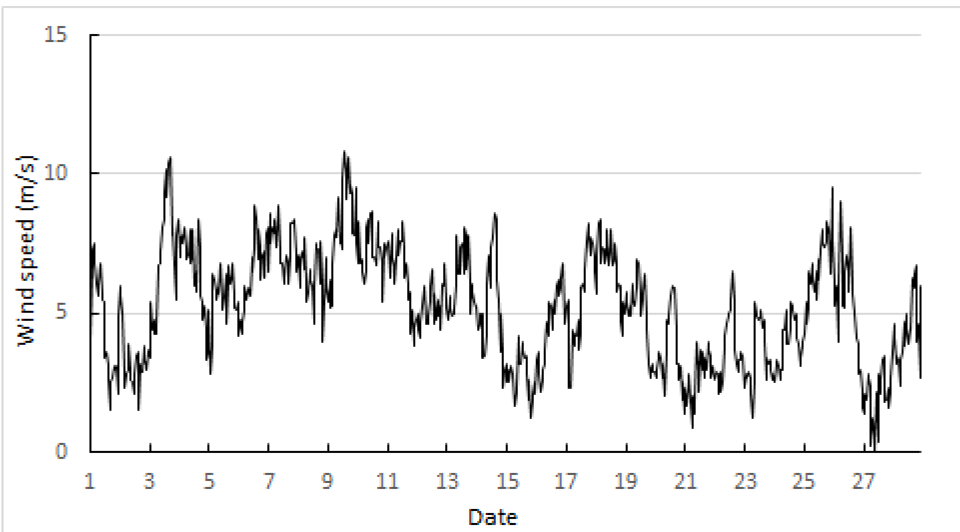


Figure R3-8: Distribution of time-averaged surface salinity from February 10 to 13, 2014 (a); and temporal variations in salinity from February 8 to 22, 2014 at hydrologic stations (b) if the upper reaches of the North Branch is blocked, and under a realistic wind and residual water levels at the open sea boundaries. Black line: Baozhen; red line: Nanmen; green line: Chongxi; blue line: Qingcaosha.

Third review

Comments to authors' reply 1: The following figure is the wind observations (2 minutes average) in February 2014. I think the location is the same as yours, located at Chongming eastern shoal as well. The shape of wind speed curve is similar to yours, but the magnitude is much weaker than yours. I also have observations at other stations along the coast, with similar magnitude even weaker. Even if the observed wind data is only used to illustrate the wind status, they should be true. In addition, why did you delete one day data (wind and water level rise on 1) in figure R3-2? But the date still began from 1. It seems that the data or figure can be changed as you want.





Reply: Thank you presenting the wind observations at Chongming eastern shoal in February 2014. It showed that the mean wind speed was approximately 7.5 m/s in February 2014 and weaker than our observed one. The wind simulated by the WRF off the Subei coast (the site was labeled in Figure R3-9) in February 2014 was shown in Figure R3-1, indicating that the wind in the Yellow Sea near the North Branch was much stronger than the observed one at Chongming eastern shoal. Now we download the wind from the European Centre for Medium-Range Weather Forecasts (ECMWF, 2014; http://apps.ecmwf.int/datasets) and choice the point which is closest the Sheshan island (labeled in Figure R3-9) to present the temporal variations in wind vector and wind speed in February 2014 (Figure R3-10). It can be seen that the wind is stronger than the observed one provided by the reviewer, and is little weaker than the author's observed one. The data of ECMWF was a post processed data and its quality is widely accepted. There existed some dissimilar among the winds from observed, simulated and ECMWF, but the phenomenon of persistent and strong wind is same. We quite agree with the reviewer's opinion that even if the observed wind data is only used to illustrate the wind status, they should be true. The following sentence was added on lines 223-226 in the revised manuscript: The temporal variations in wind vector and wind speed (b) at Sheshan island (labeled in Fig. 1) in February 2014 simulated by WRF (Fig. 10) was similar with the one observed at Chongming eastern shoal (Fig. 4b, c), indicating again that there existed a persistent and strong northerly wind in February 2014.

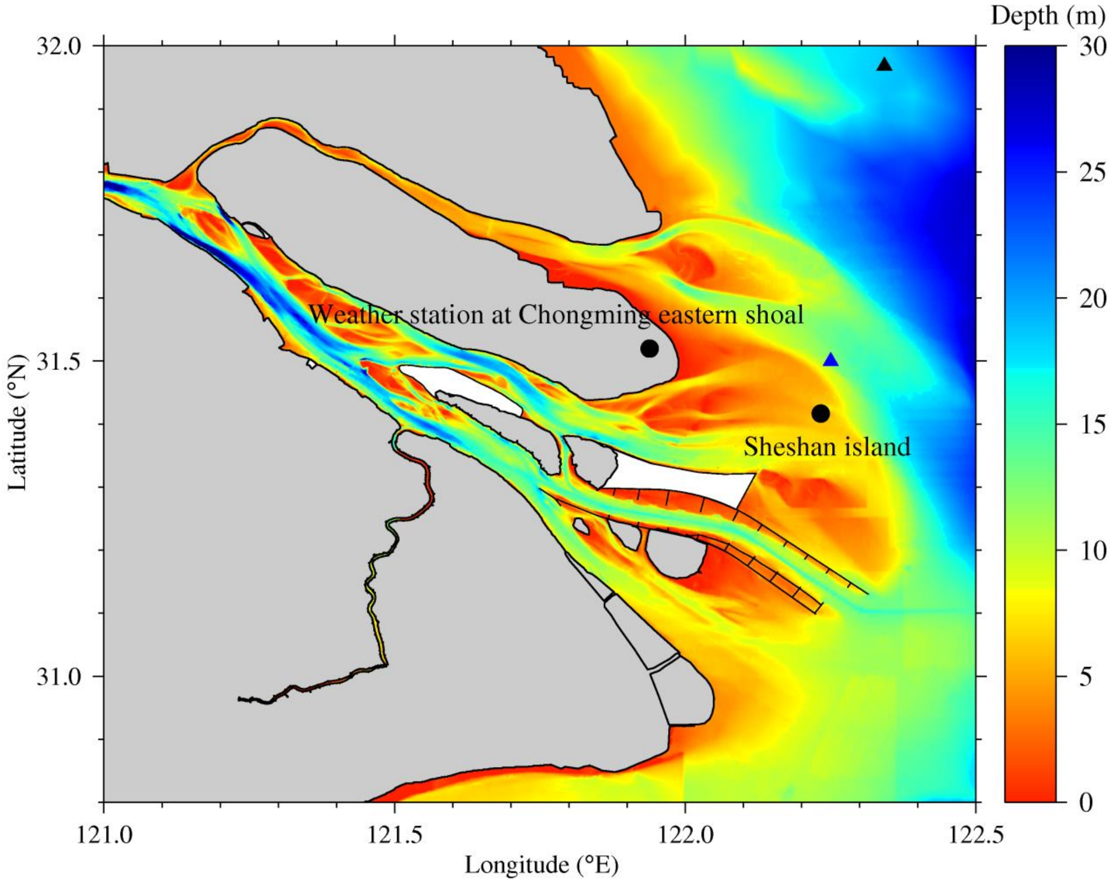


Figure R3-9: Locations of the weather station at Chongming eastern shoal, WRF output site of WRF (the triangle on the north side) and output site of ECMWF.

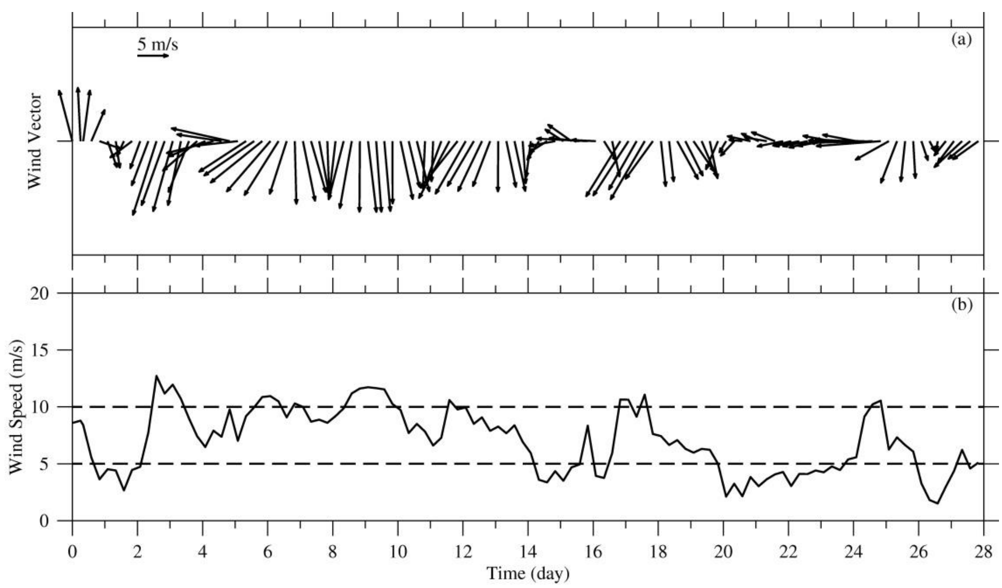


Figure R3-10: Temporal variations in wind vector (a) and speed (b) download from ECMWF in February 2014.

Thank you for pointing out the problem. The data in Figure R3-2 was from February 2, and now the data on February 1 was added.

Comments to authors' reply 2： About the modeled wind directions and speeds (figure R3-1), even if they are only shown for referee, the location or area should be off Changjiang estuary instead of Subei coast. I think it is necessary shown in the manuscript in order to show the winds you used in the model. It can be seen from figure R3-1 that the wind directions were almost all northerly. Some were not only different from station located at Chongming eastern shoal but also different from the station outside the estuary. For example, on 5-6 winds are not strong with directions of southeasterly and easterly at station near the mouth, easterly outside the estuary, but winds are strong with directions of northerly in figure R3-1 (modeled winds). On 10-11, the wind directions are northwesterly at station outside the estuary, but northerly in figure R3-1. The wind directions and speeds observed at station outside the estuary could induce water level setdown, which is consistent with the calculated water level change (I ever did). It can be seen also from plot d of figure 2 that on 5-6 and 10-11 the water level did not rise. This means the modeled wind directions and speeds may be not correct in some periods, which will induce incorrect results.

Reply: Thank you for your comment. Now we presented the figure of temporal variation in wind vector and speed modeled by WRF at Sheshan island that is just off the Changjiang Estuary (Figure 10 in the revised manuscript).

Yes, the modeled wind off the Subei coast (Figure R3-1) had some difference with the observed one at Chongming eastern shoal, indicating that the wind had spatial variation. That is why we used the WRF to simulate the wind to better reproduce spatial and temporal variation in wind. The water level change (plot d of figure 2) was certainly affected by the wind. We agree the reviewer's opinion that if the modeled wind directions and speeds are not correct in some periods, it will induce incorrect results for the model results. We have been using the WRF model for more than 15 years and can certain that this model is reliable. The wind simulated by WRF at Sheshan island in February 2014 (Figure 10) was very consistent with the one near the Sheshan island download from ECMWF (Figure R3-10). The salinity variation processes at the hydrologic stations in February 2014 (Figure 3 in the revised manuscript) were successfully repeated, indicating that the wind simulated by WRF was believable because the severe saltwater intrusion was caused by the wind.

Comments to authors' reply 3： About the water level rise shown in plot b of figures 4 and 7, authors said it is the mistake, and the "water level rise' in legend should be "mean water level". But the maximum value in legend is 0.5 m, which should not be mean water level.

Reply: Because there existed tide in the total water level, the tidal fluctuation was filtered out in in plot b of figures 4 and 7, the water level was a residual or mean water level. The maximum value in legend is 0.5 m, meaning that the mean water level near the coast is higher, that was caused by the northerly wind. In the caption of plot b of figures 7, there is “the time-averaged water level and surface current from February 10 to 13, 2014”, meaning it was a mean water level. Now the number of figure 4 and figure 7 in the original manuscript was changed to figure 5 and figure 9 in the revised manuscript, and the modified captions were marked with green.

Comments to authors' reply 4: About error of calculated water level rise in plot d of figure 2, the method used is the oldest method, authors should try other method. Authors' some argument about water level rise is not consistent with the text.

Reply: Because the water level rise cannot be directly observed, and the observed one is the total water level. We agree that method of water level rise by subtracting the data in the tide table from the measured water level is an old method, but it can roughly reflect the water level rise. The water level rise can be obtained with numerical simulation by subtracting the mean water level in Figure 5b from the mean water level in Figure 9b (in revised manuscript), which can be roughly considered the water level rise caused by the strong northerly wind. If the wind is set to 0 m/s in Figure 5b, then difference is the exact water level rise induced by the strong northerly wind.

Comments to authors' reply 5： About the mechanism of the extreme event, I think it was still not clear. Authors said that the strong northerly winds lasting 4 days can induce the higher than normal salinity in after 8 days (plot b of figure 9). In plot b the winds were set to 5 m/s beginning 9 February. But the strong northerly winds began from 7 before which the wind directions were southerly or easterly both at station near the mouth and station outside the estuary. This means that the real strong northerly winds lasted 2 days. This is why I ask the question (About plot b, can two-day strong winds induce the higher than normal salinity in after 8 days?). Authors replied that the two-day strong winds are in plot a, not in plot b. Now I know the reason, the modeled strong northerly winds lasted 4 days before 9.

Reply: The mechanism of the extreme event is that it was caused by the persistent and strong northerly wind, which drove substantial landward net water transport to form a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel. This landward net water transport overpowered the seaward-flowing river runoff and transported a large volume of highly saline water into the North Channel. Figure 9 was used to discuss how long the northerly wind can induce severe saltwater intrusions. We check again the wind in Figure R3-10 and in Figure 10 in the revised manuscript, and sure that the northerly wind began on February 6. So, the strong northerly wind in Figure 9a, b, c, and d lasted 2, 4, 6 and 8 days, respectively.

Comments to authors' reply 6: About the North Branch, even if the impact of winds on saltwater intrusion is weaker than the North Channel, the saltwater intrusion should be also much stronger than normal situation during the "extreme event" period. It can be seen from figure R3-4 the salinity on 13-16 at Chongxi station was similar to the normal situation, but the salinity at other stations dramatically increased.

Reply: Yes, the saltwater intrusion in the North Branch was enhanced by the strong northerly wind in February, 2014. In Figure R3-4, the salinity on February 13-16 at Chongxi station was similar to the normal situation, but the salinity at other stations dramatically increased, just meaning that the SSO is somewhat enhanced, but the saltwater intrusion was extremely severe at other stations because the strong northerly wind produced a net horizontal circulation that transported a large volume of highly saline water into the North Channel.

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. 7c, in revised manuscript). However, the North Channel is deeper and wider and located on the north side of the South Branch, which is conducive to strong landward Ekman water transport in the North Channel.

In the revised manuscript, the section 4.1 was added to explain how much contribution of the SSO to the saltwater intrusion event (the first reviewer suggested).

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

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Abstract. Estuarine saltwater intrusions are mainly controlled by river discharge and tides. Unexpectedly, an extremely severe saltwater intrusion event occurred in February 2014 in the Changjiang Estuary under normal river discharge conditions. This intrusion 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. No similar catastrophic saltwater intrusion has occurred since records of salinity in the estuary have been kept. During the event, a persistent and strong northerly wind existed, with a maximum speed of 17.6 m s^{-1}, lasting 9 days and coinciding with a distinct water level rise. Our study demonstrates that the extremely severe saltwater intrusion was caused by this northerly wind, which drove substantial landward net water transport to form a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel. This landward net water transport overpowered the seaward-flowing river runoff and transported a large volume of highly saline water into the North Channel. The mechanisms of this severe saltwater intrusion event, including the northerly wind, residual water level rise, landward water transport and resulting horizontal circulation, etc., were systematically investigated.

1 Introduction

Saltwater intrusion is a common phenomenon in estuaries where freshwater and saltwater converge and is mainly controlled by tides and river discharge (Prandle, 1985; Simpson et al., 1990; Geyer, 1993), but it can also be affected by wind stress (Chen and Sanford, 2009; Aristizábal and Chant, 2015; Duran-Matute et al., 2016; Giddings and Maccready, 2017) and vertical mixing (Simpson and Hunter, 1974; Prandle and Lane, 2015). Along-estuary winds can strain density gradients, and the associated destruction or enhancement of stratification depending on wind direction, and the entrainment depth ratio (Chen & Sanford, 2009). Wind-driven sea-level setups at the mouth of estuaries can produce landward flows that outcompete river runoff, resulting in the net, landward advection of salt (Aristizabal & Chant, 2015). For multi-inlet coastal systems, residual (horizontal) circulation is influenced by winds, which alters salt transports in each inlet (Duran-Matute et al., 2016). The upwelling and downwelling favorable wind can significantly influence the estuarine exchange flow (Giddings, and MacCready, 2017). Saltwater intrusions 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, the study of estuarine saltwater intrusions has scientific relevance for understanding circulation, sediment, and ecological dynamics and can facilitate the effective 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, have biweekly spring-neap signals and are highly energetic sources of water movement. The maximum tidal range reaches 3.38 m and the minimum tidal range 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 strong 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; Wu et al., 2010; Li et al., 2012; Ding et al., 2017; Zhang et al., 2019) and topography (Li et al., 2014; Chen et al., 2019b). The impact of wind on saltwater intrusion has been studied, but only with a climatic wind (Xue et al., 2009; Qiu et al. 2012; Chen et al, 2019a), 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). Xue et al. (2009) pointed out that a northerly wind tends to enhance the saltwater intrusion in the North Branch by reducing the seaward surface elevation gradient forcing. Wu et al. (2010) and Li et al. (2012) simulated the pure wind-driven current that flows into the North Channel and out of the South Channel with climatic wind to explain that the northerly wind can enhance saltwater intrusion in the North Channel, and weaken it in the South Channel. Zhang et al. (2019) reported that the frequency of saltwater intrusion events in the Changjiang Estuary is increasing in recent years due to increasing frequency of winter storms passing East China Sea.

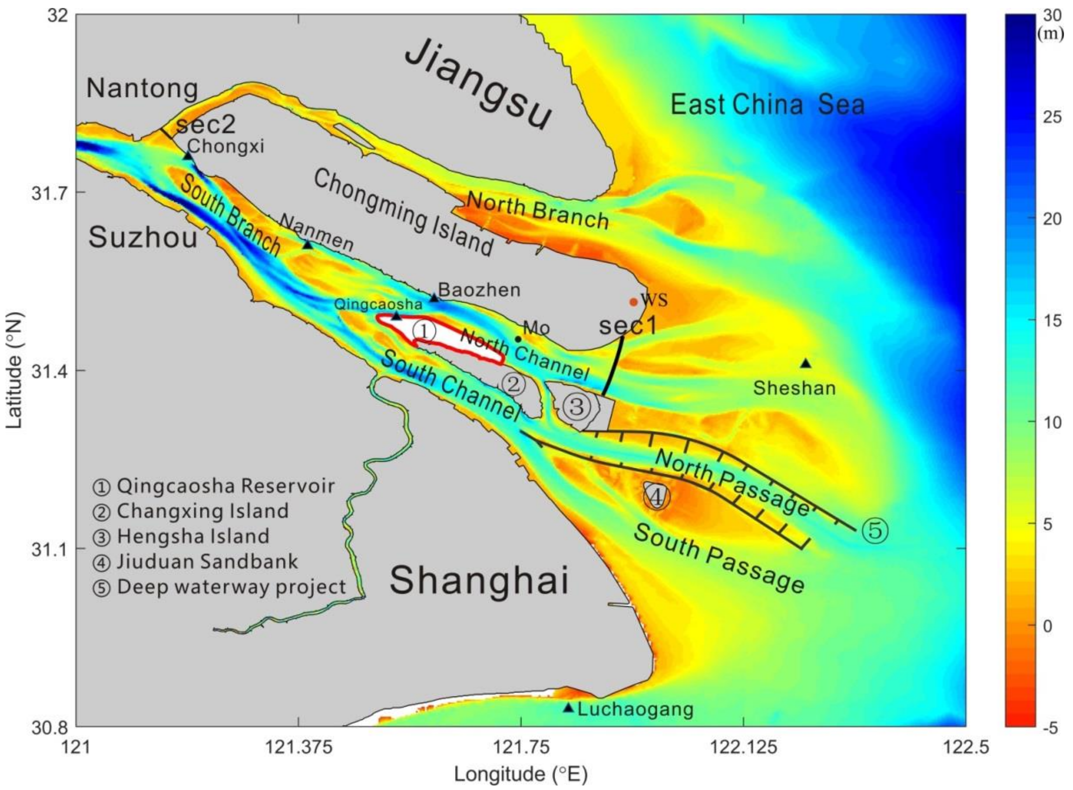

Figure 1: Topography of the Changjiang Estuary. The black triangles indicate the locations of hydrologic stations Chongxi, Nanmen, Baozhen, Qingcaosha, Sheshan and Luchaogang. WS is the location of the weather station at the Chongming eastern shoal. sec1 and sec2 are transects at the river mouth of the North Channel and upper reaches of the North Branch, respectively, and Mo is the model output site for terms in the momentum equations.

The estuaries of large rivers are often associated with growing populations and economic activity, leading to complex challenges in managing environmental conditions. Freshwater supplementation is of vital importance for industrial and home use, but estuarine freshwater is subject to frequent sea water intrusions. The Changjiang Estuary, which is surrounded by fast-developing cities, such as Shanghai, Suzhou and Nantong city, is threatened by saltwater intrusions in the winter season. Numerous efforts have been made in recent decades to meet the astronomic freshwater demand of the megacity of Shanghai, which has a population of over 24 million people. The water resources in Shanghai were strategically transferred from the Huangpu River to the Changjiang Estuary in 2010, when 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 provides a daily water supply 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 intrusions, particularly during the dry season. Limited by reservoir capacity, long-lasting saltwater intrusions are extremely harmful (Chen et al, 2019a). The most characteristic type of saltwater intrusion in the estuary is the saltwater spillover (SSO) from the North Branch into the South Branch (Shen et al., 2003; Wu et al., 2006; Lyu and Zhu, 2018). The shallow and funnel-shaped topography helps to prevent runoff from entering the North Branch, especially during the dry season, and produces a greater tidal range in the North Branch than in the South Branch. The saltwater from the SSO is transported downstream by runoff and arrives in the middle reaches of the South Branch during the subsequent neap tide, threatening the water supplies of reservoirs located in the estuary.

An extremely severe saltwater intrusion event occurred in February 2014 in the Changjiang Estuary under normal river discharge conditions and seriously influenced the water intake of the Qingcaosha Reservoir and threatened water safety in Shanghai. Two severe saltwater intrusion events were recorded in the Changjiang Estuary in the dry seasons of 1979 and 1999, which were caused by very low river discharge with a mean value of 7485 $m^3 s^{-1}$ from January 1 to March 15, 1979, and 9246 $m^3 s^{-1}$ from January 1 to March 16, 1999, both lasting 2.5 months (Zhu et al., 2013). However, the mean monthly river discharge in February 2014 was 11,510 $m^3 s^{-1}$, which approached the annual climatic mean value of 12,430 $m^3 s^{-1}$ in February from 1950 to 2019. No similar catastrophic saltwater intrusion event has occurred since salinity data have been recorded, 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 was close to the monthly mean discharge since 1950, river discharge was not the cause of the extremely severe saltwater intrusion event. The tides in February in different years have been similar, as has 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 using observation data and a numerical model.

2 Methods

2.1 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 uses a sigma coordinate system in 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. 2a). Datong hydrological station is on the western open boundary of the Changjiang River.

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:

$$\zeta = \bar{\zeta} + \sum_i^{16} a_i \cos(\omega_i + g_i) \quad (1)$$

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. The method for determining 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. 2b, 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).

2.2 Numerical validation

The numerical model 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. In this study, the model was validated with the observed water level at Baozhen, Shenshan and Luchaogang stations and salinity at Nanmen, Baozhen, Chongxi and Qingcaosha stations during the extremely severe saltwater intrusion event, and the results showed that modeled salinities were well consistent with the observed values (shown in Fig. 3 and Fig. 6 and analyzed in Sect. 3.2).

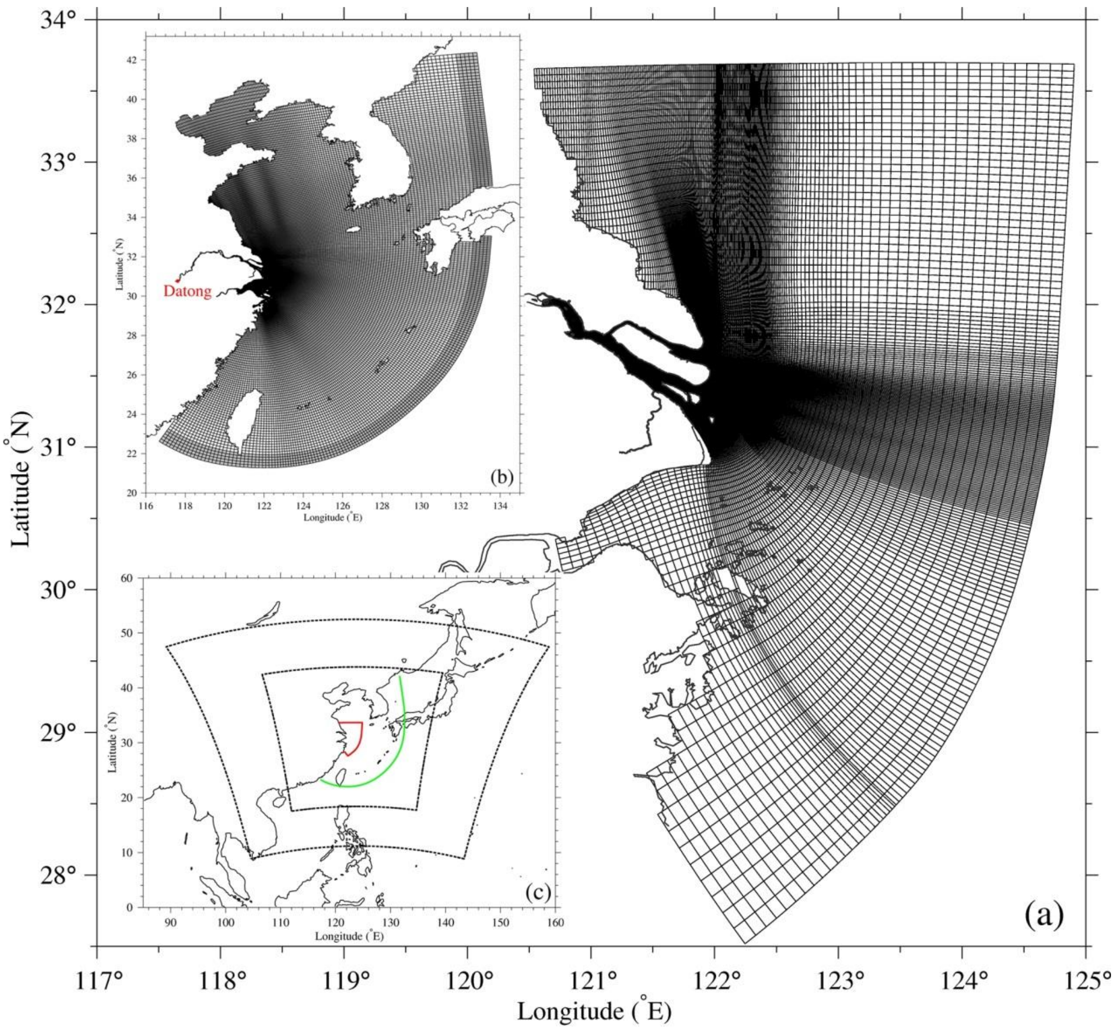

Figure 2: Model grids of the Changjiang Estuary (a) and model grids of the Bohai Sea, Yellow Sea and East China Sea (b). Domains of the models (c); within the red line: the Changjiang Estuary model domain; within the green line: model domain of the Bohai Sea, Yellow Sea and East China Sea; black dashed lines: the two-fold nested WRF model domain.

3 Results

3.1 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 salinity and wind data were from the State Key Laboratory of Estuarine and Coastal Research, East China Normal University, and the observed water level data were from the Shanghai Hydrology Administration. At the Baozhen hydrologic station, the salinity was normal before February 8, 2014 (in relation to January and February in other years) 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. 3a). At Nanmen station, the salinity was also abnormally high, with a peak salinity of 12.4. At Chongxi station, the salinity was high, with a peak salinity of 6.5 induced by the SSO. At Qingcaosha station, the salinity was greater than 0.45 (the salinity standard for drinking water, similarly hereinafter) from February 4 to 26, with a peak salinity of 8.6. Thus, the continuous period of unsuitable drinking water reached 23 days, causing a serious threat to the water intake of the Qingcaosha 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.

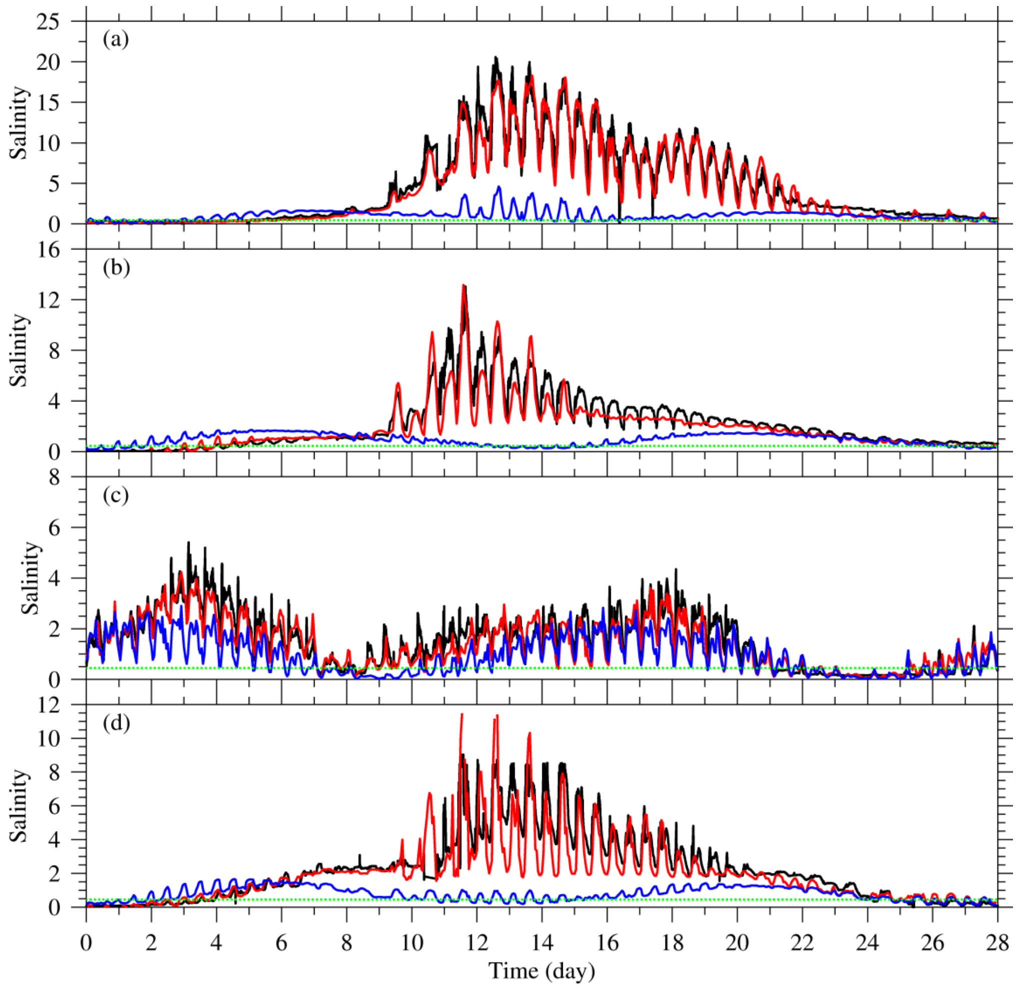

Figure 3: Temporal variations in salinity in February 2014 at hydrologic stations. a: Baozhen station; b: Nanmen station; c: Chongxi station; c: Qingcaosha station. Black line: measured salinity; blue line: simulated salinity under climatic wind and residual water level conditions at open sea boundaries (Exp 1); red line: simulated salinity under a realistic wind and residual water levels at the open sea boundaries (Exp 2). The dashed green line represents salinity of 0.45, which is the standard for drinking water.

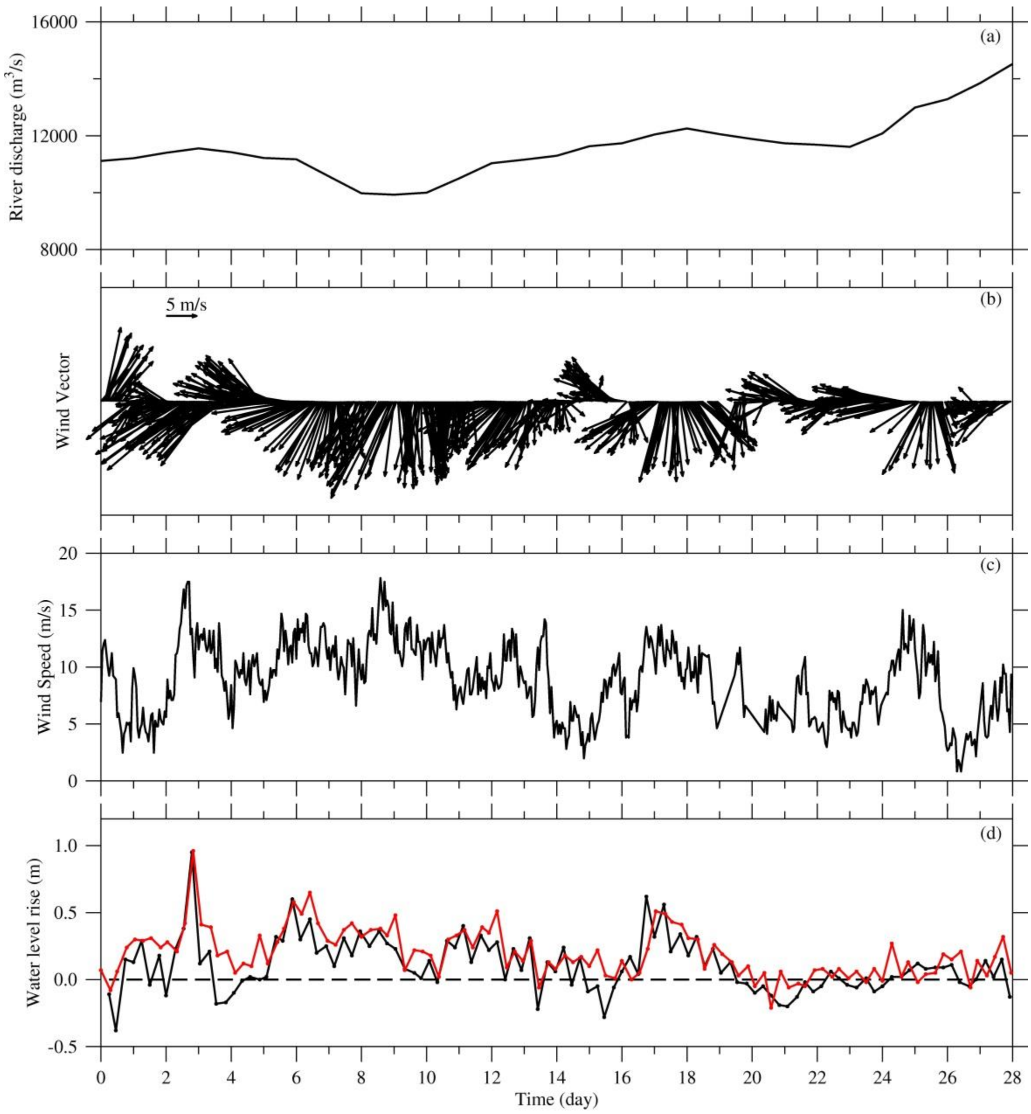

Figure 4: Temporal variations in the measured river discharge at Datong station (a), wind vector (b) and wind speed (c) at WS, and water level rise obtained by subtracting the data in the tide table from the measured water level at Sheshan station (black line) and Luchaogang station (red line) (d) in February 2014.

The mean monthly river discharge recorded at Datong hydrologic station (Changjiang Water Resources Commission) in February 2014 was 11,510 m^3/s (Fig. 4a), which approached the annual climatic mean value of 12,430 m^3/s in February from 1950 to 2019. Thus, river discharge was not the cause of the extremely severe saltwater intrusion event.

The weather station at the Chongming eastern shoal (location is shown in Fig. 1, WS) recorded a persistent and strong northerly wind (2 minutes average) from February 6 to 14, 2014, lasting nine days with an average wind speed of 10.01 m/s and a maximum wind speed of 17.6 m/s on February 10 (Fig. 4b, 4c). 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 Sheshan and Luchaogang hydrologic stations recorded a distinct water level rise, with a peak value of more than 0.5 m during the strong northerly wind (Fig. 4d). The water level rise couldn't be directly observed, and was obtained by subtracting the data in the tide table from the measured water level value.

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

3.2 Modeled results

To reveal which dynamic factor caused the extremely severe saltwater intrusion event in February 2014, two numerical experiments were designed. The first experiment considered climatic wind conditions at the sea surface and residual water levels at open sea boundaries (Exp 1), and the second considered a realistic wind in February 2014 and residual water levels at the open sea boundaries (Exp 2). The river discharge at the upper boundary at Datong station and tide at the open sea boundary were the same in Exp 1 and Exp 2.

In Exp 1, 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 7 m s^{-1} over the Yellow Sea and East China Sea (Fig. 5a). The residual water level and residual current were simulated by the model, including the Bohai Sea, Yellow Sea and East China Sea. Forced by the northerly wind, the residual water level was 10~20 cm away from the Changjiang River mouth and was mainly induced by river discharge and a climatic northerly wind, and the residual surface current flows southward off the Changjiang mouth (Fig. 5b). The residual water level was interpolated into the open sea boundary of the saltwater intrusion model as an external forcing condition.

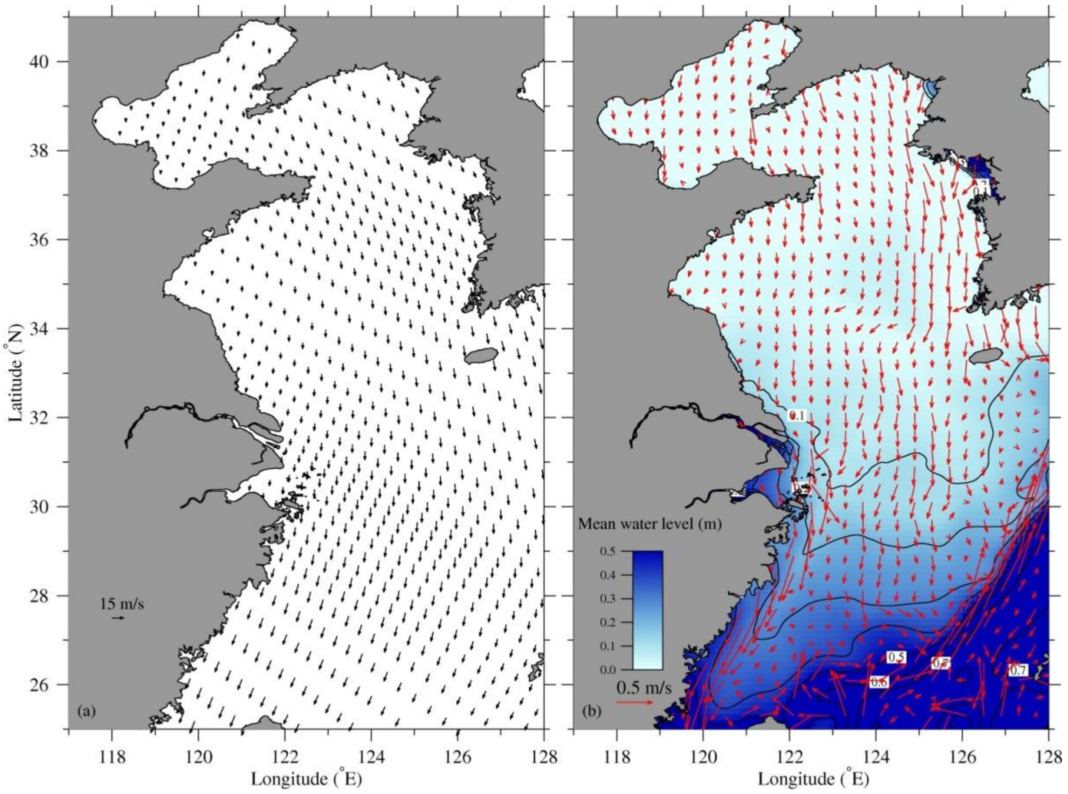

Figure 5: Distributions of the climatic wind field (a) and residual (mean) water level and surface current (b) in February.

The observed and modeled water level at Baozhen, Sheshan and Luchaogang stations is fairly consistent with the observed water level (Fig. 6), meaning that the water level is mainly determined by tide and river discharge inside the river mouth. However, during the neap tide from February 6 to 9, 2014, the modeled water level was approximately 10-30 cm lower than the observed level because the wind was not a realistically strong northerly wind.

The modeled salinity at Baozhen, Nanmen, Chongxi and Qingcaosha stations is shown in Fig. 3. Under climatic wind, the modeled salinity was significantly lower than the observed salinity at Baozhen, Nanmen, and Qingcaosha stations and was distinctly lower at Chongxi station, which is similar to the normal saltwater intrusion regularly occurring under monthly mean river discharge and wind in the dry season (Shen et al., 2003; Zhu et al., 2015).

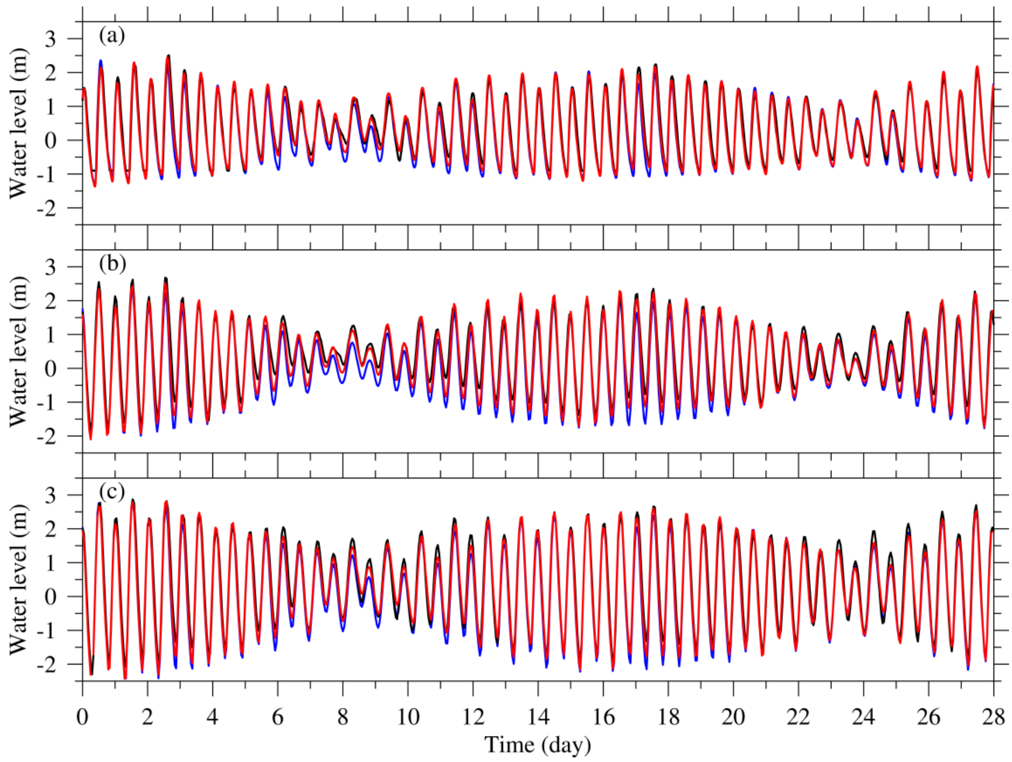

Figure 6: Temporal variations in water level in February 2014 at hydrologic stations. a: Baozhen station; b: Sheshan station; c: Luchaogang station. Black line: measured data; blue line: simulated data in Exp 1; red line: simulated data in Exp 2.

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. 7a). 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. 7b). The North Branch was occupied by highly saline water due to its topography. The funnel shape amplifies the tide in its upper reaches, and the wider tidal flat in the upper reaches lowers the amount of river discharge inflow (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; Wu et al., 2010; Lyu and Zhu, 2018).

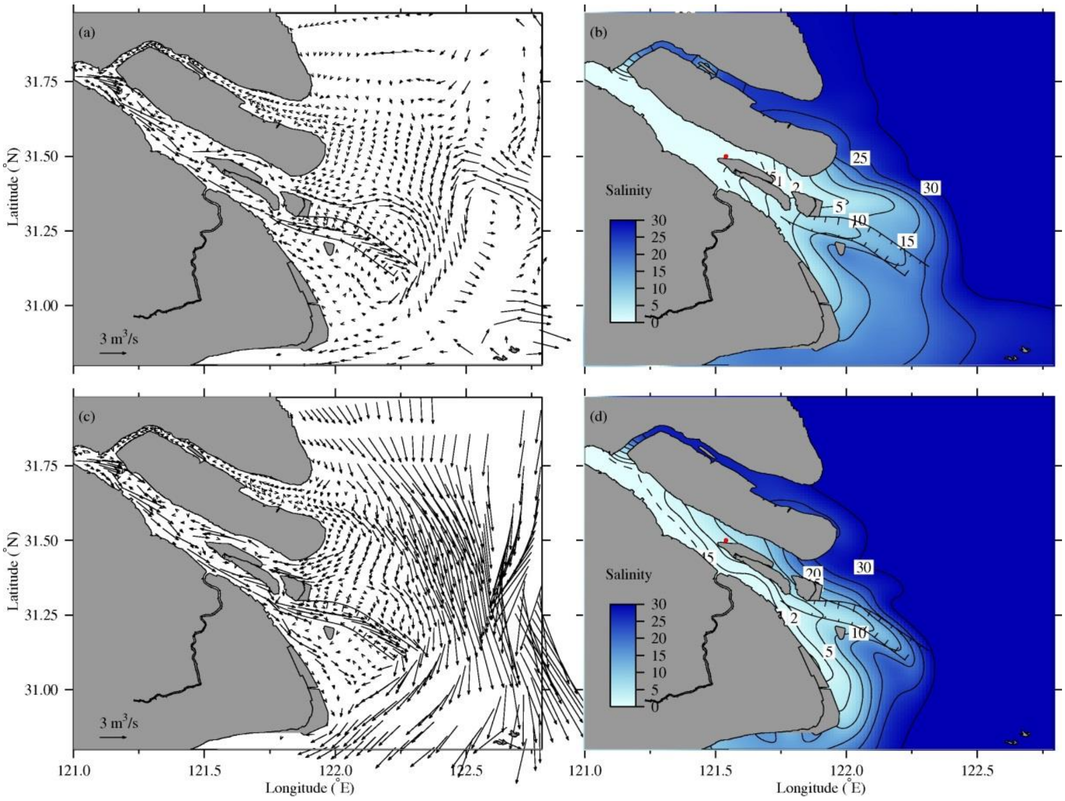

Figure 7: Distributions of residual unit width water flux (a, c) and time-averaged surface salinity (b, d) from February 10 to 13, 2014, from Exp 1 (upper panel) and Exp 2 (lower panel). The dashed isohaline represents a salinity of 0.45; the red dot denotes the location of water intake of Qingcaosha Reservoir (similarly hereinafter).

The residual water flux across the transverse section in the North Channel (sec 1 labeled in Fig. 1) from February 6 to 24, 2014, flowed seaward due to runoff force and decreased during the neap tide from February 9 to 11 (Fig. 8a). 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. 8b).

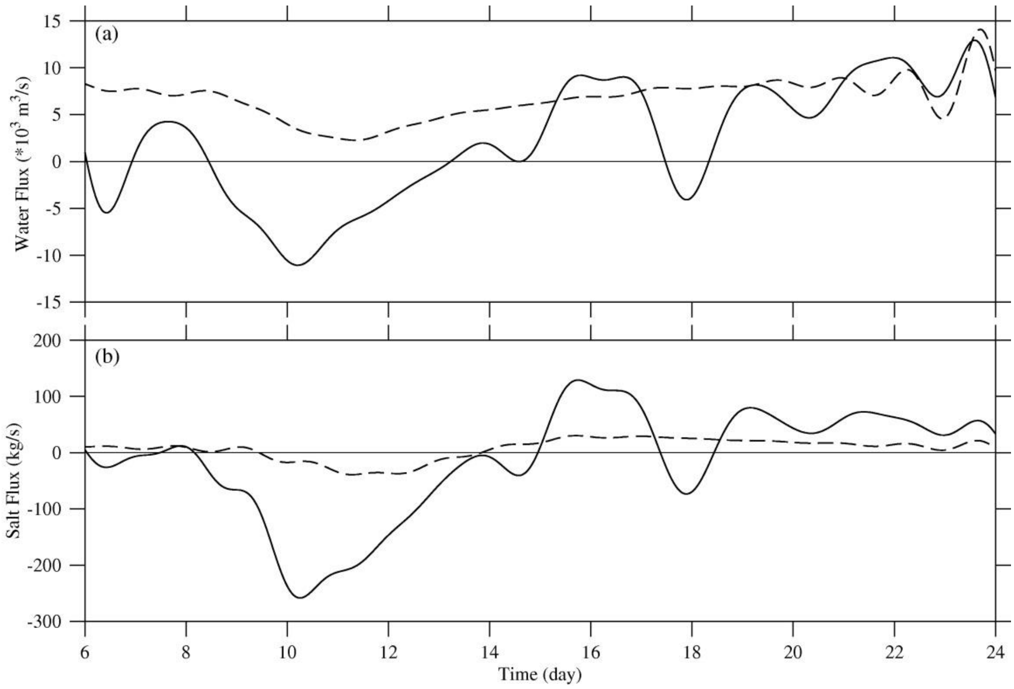

Figure 8: Temporal variations in residual water flux (a) and salt flux (c) across Sec 1 in the North Channel from February 6 to 24, 2014. Dashed line: Exp 1; solid line: Exp 2. A positive value represents seaward flux, and a negative value represents landward flux.

In Exp 1, the extremely severe saltwater intrusion event in February 2014 was not replicated, whereas the saltwater intrusion was simulated with Exp 2. The realistic wind was simulated by a mesoscale atmospheric model: the Weather Research Forecasting (WRF) model with two nested domains (Fig. 2c). 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 wind vector at the weather station located at the Chongming eastern shoal showed that the persistent and strong northerly wind in February 2014 was well simulated by the WRF model (figure omitted).

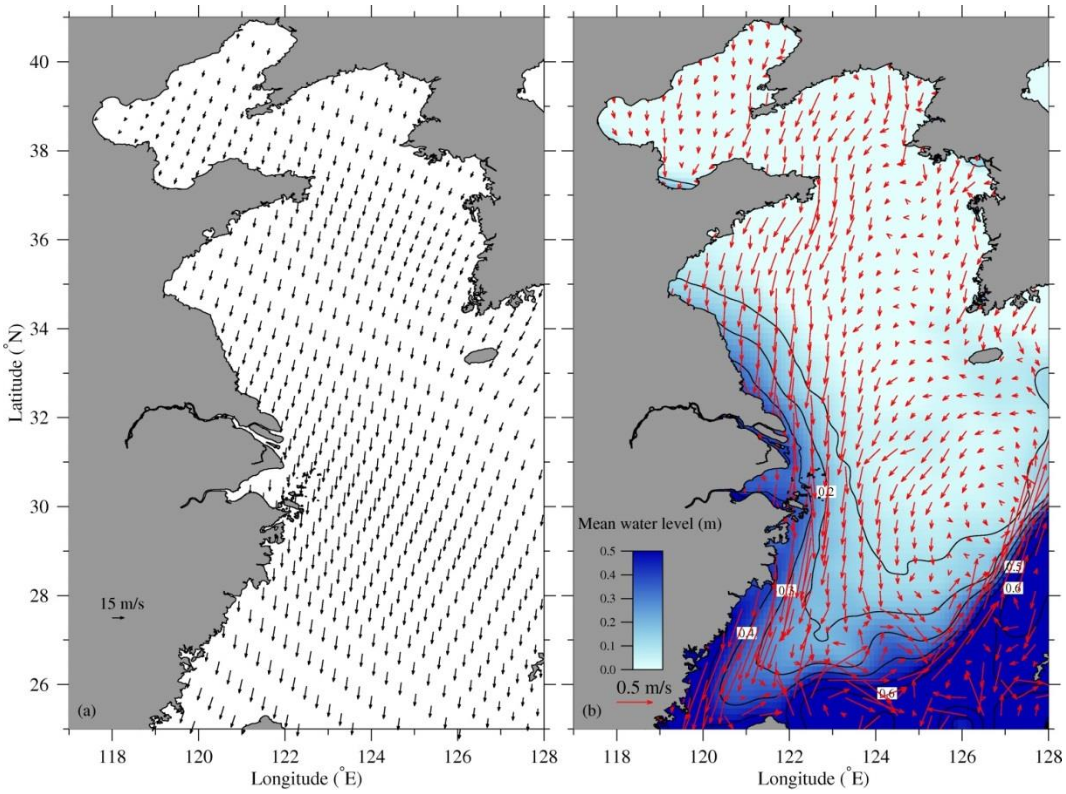

Figure 9: Distributions of the temporally averaged wind field from February 7 to 14, 2014, as simulated by the WRF model (a), and the time-averaged (mean) water level and surface current from February 10 to 13, 2014, as simulated by the model encompassing the Bohai Sea, Yellow Sea and East China Sea (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. 9a), which was much higher than that observed at the weather station at the Chongming eastern shoal (Fig. 4b, c). The residual (mean) 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 high water level along the coast of China during the extremely severe saltwater intrusion event from February 10 to 13, 2014 (Fig. 9b). The residual water level was interpolated into the open sea boundaries of the saltwater intrusion model. The temporal variations in wind vector and wind speed (b) at Sheshan island (labeled in Fig. 1) in February 2014 simulated by WRF (Fig. 10) was similar with the one observed at Chongming eastern shoal (Fig. 4b, c), indicating again that there existed a persistent and strong northerly wind in February 2014.

In comparison to the results of Exp 1, the simulated water level in Exp 2 at Baozhen, Sheshan and Luchaogang stations was closer to the observed water level, especially during the neap tide from February 7 to 11, 2014 (Fig. 6). The difference between the observed water level and modelled water level under climatic wind can be considered the water level rise by the northerly strong wind. It is seen from the Fig. 6 that the water level rise at low water level from February 5 to 12, 2014 was approximately 0.35, 0.40, and 0.30 m at Baizhen, Sheshan and Luchaogang station, respectively. The simulated salinity at Baozhen, Nanmen, Chongxi and Qingcaosha stations was significantly improved and was very consistent with the observed salinity in terms of both magnitude and phase (Fig. 3). The salinity modeled under climatic wind and residual water level conditions at open sea boundaries was significantly lower than the observed salinity, and the salinity variation process was successfully replicated under realistic wind and residual water levels at the open sea boundaries. Therefore, the persistent and strong northerly wind played an important role in the extremely severe saltwater intrusion event.

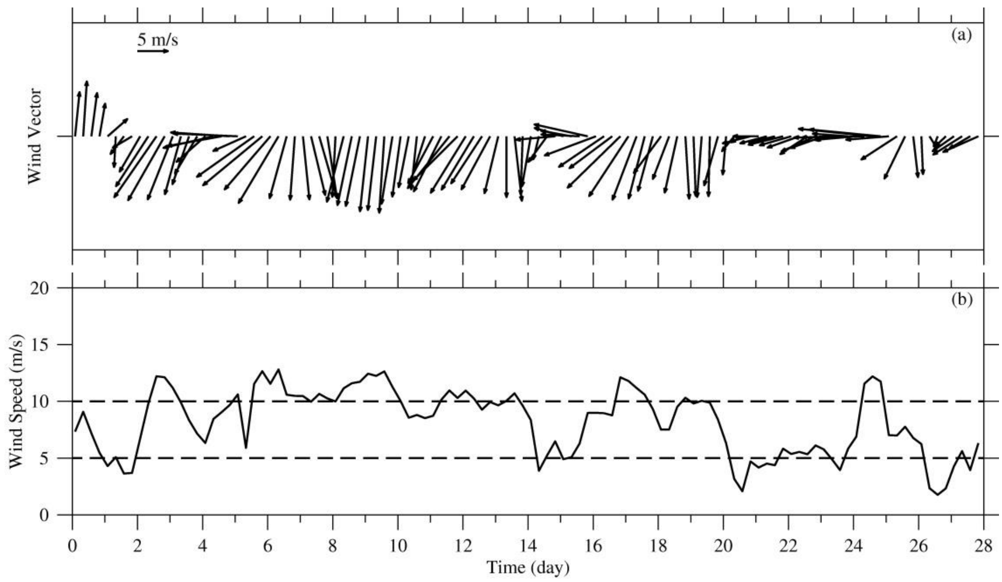

Figure 10: Temporal variations in wind vector (a) and speed (b) in February 2014 simulated by WRF.

The temporal variations in the observed and modeled water levels at Baozhen, Sheshan and Luchaogang stations (Fig. 6) and salinity at Chongxi, Nanmen and Qingcaosha hydrologic stations in February 2014 (Fig. 3) show that the model can reproduce the salinity variation processes involved in the extremely saltwater intrusion event. The model was validated again, and the results are quite robust.

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 high water level of more than 30 cm along the coast of China (Fig. 9b), which was confirmed by the observed water level rise at the Sheshan and Luchaogang stations (Fig. 4d). 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. 7c). However, the North Channel is deeper and wider and located on the north side of the South Branch, which is conducive to strong landward Ekman water transport in the North Channel.

The residual unit width water flux 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 (Fig. 7c). The Changjiang is a large river, and its river discharge was 11,510 m^3 s^{-1} in February 2014, so it is unexpected that wind-driven landward water transport could surpass the 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 into the North Channel.

The residual water and salt flux across the transverse section in the North Channel from February 9 to 13, 2014, flowed landward with a maximum value of 12,000 m^3/s and 360 kg/s, respectively (Fig. 8), which was consistent with the distribution of residual unit width water flux. In Exp 1, the residual water flux was seaward due to runoff, and the landward residual salt flux from February 10 to 12, 2014, was very small compared to that in Exp 2. Therefore, the extremely severe saltwater intrusion event in February 2014 was caused by the persistent and strong northerly wind, which produced a strong landward net transport and abnormal water level rise, induced a horizontal circulation and brought highly saline water into the North Channel.

4 Discussion

This section systematically discusses the potential mechanism of the extremely severe saltwater intrusion with regard to the SSO, how the wind affects the individual terms in the momentum equations, the relationship between residual water level and wind, the generation of Ekman transport and the resulting horizontal circulation, and the duration of the severe saltwater intrusion induced by the northerly wind.

4.1 What was the contribution of the SSO to the saltwater intrusion event?

The most obvious feature of saltwater intrusion in the Changjiang Estuary is the SSO. Previous studies showed that the SSO is the main source of saltwater intrusion in the upper and middle reaches of the South Branch and the main saltwater source of the reservoirs (Shen et al. 2003; Wu et al. 2006; Zhu et al., 2013; Lyu and Zhu, 2018). What was the extent of the contribution of the SSO to the extremely severe saltwater intrusion in February 2014? A transect Sec 2 at the upper reaches of the North Branch (location labeled in Fig. 1) was set to calculate water and salt flux.

In Exp 1, the water flux from February 6 to 8, 2014, and salt flux on February 7, 2014, were transported from the South Branch into the North Branch (Fig. 11). This phenomenon occurred during a neap tide (indicated by the water level in Fig. 6), while in the other tidal patterns, the water and salt flux was transported from the North Branch into the South Branch, especially during the spring tide from February 14 to 17, 2014. This is the famous SSO occurring during middle and spring tide in dry season.

In Exp 2, the seaward water flux on February 7 decreased and the landward water flux increased from February 4 to 6 and from February 8 to 14, and the salt flux from February 4 to 14 was landward, under strong northerly wind, which was distinctly greater than the result under climatic wind and residual water level conditions at open sea boundaries. Therefore, the strong northerly wind enhanced the SSO.

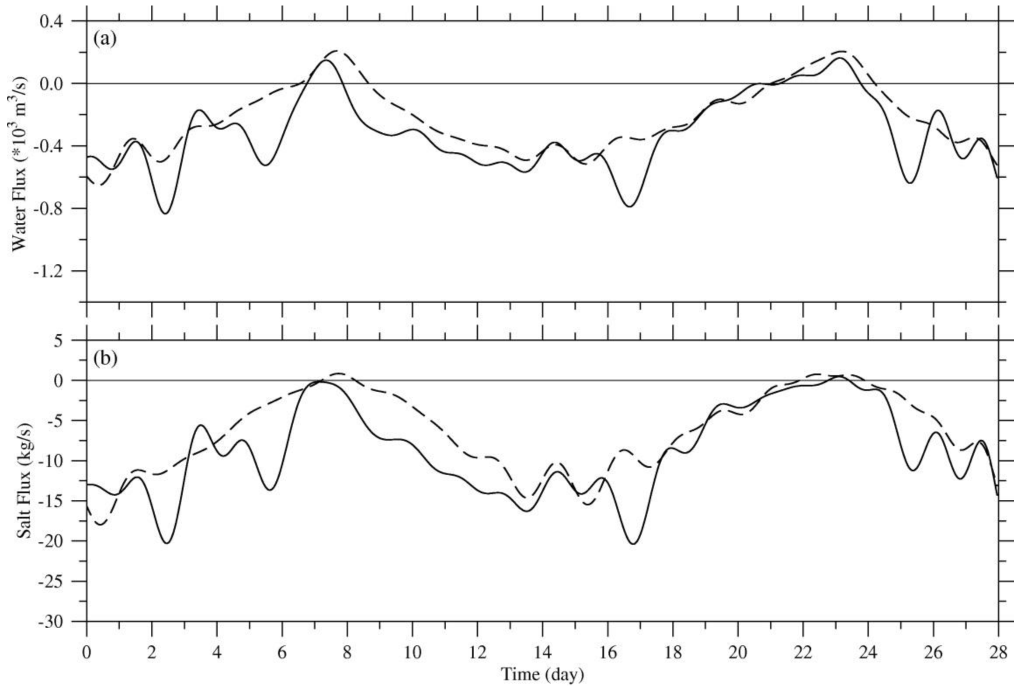

Figure 11: Temporal variations in residual water flux (a) and salt flux (b) across Sec 2 in the North Branch in February 2014. Dashed line: Exp 1; solid line: Exp 2. A positive value represents seaward flux, and a negative value represents landward flux.

A numerical experiment was designed in which the upper reaches of the North Branch were blocked (location labeled in Fig. 1) to further distinguish the contribution of SSO in the saltwater intrusion event. The distribution of time-averaged surface salinity from February 10 to 13, 2014 (Fig. 12a), and the temporal variations in salinity from February 8 to 22, 2014, at Chongxin station (Fig. 12b) show that the SSO was completely absent, while the salinity in the river mouth and near the Qingcaosha reservoir and at the Baozhen, Nanmen and Qingcaosh stations was almost identical to the results from Exp 2 (Fig. 7d, Fig. 3), indicating that the SSO had almost no contribution to the saltwater intrusion event in February 2014.

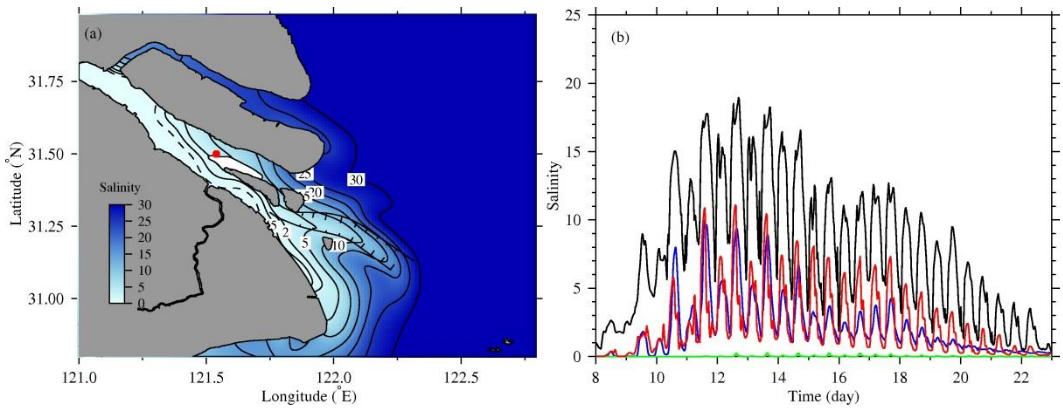

Figure 12: Distribution of time-averaged surface salinity from February 10 to 13, 2014 (a); temporal variations in salinity from February 8 to 22, 2014, at hydrologic stations (b) if the upper reaches of the North Branch are blocked, and under realistic wind and residual water levels at the open sea boundaries. Black line: Baozhen; red line: Nanmen; green line: Chongxi; blue line: Qingcaosha.

4.2 How does the wind affect the individual terms in the momentum equations?

The modeled individual terms in the momentum equations were output at site Mo in the North Channel (labeled in Fig. 1, water depth 9.62 m) to analyze how the wind affects these terms. The momentum along the river channel (ξ direction) is:

$$\frac{\partial u}{\partial t} = -\frac{\partial u^2}{\partial \xi} - \frac{\partial uv}{\partial \eta} - \frac{\partial wu}{D\partial \sigma} + vf - g\frac{\partial \zeta}{\partial \xi} + \frac{g}{\rho_0}\frac{\partial D}{\partial \xi}\int_\sigma^0 \sigma \frac{\partial \rho}{\partial \sigma} d\sigma - \frac{gD}{\rho_0}\frac{\partial}{\partial \xi}\int_\sigma^0 \rho d\sigma + \frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(K_m \frac{\partial u}{\partial \sigma}\right) + F_\xi \qquad (2)$$

The momentum across the river channel (η direction) is:

$$\frac{\partial v}{\partial t} = -\frac{\partial uv}{\partial \xi} - \frac{\partial v^2}{\partial \eta} - \frac{\partial wv}{D\partial \sigma} - uf - g\frac{\partial \zeta}{\partial \eta} + \frac{g}{\rho_0}\frac{\partial D}{\partial \eta}\int_\sigma^0 \sigma \frac{\partial \rho}{\partial \sigma} d\sigma - \frac{gD}{\rho_0}\frac{\partial}{\partial \eta}\int_\sigma^0 \rho d\sigma + \frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(K_m \frac{\partial v}{\partial \sigma}\right) + F_\eta \qquad (3)$$

where $\frac{\partial u}{\partial t}$ and $\frac{\partial v}{\partial t}$ represent the local variation, $-\frac{\partial u^2}{\partial \xi} - \frac{\partial uv}{\partial \eta} - \frac{\partial wu}{D\partial \sigma}$ and $-\frac{\partial uv}{\partial \xi} - \frac{\partial v^2}{\partial \eta} - \frac{\partial wv}{D\partial \sigma}$ are advection, vf and $-uf$ indicate the Coriolis force, $-g\frac{\partial \zeta}{\partial \xi}$ and $-g\frac{\partial \zeta}{\partial \eta}$ represent the barotropic pressure gradient force, $\frac{g}{\rho_0}\frac{\partial D}{\partial \xi}\int_\sigma^0 \sigma \frac{\partial \rho}{\partial \sigma} d\sigma - \frac{gD}{\rho_0}\frac{\partial}{\partial \xi}\int_\sigma^0 \rho d\sigma$ and $\frac{g}{\rho_0}\frac{\partial D}{\partial \eta}\int_\sigma^0 \sigma \frac{\partial \rho}{\partial \sigma} d\sigma - \frac{gD}{\rho_0}\frac{\partial}{\partial \eta}\int_\sigma^0 \rho d\sigma$ are the baroclinic pressure gradient force, $\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(K_m \frac{\partial u}{\partial \sigma}\right)$ and $\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(K_m \frac{\partial v}{\partial \sigma}\right)$ are vertical turbulence viscosity, and F_ξ and F_η are horizontal turbulence viscosity in the ξ and η directions, respectively. Each output term in the momentum equations was vertically averaged, and the vertical turbulence viscosity $\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(K_m \frac{\partial u}{\partial \sigma}\right)$ and $\frac{1}{D^2}\frac{\partial}{\partial \sigma}\left(K_m \frac{\partial v}{\partial \sigma}\right)$ equals $\frac{\tau_{a\xi} - \tau_{b\xi}}{D}$, $\frac{\tau_{a\eta} - \tau_{b\eta}}{D}$, in which $\tau_{a\xi}$, $\tau_{a\eta}$ and $\tau_{b\xi}$, $\tau_{b\eta}$ are the wind stress and bottom friction force in the ξ and η direction, respectively. The tidal fluctuations in the vertically averaged terms were filtered using the moving average method.

In Exp 1, the residual water movement along the North Channel was mainly determined by the seaward barotropic pressure gradient force and Coriolis force (Fig.

13a). The residual barotropic pressure gradient force was positive (seaward), induced mainly by river discharge, varied with spring and neap tide, and had a smaller value from February 7 to 9, 2014 (during the neap tide, Fig. 6). The seaward runoff produced a negative Coriolis force. The baroclinic pressure gradient force was very small before February 10 because the saltwater intrusion was very weak at the model output site, then became larger with the increasing tide. This term is always landward in estuaries because the saline water is downstream. Across the channel, the residual water movement was also mainly determined by the barotropic pressure gradient force and Coriolis force (Fig. 13b). The barotropic pressure gradient force was positive (northward) because the water level is higher on south side of the channel than on north side due to the effect of the Coriolis force on runoff. The baroclinic pressure gradient force was negative because salinity was higher on the north side than on the south side due to the effect of the Coriolis force on the flood current that brought saline water into the estuary.

The results of Exp 2 were considerably different from those in Exp 1 (Fig. 13c, d). The persistent and strong wind induced greater southward wind stress (red solid line in Fig. 13d) and produced landward Ekman transport and a rising water level, which significantly reduced the seaward barotropic pressure gradient force, especially from February 7 to 8, 2014. At this time, the barotropic pressure gradient force was very small, even negative (landward), and thus, the net water transport was landward, greatly enhancing the saltwater intrusion in the North Channel while distinctly increasing the landward baroclinic pressure gradient force (black dashed line in Fig. 13c).

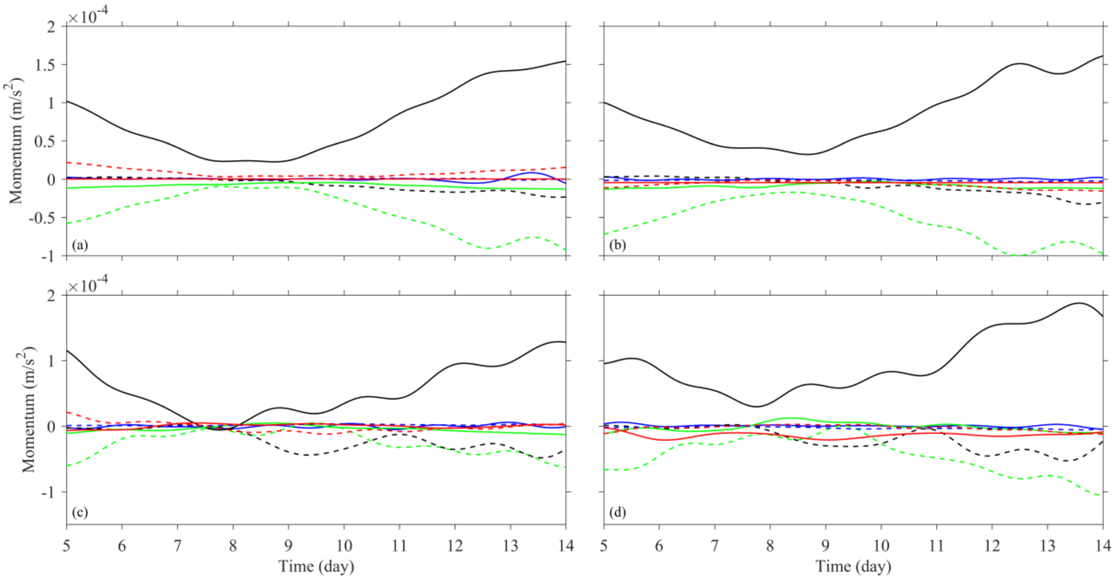

Figure 13: Temporal variations in the vertically and time averaged terms in the momentum equations along the channel (left panel, a and c) and across the channel (right panel, b and d) from February 5 to 13, 2014, in Exp 1 (upper panel) and Exp 2 (lower panel) at site Mo in the North Channel. Red solid line: wind stress at river surface; red dashed line: bottom friction force; black solid line: barotropic pressure gradient force; black dashed line: baroclinic pressure gradient force; green solid line: Coriolis force; green dashed line: advection; blue solid line: local variation; blue dashed line: horizontal turbulence viscosity.

4.3 The relationship between residual water level and wind

The residual (mean) water level in the Changjiang Estuary is closely correlated with the wind. The water level at Sheshan and Luchaogang stations rose during the northerly wind and dropped during the southerly wind in February 2014 (Fig. 4d). The water level rise of more than 50 cm corresponded to the strong northerly wind. The water level was approximately 20 cm (Fig. 5b) under climatic wind in February and 30 cm (Fig. 9b) under persistent and strong northerly wind in February 2014. At Baozhen, Sheshan and Luchaogang stations in February 2014, the modeled water level under climatic wind was lower than that under strong northerly wind, especially from February 6 to 10, 2014, when the difference reached 10-30 cm (Fig. 6). Therefore, the stronger the northerly wind is, the higher the water level in the Changjiang Estuary and adjacent sea.

4.4 The generation of Ekman transport and the resulting horizontal circulation

The northerly wind produces southward current along the China coast and pushes water landward, transported by the Coriolis force, resulting in a high water level along the coast. In the Changjiang Estuary, this dynamic mechanism causes a pure wind-driven horizontal circulation that flows into the North Channel and out of the South Channel (Fig. 14a). The wind-driven estuarine current can enhance saltwater intrusion in the North Channel and weaken it in the South Channel. Previous studies revealed the dynamic mechanism of northerly wind on the saltwater intrusion by the pure wind-driven current in the estuary (Wu et al., 2010; Li et al, 2012). In this study, the horizontal estuarine circulation was a total (net) circulation forced by the river discharge, tide and persistent and strong northerly wind (Fig. 7c) and was not a purely wind-driven circulation, which surpassed the strong seaward runoff from February 9 to 13, 2014 (Fig. 8a). This result was unexpected and surprising and was found for the first time.

Numerical experiments were performed with different northerly wind speeds to ascertain the influence of the wind on the water flux at sec1 in the landward transport in the North Channel. Except for the wind, the other dynamic factors were the same as in Exp 2. The results show that the net water flux is seaward when the wind speed is less than 8 m/s, approximately zero when the wind speed is 10 m/s, and landward when the wind speed is greater than 10 m/s (Fig. 14b). The landward water flux enhances with an increasing northerly wind. Therefore, northerly wind with speed of more than 10 m/s can be considered a strong wind that causes net water transport landward in the North Channel.

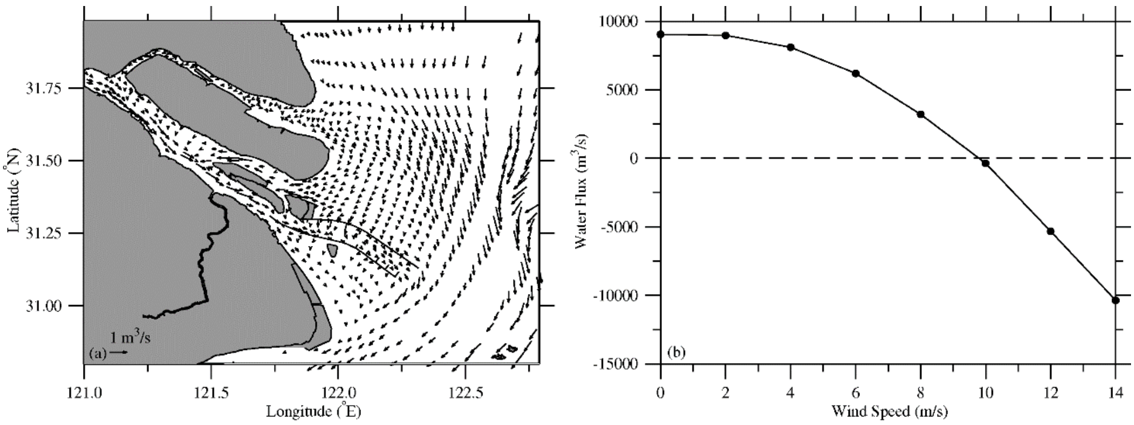

Figure 14: Distribution of pure wind-driven current time averaged from February 10 to 13, 2014, modeled under the real wind (a). Relationship between water flux across sec1 in the North Channel and northerly wind speed (b). Except for the wind, the other dynamic factors in the numerical experiments are the same as in Exp 2.

4.5 How long does the northerly wind induce severe saltwater intrusions?

In winter, frequent cold fronts pass over the Changjiang Estuary and bring strong northerly winds, enhancing saltwater intrusion (Li et al., 2012). For example, the relatively strong saltwater intrusions from February 15 to 18, 2011, and from February 23 to 26, 2017, were caused by the passing cold fronts. No extremely severe saltwater intrusion event occurred because the strong northerly wind induced by the cold fronts lasted only 1-2 days. How long does the northerly wind 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. 15), 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. It can been seen that 4 days of strong wind can induce the higher than normal salinity after 8 days because the strong wind Ekman transport brought the salinity front in the sandbar area upstream and closer to the Baozhen station and then moved upstream and downstream with the oscillation of flood and ebb currents for 8 days after the strong northerly wind became northerly wind with speed of 5 m/s. 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. Therefore, the longer the strong northerly wind lasts, the more severe the saltwater intrusion is.

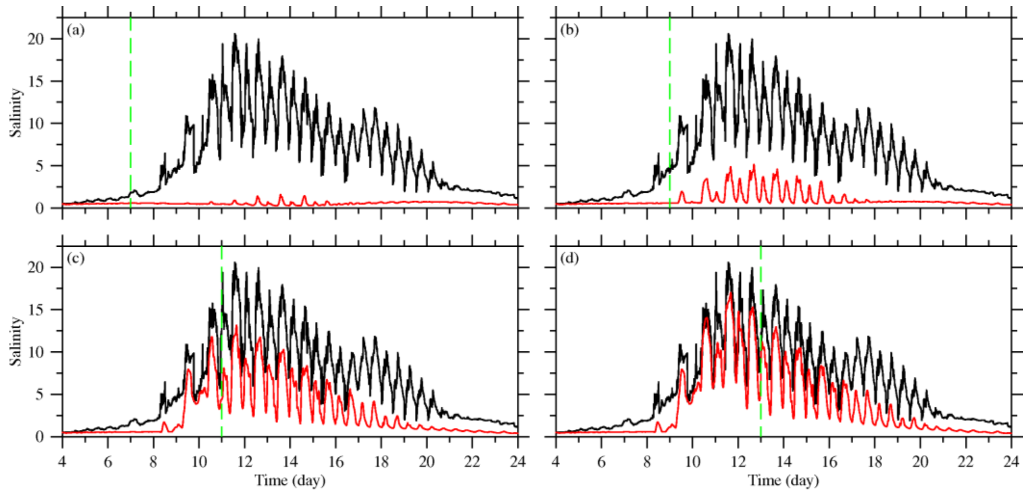

Figure 15: Temporal variation in observed (black line) and modeled (red line) salinity at Baozhen station from February 4 to 24, 2014. The green dashed lines indicate the time before it the wind was realistic and after it was set to 5 m s^{-1}.

5 Conclusions

An extremely severe saltwater intrusion event in February 2014 occurred in the Changjiang Estuary under normal river discharge conditions and caused a serious threat to water safety in Shanghai. No catastrophic saltwater intrusion of this magnitude has occurred since salinity in the estuary has been recorded. Our findings show that this extremely severe saltwater intrusion event was caused by a persistent and strong northerly wind, which produced a strong landward net transport and abnormal high water level along the coast of China and drove substantial landward water transport to form a horizontal estuarine circulation that flowed into the North Channel and out of the South Channel. This landward net water transport overcame 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.

To further reveal the dynamic mechanism of the event, numerical experiments were run, and the results were discussed. The strong northerly wind can enhance the SSO, but the SSO had almost no contribution to the saltwater intrusion event in February 2014. The individual terms in the momentum equations showed that the persistent and strong wind induced larger southward wind stress and produced landward Ekman transport and a rising water level, which significantly reduced the seaward barotropic pressure gradient force and pushed the net water transport landward, greatly enhancing the saltwater intrusion in the North Channel while distinctly increasing the landward baroclinic pressure gradient force. The stronger the northerly wind is, the higher the water level in the Changjiang Estuary and adjacent sea. The strong northerly wind can produce a pure wind-driven horizontal circulation that flows into the North Channel and out of the South Channel, which can enhance saltwater intrusion in the North Channel and weaken it in the South Channel. In this study, the horizontal estuarine circulation was a total (net) circulation induced by the persistent and strong northerly wind, which surpassed the strong seaward runoff. This effect represents a novel and unexpected finding. Only a northerly wind with speed of greater than 10 m/s can cause net landward water transport in the North Channel. A northerly wind lasting 8 days can produce extremely severe saltwater intrusion in the Changjiang Estuary. With more frequent and stronger northerly winds caused by climate change, greater attention should be paid to extremely severe saltwater intrusions and freshwater safety in the Changjiang Estuary, where the Qingcaosha Reservoir provides water from the estuary for 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.5114444.v1.

Author contributions. Jianrong Zhu analyzed the dynamics of the extremely severe saltwater intrusion in the Changjiang Estuary. Xinyue Cheng simulated the persistent and strong northerly wind with the Weather Research

Forecasting (WRF) model and analyzed the model results. Linjiang 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 salinity at the hydrological stations. Hanghang Lyu validated the saltwater intrusion model.

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

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