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Modeling the Largest Inflow of Changjiang Freshwater into the Yellow Sea in 2012 with Particle-Tracking Experiment

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Abstract – Abnormally low-salinity water originating from the Changjiang River (CR) was observed at the central Yellow Sea (YS) in 2012, which was quite unique compared to other years. In this study, the intrusion process of the Changjiang Diluted Water (CDW) into the YS interior was examined using a hindcast simulation (2003–2012) with particle-tracking experiments. The particles representing the behavior of the CDW were released at the CR mouth from May to August, and then tracked. The simulated salinity patterns coincide fairly well with those derived from observations, particularly showing a large low-salinity structure around the central YS in 2012. A substantial intrusion of freshwater into the YS occurred in 2012, and this accounted for approximately 16% of all the released particles in 2012 which is twice as high as the mean average covering the 10 years. According to the trajectories in 2012, the particles took less than 50 days to travel from the mouth to the YS interior and followed mainly two paths toward the YS. One pathway traveled northward to the central entrance of the YS and then reached the western coast of Korea. This pathway was attributed to the strong easterly winds in late June and early August when three consecutive typhoons passed through the YS, which was a unique pattern that is rarely found in other years. The other pathway involved particles trapped along the Jiangsu coast drifting farther to the north up to the Shandon Peninsula against the anticyclonic tidal residual circulations during the passage of typhoons.

Key words – low salinity water, Changjiang River, Yellow Sea, particle-tracking experiment, typhoon

1. Introduction

The Yellow Sea (YS) is a shallow marginal sea of the northwestern Pacific, semi-enclosed by the Korean Peninsula in the east and the Chinese coast in the west. The hydrographic structures in the YS are strongly affected by various factors, such as seasonally varying atmospheric conditions, tide-induced vertical mixing, and river runoff. In summer, water in the YS is vertically stratified due to surface heating and freshwater input. In particular, the freshwater input from rivers dominates surface salinity distributions near the coasts when the river discharges are large (Chen et al. 2006). The Changjiang, which is the world's fourth largest river in terms of discharge (Dai et al. 2009), contributes about 90% of the whole river discharge into the YS and East China Sea (ECS) (Beardsley et al. 1985), signifying a significant source of freshwater, inorganic nitrogen, and particulate organic carbon in these regions (Liu et al. 2003, Wang et al. 2003). The discharge forms a low-salinity water by mixing with saline ambient water (Lie et al. 2003), which is known as the Changjiang Diluted Water (CDW), causing increased eutrophication and harmful algal blooming as well as hypoxia events in these regions (Rabouille et al. 2008; Wu et al. 2014).

The CDW is an important hydrographic feature in the ECS in summer, mostly spreading from the Changjiang River (CR) mouth to the adjacent seas of Jeju Island (e.g., Moon et al. 2009a). Previous studies have discussed the movements of the CDW in the ECS, which showed a remarkable seasonal variation (Chang and Isobe 2003; Moon et al. 2009b; Wu et al. 2014). In winter, a strong northerly wind pushes the CDW around the river mouth southward along the Zhejiang coast, while in summer southerly or southeasterly winds drive the freshwater east or northeastward to the northern shelf of the ECS. The offshore spreading of the CDW has been also identified by Moon et al. (2012) who focused on the freshwater pathways in the ECS. They have shown that a large portion of the freshwater moves northeastward to Jeju Island, while

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virtually no freshwater intrusion into the YS interior was seen, except along the Jiangsu coast. Wu et al. (2014) have recently shown two major pathways of the CDW in summer: one spreads offshore to the northeast due to the summer monsoon and the other extends northwestward along the Jiangsu coast by tide-induced residual flows.

However, of particular interest is the fact that abnormally low-salinity water was observed at the central YS in the summer of 2012. Recently, Oh et al. (2014) found a large elliptical structure of low-salinity (< 29 psu) in the YS interior, which originated from the CDW. It is quite a unique phenomenon that was never detected before. Harmful events, such as algal blooming and hypoxia occurrences, may be associated with the movement of the freshwater discharged from the CR that fairly corresponds to the spatial pattern of higher chlorophyll-a concentration (Kim et al. 2009). This implies that the inflow of the Changjiang freshwater into the YS interior could impact on the ecosystem of this region. Nevertheless, so far little attention has been paid to exploring and estimating the intrusion process of the CDW into the YS interior. Using observations and numerical experiments, Oh et al. (2014) have emphasized an important role played by typhoon-induced winds in the appearance of the CDW in the YS interior, but only a qualitative description for the movement of the CDW was carried out in their study. Understanding and quantifying the freshwater inflow into the YS is of great importance in order to further explore the impacts on ecosystem in the YS. In this study, we characterize and quantify the intrusion of the CDW into the YS and related freshwater pathways, using a hindcast simulation with particle-tracking experiments. We pay particular attention to the freshwater pattern in 2012 when the abnormally low-salinity water was detected at the central YS.

The rest of this paper is divided as follows. After a description of our numerical model, comparisons between the model and observed surface salinity distributions in the YS are given in section 3. We then estimate the amount of the freshwater intruding into the YS and discuss their main pathways in Section 4 and 5, respectively. Finally, a summary is presented.

2. Model Configurations

A 3D hydrodynamic numerical model used in this study is the Regional Ocean Modeling System (ROMS). ROMS is a free surface, hydrostatic, primitive equation ocean model (Shchepetkin and McWilliams 2005) based on a vertically stretched terrain-following coordinate system, which is advantageous for regional applications (Haidvogel et al. 2008).

Fig. 1 shows the model domain, which is a rotated rectangle with a wall on the northern side and three open boundaries, including the ECS. The model grid has a 1/12° horizontal resolution with 20 vertical layers (levels) in the stretched terrain-following coordinate. The bottom topography is extracted from the Sung Kyun Kwan University Topography Dataset (SKKU) with 1-min horizontal resolution (Choi et al. 2002). This model uses the third-order horizontal advection scheme, with the Generic Length Scale (GLS, Umlauf and Burchard 2003) vertical mixing closure scheme utilizing k-kl parameterization. The bottom stress is calculated from a quadratic drag parameterization.

The initial and open boundary values for the subtidal sea surface height and momentum, temperature, and salinity are obtained from the Hybrid Coordinate Ocean Model (HYCOM, Bleck 2002, Chassignel et al. 2007). In ROMS, several options for open boundary conditions have been included. Chapman (Chapman 1985) condition is used for the free surface, a modified Flather type (Marchesiello et al. 2001) is used for the barotropic momentum, and Clamped conditions are employed for the baroclinic momentum, temperature and salinity. The model is forced by 10 tidal constituents (M2, S2, N2, K2, K1, O1, P1, Q1, Mf, Mm) from the TPXO (TOPEX/POSEIDON) 7-atlas for sea surface height and barotropic momentum along the open boundary conditions.

The surface forcing including 10 m surface winds, 2 m air temperature, relative humidity, air pressure and precipitation were obtained from National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) 6-hourly data from 2003 to 2012. The surface forcings from NCEP/CFSR are used to compute the surface boundary conditions with the bulk formulation (Fairall et al. 1996). River discharge from Changjiang, Huanghe, Han, Kuem, and Youngsan (shown in Fig. 1) are included as freshwater sources in this model. The monthly averaged discharge of the CR was obtained from available data at the Datong hydrometric station for the period of 2003–2012 (Fig. 2a). Climatological monthly mean data (Kwon 2007) were used for the other rivers (Fig. 2b). The model was initialized in January 2003, and run from 2003 to 2012 (10 years), with a 3D Lagrangian particle-tracking experiment. The particles that represent the behavior of the CDW were continuously launched once per 6-hour at two places of the CR estuary (shown in Fig. 1b) with the depth of 1 m, 3 m, and 5 m, i.e., a total of 24 particles per day were

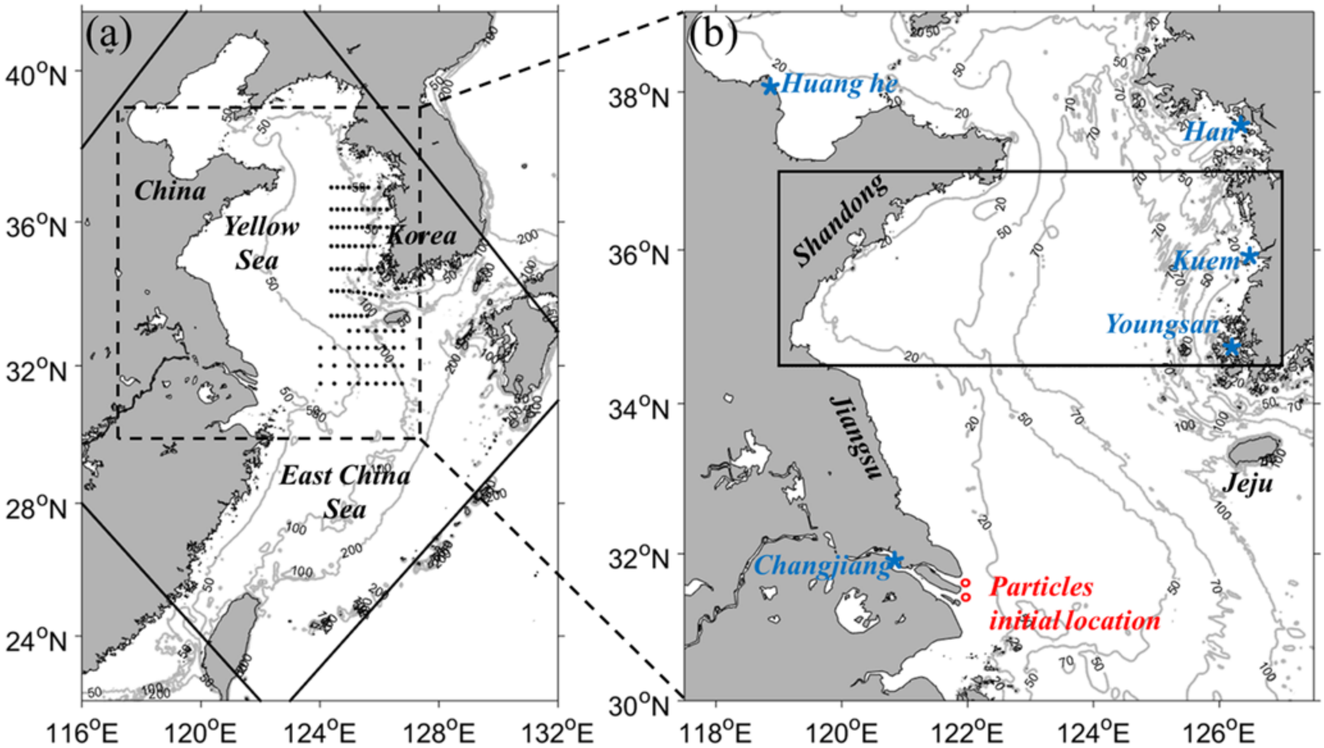

Fig. 1. (a) Model domain (rotated square box) and bathymetry (m). Black dots represent the Korea Ocean Data Center (KODC) stations. (b) Bathymetry of study area where the red dots represent launching locations of Largrangian particles. Black solid box is the region where the freshwater volume is calculated in Section 4. Star symbols indicate five river sources to take into account the river discharges

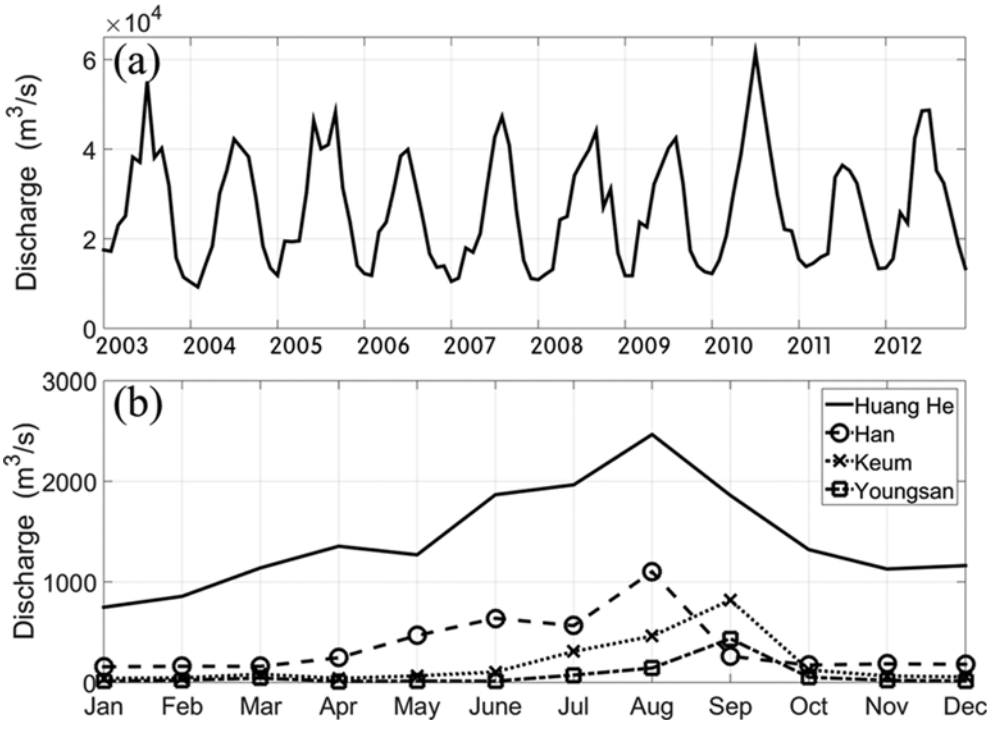

Fig. 2. (a) Monthly variation of the Changjiang River dischrage from 2003 to 2012 (at Datong station, China). (b) Climatological river discharges of the Huang He (thick solid line), Han (circle symbol), Keum (cross symbol), and Youngsan (square symbol) shown in Fig. 1b

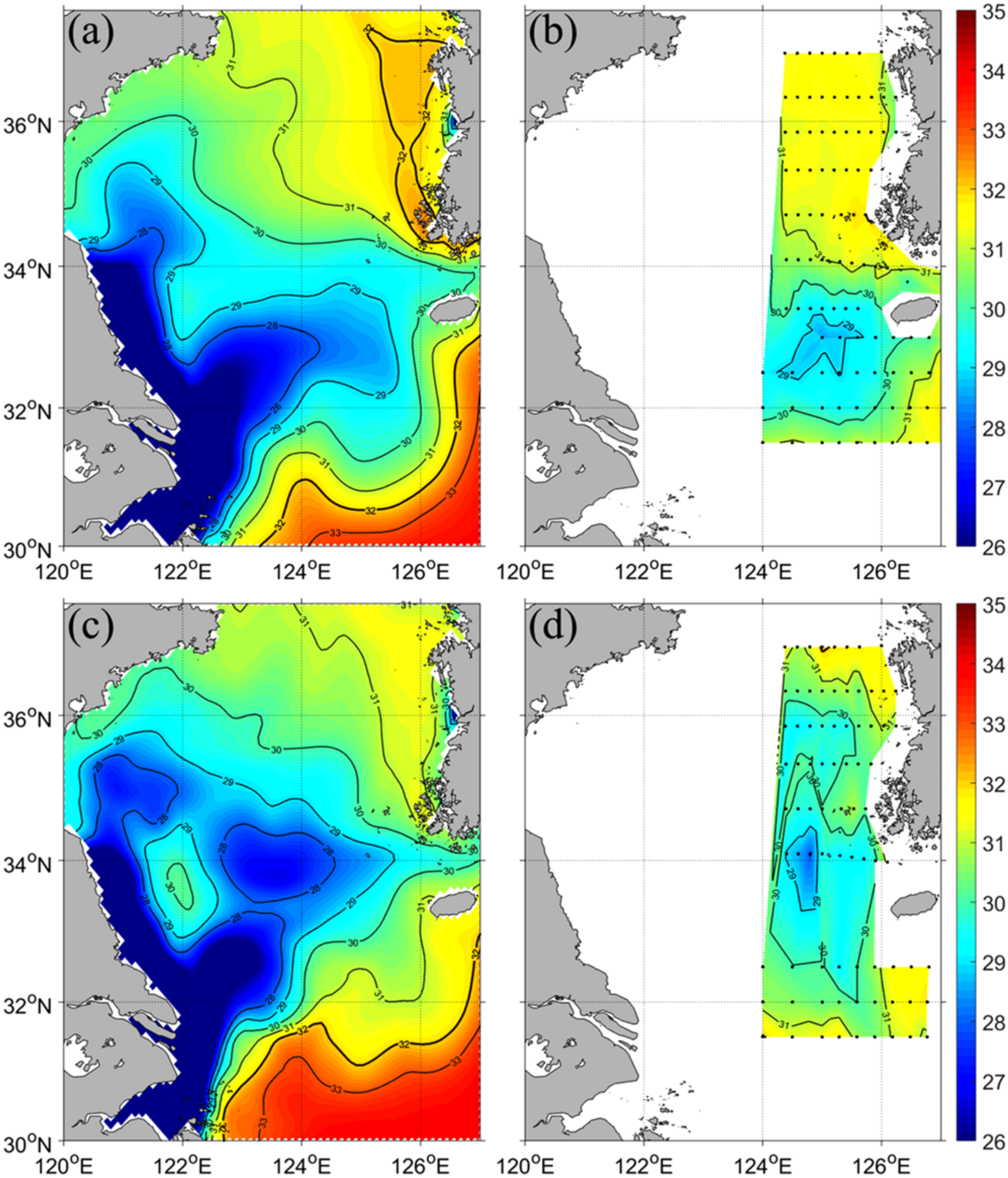

Fig. 3. Simulated monthly surface salinity in August averaged from 2003 to 2012 (upper left panel) and for 2012 (lower left panel). In-situ surface salinities in August averaged from 2003 to 2012 and for 2012 obtained from the KODC are also shown in the upper right and lower right panel, respectively, for comparison. Contour interval is 1.0 psu

released from May to August. Since the depth around the CR estuary is shallower than 10 m, the particles were released into the surface layer. The particles movements were tracked by integrating the 3D velocity fields from ROMS based on the fourth-order Runge-Kutta scheme.

$$z_{n+1} = z_n + \Delta t\left(w_{adv} + R\sqrt{\frac{2k}{\Delta t}} + \frac{\partial k}{\partial z}\right)$$

where z is vertical location. This random walk scheme adds a random vertical velocity to the advective velocity (w_{adv}) at every timestep (Δt) by adding the gradient of vertical diffusivity terms (k). The details of this scheme were well described in Visser (1997), Batchelder et al. (2002), and Banas et al. (2009).

3. Comparison of Model with Observed SSS

Figure 3 presents the spatial patterns of simulated sea surface salinity (SSS) in August for the long-term mean (2003–2012) and mean in 2012. Horizontal distributions of in-situ SSS obtained from the Korea Ocean Data Center (KODC) are also shown in the right panels of Fig. 3 for comparison. In the long-term mean SSS (Fig. 3a), low-salinity water originating from the CR is widely distributed in the northern shelf of the ECS, showing two distinct low-salinity plumes. One is a broad tongue-shaped low-salinity from the river mouth to the northern shelf of the ECS, which is a consequence of wind-driven northeastward transport (e.g., Moon et al. 2009a; Liu et al. 2013). As a result, the low-salinity water, with a range from 28 to 30 psu, predominated in the western region of Jeju Island in summer. This matches well the typical distribution of the CDW suggested by previous studies (e.g., Chang and Isobe 2003; Lie et al. 2003; Moon et al. 2009a). The other is a low-salinity band along the Jiangsu coast. The Changjiang plume toward the northwest has been reported by Wu et al. (2014) who reported that tide-induced current drifts the plume northwestward along the Jiangsu coast. The YS interior has a salinity range from 30 to 32 psu, becoming higher toward the western coast of the Korean Peninsula. The spatial pattern of the simulated mean salinity is quite similar to that of the CTD observation (Fig. 3b) cruise data in August in Wang et al. (2003), and summer observation in Xuan et al. (2015).

In 2012, the salinity distribution shows a similar structure to that of the 10-year mean, but a distinct difference is found in the central entrance of the YS (Fig. 3c). Unlike the 10-year mean distribution, the low-salinity water originating from the CR moved northward to the central entrance of the YS, with a large patch structure of < 28 psu. As the CDW flowed into the YS interior, relatively low-salinity water was distributed over the central region of the YS. Compared with the mean distribution, the surface salinity is lower (approximately 1 psu) at the western coastal region of Korea, while higher at the western seas of Jeju Island. These characteristics were also seen in the observed salinity field (Fig. 3d). Time series of area-averaged surface salinity anomalies in August from 2003 to 2012 are presented in Fig. 4. The salinity values are spatially averaged from 123°E to 126°E, and 34.5°N to 38°N. Over the last decade, both observed and modeled salinity changes in the YS interior were only within a range of ± 0.5 psu, with the exception of 2012. In 2012, the surface water in the YS was fresher by more than 1 psu compared to those of the normal years, which indicates more freshwater input into the YS.

4. Particles Entering into the YS

To better identify the temporal and spatial behavior of the CDW, a Lagrangian particle-tracking experiment was conducted.

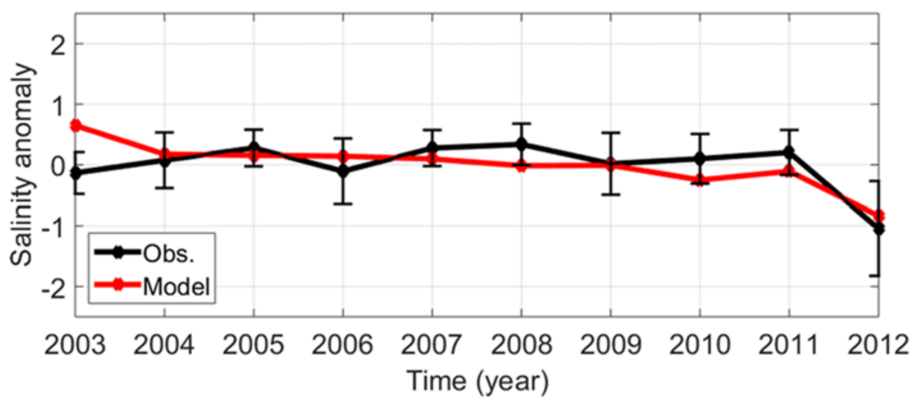

Fig. 4. Time series of area-averaged surface salinity anomalies in August from 2003 to 2012 for observation (black) and model result (red line). The salinity values are spatially averaged from 123°E to 126°E, and 34.5°N to 38°N

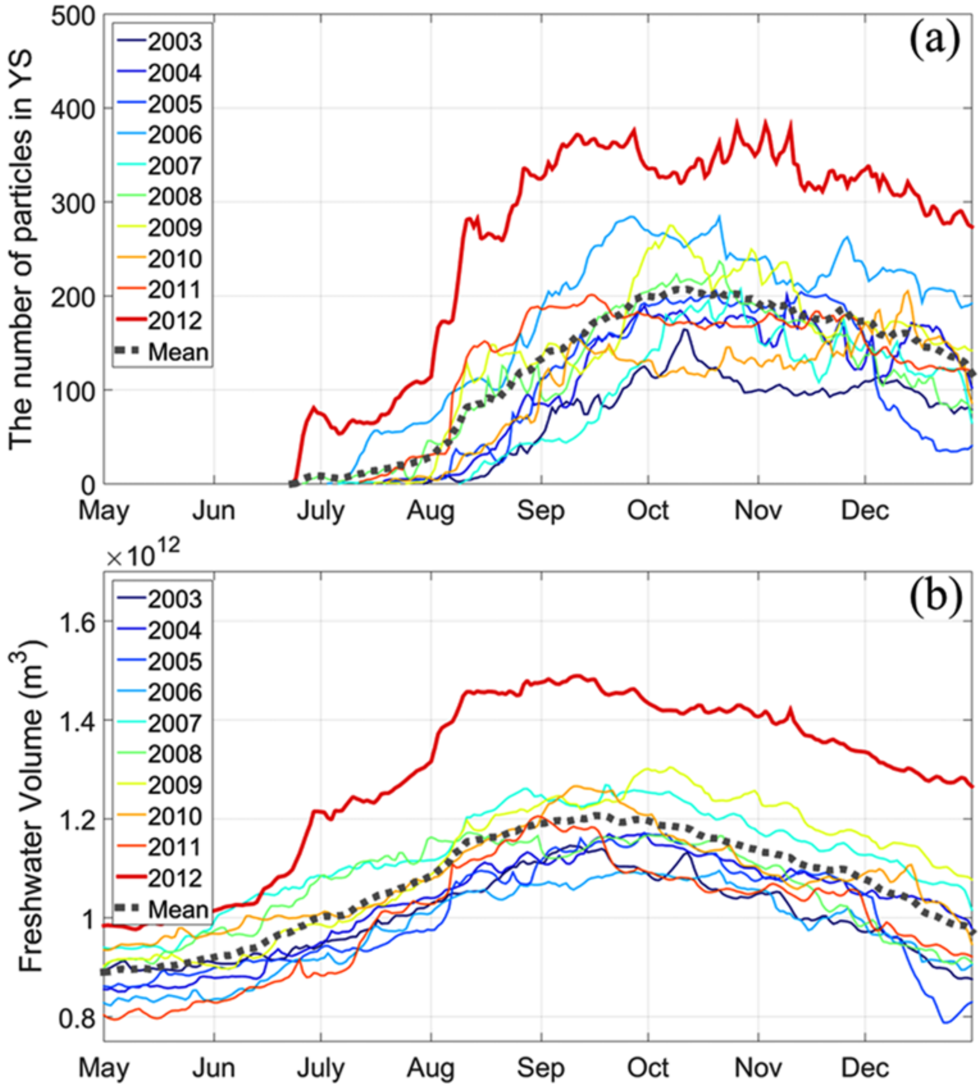

Fig. 5. Time series of (a) total number of the particles accumulated in the YS and (b) the freshwater volume calculated in the box shown in Figure 1b from May to December. The gray-dotted lines denote the 10-year mean values

Based on the results from the particle-tracking experiment, we quantified the freshwater in the YS that originated from the CR. The time series of the total number of the particles accumulated in the YS is shown in Fig. 5a. The particles were counted daily from the release within the YS area marked by a box in Fig. 1b (The YS region used here is from 119°E to 127°E and from 34.5°N to 37°N). In general, the number of particles entering the YS gradually increased from July to early October, and thereafter decreased in time (gray-dashed line). Unlike normal years, in 2012 there were two distinct periods when the number of particles largely increased. In 2012, the number of particles started to rapidly increase from mid-June to early July. Thereafter, the number of particles continuously increased until mid-September with a sharp increase in early August, and reached its maximum in early September, which is about two times the amount for a normal year.

Because the particles used here only represent the advective motion of a water parcel as pointed out by Moon et al. (2009), the result of a particle-tracking experiment needs to be compared with the freshwater volume that includes the diffusion processes. The freshwater volume (V_f) in the box of Fig. 1b is estimated by

$$V_f = \iiint \frac{s_0 - s}{s_0} dV$$

where s_0 is reference salinity and s is the salinity of the water column (Choi and Wilkins 2007). We used for reference salinity, s_0, the maximum value (34 psu) of salinity in the YS that ensures the freshwater thickness is always positive. The reference salinity represents the saline water of the ECS into which the Changjiang plume flows. On average the amount of freshwater volume gradually increased until October, and then decreased in time (gray-dashed line of Fig. 5b). Compared to a normal year, in 2012 the amount of freshwater largely increased from June to September, with an abrupt increase in late June and early August (red line of Fig. 5b). During this period, freshwater of more than ~0.2 × 10^{12} m^3 intruded into the YS, which corresponds to an increase of ~25% relative to a typical normal year. This result is fairly consistent with those of particle-tracking experiment. The amount of freshwater volume in the YS interior can be mainly determined by changes in air-sea freshwater flux (evaporation (E) minus precipitation (P)) and freshwater input discharged from the CR. As the changes of E-P in the YS are within the normal level in 2012 (not shown) and freshwater from the ECS can be regarded as negligible due to saline ambient water when compared to the reference salinity, the Changjiang freshwater transported into the YS is a major contribution to the freshwater increases in the YS in 2012, which reflects horizontal movements of the particles. It should be noted that the river discharge itself is not a sufficient condition for the freshwater increase in 2012. As shown in Fig. 2, the summer discharge was much smaller in 2012 than in 2003 and 2010, but the freshwater in the YS reached a maximum in 2012. It is considered that the summer

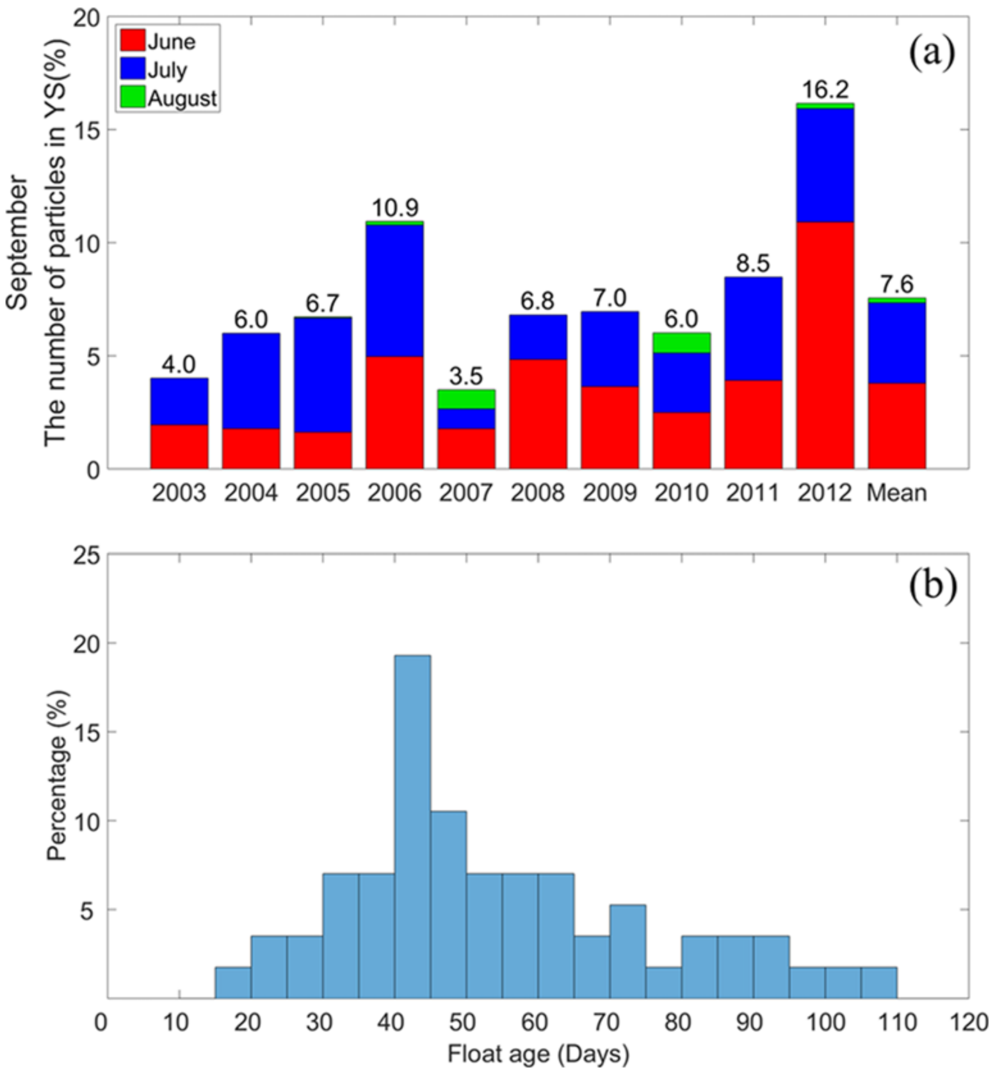

Fig. 6. (a) Maximum rates of the particles released during June (red), July (blue), and August (green) in the YS from 2003 to 2012. (b) Histogram of the particle age, defined as the average time since release of the particles, in the YS in 2012

discharge has little influence on the freshwater transported into the YS although the discharge contributes to the amount of freshwater in the form of a linear relationship. As will be discussed later, wind pattern in each year is an important factor to determine the freshwater volume in the YS, which is consistent with previous studies (Moon et al. 2009, 2012).

The changes in freshwater volume in the YS are also evident in Fig. 6a that shows that particles entered the YS at maximum rates during the last 10 years, with the contributions of each starting month for the particles. Approximately 16% of particles over the year entered into the YS in 2012, which is two times greater than that of the 10-year mean (7.6%). On average, the particles entering the YS were mainly released during June–July, with negligible contribution from the particles released in August. With regard to 2012, approximately 10% of the particles came from the particles released in June, which is 2.5 times the mean. Based on the particle age defined as the average time since release of the particles (Fig. 6b), most of the particles took less than 50 days to travel from the Changjiang mouth to the YS interior, but some particles moved quickly within 30 days. Fig. 7 compares the mean salinity of the particles entering in the YS with the area-averaged surface salinity in the YS. As expected, the time when the particles are entering the YS interior corresponds to the time when the mean surface salinity in the YS decreases. This result indicates that the abnormal low-salinity water in the YS in 2012 was attributed to the intrusion of the CDW into the YS during June-July.

5. Movement of the Particles toward the YS in 2012

Spatial distribution of the particles

Because many particles drifted into the YS interior from mid- to late June and from late July to early August 2012, spatial patterns of the particles during those periods were compared to examine how the CDW flowed into the YS interior (Fig. 8). On June 18, 2012 many particles were located around the Changjiang mouth, and then some particles traveled north and entered the central entrance of the YS after mid-June (Fig. 8a–c). The trajectories of the particles released during June are shown in Fig. 9a. The particles were plotted from June 24 to June 30, and closed circles indicate the particle locations on June 30. During this period, many particles were tracked toward the YS interior after passing through the central entrance of the YS, indicating that the particles quickly drifted into the YS by some forcing. One of the most critical factors pushing the particles into the YS may be wind-induced surface currents (e.g., Bang and Lie 1999; Moon et al. 2009a). Fig. 10a shows the stick diagram of daily mean wind from June 15 to June 30, 2012 averaged spatially from 122°E to 126°E, and from 31°N to 34.5°N. During this period, the winds changed to southeasterly or northeasterly with time, which means the easterly winds prevailed after mid-June. The strong easterly wind was a unique pattern rarely found in other years as shown in Fig. 10b, which compares the mean wind patterns at the same period from 2003 to 2012. The easterly wind drove the particles released during June to the

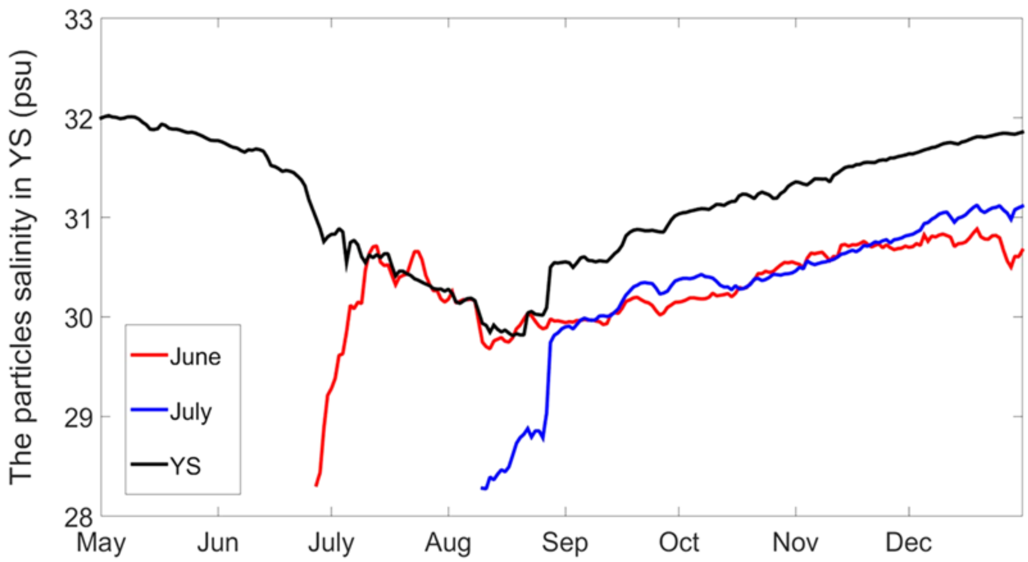

Fig. 7. Comparison of mean salinity of the particles entered into the YS with area-averaged surface salinity of the YS (black line) in 2012. Red and blue lines indicate the mean salinity of particles launched in June and July, respectively

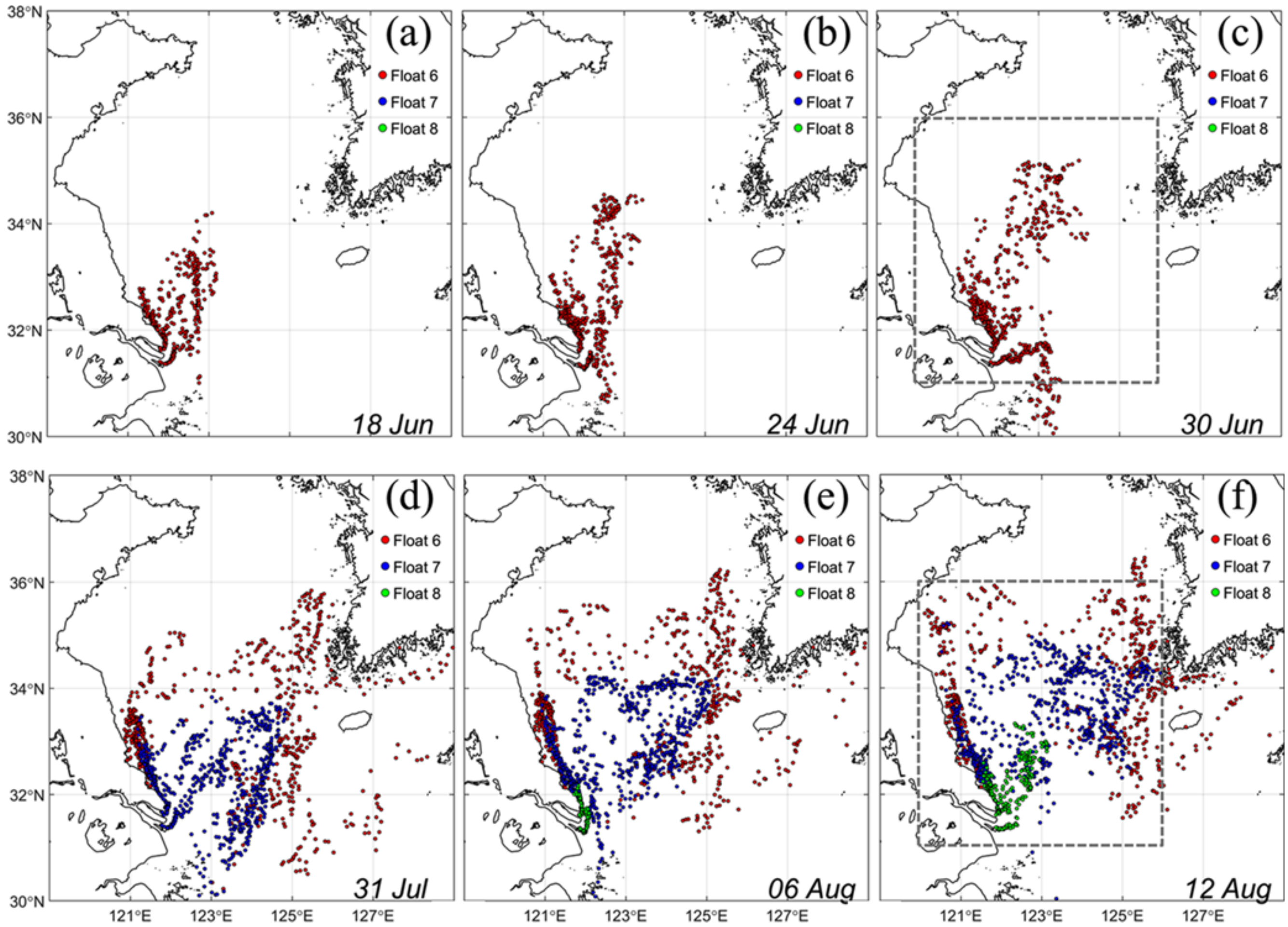

Fig. 8. Spatial distributions of accumulated particles during mid- to late June (upper panels) and late July to early August (lower panels) in 2012. The particles were launched in June (red), July (blue), and August (green) from the Changjiang River mouth

central YS interior, and therefore the amount of freshwater in the YS increased largely (see Fig. 5b) as a consequence of Ekman transport toward the YS.

On July 31, 2012 most of the particles released during June appeared off the southwest of Korea and along the Jiangsu coast, while those released during July were widely distributed between the Changjiang mouth and west of Jeju Island (Fig. 8d). The particles were quickly moved toward the YS interior after early August (Fig. 8e, f). The particles released during July moved either northward toward the central YS and/or north-northeastward toward the southwest coasts of Korea. On the other hand, some of particles released during June moved northwestward north of 35.5°N along the Jiangsu coast (Fig. 9b). From late July to mid-August, the wind vector changed abruptly to southeasterly or northeasterly (Fig. 10c), which means strong easterly winds were predominant in early August when the particles quickly drifted into the YS. The strong easterly wind is closely associated with three consecutive typhoons in 2012. As shown in Fig. 11, Typhoons Damrey, Saola, and Haikui passed through the YECS from late July to early August and caused a dominant easterly wind pattern over the YS, with an average speed of ~8 m/s. The strong easterly wind produced by the typhoons induced the northward flow toward the central YS and northwestward flow along the Jiangsu coast, carrying a number of particles into the YS interior. This is fairly consistent with the result of Oh et al. (2014) who focused on the role of typhoon-induced winds in driving the low-salinity water toward the YS.

Two types of pathway

In order to identify the freshwater pathways toward the YS interior, mean distributions of the particles during 2003–

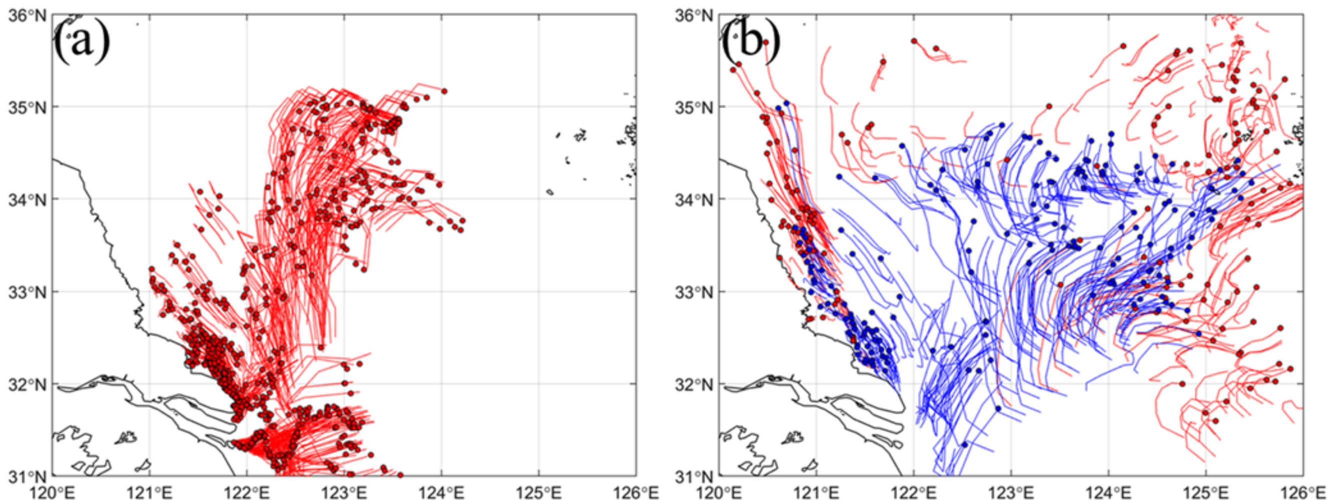

Fig. 9. Trajectories of the particles (a) from June 24 to June 30 and (b) from August 4 to August 10, 2012. The paths of particles launched in June and July are shown by red and blue color, and circle symbols indicate the particle locations on June 30 and August 10, respectively

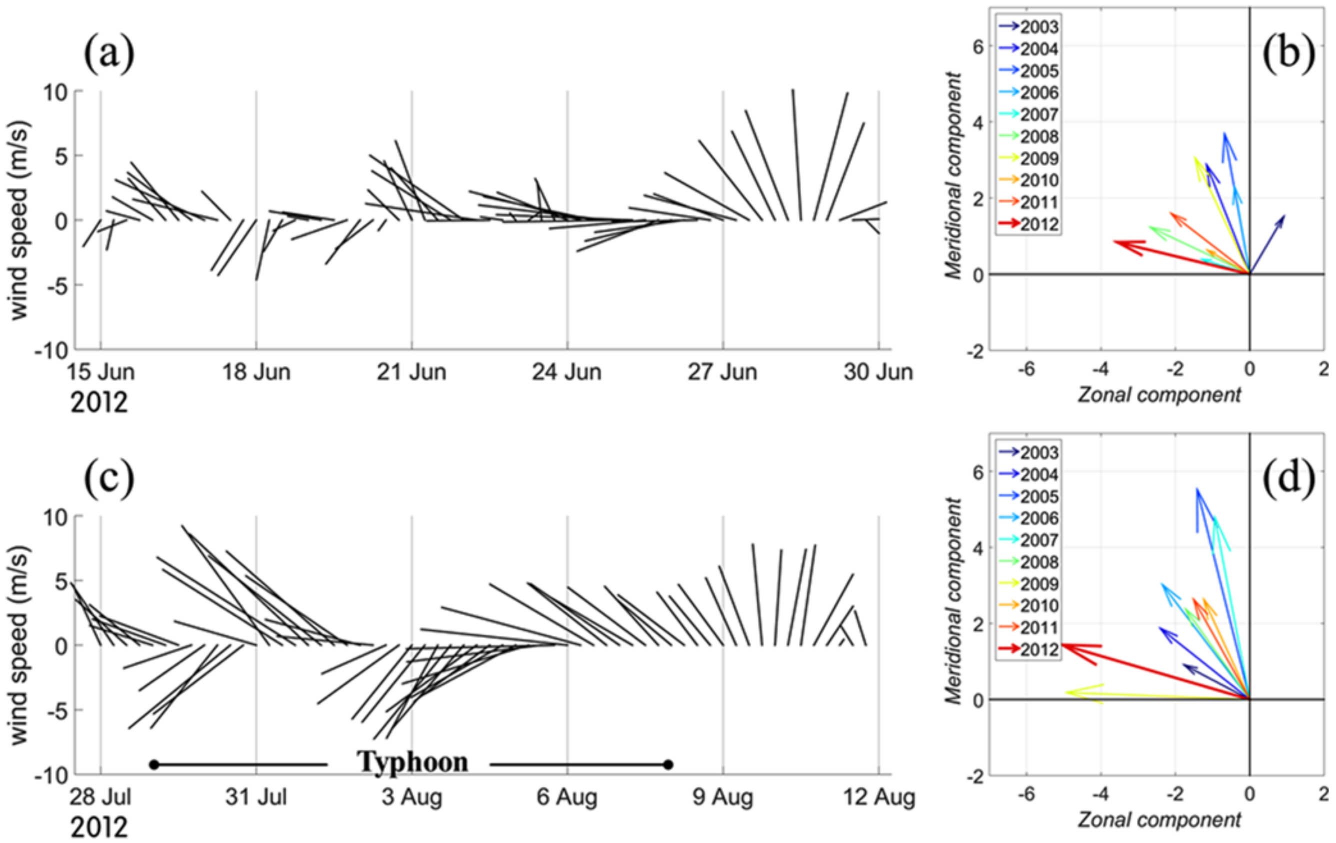

Fig. 10. Stick diagrams of daily mean wind (a) during mid- to late June in 2012 and (b) their mean vector over the 10 years. (c) and (d) are the same as (a) and (b) except during July 28 to August 12 in 2012. The winds were spatially averaged from 122° to 126°E, and from 31° to 34.5°N

2012 are compared with those in 2012 (Fig. 12). All the particles released during June-August were counted within the grid by 0.5° × 0.5° to easily visualize the spatial patterns. Based on the 10-year mean spatial patterns (Fig. 12a–c), the particles

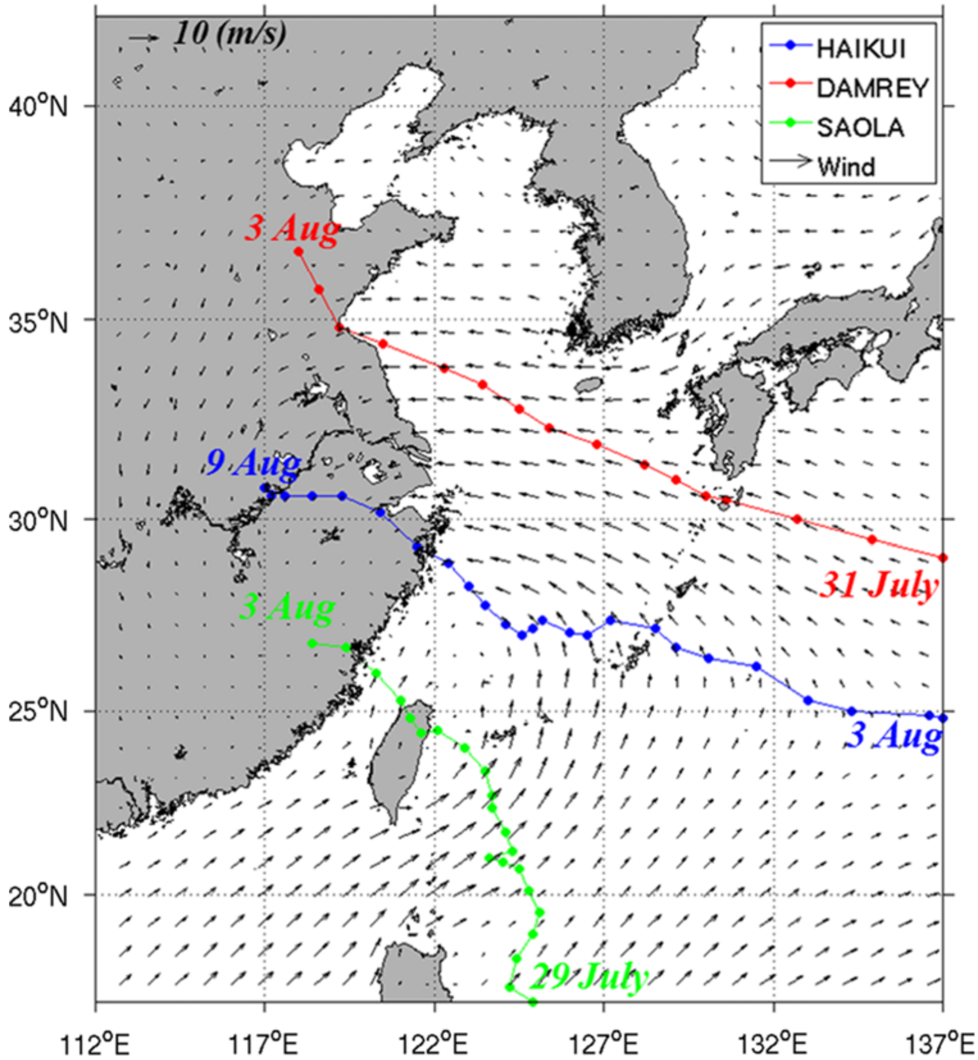

Fig. 11. The tracks of three consecutive typhoons in early August 2012. The wind fields are averaged from 29 July to 9 August. The track Data was from the National Typhoon Center

released in the CR were mainly distributed around the river mouth in late June, and then some particles spread widely to Jeju Island from July to early August. The northeastward pathway of the freshwater discharged from the CR has been identified in numerous previous studies (e.g., Chang and Isobe 2003, Moon et al. 2009a). During this period, a substantial portion of the particles were confined to a narrow band along the Jiangsu coast, while only a small portion entered the YS interior, showing widely dispersed distribution. The distributions of the particles along the Jiangsu coast are closely associated with an anticyclonic regional-scale tidal residual circulation around the Changjiang Bank, which has been noted by Wu et al. (2014) and Xuan et al. (2015). The tidal residual circulation that has a permanent nature starts from the Changjing mouth, flowing northwestward along the Jiangsu coast, and then turning eastward at approximately 34°N and finally flowing southeastward along the northeastern edge of the Changjiang Bank. As a result, most of the particles released in the Changjiang mouth were trapped within the anticyclonic tidal residual circulation that does not allow the particles to extend farther northward along the coast up to the Shandong Peninsula.

By contrast, in 2012 the particle distributions showed a different spatial pattern to those discussed above (Fig. 12d–f). The particles released in June stayed mostly around the CR mouth and some portions moved to the central entrance of the YS in late June. The particles around the river mouth slowly moved northwestward along the Jiangsu coast, while the particles moving northward to the central YS drifted

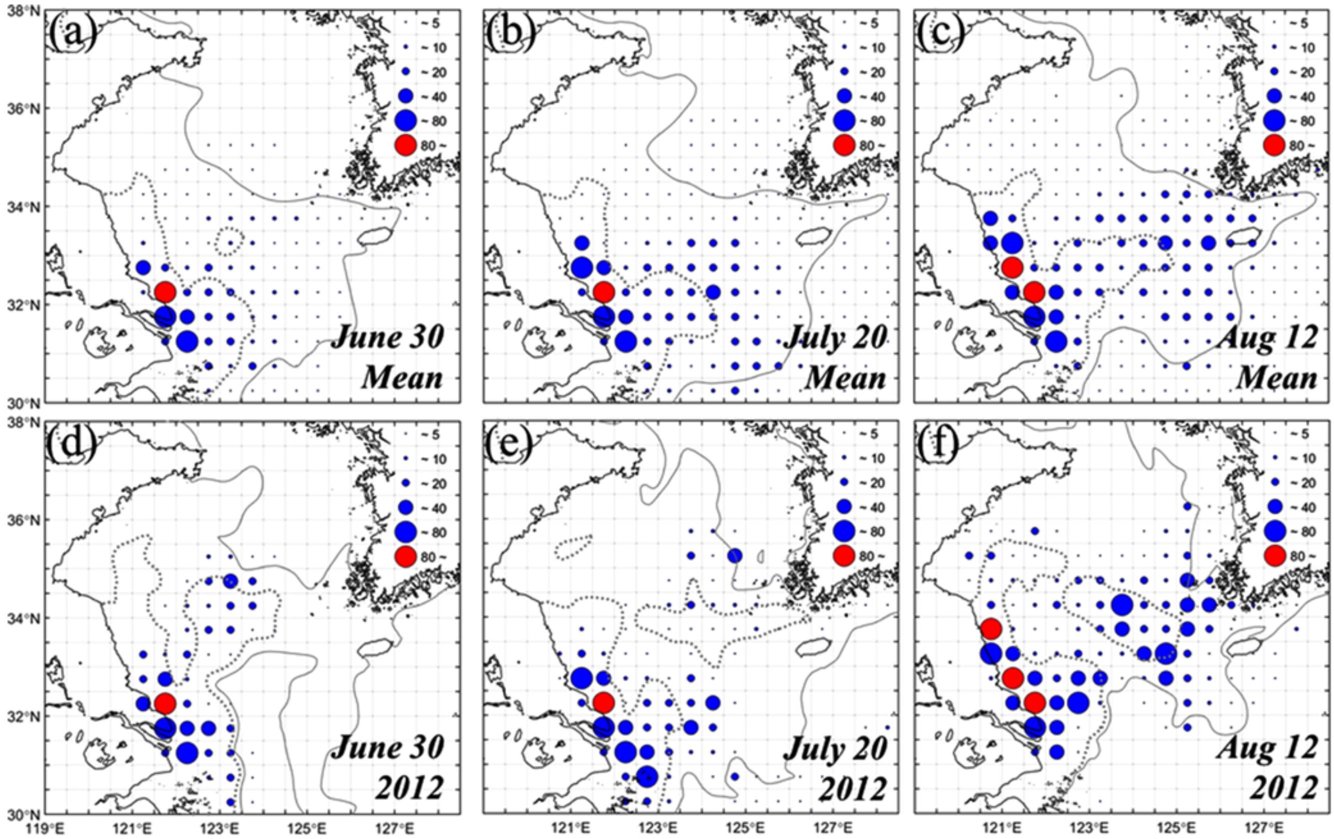

Fig. 12. Distributions of the particles for 10-year mean (upper panels) and 2012 (lower panels) on June, July, and August. The particles are counted daily from the release within the grid by 0.5° × 0.5°. The abundance of the particles is depicted in the upper-right corner of each panel. Solid and dashed lines indicate the surface 31-psu and 28-psu isohalines, respectively

farther to the southwest coast of Korea in mid-July. Meanwhile, the particles released in July were mainly accumulated along the Jiangsu coast and some particles spread offshore to the northeast of the Changjiang Bank. Thereafter, the particles follow two main paths toward the YS interior (Fig. 12f). One involved particles moving northward to the central entrance of the YS and reaching the western coast of Korea. As aforementioned, this pathway is attributed to the strong easterly winds produced by three consecutive typhoons, which passed through the YECS in early August 2012. The other pathway involved particles spreading northwestward along the tidal residual circulations, forming a narrow band along the Jiangsu coast. As discussed above, many particles were trapped into a coastal band owing to the anticyclonic tidal residual circulations that flow along the Jiangsu coast and turn clockwise at 34°N. It can be considered that the freshwater discharged from the CR hardly extends farther to the north into the YS. However, of particular interest is that in 2012 some particles that were trapped within the anticyclonic tidal residual circulations quickly drifted to the north up to the Shandong Peninsula. This is attributed to the typhoon-induced winds in early August that strongly pushed the particles to the north up to the Shandong Peninsula against the anticyclonic tidal residual circulations along the Jiangsu coast. This result suggests that when wind is strong enough to overcome the tide-induced circulations, the CDW which was trapped along the coast will be farther transported to the north, resulting in an increasing freshwater input into the YS interior. The role of typhoon-induced winds in the two paths toward the YS is also evident in Fig. 13, which shows a longitude-time diagram for temporal variation of surface velocity averaged over 33.5°N–34.5°N. The magnitude and direction of surface velocity varied rapidly with time, strongly influenced by the wind patterns. In particular, the current direction changed abruptly to the north at east of 122°E and to the northwest along the Jiangsu coast when the typhoons passed through the YECS in early August. The typhoon-driven surface currents brought the Changjiang freshwater into the YS interior.

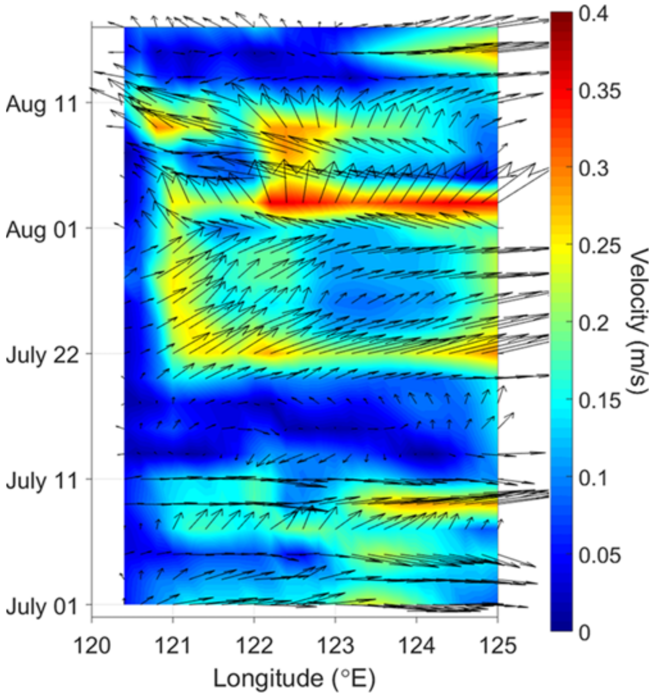

Fig. 13. Longitude-time diagram for temporal variation of surface velocity averaged over 33.5°N–34.5°N in 2012. Color bar indicates the magnitude of surface current

6. Summary

Long-term observations and previous studies have shown that in summer the CDW usually spreads east/northeastward over the northern ECS shelf region and toward Jeju Island. During flooding periods, the surface salinity in the northern shelf of the ECS between the Changjiang estuary and Jeju Island is roughly less than 30 psu, while relatively saline water more than 31 psu is distributed in the YS interior. However, in 2012 abnormally low-salinity water less than 30 psu appeared in the central YS interior that had never been detected before. This study evaluated the amount of the CDW flowing into the YS interior and investigated the pathways, using long-term (1993–2012) model simulation with a particle-tracking experiment. We first reproduced the CDW over the period of 2003–2012 and then verified the model results with the KODC observations. The simulated low-salinity water pattern in the YECS generally coincided with the observational salinity distribution, particularly showing a large low-salinity structure in the central YS in 2012. We then compared the long-term mean with the year of 2012. According to the results of the particle-tracking experiment, from 2003 to 2011 the particles released in the CR gradually drifted into the central entrance of the YS from late June to September and a small portion (7.6%) of the particles reached the YS interior in September. Unlike the normal years, however, a large portion of the particles (approximately 16% of all the particles in 2012), which is two times the amount in normal years, rapidly flowed into the YS interior in late June and early August in 2012. In this same time period –late June and early August–, the variations of freshwater volume in the YS were quite similar to those of particles, indicating that the spatial and temporal patterns of the CDW fairly corresponded to the movements of particles driven by wind forcing in June and August 2012. In late June, the easterly wind prevailed over the northern ECS shelf region, which was a unique pattern rarely found in other years. The easterly wind drove the particles to the central YS interior, and therefore the amount of freshwater in the YS largely increased as a consequence of Ekman transport. In addition, three consecutive typhoons passed through the YS causing strong easterly winds in early August that resulted in a substantial intrusion of the CDW into the YS, revealing two dominant pathways. One involved the CDW moving northward to the central entrance of the YS and reaching the western coast of Korea. The other involved the CDW drifting to the northwest up to the Shandong Peninsula against the anticyclonic tidal residual circulation along the Jiangsu coast. Recently, some studies have found that harmful algal blooming such as green tide occasionally occur around the Shandong Peninsula and their origin is believed to come from the Jiangsu coast (Liu et al. 2009; Lee et al. 2011). Our result suggests that when wind is strong enough to overcome the tide-induced circulations, the CDW which was trapped along the Jiangsu coast can be farther transported to the north, resulting in an increasing freshwater and blooming of harmful algal in the YS.

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