Dynamical Response of Changjiang River Plume to a Severe Typhoon With the Surface Wave-Induced Mixing

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Abstract

Typhoons (or hurricanes) are the most energetic atmospheric forcing acting on coastal waters. Here in this study, we investigated the response of the summertime Changjiang River plume to a typical typhoon, Chan-hom (1509), with a combination of field observation and numerical simulation. Surface wave-induced mixing was considered in the model configuration. The results showed that the typical offshore-extending summer Changjiang River plume completely disappeared under the influence of typhoon wind. Instead, it extended southward along the Zhejiang and Fujian (Zhe-Min) coast as a typical wintertime Changjiang River plume. The along-shelf plume extension lasted for extra ~10 days after the typhoon passage, until another strong weather event came. The competition between wind-driven current and buoyancy-driven current dominated the recovery of the Changjiang River plume. Through calculation, we found that the freshwater transported to the Zhe-Min Coastal Water reached ~4.7 × 10^10 m^3 as influenced by typhoon Chan-hom, which was ~5% of the total Changjiang River discharge in 2015 or ~12% of the total dry season Changjiang River discharge (October-April) when the majority of Changjiang River plume extended to Zhe-Min Coastal Water. The remote sensing data of chlorophyll-a from Geostationary Ocean Color Imager also showed that significant algal bloom occurred when the southward extending Changjiang River plume retreated. Surface wave-induced mixing caused by typhoon wind was found to be important in destroying the vertical plume stratification and elongating the recovery processes from the typhoon influence.

Plain Language Summary

Large rivers discharge a great amount of freshwater and riverine materials to the receiving waterbody, causing significant ecological effects such as algal blooms and hypoxia. The associated river plume is highly mobile and can be easily disturbed by external forcings. Here in this study, we used the numerical simulation to examine the effect of one of the strongest atmospheric forcings, that is, the typhoon, on the horizontal and vertical structures of the Changjiang River plume. Strong wind-induced intensive surface wave and its effect on vertical mixing were also investigated. The results showed that the typical typhoon Chan-hom can dramatically shift the Changjiang River plume from the summer pattern to the winter pattern. It cannot recover to its initial state until after 2 weeks. Wave mixing made the recovery time even longer. Massive freshwater was transported by the typhoon to the south of the Changjiang River mouth, which rarely happens in summer season. The resultant buoyant coastal current can self-sustained until another strong weather event came. We also found that the abnormal typhoon-induced transport of the Changjiang River plume by typhoon can cause massive algal blooms in the offshore Zhejiang coastal water, which rarely happens under normal weather.

1. Introduction

Coastal waters are co-influenced by river outflow, shelf circulation, tides, and wind stress. The associated river plume forms a nutrient rich, primary production active, and spatiotemporally varied environment. Among these forcings, tropical cyclones (i.e., typhoons or hurricanes) are the most energetic ones acting on some coastal oceans. Although lasting only for a short period, their strong winds substantially change the vertical structures of temperature and salinity (M. Li et al., 2006; Y. Li et al., 2012; Price, 1981; Yue et al., 2018), as well as the horizontal circulations (Chen et al., 2003; Morimoto et al., 2009). Consequently, they affect the biogeochemical processes in coastal waters. For instance, under the typhoon Morakot (0908), the terrigenous materials could be transported to the region northeast of Taiwan, even far-reaching to the southern Okinawa Trough (He et al., 2014). The typhoon-induced episodic transports of terrigenous materials often led to primary production alterations, which were found in the Gulf of Mexico (Conner et al., 1989), Pamlico...
Sound (Paerl et al., 2001), Sargasso Sea (Babin et al., 2004), South China Sea (Lin et al., 2003), Pearl River Estuary (Zhao et al., 2009), and Changjiang River Estuary (Wang et al., 2015). Moreover, dissolved oxygen concentrations in the bottom water are also modulated after the typhoon passage, for instance in the Charlotte Harbor (Tomasko et al., 2006) and the Changjiang River Estuary (Ni et al., 2016).

China coastal water is one of the most threatened areas by tropical cyclones (L. Wu et al., 2005). In past decades, there were nine typhoons hitting the China coastal water annually (http://www.typhoon.org.cn/), about one third entered the coastal East China Sea in summer season (Figure 1a). The coastal East China Sea is covered by the extensive Changjiang River plume. Normally, the Changjiang River plume extends offshore toward the Jeju Island in summer under the upwelling-favorable southerly summer monsoon, unlike the wintertime plume that extends southward under the downwelling-favorable northerly winter monsoon (Beardsley et al., 1985; Mao et al., 1963; H. Wu et al., 2014; see Figure 1a). The summer Changjiang River plume caps the waters offshore of the river mouth, stimulates the primary production, and shuts down the vertical dissolved oxygen mixing, thereby causes the bottom water hypoxia (D. Li et al., 2002; Zhu et al., 2011).

Usually, the summer wind adjacent to the Changjiang River Estuary is mild with magnitude lower than 5 m s\(^{-1}\) (Xu et al., 2006). However, when the typhoon comes, the wind speed often exceeds 20 m s\(^{-1}\) (Ding, 1994). The typhoon wind intensifies the vertical mixing (Wang et al., 2015), which could destroy the stratification and relax the bottom water hypoxia. This effect was observed by Ni et al. (2016) via a seabed mooring system during the typhoon Morakot (0908). On the other hand, the strong typhoon wind also had a profound influence on nutrient and biological variations (Wang et al., 2015).

These previous studies have revealed the important role typhoon played in regulating the Changjiang River plume structure and the associated biogeochemical processes. However, the detailed physical response mechanisms remain unclear. For the vertical mixing, the typhoon affects the vertical mixing not only via its strong wind stress but also through the strong surface wave-induced mixing. The peak significant wave height during a typhoon exceeds 5 m (Doong et al., 2015), which should induce significant vertical wave mixing (Qiao et al., 2004). However, this effect on the Changjiang River plume was not investigated in past

Figure 1. (a) The map of Changjiang River Estuary and adjacent seas. Dots represent the 6-hourly track of typhoon Chan-hom and the associated times and categories. Gray lines are the typhoon tracks passing over the East China Sea from 1949 to 2016. The thick blue and red lines are the climatological 31-practical salinity unit contours in July and February, respectively. Two square dots represent the two sites (i.e., sites A and B) selected for analysis. (b) Dots are National Natural Science Foundation of China cruise sites in July 2015. Red dots represent the surveyed sites near the river mouth; blue dots represent the offshore sites. Triangles are the two hydrologic stations for wind wave.
studies. In addition, the varied typhoon wind directions could also change the spreading direction of the Changjiang River plume. Lee et al. (2017) found that the typical extension of Changjiang River plume toward the Jeju Island disappeared under the typhoon Ewiniar (0603) and Dianmu (1004), but where the “lost” plume waters were going was unclear. Another unknown is the recovery mechanism and time scales of the horizontal and vertical structures of the plume after being hit by a typhoon.

Direct field observations during and immediately after the typhoon were rare due to dangerous sea conditions. Here in this study, field data around the river mouth were collected after a typical typhoon Chan-hom (1509) in July 2015. We also used a numerical model to study the detailed response of the Changjiang River plume to Chan-hom and its recovery mechanisms. Details of the numerical model, experiment settings, and field data are given in section 2. In section 3, model validations and the Changjiang River plume responses to typhoon Chan-hom are described in details. In section 4, we discuss the breakdown and recovery mechanisms of the Changjiang River plume as well as the associated ecological effects. Finally, the conclusion is drawn in section 5.

2. Data and Methods

2.1. Numerical Model

The numerical model used here included a circulation model component, the East China Normal University version of ECOM-si (Blumberg, 1994; H. Wu & Zhu, 2010), and a wave model component, the SWAN (Booij et al., 1999). In the East China Normal University ECOM-si, the tracer advection is calculated with a third-order, oscillation free advection scheme HSIMT (H. Wu & Zhu, 2010). The circulation model simulates the extension of Changjiang River plume under the combined effects of wind, tide, and shelf circulations. The wave model simulated the wind wave parameters, which were used to calculate the wave-induced mixing for the circulation model.

The circulation model domain covered the entire Yellow Sea, East China Sea, and Bohai Sea and parts of the Pacific Ocean and the Japan Sea (see H. Wu et al., 2011). The grid mesh was refined to 367 × 319 cell indices in the horizontal. The open boundary was roughly parallel to the Ryukyu Islands. The model horizontal resolution was several hundred meters inside the river mouth, 2–3 km outside the river mouth, ~3 km in the coastal area of Zhejiang and Fujian, and ~10 km in the Kuroshio region. In vertical, the model had 20 nonuniform sigma layers that were refined near the surface. The open boundary of the circulation model was driven by the momentum flux containing the shelf currents and the tide currents (H. Wu et al., 2011). The boundary and initial conditions for the temperature and salinity were from the Simple Ocean Data Assimilation data set, whose resolution was 0.5° × 0.5°. Sea surface momentum and heat flux were calculated with the 6-hourly data from the European Center for Medium-Range Weather Forecasts (ECMWF) with a bulk formula (Ahsan & Blumberg, 1999), which includes wind, air temperature, air pressure, cloud, and dewpoint temperature data with spatial resolutions of 0.125° × 0.125°. The hourly Changjiang River discharge was measured by the Changjiang Water Resource Commission at the Datong Station. For the wind stress, we used an improved formula suggested by Hwang (2018), which has a better description on the surface wave-induced roughness under various wind speed.

SWAN is the third-generation numerical wave model, which features high stability, adaptability, and precision. The SWAN model domain included the entire Yellow Sea, East China Sea, and the Bohai Sea boxed by 117°E, 134°E and 21°N, 42°N, with a 3° × 3° resolution. The 6-hourly wind data from ECMWF with resolution of 0.125° × 0.125° were used to force the wave model. The modeled frequency spectrum was output to calculate the surface nonbreaking wave-induced mixing. The surface nonbreaking wave can transfer the turbulence kinetic energy (TKE) into the ocean by wave-turbulence interaction. The vertical viscosity or diffusivity \( B_v \) induced by surface nonbreaking wave was calculated by the Qiao formula (Qiao et al., 2004).

\[
B_v = \alpha \oint \frac{E(k)}{k} \exp(2kz) \left\{ \frac{\partial}{\partial z} \left[ \oint \frac{\omega^2 E(k)}{k} \exp(2kz) \right] \right\}^{1/2},
\]

where \( \alpha \) is a nondimensional coefficient (here \( \alpha = 1 \)), \( k \) is wave number, \( z \) is the vertical coordinate (upward positive) with \( z = 0 \) at the surface, \( \omega \) is the wave angular frequency, and \( E(k) \) is the wave number spectrum.
Since SWAN outputs the frequency spectrum instead of wavenumber spectrum, the above formulation was rewritten with frequency spectrum:

\[
Bv = \alpha \int \int S(\omega, \theta) \exp(2kz) d\omega d\theta \frac{\partial}{\partial z} \left[ \int \omega^2 S(\omega, \theta) \exp(2kz) d\omega d\theta \right]^{1/2}.
\]  

(2)

Here \( S(\omega, \theta) \) is the wave frequency spectrum. The wave-turbulence interaction was incorporated into the Mellor-Yamada scheme as an additional TKE production. Then the total turbulent mixing in the circulation model is given as

\[
K_m = K_{mc} + Bv, \quad K_h = K_{hc} + Bv,
\]

(3)

where \( K_m \) and \( K_h \) are the vertical viscosity and diffusivity used in the model, \( K_{mc} \) and \( K_{hc} \) represent the turbulent mixing derived from the Mellor-Yamada scheme (Mellor & Yamada, 1982).

Qiao et al. (2004) did not consider the breaking wave mixing. However, as pointed out by Huang and Qiao (2010) and Huang et al. (2011), the nonbreaking wave mixing has a more important contribution than does the breaking wave, because the later only affects a thin surface layer shallower than the plume thickness. On the contrary, the nonbreaking wave mixing can penetrate downward much deeper. There are some other wave effects such as the wave-induced bottom friction and the wave-current interaction (Akan et al., 2017; Rong et al., 2014), which were not considered in this study.

### 2.2. Numerical Experiment Settings

Three numerical experiments were set in this study. In Exp1, the model was forced with realistic forcings, including the surface wave-induced mixing, that is, \( Bv \). In Exp2, the surface wave-induced mixing \( (Bv) \) was removed from Exp1. Both Exp1 and Exp2 were forced with the wind field during typhoon Chan-hom. In Exp3, the wind field during Chan-hom (1–12 July 2015) was replaced with the climatological daily winds in July; all other settings were the same as Exp2. The climatological winds are composed of the averaged wind on each calendar day in the past 20 years. The experiments were started from 1 January 2014, and the first year was run as spin-up.

### 2.3. Hydrological and Typhoon Data

The salinity and temperature data used in this study were obtained from the National Natural Science Foundation of China Sharing Cruise from 9 to 20 July 2015 (see Figure 1b for the survey area and time). The survey measured the sites inside and near the Changjiang River mouth on 9 July and then was paused as influenced by the Chan-hom. It was recovered on 13 July after the passage of Chan-hom. Hence, the observed data mainly represent the river plume after the Chan-hom. These data are uploaded as supporting data set S1.

The typhoon track data were obtained from the China Meteorological Administration Tropical Cyclone Data Center (http://tdata.typhoon.org.cn). The data consist of identifiers and names of typhoon, longitude and latitude positions, wind speed, and typhoon categories with a 6-hr interval from 1949 to 2016. The satellite-derived chlorophyll-\( \alpha \) data were obtained from the Geostationary Ocean Color Imager (GOCI; http://kosc.kiost.ac.kr/eng/). Most GOCI images were covered by thick cloud in July 2015. Useful images were available only on 19, 25, and 31 July after Chan-hom passage.

### 3. Results

#### 3.1. Observed Plume Distribution After the Chan-Hom Passage

The typhoon Chan-hom was formed in the western Pacific on 30 June 2015, and then it moved westward steadily. Later on 10 July, Chan-hom was categorized as a Super Typhoon (\( >51.0 \text{ ms}^{-1} \)), passing the gap between Okinawa and Miyako-jima Islands, and reached its peak with an estimated wind speed of \( 58 \text{ ms}^{-1} \) and a barometric pressure of 925 mbar. After then, Chan-hom was slightly weakened and moved northwesward to landfall on Zhoushan Island on 11 July as a severe Typhoon (\( 41.5–50.9 \text{ ms}^{-1} \)). Next, Chan-hom accelerated to northeast and quickly degraded its intensity. Finally, it was dissipated over the
Korean Peninsula on 13 July. Hence, typhoon Chan-hom directly passed the majority of the Changjiang River plume. Normally, the Changjiang River plume extends offshore to the northeast in summer season under the south-eary monsoon (Figure 1a). However, the plume characteristic observed in July 2015 was distinct. After the passage of typhoon Chan-hom, the majority of Changjiang River plume was con-fi ned shoreward of 123.5°E (Figures 2a–2d, indicates by the 31-practical salinity unit [psu] isohaline), seemingly extending southward along the coast as a typical wintertime Changjiang River plume. However, the observation only covered limited domain outside the Changjiang River mouth. The detailed characteristics of the Changjiang River plume and the associated response mechanisms to typhoon Chan-hom need to be investigated by numerical model simulations.

Figure 2. Observed salinity on 3 (a), 5 (b), 10 (c), and 20 m (d) layers and the modeled results with wave-induced wave mixing (Exp1, e–h) and without wave-induced mixing (Exp2, i–l). psu = practical salinity unit.
3.2. Model Validations

a Wave validation

The capacity of SWAN model with the configuration of the same grid has been validated in a previous study (Luo et al., 2017). Here in this study, we further validated it with the wave data measured during typhoon Chan-hom at Niupijiao (NPJ) and Nancaodong (NCD) hydrologic stations (for locations, see Figure 1b) around the Changjiang River mouth. As shown in Figure 3, the significant wave height at NPJ and NCD stations both reached 3 m during the Chan-hom passage. The root-mean-squared error (RMSE) and correlation coefficient (CC) of the simulated results were calculated. In NPJ station, RMSE = 0.399 m and CC = 0.793. In NCD station, RMSE = 0.223 m and CC = 0.907. During the typhoon passage, the modeled peak significant wave height was lower than the observed data. The reason could be that the 6-hourly ECMWF wind could not precisely capture the maximum typhoon wind. Another cause is the SWAN model resolution (~5 km) was not high enough to fully characterize the complicated topography around the survey site, which was close to the channels and sand shoals of the Changjiang River Estuary. Nevertheless, modeled significant wave height fairly matched the observed data.

b Salinity validation

The circulation model used in this study has been extensively validated with in situ salinity, temperature, current, and elevation data, showing reasonable performances (H. Wu, 2015; H. Wu et al., 2011, 2014). However, the previous validations did not look at the plume distribution as influenced by a typhoon, and the wave-induced mixing was not considered. Here we validated the salinity data obtained after the passage of typhoon Chan-hom (i.e., Figures 2a–2d). The RMSE, CC, and skill score (SS; Murphy, 1988) of the simulated results were calculated to quantify the model performance (Table 1). The SS was categorized as >0.65, excellent; 0.5–0.65, very good; 0.2–0.5, good; and <0.2, poor.

Both simulations with (Exp1) and without (Exp2) surface wave-induced mixing captured the abnormal alongshore extension of the Changjiang River plume after the passage of typhoon Chan-hom (Figure 2). The overall RMSE and CC showed a reasonable model.
performance for both Exp1 and Exp2 (Table 1, all sites). Model with surface wave-induced mixing gave smaller RMSE, higher CC, and higher SS only on 3-m layer. However, we noticed that the red dots in the Figure 1b had a great contribution to the poor statistics for Exp1. The surface wave mixing did not improve the model performance in area near the river mouth. It is well-known that the Mellor-Yamada scheme overestimates the vertical mixing when the actual physical mixing is already strong (Burchard & Bolding, 2001; Warner et al., 2005). Hence, it is unclear whether or not the additional wave-induced mixing gave excess mixing in the model. However, when we only compared the results away from the river mouth (blue dots in Figure 1b), which were the focus of this study, it was found that the model performance was notably improved with wave mixing included (Table 1, offshore sites). The overall SS of Exp1 entered the excellent category (0.77), better than that from Exp2 (0.68). The SS on each layer were also improved especially in the upper 10-m layers. The CCs and RMSEs were improved notably as well. Therefore, although including the wave-induced mixing did not improve the model performance around the river mouth, it improved the simulation of plume extension outside the river mouth. The wave-induced mixing should be more important when the wind was strong and a pre-wind pycnocline existed. However, we did not have the data at that time due to the bad sea condition.

The modeled river plume was further compared with the GOCI images of chlorophyll-α in section 4.2. Remote-sensed chlorophyll-α is a recognized proxy that indexes the distributions of many river plumes including the Changjiang River plume (Kim et al., 2009). It will be shown that the pattern of the modeled river plume offshore of the turbid nearshore water was similar to the GOCI image.

3.3. Response of Changjiang River Plume to Typhoon Chan-Hom

3.3.1. Horizontal Characteristics

a Horizontal plume pattern

Horizontal distributions of the Changjiang River plume before, during, and after the arrival of typhoon Chan-hom from three experiments were shown in Figure 4. Before the arrival of Chan-hom (on 1 July), the Changjiang River plume behaved as a typical summertime pattern, with its majority extending offshore toward the Jeju Island under the southerly winds. Meanwhile, portions of the Changjiang River plume also extended northward to 34°N along the Jiangsu Coast and southward to ~28.5°N along the Zhe-Min Coast, as was previously discussed in H. Wu et al. (2014).

However, such a typical summertime plume completely changed after the arrival of typhoon Chan-hom on 12 July (Figures 4b and 4e). When typhoon center located some distance southeast of the Changjiang River mouth, such a northeasterly or easterly wind in the plume area pushed the Changjiang River plume toward the coast and forced it to propagate southward along the coast to 27°N, similar to the wintertime plume pattern. A sharp cross-shelf front was therefore formed. Comparing with the nontyphoon case (Figure 4h), in both simulations with and without wave mixing, the salinity offshore of the river mouth was greatly increased and the plume extension toward the Jeju Island was greatly weakened, as found by Lee et al. (2017). On the contrary, the plume in the Jiangsu coastal water was less affected. Previous studies suggest that the plume extension in this area is highly controlled by tidal mixing and tidal residual current, which could be insensitive to the wind forcing (H. Wu et al., 2014, 2018).

The Changjiang River plume recovered gradually from the typhoon influence after the Chan-hom passed the Changjiang River Estuary (28 July, Figures 4c and 4f). The plume water previously extended to the Zhejiang Coast retreated, but its retreating pathway was offshore first and then northward, similar to the typical plume response to an upwelling-favorable wind (Fong & Geyer, 2001). Such a process brought plume water to the offshore area of Zhe-Min Coastal Water, where summertime Changjiang River plume rarely reached. The simulations with (Exp1) and without (Exp2) wave mixing showed detectable difference (Figures 4c and 4f). Without wave mixing, the recovery of river plume from the typhoon influence was much faster. More detailed analyses will be discussed later.

b Temporal evolution

Another thing should be highlighted was that the Changjiang River plume did not fully recovered from the typhoon influence even 2 weeks after its passage. Low-salinity water still existed near the Zhe-Min Coast and reached 28°N. It suggested that the Changjiang River plume responded rapidly to the typhoon but recovered slowly afterward. To better understand the evolution of Changjiang River plume as influenced by typhoon
Chan-hom, we output the model results at two representative sites (sites A and B in Figure 1, representing the Changjiang River Estuary and Zhe-Min Coastal Water, respectively.). Site A located outside the Changjiang River mouth, which was in the core area of the Changjiang River plume. The time series of the wind speed and wind vector at site A indicates that strong typhoon winds reached up to 20 ms\(^{-1}\) (Figure 5a), which was far stronger than summer climatological level (Figure 5b). The actual wind could be even stronger, since the ECMWF wind only have an interval of 6 hr. The wind directions at site A kept northeasterly from 5 to 11 July and then rotated clockwisely to westerly. After the passage of Chan-hom, the wind turned southeasterly in 14–20 July with relatively low magnitude. On 22 July, the southerly wind became strong again with a speed of ~10 ms\(^{-1}\). The time series of the sea surface salinity (SSS) in the site A indicates that with the Chan-hom approaching and leaving the studied area, the SSS increased gradually from 22 psu on 1 July to 32 psu on 12 July and then dropped to the climatological level in ~20 days. Short-term variations of SSS were due to tidal currents. As can be seen from Figure 4, the easterly wind during the Chan-hom passage pushed the plume shoreward, which increased the salinity at site A. The recovery of SSS from the typhoon influence was closely related to the wave mixing. Without the surface wave-induced mixing, it only took ~7 days for SSS at site A to recover to the nontyphoon case. However, when the surface wave-induced mixing was considered, the recovery period extended to ~19 days (Figure 5c).

Figure 4. Modeled surface salinity in Exp1 (a–c), Exp2 (d–f), and Exp3 (g–i) before (1 July), during (12 July), and after (28 July) the passage of typhoon Chan-hom. psu = practical salinity unit.
Site B was in the Zhe-Min Coastal Water (Figure 1). The wind at site B was similar to that at site A during and after the Chan-hom passage (Figure 6a). With the surface wave-induced mixing considered, SSS started to decrease 2 days after being affected by the periphery of Chan-hom, dropped sharply to ~31.5 psu after its passage, kept this salinity for ~1 week until another strong southerly wind event came on 20 July, and then recovered to ~33.5 psu in another week (Figure 6c). During the recovering process, the plume extended offshore, which weakened the cross-shelf salinity gradient (Figure 4). Hence, the tidal variation of SSS was greatly reduced (Figure 6c). While without considering the surface wave-induced mixing, the SSS at site B was 1–2 psu lower. The overall recovering period with and without wave mixing was both ~17 days. Actually, the salinity at site B was not fully recovered to the nontyphoon case but was ~0.5 psu lower. From Figure 4, one can see that the arrived plume water in Zhe-Min Coastal Water was somewhat trapped and resisted to the subsequent southerly wind, unless the southerly wind became strong enough on 20 July. Detail dynamic mechanism will be discussed in section 4.1. It can be expected that if there was no strong southerly wind, the freshwater brought by typhoon Chan-hom to the Zhe-Min Coastal Water would stay there for a longer period. Thus, the typhoon wind played a first-order role in the abnormal southward river plume transport.

c  Freshwater transport to the Zhe-Min Coastal Water

To further quantify the typhoon effect on the Changjiang River Plume extension in the Zhe-Min Coastal Water, the total freshwater flux \( Q_f \) across a cross-shelf transection (Sec 3, see Figure 1) was calculated for all three experiments (Figure 7):

![Figure 5](image)

**Figure 5.** (a) Realistic wind speed and vector at site A provided by European Center for Medium-Range Weather Forecasts. (b) Wind in 1–12 July was replaced with climatological wind on each date. (c) Modeled surface salinity from three experiments. psu = practical salinity unit.
\[
\delta f = \int \eta/C_0 h S_0/C_0 S_0 Vz dz;
\]

\[
Q_f = \int_{l_0} \delta f dw; \tag{4}
\]

where \( \delta f \) is the residual freshwater flux, \( S \) is the salinity of the water column, \( S_0 \) is the ambient salinity (here \( S_0 \) was 34), \( V \) is velocity normal to the transection, \( \eta \) is sea water level, \( h \) is bottom depth, and \( l \) is the width of the transection. Negative \( \delta f \) and \( Q_f \) indicates the southward transport. Both \( \delta f \) and \( Q_f \) were low-pass filtered with a cutoff window of 75 hr to remove the tidal oscillations.

The results indicate that there was abundant freshwater transported to the Zhe-Min Coastal Water, not only during the Chan-hom passage but also in 1 week since then (Figure 7b). Without wave mixing (i.e., Exp2), the transport to the Zhe-Min Coastal Water was exaggerated to some extent (Figure 7b). The total freshwater flux \( Q_f \) across the transection from Exp1 reached \( \sim 7 \times 10^4 \) m\(^3\)/s during the Chan-hom passage, which was about \( \sim 1.4 \) times of the Changjiang River discharge in the same period \( (\sim 5 \times 10^4 \) m\(^3\)/s). Obviously, the excess freshwater flux was from the accumulated freshwater inside the river plume that arrived previously. Such a massive freshwater flux to the Zhe-Min Coastal Water was far larger than that in winter seasons, which is similar to the Changjiang River discharge then (H. Wu et al., 2013). The total freshwater transport reached \( \sim 7.4 \times 10^{10} \) m\(^3\) during the typhoon-influenced period (1–20 July). This number was surprisingly large, because the total Changjiang River discharge during the same period was just \( \sim 8.9 \times 10^{10} \) m\(^3\). To some extent, the typhoon Chan-hom transported almost all of river discharge to the Zhe-Min Coastal Water. Under the climatological wind conditions, although the wind was southerly, there were still weak southward freshwater transport, and the total freshwater transport during 1–20 July was \( \sim 2.7 \times 10^{10} \) m\(^3\), only one third of that under the typhoon effect. The mechanism why there was still a southward along-shelf transport was the combined effect of tidal-mixing front and the thermal-wind balance, which will be discussed in a separate
paper. If we removed this background freshwater transport, we could see that the typhoon Chan-hom added \( \sim 4.7 \times 10^{10} \text{ m}^3 \) extra freshwater to the Zhe-Min Coastal Water in 1–20 July, which was \( \sim 53\% \) of the total river discharge in the same period, \( \sim 12\% \) of the total Changjiang River discharge in dry season (October-April) when the majority of Changjiang River plume extended to Zhe-Min Coastal Water, or \( \sim 5\% \) of the annual total river discharge in 2015. Such a dramatic freshwater transport in a short period significantly changed the fate of terrestrial materials.

### 3.3.2. Vertical Characteristics

In summer monsoon, the Changjiang River plume usually leaves the estuary as a surface-advected plume, developing significant vertical stratification in the East China Sea. The plume stratification responses to the typhoon Chan-hom are investigated below.

#### a Role of wave-induced mixing

The previous results showed that characteristics of the Changjiang River plume under typhoon influence were related to the wave mixing. The wave mixing transferred the TKE into the ocean, which was incorporated into the Mellor-Yamada scheme as an additional TKE production (Huang & Qiao, 2010; Qiao et al., 2004). With additional energy input, the vertical viscosity and diffusivity were adjusted, which result in the variation of the vertical plume structure. Hence, the surface wave-induced viscosity and diffusivity were calculated with equation (2). Figure 8 showed the simulated significant wave heights, the surface \( B_v \), and associated D5 along the Sec 1. D5 is defined as the depth at which \( B_v \) decreases to \( 0.005 \text{ m}^2/\text{s} \) (Qiao et al., 2004), which signifies the vertical extent that is influenced by wave mixing. The results showed that high surface \( B_v \) were associated with large significant wave heights. We found that the 1-m wave only generated a surface \( B_v \) of \( \sim 0.007 \text{ m}^2/\text{s} \), but the 3-m waves produced a surface \( B_v \) of \( \sim 0.07 \text{ m}^2/\text{s} \), and 6-m typhoon-induced waves caused a strong surface \( B_v \) of \( \sim 0.3 \text{ m}^2/\text{s} \). Typical vertical turbulent viscosity calculated with Mellor-Yamada scheme was only on the order of \( 10^{-3} \text{ m}^2/\text{s} \). Hence, wave mixing dominated the vertical mixing under the strong typhoon period.

\( B_v \) decays exponentially downward at a rate in proportional with the wave length (equation (2)). Figure 8 showed that the surface wave-induced mixing can hardly penetrate to depth (D5 > 10 m) in the coast when the significant wave height was smaller than 2 m. Only when the typhoon was passing and the significant wave height exceeded 6 m could the wave-induced mixing reach depth (\( \sim 50 \text{ m} \)). Comparing with that in the open oceans where D5 can reach 60 m under a significant wave height of \( \sim 3 \text{ m} \) (Qiao et al., 2004), the D5 in the studied area was much shallower. However, it was still deeper than the river plume thickness that was less than 10 m. Hence, it would significantly influence the plume stratifications.
When the surface wave-induced mixing \((Bv)\) was added to the model with equation (3), the vertical structure of salinity changed significantly during and after the typhoon passage (Figure 9). Before the typhoon, the significant wave height was small, and the associated surface wave-induced mixing was weak. Hence, the modeled salinity profiles on Sec 1 and 2 were nearly identical with (Exp1) and without (Exp2) the wave mixing (Figures 9a1, 9a6, 9b1, and 9b6). Whereas, during or just after the typhoon passage, the wave mixing was strong with \(D5\) reaching the sea bed. Hence, the water column was fully mixed with isohalines almost vertical in Sec 1 on 12 July and in Sec 2 on 9 July. A dramatic difference was found on 23 July that was 10 days after the typhoon passage. The plume was much thicker and more diffusive in vertical under the effect of wave mixing (Figures 9a4 and 9a9).

Therefore, surface wave-induced mixing significantly changed the vertical characteristics of the Changjiang River plume. If there was no surface wave-induced mixing, the Changjiang River plume would be more stratified and recovered more rapidly from the typhoon influence, as suggested in section 3.3.1. The extended recovery time under wave mixing can be explained by the wind-driven Ekman transport under stratification conditions. The plume recovered to its original state under the realistic winds. The pycnocline inhibit the turbulent mixing, which prevents the further downward transmission of wind-driven Ekman motion. Thus, the wind-driven current above the pycnocline can be scaled as \(V = \tau/\rho_0 fh\), where \(\tau\) is wind stress, \(h\) is the smaller one of the Ekman thickness and the plume thickness. Here the plume thickness (~10 m) is much smaller than the Ekman thickness (~ 50 m). The increase of \(h\) therefore reduces the wind-driven current and increases the adjustment time. It is thus understandable that the wave mixing increases the plume thickness and then
elongates the recovery time. In the following discussions, we only focused on the modeled river plume with surface wave-induced mixing, that is, the Exp1.

b Vertical stratification

To address the overall typhoon influence on water column stratification, we calculated the salinity difference between surface and bottom (bottom salinity minus surface salinity) and the potential energy anomaly parameter (Simpson et al., 1990):

$$
\varphi = \frac{1}{h} \int_0^h (\rho - \rho_v) g \rho \, dz,
$$

where $h$ is the depth, $\rho$ is the density at the depth $z$, and $\rho_v$ is the vertically averaged density. $\varphi$ (unit J/m$^3$) represents the work needed to completely mix the water column, with a large value indicating a strong stratification. According to Lewis (1997), $\varphi < 10$ J/m$^3$ means the water column is completely mixed; $\varphi > 180$ J/m$^3$ means the density has acutely changes in the vertical and the water column is highly stratified.

The spatial distribution of salinity difference at the three selected moments (Figures 10a–10c) revealed that when typhoon Chan-hom was passing the studied area, the surface-bottom salinity difference was greatly reduced in the entire Yellow Sea and East China Sea due to the intensified vertical mixing, except in a narrow band along the Zhe-Min Coast where the majority of the Changjiang River plume was pushed to propagate along the coast (Figure 4b).

We further analyzed to the temporal evolution of stratification at sites A and B. For site A (Figure 10d), under typhoon condition (Exp1), the salinity difference (Exp1) rapidly decreased from 12 psu on 1 July to 0.7 psu on 12 July, which matched well with temporal evolution of the SSS that increased from 20 to 32 psu, considering that the salinity difference remained larger than 12 psu under the climatological condition (Exp3).
Furthermore, the φ also dropped from 400 J/m³ on 6 July to 300 J/m³ on 10 July, and the sharpest reduction occurred during the typhoon passage, from 300 to ~50 J/m³ in 1 day (Figure 10f), while the φ kept at a relatively high value (larger than 400 J/m³) during the entire July under the climatological condition, which means that the surface-trapped river plume was well-developed. It indicated that the stratification disappeared and the seawater was fully mixed (see Figures 9a1–9a3). After the Chan-hom passage, the salinity difference (Exp1) gradually increased from 0.7 psu on 12 July to 12 psu on 30 July, indicating that the seawater began to be restratified as the plume recovered gradually (see Figures 9a3–9a5) which matched well with the φ variation that φ took 10 days to recover to the climatological level, which was shorter than the recovery times of SSS (~20 days) and surface-bottom salinity difference (~20 days; Figures 5c and 10f).

Different from site A, surface-bottom salinity difference at site B increased as the arrival of river plume under the typhoon wind. As influenced by typhoon, the φ exhibited strong stratification characters (Figures 10e and 10g). Since in site B the river plume was bottom trapped, the overall surface-bottom salinity difference was much smaller than at site A. One significant feature was that the peak surface-bottom salinity difference and the φ (Exp1) occurred not during the arrival of typhoon but at ~10 days later before another strong southerly wind event occurred. It indicated that the buoyant plume water was continuously transported to Zhe-

Figure 10. Surface-bottom salinity differences before (1 July, a), during (12 July, b), and after (28 July, c) the passage of Chan-hom. Time series of surface-bottom salinity difference were calculated at sites A (d) and B (e) from both Exp1 and Exp3. Time series of potential energy anomaly (φ) from Exp1 and Exp3 at sites A (f) and B (g). The shadowed area represents the period with typhoon passage. psu = practical salinity unit.
Min Coastal Water during and after the typhoon arrival, as was also suggested by the freshwater flux analysis (Figure 7b). Another thing should be highlighted that the surface-bottom salinity difference and the $\varphi$ were adjusted back to the climatological level around 30 July. The overall adjustment time in site B was ~18 days, which was similar to the salinity recovery time (Figure 6c).

4. Discussion

One surprising response of the Changjiang River plume to typhoon Chan-hom is the massive extension along the Zhe-Min Coast that usually occurred in the winter season. One typhoon transported ~5% of total annual Changjiang River outflow to Zhe-Min Coastal Water, and the associated plume extension persisted even after the typhoon passage when the wind had already turned southerly. The dynamic mechanisms “trapping” the plume in the Zhe-Min Coastal Water need to be examined. Furthermore, the huge amount terrestrial nutrients carried by the river plume were transported to the Zhe-Min Coastal Water, which might stimulate algal blooming. Here in this session, we further discuss these two issues.

4.1. Sustention and Retreating of the Changjiang River Plume in the Zhe-Min Coastal Water

If there had been no typhoon, the summertime Changjiang River plume seldom extends to the south of 29°N along the Zhe-Min Coast. Once the Changjiang River plume extends along the Zhe-Min Coast under the typhoon effect, it forms a bottom-trapped river plume that is associated with a buoyant coastal current. For a buoyant coastal current, the strong density gradient in the cross-shelf direction produces a surface-intensified down-shelf jet under the thermal wind balance (Chapman & Lentz, 1994). Wind is another forcing driving a coastal current. The relative importance of these two mechanisms can be quantified with a wind strength index ($W_s$) that was suggested by Whitney and Garvine (2005). $W_s$ is defined as to scale the importance of the wind-driven current to the buoyancy-driven current:

$$W_s = \frac{U_{\text{wind}}}{U_{\text{buoyancy}}},$$

where the $U_{\text{wind}}$ is the estimate for the wind-driven along-shelf velocity, which was calculated with the formula derived by Sandstrom analysis data (Sandstrom, 1980) and Garvine observations (Garvine, 1991):

$$U_{\text{wind}} \approx 2.65 \times 10^{-2} U,$$

where the $U$ is the along-shelf wind velocity. $U_{\text{buoyancy}}$ is the buoyancy-driven velocity scale:

$$U_{\text{buoyancy}} = \frac{1}{R} \left(2g_\rho Qf\right)^{1/4},$$

where $K$ is the internal Kelvin number ($K = L_y/R$), $L_y$ is the plume width (here $L_y$ was 58 km), $R$ is the internal Rossby radius of deformation of the river plume, $Q$ is the river discharge, $f$ is the Coriolis parameter, $g_\rho$ is the reduced gravity, $\rho_o$ is the ambient seawater density, and $\rho_r$ is the freshwater density.

From Figure 11, one can see that the magnitude of $W_s$ turned sharply from ~1 on 1 July to ~1.7 on 4 July. It meant that the wind direction shifted from southerly to northerly and the wind overwhelmed the buoyancy in driving the coastal current. The salinity variation at the site B lagged the $W_s$ for ~1 day (Figure 6c). From Figure 7, we could also find the signal that the freshwater transport to south was evidently strengthened. The total freshwater flux ($Q_f$) reached about $-5 \times 10^4$ m$^3$/s. Therefore, along-shelf extension of the Changjiang River plume was formed.

From the 4 to 10 July, the $W_s$ kept approximately ~1.5, corresponding to the period of typhoon passage (Figure 11). After that, the $W_s$ turned from ~1.8 on 10 July to 1.2 on 12 July. It suggested that the strong northerly wind ceased and southward wind-driven current reached its peak. Meanwhile, the salinity kept decreasing and reached the minimum on the 12 July (Figure 6c). The southward freshwater flux gradually increased from $-5 \times 10^4$ to $-7 \times 10^4$ m$^3$/s (Figure 7b), and the surface-bottom salinity difference slightly increased from...
4 to 10 July (Figure 10e). It indicated that the freshwater was continuously transported southward. The $Q_f$ kept $-7 \times 10^4 \text{ m}^3/\text{s}$ and the surface-bottom salinity difference increased from 10 to 12 July.

After the Chan-hom passage, according to the $W_s$, the plume extension in the Zhe-Min Coastal Water experienced two periods, that is, the retention phase (from the 13 to 20 July) and the retreating phase (from the 21 to 28 July). During the retention phase, $W_s$ kept about $-0.3$ (Figure 11), which meant the coastal current was at a buoyancy-driven state. Therefore, the southerly wind was not strong enough to reverse it, and southward flow was maintained. During this period, the salinity kept at $\sim 31.5$ psu, much lower than the normal level. The freshwater was continuously transported to the south until the $Q_f$ reduced from $-7 \times 10^4 \text{ m}^3/\text{s}$ to 0 (Figure 7b). The arrival of freshwater increased the surface-bottom salinity difference continuously (Figure 10e). In other words, the south current triggered by the typhoon lasted for a considerable period even the typhoon had disappeared already. Until new external force occurred, this buoyancy-driven current would be self-sustained (Chapman & Lentz, 1994). For the retreating phase, the $W_s$ was greater than 1 (Figure 11) due to another weather event with wind speed larger than 10 m s$^{-1}$ (Figure 6a), which was strong enough to reverse the buoyant coastal current. At the same period, the salinity at site B gradually returned to the climatological level (Figure 6c). The total freshwater flux (Figure 7b), the surface-bottom salinity difference (Figure 10e), and the potential energy anomaly (Figure 10g) all recovered to the climatological levels.

### 4.2. Ecological Effect

The Changjiang River carries a large amount of terrestrial materials such as nutrients (Shen et al., 2001; Zhang et al., 2007). The huge transport of plume water to the Zhe-Min Coastal Water due to typhoon Chan-hom also brought massive nutrients to this area, potentially promoting the phytoplankton growth. To verify this hypothesis, we analyzed the remote sensing data of chlorophyll-$\alpha$ obtained from GOCI satellite. Due to the heavy cloudiness, there was no available GOCI image before and during the Chan-hom passage. However, three images were available after the Chan-hom passage (although cloud cover was still heavy), that is, on 19, 25, and 31 July, shown as Figure 12. Accuracy of the remote sensing chlorophyll-$\alpha$ data often suffers from the turbidity in coastal waters (Dall’Olmo et al., 2003; Gitelson, 1992; Gitelson et al., 2007; Gons, 1999). Hence, we only focused on the chlorophyll-$\alpha$ concentration in the water area deeper than 30 m where surface turbidity was low.

Under such circumstances, we found that there was significant primary production increase 2 weeks after Chan-hom, on 25 and 31 July in the offshore Zhe-Min Coastal Water (Figures 12d and 12f). On 19 July, the plume water was still in the retention phase; hence, the Changjiang River plume extended and was confined to the coast (Figure 12a). Due to the high sediment resuspension in nearshore waters (Y. Li et al., 2012), primary production was restricted by the high turbidity. Hence, no high chlorophyll-$\alpha$ was observed in the offshore Zhe-Min Coastal Water (Figure 12b). When a strong southerly wind came on 20 July, the Changjiang River plume entered a retreating phase, with plume water in the Zhe-Min Coastal Water shifted both northward and seaward (Figures 12c and 12e). The reduced turbidity, which removed the light limitation (Cloern,
1987), stimulated the primary production in the plume water (Figures 12d and 12f). The massive algal blooming occurred at least after 19 July, which was at least 1 week after the typhoon passage. Moreover, the algal blooming detected on 25 July (~2 weeks after typhoon) and 31 July (~3 weeks after typhoon) should not be the direct impact of typhoon through upwelling or rainfall. Therefore, the local primary production was enhanced via the nutrient-rich plume water transport induced by typhoon Chan-hom.

In addition, the GOCI images (Figure 12) proved that the model produced the river plume correctly, because from Figure 12, one can see that the shape and location of the simulated plume were close to the area with high chlorophyll-α concentration. This agrees with the previous finding that high chlorophyll-α concentrations water coincides with the movement of the Changjiang River plume discovered by Yamaguchi et al. (2012).
5. Conclusion

In this study, we investigated the detailed responses of the Changjiang River plume to a severe typhoon Chan-hom (1509). The observed data showed that the typical offshore-extending summertime Changjiang River plume disappeared completely after the typhoon passage. Instead, it extended southward similar to a typical wintertime situation. A well-validated numerical model, including a circulation model component, the ECOM-si, and a wave model component, the SWAN, was used to simulate the evolution and response mechanisms of the Changjiang River plume under both the wind-driven currents and wave-induced mixings. Surface wave-induced mixing was calculated with a formula suggested by Qiao et al. (2004) based on wave spectra simulated with SWAN. Model validation suggested that the model well reproduced the plume pattern after the typhoon passage, and the simulation with the surface wave-induced mixing provided a better result.

The typhoon wind in the Changjiang River Estuary was northeasterly to northerly since the Chan-hom path was east of it. Although the northeasterly-northerly typhoon wind lasted for a short period, the majority of Changjiang River plume dramatically propagated along the Zhe-Min coast to form a buoyant coastal current. The along-shelf plume extension lasted for ~10 days after the typhoon passage, until another strong weather event came. Through calculation, it was found that the freshwater transported to the Zhe-Min Coastal Water reached ~4.7 × 10^10 m^3 as influenced by typhoon Chan-hom alone, which was ~5% of the total Changjiang River discharge in 2015 or ~12% of the total dry season (October-April) discharge when the majority of Changjiang River plume extended to Zhe-Min Coastal Water. Surface wave-induced mixing caused by typhoon wind was found to be important in destroying the plume stratification and elongating the recovery processes.

The strong northerly typhoon wind was the most significant contributor for the breakdown of Changjiang River plume. However, in the recovery process, the competition between wind-driven current and buoyancy-driven current was more important. Even the northerly typhoon wind ceased and the wind had turned upwelling-favorable, the buoyant coastal current triggered by typhoon Chan-hom still sustained, until the southerly wind became strong enough to reverse the buoyant coastal current. The wind-induced current plays a significant role in redistributing the river plume in horizontal, while the wave-induced mixing is important in changing its vertical structure. The remote sensing data of chlorophyll-a from GOCI also showed that significant algal blooms occurred via nutrient-rich plume water redistribution induced by typhoon. This study shows that one single typhoon can dramatically change the fate of terrestrial materials from the Changjiang River.

References


