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Origins and transports of the low-salinity coastal water in the southwestern Yellow Sea

ZHU Ping[1], WU Hui[1, 2*]

[1] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

[2] School of Marine Sciences, East China Normal University, Shanghai 200062, China

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Abstract

In the southwestern Yellow Sea there is a low-salinity and turbid coastal water, the Subei Coastal Water (SCW). The origins of freshwater contents and thus the dissolved terrigenous nutrients in the SCW have been debated for decades. In this study, we used a well-validated numerical model to quantify the contributions of multiple rivers, i.e., the Changjiang River in the south and the multiple Subei local rivers (SLRs) in the north, in forming this year-round low-salinity coastal water. It is found that the freshwater contents in the SCW is dominated by the Changjiang River south of 33.5°N, by the SLRs north of 34.5°N, and by both sources in 33.5°–34.5°N. Overall, the Changjiang River contributes ~70% in the dry season and ~80% in the wet season of the total freshwater contents in the SCW, respectively. Dynamics driving the Changjiang River Plume to flow northward is the tidal residual current, which can even overwhelm the wind effects in winter seasons. The residual currents turn offshore near the Old Yellow River Delta (OYRD) by the collision of the two tidal wave systems, which transport the freshwater from both sources into the interior Yellow Sea. Water age experiments show that it takes 50–150 d for the Changjiang River Plume to reach the SCW in the spring and summer seasons, thus there is a 2-month lag between the maximum freshwater content in SCW and the peak Changjiang River discharge. In the winter and autumn seasons, the low salinity in inner SCW is the remnant Changjiang River diluted water arrived in the previous seasons.

Key words: Subei Coastal Water, origins, river plume, numerical modeling

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1 Introduction

The Yellow Sea is a semi-enclosed embayment of the marginal seas for the northwestern Pacific Ocean. It connects the East China Sea in the south and the Bohai Sea in the north. The topography of Yellow Sea features a northwestward penetrating trough in the middle and the eastern sea basin, with the maximum depth of ~80 m at its southeast corner. The eastern flank of the Yellow Sea Trough is narrow; whereas, its western flank, which is known as the Yangtze Bank or the Subei Coastal Water (SCW), is wide and shallow due to the historic sediment depositions from the Changjiang River and the Old Yellow River (Yang et al., 1992; Sun et al., 2000; Yuan et al., 2008). Subei literally means the northern Jiangsu Province in Chinese. The SCW is one of the most turbid coastal waters around the world. Numerous studies have been done on the origins, transports, and depositions/erosions of the sediments in the SCW, but a consensus has not been reached yet (Dong et al., 1989, 2011; Cai et al., 2003; Yuan et al., 2008; Bian et al., 2013). The SCW is also a place with massive macroalgal blooms, an environmental disaster sometimes known as the Green Tide, which once nearly derailed the 2008 Beijing Olympics sailing regatta in Qingdao (Leliaert et al., 2008; Liu et al., 2009; Lee et al., 2011). Because of the great social impacts, the origin of the macroalgal seeds and their fueling nutrients, as well as their transport pathways, have received intense research focuses since 2008 (Liu et al., 2009; Lee et al., 2011).

A more fundamental question is that what make up the water mass in the SCW, the answer of which may lead to a better understanding on the above phenomena. A notable characteristic of the SCW is its low salinity year-round, with the minimum salinity below 26 (Su and Yuan, 2005). Climatologically, the SCW is significantly diluted in the summer and autumn seasons, with a salinity of less than 30 almost everywhere; while in the winter and spring seasons, the low salinity stays near the coast (Editorial Board for Marine Atlas, 1992; Fig. 1). It was speculated that the freshwater source for the SCW was mainly from the Subei local rivers (noted as SLRs hereinafter), such as Guanhe River and Sheyang River, or from the modern Yellow River that discharges into the Bohai Sea (Zou et al., 2000; Wang et al., 2012; Zhang et al., 2016). Although the Changjiang River is an overwhelming freshwater source around the SCW, it was thought to play only a minor role in diluting the SCW (Zhang et al., 2016). The reason is that the SCW, as well as the entire Yellow Sea and East China Sea, is controlled by the northerly winter monsoon in the non-summer seasons, which was thought to drive a southward and down-shelf coastal current (i.e., the Yellow Sea Coastal Current, YSCC). Such an YSCC was unfavorable for the Changjiang River Plume to

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*Corresponding author, E-mail: hwu@sklec.ecnu.edu.cn, hwusklec@gmail.com

reach the SCW in the non-summer seasons.

However, given the vast distribution of the low-salinity water in the SCW, one or multiple large freshwater sources would be necessary. Unlike those from the large rivers such as Changjiang, discharges from the SLRs are poorly monitored. The only available runoff data were published on the website of the Jiangsu Water Resource Office (http://www.jswater.gov.cn/), which reports the overall freshwater discharges into the SCW each year. According to Yang et al. (2012), the multi-year mean annual runoff into the SCW was 297.6×10^8 m^3. Over 90% of these freshwaters enter the SCW north of the Doulonggang (shown in Fig. 1), in the vicinity of Old Yellow River Delta (OYRD), mainly through the Guanhe River and Sheyang River. The river discharges of SLRs varied greatly in different seasons, accounting for 68% in flood season (June–September) and 10.6% in dry season (December–March). In other words, the total flow rate of SLRs was ~1 920 m^3/s during wet months, which was a striking number that was far larger than the common impression. Unfortunately, the underlying calculation method was unclear to us. The question is that even with this flow rate, can it explain the SCW that covers such a large area? Recently, Zhang et al. (2016) analyzed the freshwater budget in the SCW based on the observed salinity data during 2006–2007 (Fig. 2) and the discharge data reported by Yang (2012). Their conclusion was that the discharges from SLRs alone could maintain the low salinity in the SCW. However, in their calculation, the mixing and movement of the SCW influenced by the energetic oceanic processes, such as the tidal and wind-driven currents, were not considered explicitly. Therefore, they could underestimate the freshwater exchange volume in this area and perhaps more riverine discharges are needed to balance the freshwater budget in the SCW.

Since the Changjiang Estuary is adjacent to the SCW, could the Changjiang River be a major source for the SCW, thus also the sources for nutrients and sediments out there? Although this seems to be prevented by the northerly winter monsoon and the YSCC, many studies cautiously suggested that the Changjiang River Plume could extend to the SCW. Pu (1981) and Pu and Xu (1983) analyzed the *in situ* salinity data in the SCW and the Changjiang Estuary, and proposed that there should be a year-

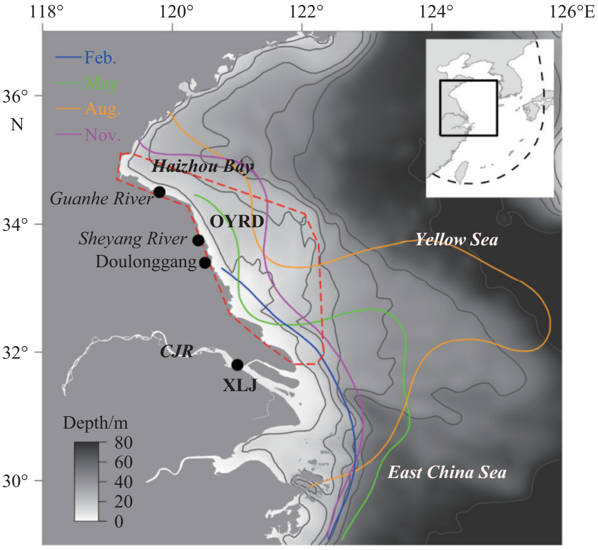

Fig. 1. The topography of the Subei Coastal Water and the adjacent areas. The 30 salinity contours digitized from the Editorial Board for Marine Atlas (1992) in February, May, August, and November are labeled with different colors. The circled area with red dashed line is the region selected to calculate freshwater content. CJR stands for the Changjiang River, OYRD the Old Yellow River Delta, and XLJ Xuliujing. The model boundary was shown with dashed lines in the inset.

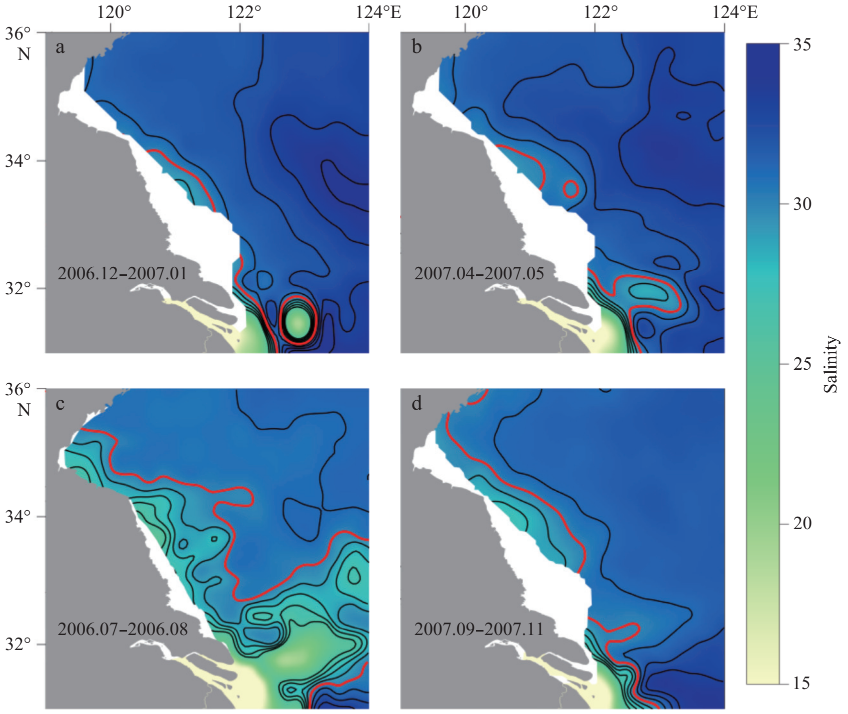

Fig. 2. Surface salinity distributions in 2006–2007 from observations. The salinity contour interval is 1, with the 30 isohaline highlighted by the thick red line. a. Winter, b. spring, c. summer, and d. autumn.

round northward coastal current in the SCW that transports the Changjiang diluted water northward to 33°N. Later, Zhao et al. (1995) pointed out that the active tide in the SCW can generate a northward tide-induced residual current, and speculated that it may push a part of the Changjiang River Plume water to the SCW. Wu et al. (2014) found this tidal residual current can overwhelm the northerly wind during spring tides, which brings a portion of the Changjiang River Plume to the SCW at least during the summer and autumn seasons. Wu et al. (2014) defined this plume as the third pathway of the Changjiang River Plume, besides the well-known northeastward offshore extension during summer and southward alongshore extension during winter (Mao et al., 1963; Beardsley et al., 1985). This plume flowed northward along the Subei coast after leaving Changjiang Estuary, and then it turned offshore-ward around 33.5°N (Oh et al., 2014; Xuan et al., 2016). However, Wang et al. (2017) argued that the offshore extension of the low-salinity water around 33.5°N was not originated from the Changjiang River, but from the SLRs.

Based on the previous studies on SCW, both Changjiang River and SLRs could contribute to form the low-salinity SCW. Quantifying their contributions in different areas of the SCW and revealing the associated transport mechanisms are challenging. The *in situ* hydrological data in the SCW were very sparse due to the shallow bathymetry and stormy weather during the non-summer seasons. Interpreting the *in situ* data might be subjective since the salinity alone could not index the sources, nor could it tell the time after the freshwater leaves the estuary. Numerical simulation might be an alternative method, but the previous modeling studies only concentrated on the fate of the Changjiang River Plume in the SCW. The fate of SLRs plume has not been evaluated yet.

In this study, we used a well-validated numerical model to investigate the fates of river discharges from both the Changjiang River and the SLRs in the SCW, to compare their contributions in diluting different parts of the SCW, and to calculate the time scales for the plume waters from both sources to reach the SCW. The remaining part of this paper is organized as follows. The *in situ* data, model configurations, and the water age method are presented in Section 2. Seasonal variation of the salinity in the SCW and the influence from different river sources are shown in Section 3. In Section 4 we discuss the transport mechanism and time scales. Conclusions will be drawn in Section 5.

2 Data and methods

2.1 *In situ data*

The salinity and temperature in the SCW were measured by a CTD (Seabird Electronics) in the summer (July–August 2006), winter (December 2006–January 2007), spring (April–May 2007) and autumn (September–December 2007) seasons, under the Project on Coastal Investigation and Research (a.k.a. the Project 908). This data was published previously by Zhang et al. (2016). The sampling sites covered the major part of SCW except the very shallow area, where it was difficult to access safely (Fig. 2; Zhang et al., 2016). The freshwater discharge from Changjiang River is measured by the Changjiang Water Resource Commission at the Datong station, which is located at ~630 km upstream of the river mouth. Discharges from the SLRs used the data reported by the Jiangsu Water Source Office (http://www.jswater. gov.cn/). According to this data source, the total discharge from SLRs was 277.0×10^8 m^3 in 2006, 366.3×10^8 m^3 in 2007, while the multi-year mean was 297.6×10^8 m^3.

2.2 *Numerical model*

The numerical model used in this study was ECOM-si (Blumberg, 1994), originally from POM. The model uses the modified MY 2.5 turbulence closure model (Mellor and Yamada, 1982) for the vertical mixing and the Smagorinsky (1963) scheme for the horizontal mixing, respectively. A third-order accuracy, nonoscillatory HSIMT advection scheme (Wu and Zhu, 2010) was used to solve the tracer equations. The model domain covered the entire East China Sea, Yellow Sea, and Bohai Sea, and parts of the Pacific Ocean and the Japan Sea. Twenty σ layers were set in the vertical with refined upper layers. The model was previously used to study the dynamics of Changjiang River Plume in Wu et al. (2011, 2014), Wu (2015), and Yuan et al. (2016), showing reliable performance in reproducing the salinity, temperature, tide, and shelf circulations around the Changjiang Estuary.

In this study the mesh resolution was refined to 1.0 km inside the Changjiang River mouth, 1.5 km outside the Changjiang River mouth, and 3 km in the SCW, respectively. The model was further validated with data from the SCW area. The runoffs from the Changjiang River and SLRs were both included in the model. The SLRs discharge was distributed to the Guanhe River (8.6%), Sheyang River (16.4%), and other small rivers (75%), according to Ma et al. (2010) and Yang (2012). The numerous small rivers distribute along the Subei coast and are mostly north of the Doulonggang. We allotted 68%, 10.6%, and 21.4% of the total discharge to June-September, December-March, and other months, respectively, according to Yang (2012). Six-hourly wind and other atmospheric parameters, including air temperature, air pressure, relative humidity, and total cloud cover, from European Center for Medium-Range Weather Forecasts (ECMWF) were used to calculate the momentum and heat flux through the sea surface. The heat flux was calculated with the bulk formula suggested by Ahsan and Blumberg (1999). The hydrodynamic open ocean boundary was driven by velocity, which combined the shelf and tidal currents (Wu et al., 2011). The open boundary of the shelf circulation was derived from the daily HYCOM Global reanalysis product. The initial salinity and temperature used the Simple Ocean Data Assimilation (SODA) dataset.

After the validations, three experiments were performed to identify freshwater content compositions from different river sources. In Exp. 1, only the Changjiang River runoff was added; in Exp. 2, only the SLRs runoff was added; in Exp. 3, runoffs from both the Changjiang River and the SLRs were added. To make the discussion more general, only climatological forcing was used. The monthly discharge data since the 1950s at the Datong Station was used for the Changjiang River discharge. The multi-years mean SLRs runoff was allotted to different rivers in different seasons with the same method as for the validation. The monthly mean wind and atmospheric parameters were from NCEP (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.surface.html). In all three experiments the initial salinity was set to 34. All experiments ran for two years for spin-up and the results in the third year were output for analyses.

To quantify the contributions of the different freshwater sources, passive tracers were released from the Changjiang River and the SLRs in the Exp. 3. The tracer concentrations were set to 1 at the river boundaries, which can be used to represent the freshwater concentrations.

2.3 *Water age*

Water age is defined as the time elapsed since the water parcel under consideration left the region in which its age is prescribed to be zero (Delhez et al., 1999; Deleersnijder et al., 2001).

Passive tracers were released at the upstream of Changjiang River, Sheyang River and Guanhe River, respectively, calculating the transport time of freshwater water from these three estuaries to the SCW area. The water age can be determined by solving the following three equations:

$$\left.\begin{aligned}&\frac{\partial F(x,y,z,t)}{\partial t}+\nabla\cdot\left(\vec{V}F(x,y,z,t)-K\nabla F(x,y,z,t)\right)=0\\&\frac{\partial \alpha(x,y,z,t)}{\partial t}+\nabla\cdot\left(\vec{V}\alpha(x,y,z,t)-K\nabla \alpha(x,y,z,t)\right)=F(x,y,z,t)\\&a(x,y,z,t)=\frac{\alpha(x,y,z,t)}{F(x,y,z,t)}\end{aligned}\right\}, \quad (1)$$

where $a(x, y, z, t)$ is the water age, $\alpha(x, y, z, t)$ is the age concentration, $F(x, y, z, t)$ is the tracer concentration, $\vec{V}(x, y, z, t)$ is the advection velocity, and K is the diffusivity tensor. The water age method has been successfully used in many coastal and estuarine studies (Delhez et al., 2004; Shen and Lin, 2006; Shen and Wang, 2007), including in the Changjiang Estuary (Wang et al., 2010, 2015).

3 Results

3.1 *Seasonal variation of the SCW salinity distribution in 2006–2007*

The low-salinity water extended from Changjiang Estuary all the way northward along the Jiangsu coast to Haizhou Bay, during almost all seasons (Fig. 2). The summer cruise covered almost all the areas of SCW, from which one can see that the brackish water band along the Jiangsu coast had nearly the same magnitude as the northeastward branch of the Changjiang River Plume. This brackish water band was still apparent during autumn, although the wind had turned northerly. It shrank during the winter and spring seasons. Another remarkable feature was the offshore extension of low-salinity water around the 33°–34°N during almost all seasons, at a location near the SLRs estuaries. This may lead to an immediate speculation that the diluted water in 33°–34°N could originate from the SLRs, which was proposed by Zhang et al. (2016). However, Wu et al. (2014) suggested that the Changjiang River Plume can also extend northward to ~34°N driven by the tidal residual currents. Therefore, it is necessary to further evaluate the real origins of freshwater in this coastal area.

3.2 *Model validation results*

Figure 3 shows the comparisons between observed data and model results at the sea surface. The root-mean-square error (RMSE) of the surface temperature and salinity were 1.32°C and 1.95, respectively. It can be seen from Fig. 4 that the model reproduced the horizontal salinity distributions fairly well. In summer and autumn, surface salinities from the model matched the observed data better, when there was a great amount of low-salinity water along the Jiangsu coast. In winter and spring, salinity from the model was slightly lower than the observations, but with similar patterns. SLRs discharges were much more uncertain during the winter and spring seasons. In this study we assumed that the SLRs discharged 10.6% of the total runoff in December–March, according to Yang (2012). Such an assumption is problematic. Many rivers in the Subei area were built with gates, which were often closed in the non-summer seasons to prevent saltwater intrusion. It is possible that in this study we overestimated the SLRs discharges in the winter season, thus underestimate the salinity around the OYRD.

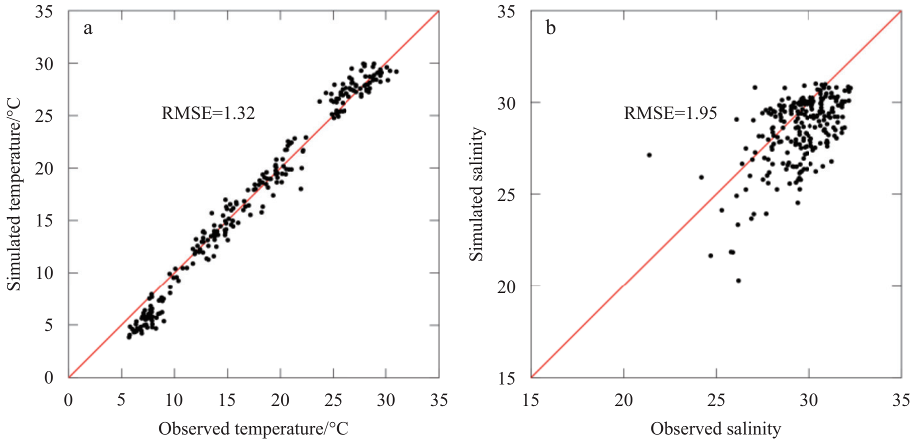

Fig. 3. Validations on the surface temperature (a) and salinity (b) in 2006 and 2007. The root-mean-square error values are labeled.

3.3 *Low-salinity water distribution influenced by different sources*

After the two year spin-up with given climatological runoff conditions, monthly surface salinity distributions were shown in Fig. 5. The months of February, May, August and November were selected to represent winter, spring, summer and autumn seasons, respectively.

3.3.1 *Salinity distribution under the Changjiang River discharge only*

When driven with the Changjiang River runoff only, low-salinity water was found along the Subei coast year-round (Figs 5a–d). Since there was no other river inflow, and the initial salinity was set to 34, the low-salinity water in this experiment must be from Changjiang River. In spring (Fig. 5b), a portion of the Changjiang River Plume started to extend northward to the SCW, with the 30 contour reaching 32.5°N. In summer, under the southerly summer monsoon, such a northward plume branch reached its peak in the year, which can reach the vicinity of the OYRD; thereafter it turned offshore. In autumn, when the East Asian monsoon turned to north, the major pathway of the Changjiang River Plume shifted to southward. Interestingly, although the 30 isohaline shrank southward, there was still low-sa-

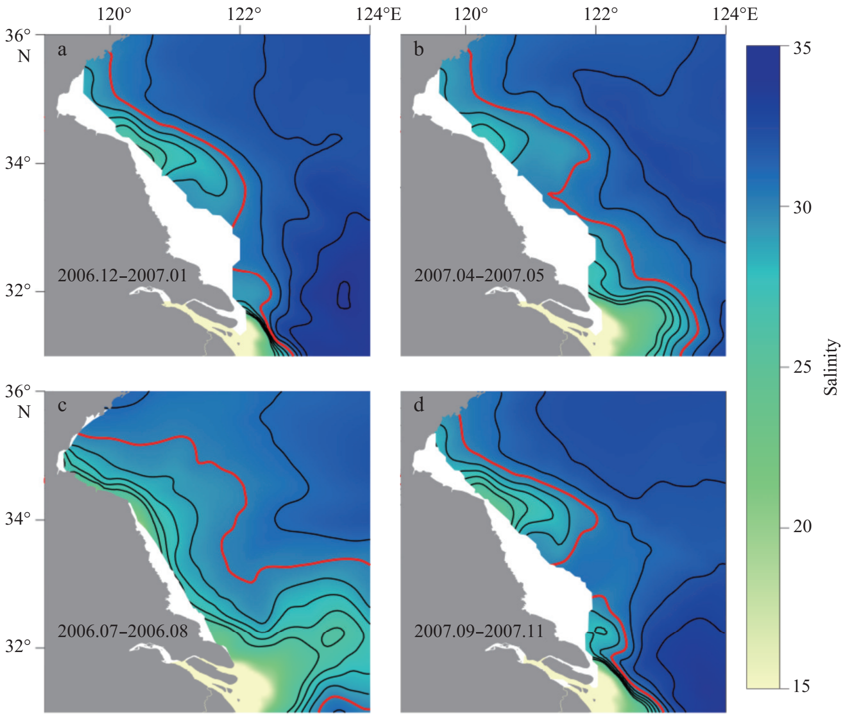

Fig. 4. Surface salinity distributions in 2006–2007 from the model. The salinity contour interval is 1, with the 30 isohaline highlighted by the thick red line. a. Winter, b. spring, c. summer, and d. autumn.

linity water in the SCW, which was lower than 30. Even in winter, under the prevailing northerly winter monsoon, diluted water still existed throughout the SCW. Notably, a closed salinity contour was observed around the OYRD, which appears to be from a local freshwater source. Since the SLRs discharges were not included in this experiment, it must be the remnant freshwater from the Changjiang River.

In general, the Changjiang River Plume has a great impact on the SCW. However, it seems that the Changjiang River Plume can only affect south of the OYRD, which, to some extent, is the northern limit of the Changjiang River Plume extension. Such a northward Changjiang River Plume branch was previously suggested by Wu et al. (2014). Despite the strong northerly winter monsoon and energetic currents in the SCW, low-salinity remained there. Wu et al. (2014) suggested that it was due to the northward residual current along the Subei coast. Xuan et al. (2016) pointed out that the tidal residual currents formed a closed loop in the SCW, which might be favorable for trapping the diluted water in the SCW.

3.3.2 *Salinity distribution under the SLRs runoff only*

The SLRs plume was restricted to the vicinity of OYRD (Figs 5e–h). There were two low salinity centers near the Sheyang and Guanhe river estuaries. In all seasons, the major SLRs plumes spread offshore of the OYRD, with only a small portion potentially extending to south of 33.5°N. Interestingly, the behavior of the SLRs plume was distinct from the classical surface- or bottom-trapped river plumes, which should be either rotating off the estuary or propagating downstream along the coast (Yankovsky and Chapman, 1997). The baroclinic Rossby deformation radius of the SLRs plume, $R_d = \sqrt{g'h}/f$, was 6.6 km given a salinity anomaly of 4 and a depth of 10 m. However, the offshore extent of the SLRs plume was on the order of 100 km, which was much larger than that of an unforced weak inflow river plume, i.e., $4.24R_d$ (Yankovsky and Chapman, 1997). Hence, the SLRs plume must be forced by the external forcings that were favorable for offshore movements.

After spreading offshore, the SLRs plume drifted southeastward along the slope of the Yangtze Bank. It is remarkable that, although during summer the SLRs discharges reached the yearly maximum, the resultant river plume was not the largest. The reason was that the SLRs plume spread offshore much faster and farther in summer than in other seasons, hence the diluted water remained in the SCW was less. This was probably due to the southerly summer monsoon, which favored an offshore extension under the Ekman effect.

3.3.3 *Salinity distribution under both the Changjiang and the SLRs runoffs*

Driven by the discharges from both the Changjiang River and the SLRs, the salinity distributions (Figs 5i–l) in the SCW were similar to those observed in 2006–2007. Comparing the surface salinity distribution under different runoff conditions in Fig. 5, it seems that the low-salinity water in the SCW was dominated by the Changjiang River in south of 33.5°N, by the Guanhe River north of 34.5°N (i.e., the Haizhou Bay), and by both the SLRs and the Changjiang River in 33.5°–34.5°N. During the winter, spring, and autumn seasons, the low-salinity water was mostly confined to the Yangtze Bank, except a small portion leaked from the bank at the southeastern corner. Whereas in the summer, the low-salinity water spread offshore and entered the interior Yellow Sea.

To quantify the freshwater content compositions in the SCW, passive tracers were released from the Changjiang River and the SLRs, respectively. These tracers were assigned with a concentration of 1 at the river boundary, hence they equivalently represented the freshwater concentration F. F was integrated in the dashed box area shown in Fig. 1:

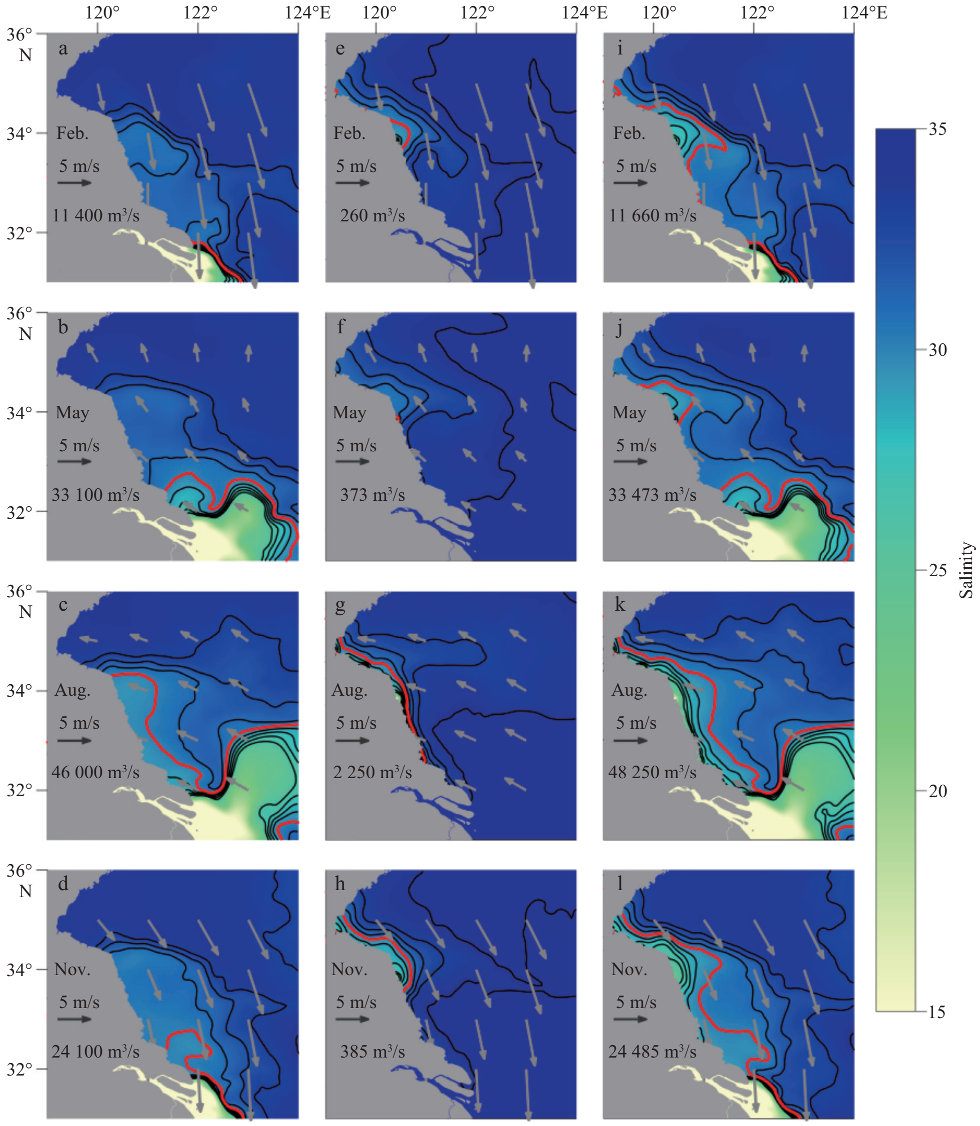

Fig. 5. Modeled monthly surface salinity distribution under the Changjiang River runoff only (a–d), SLRs runoff only (e–h) and both the Changjiang River and SLRs runoffs (i–l). The climatological monthly winds and the corresponding River discharges are also labeled. The salinity contour interval is 1, with the 30 isohaline highlighted by the thick red line.

$$FW = \left\langle \int_{v} F\mathrm{d}v \right\rangle, \tag{2}$$

where FW is the freshwater, $\langle\cdot\rangle$ is the monthly mean operator, and v is the water volume considered.

The freshwater contents from the Changjiang River and the SLRs within a year are shown in Fig. 6. The Changjiang River plays an overwhelming role in forming the low-salinity SCW during all seasons. Interestingly, the maximum Changjiang-derived freshwater content in the SCW (peaked in September–October) lagged the Changjiang River discharge (peaked in July–August) for ~2 months, noting that the wind usually turns to northerly after September. The SLRs-derived freshwater content reached its minimum during June, July, and August, in contrast to the high runoff in this period. The reason can be inferred from Fig. 5g, that during the summer season the SLRs plume escaped the SCW and extended farther offshore into the interior Yellow Sea. In summer, the Changjiang River contributed ~80% of the total freshwater content in the SCW, with the rest resulting from the SLRs. In winter, the contribution of the Changjiang River slightly decreased to ~70%. Above all, the freshwater source in the SCW was mainly from the Changjiang River, and the SLRs contribution was restricted to the OYRD vicinity.

4 Discussion

4.1 *Transport mechanism in the SCW*

The above results indicate that the movements of the river plumes in the SCW are highly controlled by the external forcings. The flow direction in the SCW was conventionally thought to be southward due to the prevailing northerly wind and geostrophic balance (Su and Yuan, 2005), but in recent years some studies pointed out that the flow direction in the SCW could be northward, especially in the summer (Xia et al., 2006; Liu and Hu, 2009; Qiao et al., 2011; Wu et al., 2014; Xuan et al., 2016; Yuan et al., 2017). Here we calculated the residual transport velocity in each season, which showed that the depth-mean transport was northward along the Subei coast south of 33.5°N, regardless of

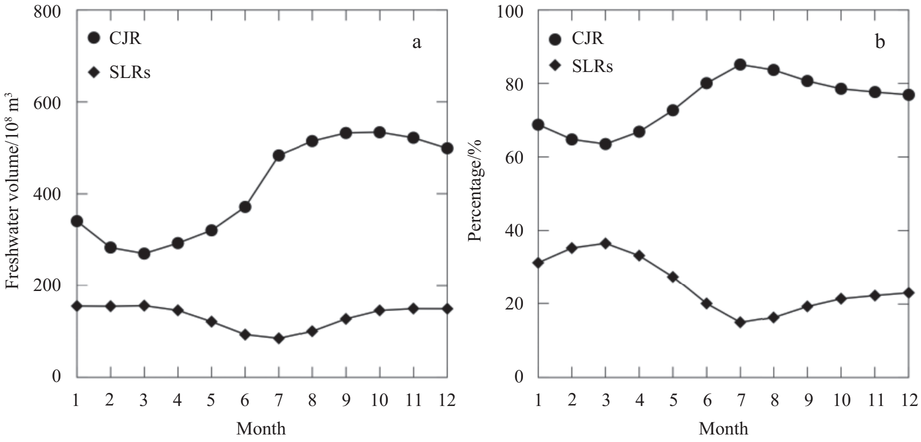

Fig. 6. The freshwater content in the Subei Coastal Water (for selected area see Fig. 1) in each month (a) and the percentage of contributions from different sources (b).

the wind direction in different seasons. Tide-induced Stokes drift is the essential component of this northward transport (Wu et al., 2014). North of 34.5°N the residual transport velocity was southward. These two opposite currents converged around the vicinity of the OYRD, from where both turn to offshore. The offshore current around ~34.5°N continued along the slope of the Yangtze Bank, forming a semi-enclosed loop on the Yangtze Bank, which was also suggested by Lee and Beardsley (1999) and Xuan et al. (2016). Such a loop was stronger during the summer and autumn seasons. Because of the intense offshore transport in summer, the freshwater from the SLRs did not stay in the SCW for a long time, which explained why the freshwater content from the SLRs was minimum in summer.

Figure 7 was derived from a numerical simulation driven by combined forcings, and its pattern was quite similar to that from a purely tidally-driven simulation (e.g., Figs 11 and 12 in Wu et al., 2014). It means that the transports of the low-salinity water are highly controlled by tide. Off the Subei coast tide is controlled by two different systems, i.e., a northwestward progressive tide from the East China Sea and a rotating tide in the Yellow Sea. These two tidal waves collide near the OYRD, where the residual transport velocity converges and turns offshore (Wu et al., 2014). As a result, a dynamic barrier is formed near the OYRD, which prevents the Changjiang River Plume from going further north and the SLRs plume going further south.

4.2 *Transport time scale from different river sources*

To further understand the transport timescales of the freshwater in the SCW, we calculated the water age. Passive tracers were released at the Changjiang River (at Xuliujing, for location see Fig. 1) and the SLRs estuaries, respectively. Four simulations were carried out, driven by the constant climatological forcing of

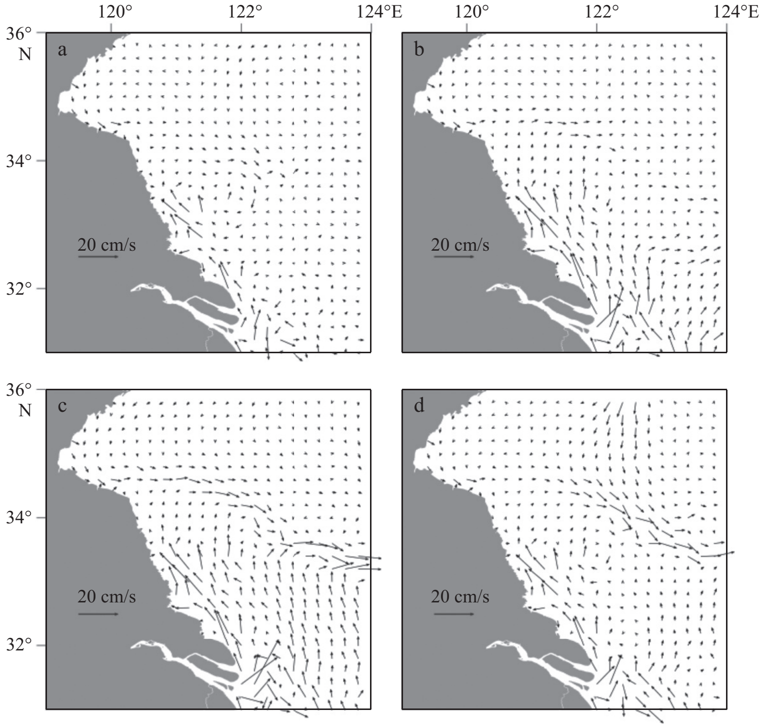

Fig. 7. Seasonal variations of the residual transport velocity. a. Winter, b. spring, c. summer, and d. autumn.

the four seasons, respectively. The models were spun up for 2 months, and the tracers were released continuously for 300 d. Such a setting can isolate the transport mechanisms and time scale for different seasons. It should be noted that the water age method calculates the mean elapsed time of all tracers arriving at a specific location during the simulation period. The water age simulation results are influenced by the simulation period. The 300-d simulation was reasonable, because the seasonal variation of the Changjiang River Plume is very strong, thus the old tracers in previous year have basically lost their riverine properties under the strong ambient mixing.

The surface tracer and associated water age distributions from the Changjiang Estuary are shown in Fig. 8. The water age was ~50 d at the southern boundary of the SCW. Very few tracers reached the SCW under the autumn (represented with November) and winter conditions (represented with February) when the wind was northerly (Figs 8a and d), thus the water ages during these times in the SCW were meaningless. However, during the spring (represented with May) and summer (represented with August) seasons when southerly wind dominated, the tracers reached the SCW and drifted northward to the OYRD vicinity. Water ages were 100–200 d relative to the releasing site, Xuliujing, or 50–150 d relative to the river mouth (represented with the 50 d contour). This time scale was comparable to the seasonal time scale (~90 d), suggesting that the tracers released in spring could hardly reach the interior SCW. This explained why there were a 2-month lag between the peaks of the freshwater content in the SCW and the Changjiang River discharge (Fig. 8). The northward tidal residual currents along the coast and the overall loop residual current over the Yangtze Bank helped to keep the diluted water from being flushed out by the wintertime winds.

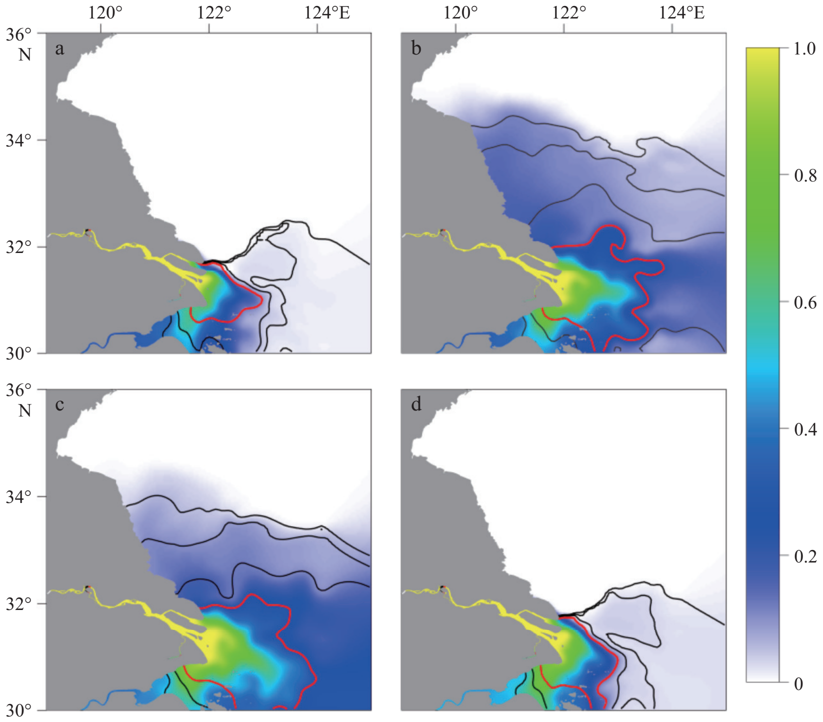

Fig. 8. Surface tracer distribution (the color shadings) from the Changjiang River under the climatological conditions of winter (a), spring (b), summer (c), and autumn (d) seasons, respectively. The water age are labeled with contours at an interval of 50 d. The 50-d water age contour is labeled with the red thick line.

The tracers from the Guanhe and Sheyang Rivers were restricted to the Subei coast under the winter and autumn conditions, with their water age distributions showing a southeast extension (Figs 9 and 10). For the Guanhe tracer, the water age was ~200 d south of the OYRD. It could not go south of 33°N. The drift speed was slow as indicated by the dense water age contours. The Sheyang tracers extended along the coast much farther to 32°N under the autumn and winter conditions. But by checking the tracer and age patterns, it seems that the Sheyang tracer did not go southward directly; instead, it went offshore first and then returned to the coastal region. The northward tidal residual current prevented the southward flows (Fig. 9). It took 200–250 d for the Sheyang tracer to reach 33°N under winter condition, a time scale much longer than that of the season. Hence, in reality, the Sheyang Plume cannot reach south of 33°N.

5 Summary

The freshwater content compositions in the Subei Coastal Water (SCW) and its transport mechanism were studied with a validated numerical model. The results showed that both the Changjiang River and Subei local rivers (SLRs) can dilute the SCW, but their contributions differ in different parts of the SCW. Overall, the Changjiang River is dominant in diluting the SCW, contributing 70% and 80% of the total freshwater contents in the winter and summer seasons, respectively. The Changjiang-derived freshwater content reaches a maximum in September and October, ~2 months lagging the peak river runoff. Although the SLRs discharge is the highest in summer, the associated freshwater content in the SCW is the lowest. The reason is that the southerly wind in summer favors the SLRs plume to extend offshore rapidly into the interior Yellow Sea.

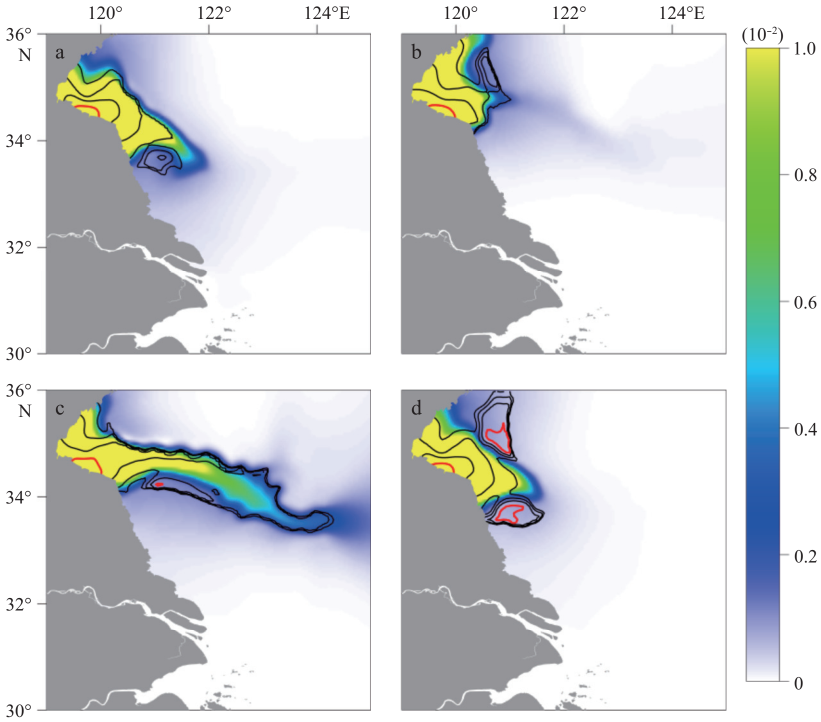

Fig. 9. Surface tracer distribution (the color shadings) from the Guanhe River under the climatological conditions of winter (a), spring (b), summer (c), and autumn (d) seasons, respectively. The water age are labeled with contours at an interval of 50 d. The 50-d water age contour is labeled with the red thick line.

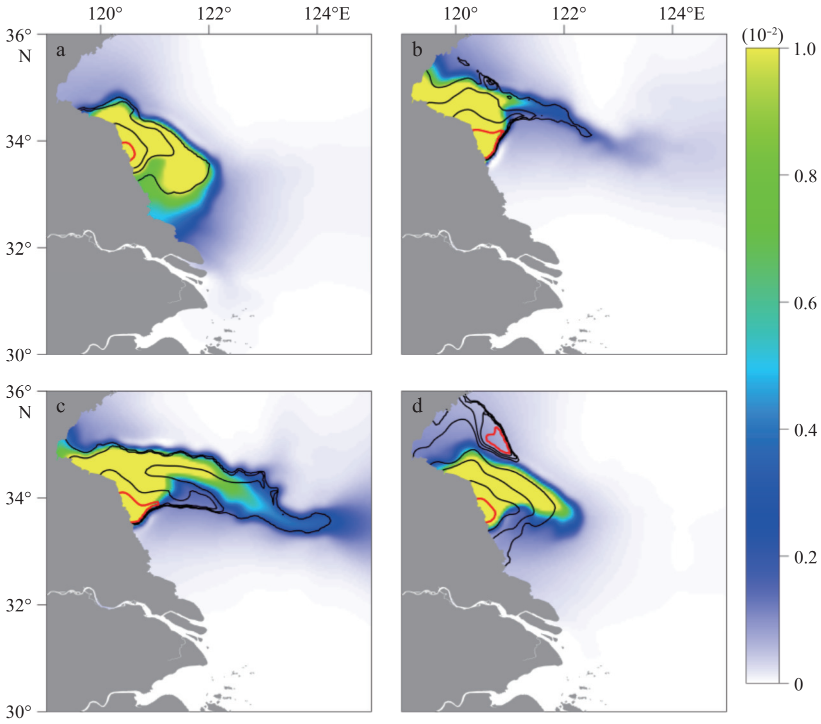

Fig. 10. Surface tracer distribution (the color shadings) from the Sheyang River under the climatological conditions of winter (a), spring (b), summer (c), and autumn (d) seasons, respectively. The water age are labeled with contours at an interval of 50 d. The 50-d water age contour is labeled with the red thick line.

The transports of the Changjiang River and the SLRs plumes are greatly controlled by the tidal residual currents. The unique tide system in southwestern Yellow Sea generates a northward residual current in south of 33.5°N and a southward residual current in north of 34.5°N, which converge and propagate offshore in the vicinity of the Old Yellow River Delta (OYRD). Such a residual current system exists throughout the year, regardless of the wind direction. As a result, a dynamic barrier is formed near the OYRD, so that the Changjiang River Plume cannot go further north and the SLRs plume can hardly go further south. The low-salinity characteristics of the SCW is controlled by the Changjiang River in south of 33.5°N, by the SLRs in north of 34.5°N (i.e., the Haizhou Bay), and by both the SLRs and the Changjiang River in 33.5°–34.5°N. The semi-enclosed residual current loop on the Yangtze Bank further traps the freshwater in the SCW.

The Changjiang River Plume spends 50–150 d to move from the river mouth to the SCW under the spring and summer conditions (i.e., the southerly winds). This time scale is comparable to the seasonal time scale. Hence, there is a 2-month lag between the maximum freshwater content in the SCW and the peak Changjiang River discharge. Little Changjiang River Plume water reaches the SCW under the winter and autumn conditions. The Guanhe River freshwater are mainly remained in the Haizhou Bay or transported offshore around the OYRD. Under the winter and autumn conditions, part of the Sheyang River freshwater penetrates offshore first then circulates back to the coast at ~33°N, but this process takes 200–250 d. Hence, in winter the low salinity in the SCW are not from the Sheyang River, Guanhe River, or other small rivers, but the remnant Changjiang River diluted water that arrived in the previous seasons.

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