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Storm-induced hydrodynamic changes and seabed erosion in the littoral area of Yellow River Delta: A model-guided mechanism study

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Highlights

- Storm-induced energetic hydrodynamic forces intensify sediment resuspension and dispersal significantly.
- Wave-induced bottom stress promotes sediment plume and enhances local resuspension.
- Storms increase suspended sediment concentration and offshore sediment transport.
- Storm-induced accumulative effect on seabed scour tends to cause long-term erosion.

Abstract

Morphological evolution of large river deltas is highly vulnerable to extreme storm events due to insufficient sediment supply. As an abandoned delta lobe, the coasts along the northern Yellow River Delta (YRD) and Gudong Oil Field have recently suffered serious erosion due to extreme storm events and become increasingly vulnerable. In this study, a well validated and tested Delft 3D module by the observing hydrodynamic and sediment data to simulate the hydrodynamics and seabed erosion during a storm event in the littoral area of YRD. Observed wave, current and sediment data under both fair-weather and storm conditions were collected in the study area and used to validate the model. The results indicated that the model can reproduce well the hydrodynamic and sediment transport processes. A series of numerical experiments were carried out to examine the hydrodynamic changes and sediment transports. In the numerical experiment of normal condition, there is hardly any sediment transport off the YRD. The numerical experiment of storm condition showed that storms enhanced tidal residual currents, weakened tidal shear front, and significant wave heights up to 2 m, considerably intensified the sediment resuspension and dispersal. The local sediment resuspension due to the increased wave-induced bottom stress promoted the sediment plume to expand to the central area of Laizhou Bay, which seemed to provide sediment source for offshore and southward transport. During the storm, the active nearshore sediment resuspension provided sediment source for offshore and southward transport. The intensive dynamics and sediment transport under storm conditions caused significant

changes in seabed erosion and siltation. The main erosion occurred off the Gudong and northern YRD, while the main siltation appeared in the central area of Laizhou Bay. No significant recovery after a storm and frequent strong winds have an accumulative effect on the erosion, which is very likely to dominate the erosive states of the YRD coast in the future.

Keywords: Yellow River Delta; Storms; Tidal shear front; Sediment transport; Seabed erosion; Morphodynamics

1 Introduction

Fluvial discharge, wave energy and tidal range are critical in determining morphological evolutions of most deltas worldwide. Sediment input to deltas has been reduced or eliminated (Syvitski and Kettner, 2011; Wang et al., 2011; Dai et al., 2016; Liu et al., 2019), which causes delta erosion and sinking, and increasing delta's wetlands will be drowned (Tessler et al., 2015; Wolters and Kuenzer, 2015; Murray et al., 2019). Lack of knowledge on erosion mechanism and deltaic processes may lead to erroneous conclusions about how deltas function. More recently, sea level rise, insufficient supply of sediment, human interventions and climate changes, which may cause more extreme event, such as flood and storm have been the emerging key factors to reshape mega-deltas (Nicholls and Cazenave, 2010; Blum and Roberts 2009; Yang et al., 2011a; Bi et al., 2014; Liu et al., 2017; Becker., 2020).

As we known, hydrodynamic changes and sediment transport control morphological evolution of deltas (Gong et al., 2014; Wu et al., 2015). These control impacts varied at different time scales. Wherein, hydrodynamic changes and sediment transport in storm event can belong to a short-term effect (Ralston et al., 2013; Anthony, 2015; Florin et al., 2017). However, it is difficult to observe them during the storm event. Therefore, the numerical model, which integrate hydrodynamics, wave propagation, sediment transport and morphological changes numerical model, has provided new indispensable tools to examine the effects of storm events. Numerous numerical models have been developed with enhanced capability of simulating the processes of currents, waves, salinities and sediments in delta areas, such as ECOM-si, and FVCOM for estuarine circulations; ECOMSED for sediment transport; SWAN for nearshore wave climates; and many other modelling systems, such as ROMS, MIKE 3 (DHI Water and Environment), and Delft3D for regional hydrodynamics and morphodynamics.

The YRD has been gradually formed in the western Bohai Sea (Fig. 1a), since the Yellow River migrated its main watercourse from the Yellow Sea to the Bohai Sea in 1855. With the subsequent frequent avulsions both natural and engineered, the YRD has developed several delta lobes (Fig. 1b), and the significant morphological evolution of the abandoned delta lobes have been observed in recent decades. For example, the coastline along the northern YRD and Gudong Oil Field have suffered serious erosion in recent years (Qi and Liu 2017). Moreover, the energetic winds and waves generated by storm events have been found to significantly impact on this coastal region. During storm events, the wave action is particularly prominent off the YRD, becoming a key factor in controlling sediment resuspension (Jia et al., 2012; Zhang et al., 2018). Many studies have addressed its shoreline dynamics (Zhang, 2011;

Kuenzer et al., 2014; Fan et al., 2018), morphological changes (Kong et al., 2015; Xu et al., 2016; Jiang et al., 2017; Wu et al., 2017) and sediment dispersals (Wang et al., 2010; Bi et al., 2014; Wu et al., 2015).

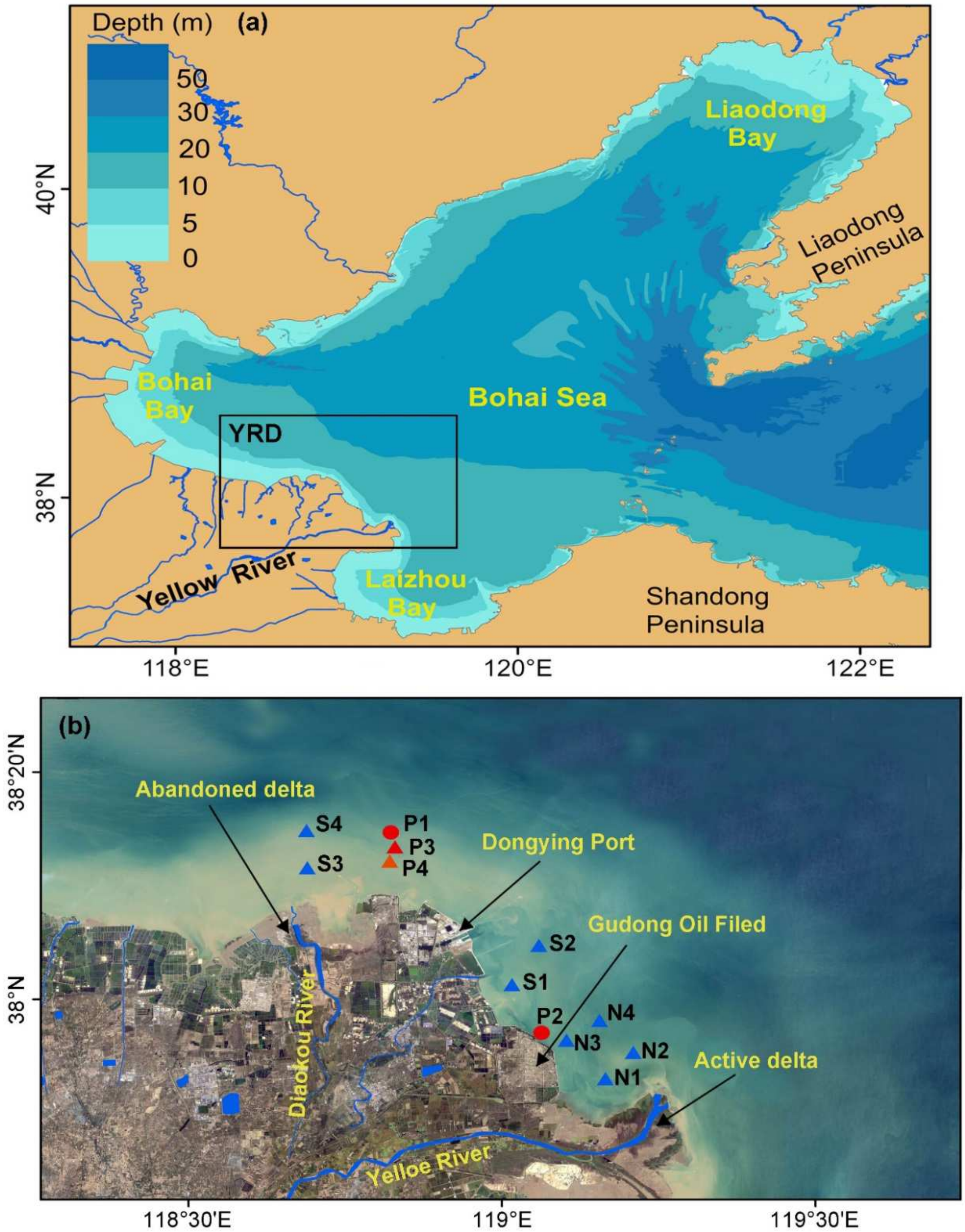

Fig. 1. (a) Computational domain and topography of the Bohai Sea; (b) Detailed study area, where blue triangles mark the locations of the vertical hydrological and sediment measurements and other marks represent the locations of continuous survey during the storm event in April 2013. Two alongshore sections are also indicated for detailed comparisons.

However, little research has been focused on the storm-induced hydrodynamic and morphological processes, especially in relation to the mechanism of coastal erosion. Therefore, this study focuses on exploring the hydrodynamic and sediment characteristics in the YRD during storms using the Delft3D model together with the measured sediment, wave, and tidal data during a storm event in April 2013, in an attempt to reveal the storm-induced hydrodynamic changes and seabed erosion.

2 Model description

2.1 Study area and model grid

The YRD, located in mid-latitude region, is susceptible to storms throughout the year, especially storms generated by cold-air outbreaks in winter, or in autumn-to-winter and winter-to-spring seasonal transition (Wu et al., 2002). Such storms usually lead to intense hydrodynamic changes and significant sea-level anomalies around the YRD nearshore zone. In 2013, 12 storm surges occurred in the littoral area of Yellow River Delta, all of which were extratropical storm (Beihai Branch of State Oceanic Administration People's Republic of China, 2014). Among them, the storm occurring in April 2013 was selected to simulate based on a coupled model, which combines hydrodynamic model (Delft3D-FLOW), wave (Delft3D-WAVE) and sediment transport (Delft3D-SED). In the early stage of this storm, the northwest wind was dominant. On April 13, 2013, the wind direction turned to north, and then gradually turned to northeast. The storm event began at 2:00 on April 13 and ended at 3:00 on April 15, and lasted nearly 50 hours from growth to decline, covering two tidal cycles, in which the wind speed maintained at about 20 m/s for 20 hours, from 12:00 on the 13th to 8:00 on the 14th (Fig. 2).

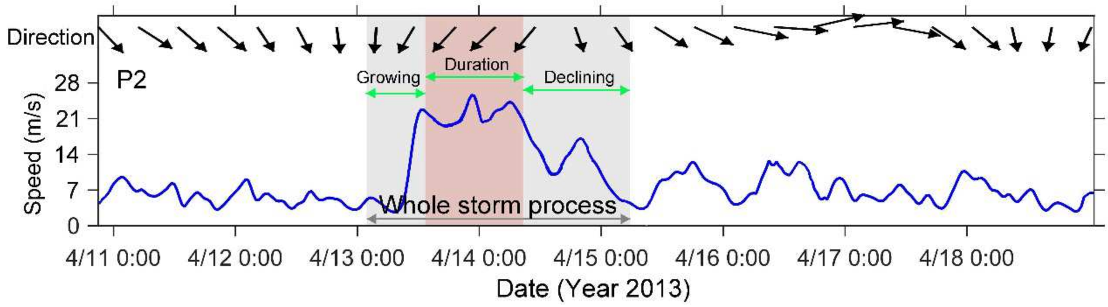

Fig. 2. The wind process during the examined storm.

Since the Bohai Sea is a semi-enclosed sea, and cold-air outbreaks mostly occur northerly in this region, the model domain was set to cover the entire Bohai Sea, with an open boundary in the north Yellow Sea near the Bohai Strait. Curvilinear grid cells that cover this domain were generated by Delft3D-RGFGRID with a refined high grid resolution used in the areas of interest at the Yellow River subaqueous delta. The total number of grid cells was 771×432 (Fig. 3 a). The average grid cell spacing was about 1 km; varying from the maximum mesh size of nearly 2 km at the open boundaries to the minimum mesh size of approximately 150 m along the YRD coast (Fig. 3 b-d). The topography data were based on the YRD surveys carried out in 2012 for the subaqueous delta, with a spatial resolution of 300-500 m, and coastal surveys carried out in 2009 for the other part of the Bohai Sea, with a spatial resolution of 1000-5000 m, respectively (Fig. 3 a). In winter, due to the prevalence of strong northerly wind and concomitant high waves (Bi et al., 2011), the distribution of salinity, temperature and sediment in the littoral area of YRD is found to be vertically homogeneous, indicating a well-mixed water column (Yang et al., 2011). Thus, the model adopted seven layers in the vertical direction, and from the bottom layer to surface layer, the values of σ were set to 0.1, 0.1, 0.2, 0.2, 0.2, 0.1, and 0.1.

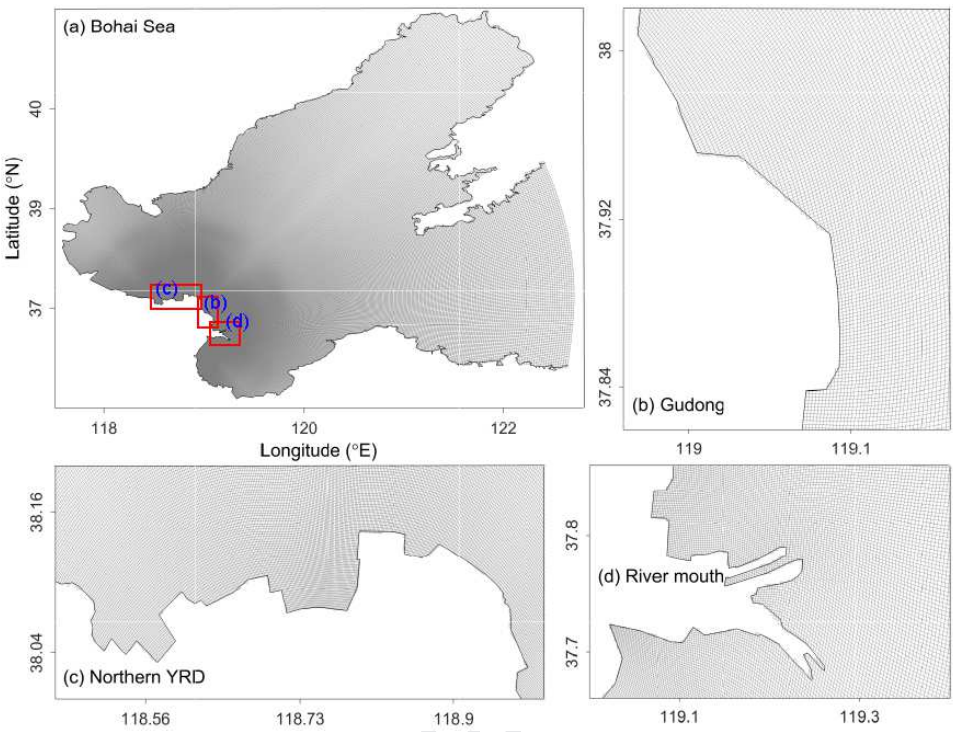

Fig. 3. (a) Numerical model mesh with the details of: (b) the Gudong coast (c) the northern YRD, and (d) the active river mouth. The three red boxes in (a) from top to bottom mark the northern YRD, the Gudong coast and the active river mouth, respectively.

2.2 Initial and boundary conditions

Using the modelling system above described, simulations started initially with a static state from the mean sea level, and zero flow velocity and sediment concentration in the domain. The coastline boundaries were determined from the high-water lines with a spatial resolution of 15 m, which were extracted from the false color composite images of Landsat OLI data. The model was driven by the tide forcing along the open boundary, consisting of 8 main tidal constituents, i.e. M2, S2, N2, K2, K1, O1, P1 and Q1, as well as surface forcing from the ECMWF (European Centre for Medium-Range Weather Forecasts) wind and atmospheric pressure data with a spatial resolution of 0.25°×0.25° (latitude× longitude). Compared with the storm scale in the Bohai Sea, this resolution is sufficient for modeling land-ocean gradients (Lv et al, 2014).

Suspended sediment concentration (SSC) at seaward boundary was set to 0, since the open boundary is far from the interested area and the water depth is mostly deeper than 30 m, so that the impact of sediment conditions from the open boundary on the sediment transport in the nearshore region which was based on the local equilibrium transport formula can be neglected. At landward boundary, distinct seasonal variation of sediment delivery occurs from the Yellow River. River discharge boundary conditions were imposed appropriately based on daily-averaged water discharge and sediment concentration recorded from the Lijin hydrological station, provided by the Yellow River Water Resource Commission.

2.3 Parameter settings

The bottom friction was parameterized using the Manning coefficient n, calculated from the water depth (Xing et al., 2012):

$$n=(0.015 + 0.01/h) \quad , \; h>1 \qquad (1)$$

where h is the water depth (m). The bottom roughness for regions water depth below 1 m is prescribed by a uniform Manning coefficient of 0.025, which is the result of verification of the coupled model. It should be noted that the Manning coefficient was defined differently in Delft3D as $M_n=1/n$. The horizontal eddy viscosity and diffusivity are calculated with the Horizontal Large Eddy Simulation (HLES) sub-grid model.

According to Ren et al. (2012), the seabed composition off the YRD is highly variable in space, and the median grain size (D_{50}) varies widely from ~ 5 to ~133 μm. Therefore, multiple sediment fractions were considered in the morphological model. In this study, four mud fractions (fine to coarse, denoted as md1–md4) were used to represent nearly the full range of cohesive sediment grain sizes (4, 7.5, 28, and 62.5 μm). Specifically, one sand fraction (100 μm) was included in the model, i.e., the dominant fine sand fraction (denoted as sd1), to reduce the overestimation of erosion along the coasts. The settling velocity (w_s) of each mud fraction was determined relative to the grain size after calibrating the model against the spatial distribution of depth-averaged SSC.

Critical erosion shear stress τ_{ce} was a key parameter for simulating fine-grained sediment transport. For the critical shear stress of the cohesive sediment, the following formulas were used (Dou, 1999; Lu et al., 2011):

$$\tau_{ce}=k^2\rho\left(\frac{d'}{d^*}\right)^{\frac{1}{3}}\left[3.6\frac{\rho_s-\rho}{\rho}gD_{50}+\left(\frac{\gamma_0}{\gamma_0{}^*}\right)^{\frac{5}{2}}\left(\frac{\varepsilon_0+gh\delta\sqrt{\delta/D_{50}}}{D_{50}}\right)\right] \quad (2)$$

where ρ_s is the specific sediment density, 2650 kg m^{-3}; ρ is the fresh water density, 1000 kg m^{-1}; g is gravity acceleration, and D_{50} is median size of sediment; ε_0 is comprehensive cohesion coefficient, 1.75 cm^3/s^2; k is a coefficient of different status of incipient motion, 0.128; δ is the thickness of pellicular water, and $\delta = 2.31\times10^{-5}$ cm. In this study, d'= 0.5 mm when D_{50} < 0.5 mm, and d^*= 10 mm accordingly. Initial dry bulk density γ_0 is:

$$\gamma_0=\rho_s(1-e_0\eta) \quad (3)$$

and steady dry bulk density $\gamma_0{}^*$ is:

$$\gamma_0{}^*{=}\rho_s(1\text{-}\frac{\pi}{6}(1\text{-}2\sqrt[3]{D_{50}})\qquad(4)$$

where e_0 is the maximum porosity, and we used e_0 =0.625. For all the mud fractions, the erosion parameter M is 5.0×10^{-5} kg/m^2/s, the specific density is 2650 kg/m^3, and the dry bed density is 500 kg/m^3.

The erosion and deposition fluxes for cohesive sediment (< 64 μm) were calculated applying the following Partheniades-Krone formulations:

$$E_i{=}M_i\left(\frac{\tau_b}{\tau_{b,i}}\text{-}1\right),\ \text{when } \tau_{cw}>\tau_{cw,i},\ \text{else } E_i{=}0\qquad(5)$$

$$D_i{=}w_{s,i}c_{b,i}\qquad(6)$$

where E_i, D_i and M_i are the erosion flux, deposition flux and erosion parameter of the ith mud fraction (kg/m^2/s), respectively; $w_{s,i}$ is the settling velocity of the ith mud fraction (m/s); $c_{b,i}$ is the depth-averaged concentration of the ith mud fraction (kg/m^3); τ_b is the combined bed shear stress due to currents and waves (N/m); and $\tau_{b,i}$ is the critical shear stress for erosion of the ith mud fraction (N/m^2). For 2D depth-averaged flow bed shear stress induced by a turbulent flow is assumed to be given by a quadratic friction law:

$$\tau_b{=}\frac{\rho_0 g\vec{U}|\vec{U}|}{C_{2D}^2}\qquad(7)$$

Where $\vec{U}$ is the magnitude of the depth-averaged horizontal velocity. Due to finest fractions can be entrained into the seabed (Winterwerp et al., 2007), the critical shear stress for deposition was omitted in the model, which means that continuous deposition was specified in the model. All those parameters used in the mode simulations are summarized in Table 1.

Table 1

Sediment and mud fractions considered in the morphological model

Type	Fraction	D_{50} (μm)	τ_{ce} (N/m^2)	w_s (mm/s)	M (kg/m^2/s)
Mud	md1	4	Spatially varying	0.06	5.0×10^{-5}
	md2	7.5		0.14	
	md3	28		0.22	
	md4	62.5		0.26	
Sand	sd1	100	–	–	–

The sediment transport processes responsible for bed-level changes vary greatly off the YRD due to the spatial variations of the bed sediment grain size. Therefore, our model considers both non-cohesive (sand) and cohesive sediment (mud), which are treated separately in Delft3D, and sand-mud interactions are excluded as a first approximation. Suspended sediment transport is calculated by solving the depth-averaged advection-diffusion equation, which includes source and sink terms and is presented below:

$$\frac{\partial hc_i}{\partial t} + \frac{\partial huc_i}{\partial x} + \frac{\partial hvc_i}{\partial y} = \frac{\partial}{\partial x}\left(h\varepsilon_h \frac{\partial c_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\varepsilon_h \frac{\partial c_i}{\partial y}\right) + S_i \qquad (7)$$

where c_i is the sediment concentration of the *i*th sediment fraction (kg/m^3), u and v are horizontal velocity components (m/s), ε_h is horizontal eddy diffusivity (m^2/s), and S_i is the source and sink term of the *i*th sediment fraction representing the exchange between the water colum and the bed. For non-cohesive sediment transport (≥ 64 μm), we follow the approach of Van Rijn (1993).

3 Model validations

3.1 Tidal regime

The tides in the Bohai Sea are relatively small and fall into the micro-tidal/mixed-semidiurnal categories. Tides from the northwest Pacific propagates into the Bohai Sea through the Bohai Strait. There are two amphidromic points for semidiurnal tidal constituents (M2 and S2) in the Bohai Sea: one at the offshore area of Qinhuangdao and the other near the Yellow River mouth. One amphidromic point for diurnal tidal constituents (K1 and O1) appears in the Bohai Strait. The tidal model ran 30 days in order to obtain tidal constituents harmonic constants. Harmonic constants of tidal elevation of each constituent are obtained by applying harmonic analysis to modeled time series of sea level at each model grid. The results showed that our model successfully simulated tide systems. The co-tidal and co-range lines for M2, S2, K1, O1 constituents (Fig. 4) fitted well with observations (Chen et al., 1992) and the results of Huang (1995). The changes of the YRD influenced its surrounding tidal wave and obstructed tidal energy (Pelling et al., 2013), and the amphidromic points here calculated using new coastlines were farther to land than previous studies. Also, this result agreed well with other publications (Hao et al., 2010).

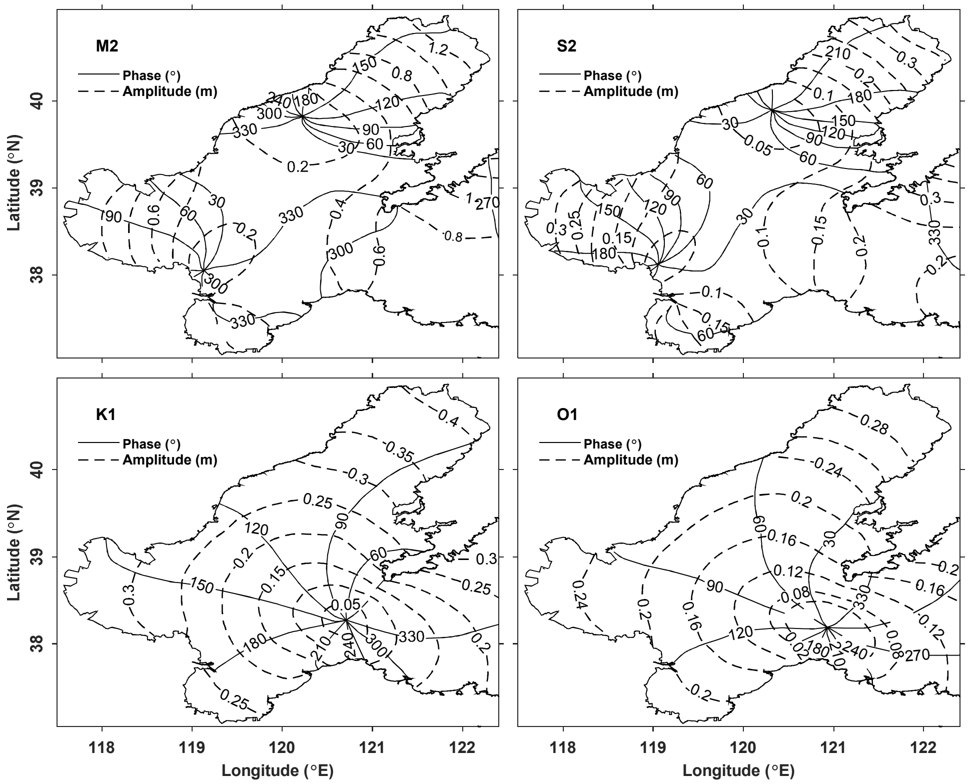

Fig. 4. Co-tidal charts of M2, S2, K1, O1 constituents from the model simulations (dotted and solid lines indicating the amplitude and phase, respectively.

3.2 Tide velocity

The accurate prediction of flow velocity and direction was a crucial step for the simulations of sediment transport which strongly depends on the shear stress, deposition criterion, and turbulence characteristics in the bottom boundary layer. The time series of currents and SSCs measured along the YRD coast were used to validate the model in normal conditions. The observations were taken at eight sites, as shown in Fig. 1b, at N1, N2, N3 and N4 in July 2009, and S1, S2, S3 and S4 in October 2009. The correlation coefficient (CC), the skill score (SS), and the root mean square errors (RMSE) were calculated to evaluate the quality of the model performance:

$$CC=\frac{\sum(X_{mod}-\overline{X_{mod}})(X_{obs}-\overline{X_{obs}})}{[\sum(X_{mod}-\overline{X_{mod}})^2\sum(X_{obs}-\overline{X_{obs}})^2]^{1/2}} \qquad (8)$$

$$SS=1-\frac{\sum(X_{mod}-X_{obs})^2}{\sum(X_{mod}-\overline{X_{obs}})^2} \qquad (9)$$

$$RMSE=\sqrt{\frac{\sum(X_{mod}\text{-}X_{obs})^2}{N}} \qquad (10)$$

where X_{mod} is the modeled result and X_{obs} is the observed data. The performance of model is classified as suggested by Allen et al., 2007; Ralston et al., 2010; Luo et al., 2017 as show in Table 2.

Table 2

Classification of model performance

SS	>0.65	0.65-0.5	0.5-0.2	<0.2
Performance	Excellent	Very good	Good	Poor

We first validated the simulations with the normal conditions. The model simulation began June 15, 2009. After running for half a year with the observed runoff and 6-hourly ECMWF re-analyzed wind, the model results were output for comparison. Comparisons of the depth-averaged flow velocity and direction with the model results and the observation data are shown in Fig. 5. The type of tidal current was semidiurnal and rectilinear, and the velocity curve showed four peaks and four valleys within one day. Statistical assessments of validation are shown in Table 3. It is clear that the average *CC* of flow velocity at N1-N4 was 0.78, which was lower than those at S1-S4, 0.89, because those sites locate at the river mouth, the estuarine circulation is rather complicated. The average *SS* at S1-S4 and N1-N4 was 0.62 and 0.49 (Table 3), respectively, ranking ‘‘very good’’ and ‘‘good’’ according to the categories described above. The *RMSE* were also reasonable.

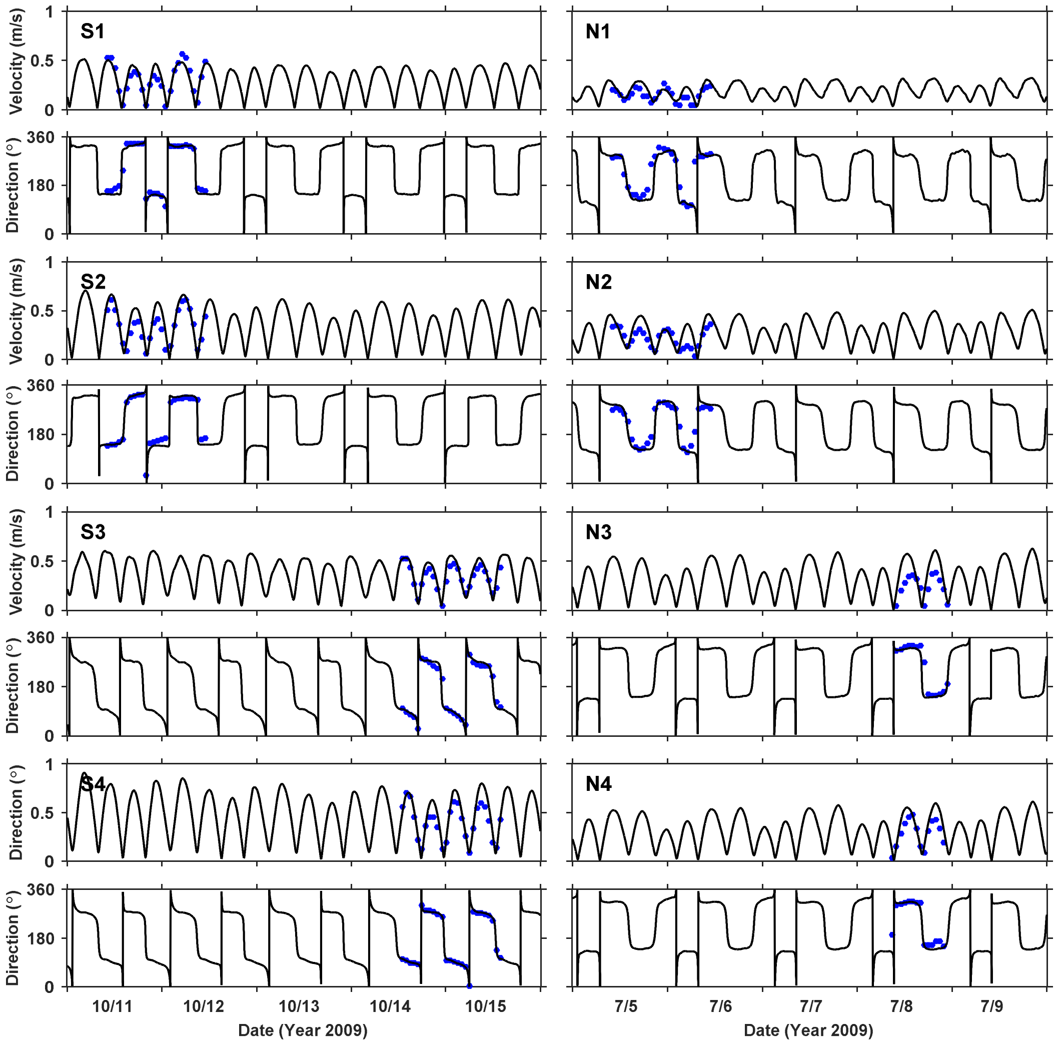

Fig. 5. Comparison of measured depth-average flow velocity and flow direction (blue dots) with the computed results (solid line) at eight measurement locations.

3.3 Suspended sediment concentration

The computed SSCs were compared with the observed SSCs at Sites S1-S4 and N1-N4 (Fig. 6). The computed SSC was well reproduced with tidal variation. For example, the tide had a transition from spring tides to neap tide during Oct 11 to Oct 15, 2009, so the modeled SSCs of sites S1-S4 during the period had decrease trends. The modeled SSC had the same order of magnitude as the measurements. The relatively large errors between the modeled and observed data appearing at sites S3 and S4 were mainly due to the erosion caused by waves, which was difficult to estimate during neap tides. The average *SS* of SSC at sites S1-S4 and N1-N2 (not with N3 and N4 because of less samples) were 0.24 and 0.26 (Table 3), indicating that the model preformed satisfactory. The *CC* and *RMSE* in Table 2 also illustrated the good performance of the model. The results clearly indicate that the model was properly set up and can be used to study the dynamics of sediment process off the YRD coast during normal conditions.

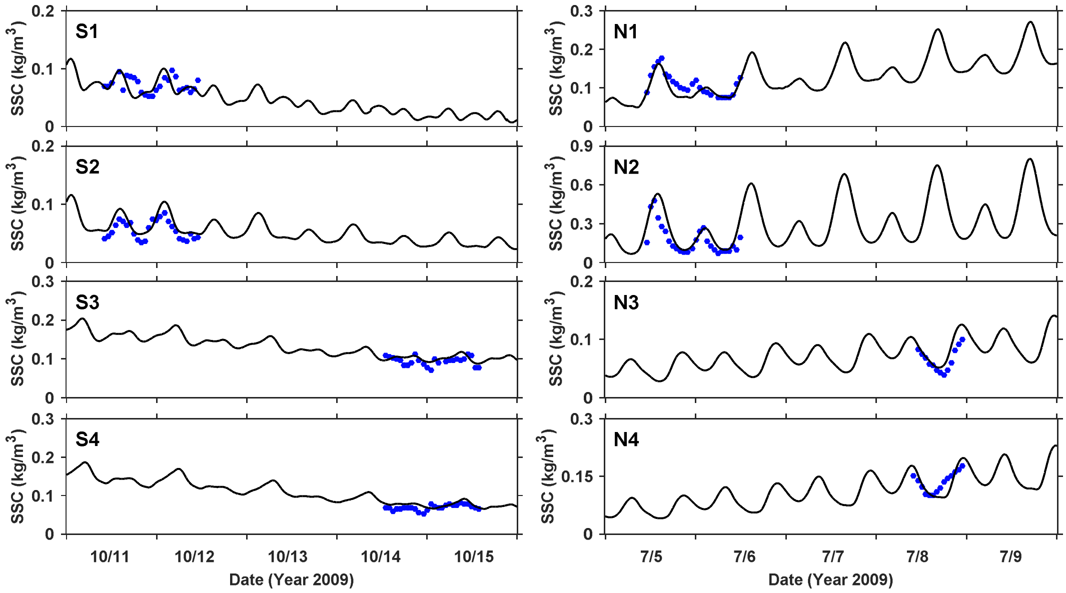

Fig. 6. Comparison of depth-average flow velocity and flow direction between the simulated (solid line) and the observed (blue dots) at eight sites.

Table 3

Correlation Coefficient, Root-Mean-Square Error, and Skill Score of each measured site

	S1-S4 (average)			N1-N4 (average)		
	CC	SS	RMSE	CC	SS	RMSE
Velocity (m/s)	0.89	0. 62	0.08	0.78	0.49	0.11
SSC (kg/m^3)	0.57	0.24	0.05	0.62	0.26	0.04

3.4 Storm validations

The measured data during a storm in April 2013 were employed for storm verification of hydrodynamic and sediment characteristics. More details of this survey can be seen in the work by Quan (2014) and Bian et al (2016). The water levels data were provided by Central Platform of Shengli Oil Field (P1, locations are labeled in Fig. 1b) and Gudong gauge station (P2). The flow and wave data were collected with an ADCP (Acoustic Doppler Current Profilers) at P3, and the SSC data were collected with a turbidity meter (OBS-3D) at P4.

To verify the accuracy of the coupled Delft3D-WAVE model, the P3 site was selected to compare the wave height and period between observation and simulation during the storm period of April 15-17 2013 (Fig. 7). The SWAN model generally well-reproduced variations of the significant wave height and period (Fig. 7a). A cold front passed on the April 13, resulting in a marked increase in wave height (maximum wave height of approximately 2.0 m). The simulated wave heights were slightly underestimated due to the low temporal resolution of the meteorological forcing, which was unable to capture the peaks of wind velocities values adequately. The skill assessments are summarized in Table 4. The *SS* of wave height was 0.41, ranking ‘‘good’’ according to the categories described above. The *CC* and *RMSE* were also reasonable. Through comparison between simulated and observed storm tide at P1 and P2 sites (Fig. 7b), the maximum and minimum water level as well as the phase were in reasonable agreement with the measurements. The *SS* of storm tide at site P1 and P2 was 0.26 and 0.27, respectively, which indicated the reasonableness of storm tide verification. The flow and SSC validations are shown in Fig. 7c and Fig. 7d. The model reproduced a similar sectional pattern to the survey, specifically, the *SS* of flow velocity and SSC were 0.51 and 0.21, and the *CC* were 0.65 and 0.49, respectively. Verification results showed that model predictions during storm period based on the model were quite consistent with the observations at these sites.

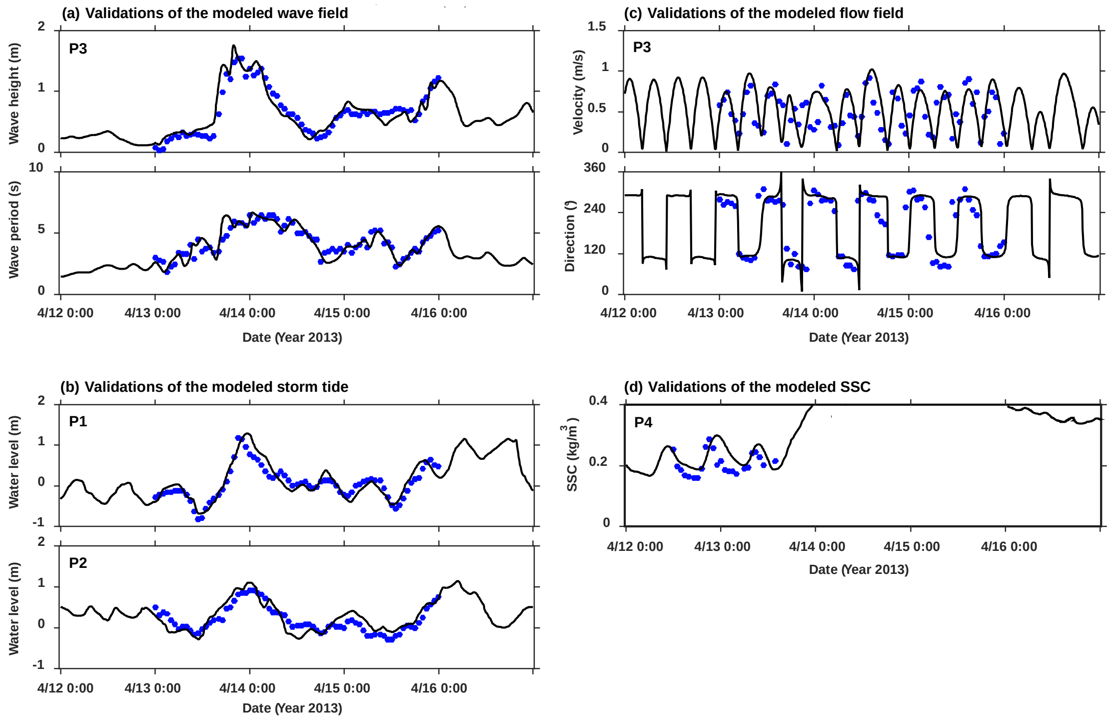

Fig. 7. Comparison of depth-average flow velocity and direction between the simulated (solid line) and the observed (blue dots) at eight sites.

Table 4

Correlation Coefficient, Root-Mean-Square Error, and Skill Score of each measured site

	P1, P2 (average)			P3			P4		
	CC	SS	RMSE	CC	SS	RMSE	CC	SS	RMSE
Wave height (m)	-	-	-	0.84	0.71	0.13	-	-	-
Storm surge (m)	0.89	0.73	0.18	-	-	-	-	-	-
Velocity (m/s)	-	-	-	0.65	0.51	0.11	-	-	-
SSC (kg/m^3)	-	-	-	-	-	-	0.49	0.21	0.06

4 Results and discussion

In total, three runs were considered in this study to examine the impacts of storm conditions on hydrodynamics and sediment transport over the nearshore seabed of YRD, as shown in Table 5. Run 1 (control run) was embedded into a wave-tide-circulation coupled model and driven by climatological daily mean river discharge and calm wind (speed below 3 m/s) as well as water flux and salinity in open ocean boundary. We can understand the characteristics of hydrodynamics and sediment in normal conditions from the control run. In Run 2, the calm wind and normal atmospheric pressure conditions used in Run 1 were replaced by strong wind and low atmospheric pressure conditions (data from ECMWF) for setting storm conditions. By comparing the results of these two runs, we can quantitatively identify storm impacts. In addition, Run 3 was conducted with storm conditions without tides. The impacts of storm-induced wave on the seabed erosion were examined by comparing the results of three runs.. All the numerical experiments were run over a period of one month, beginning on April 1, 2013, and the data calculated by the model from April 13 to April 15 were used to analyze the hydrodynamic processes and sediment transport.

Table 5

Three different conditions for model simulations

Simulation	Tide	Wind	Waves
Run 1 (control run)	Yes	No (normal condition)	Yes
Run 2	Yes	Strong	Yes
Run 3	No	Strong	Yes

4.1 Waves

Calm winds forcing for Run 1 typically produced waves with significant wave height of less than 0.8 m (Figure 8a), and period of less than 3 s in the study area. The weak wave dynamic is attributed to the causes of wave in this area. The Bohai Sea has poor water exchange capacity with open ocean due to its narrow strait occupied by islands. Surface waves are generated by local winds.

The time series of wind stress for Run 2 are shown in Fig. 8c from April 12 to 14, 2013. The wind vectors were surface area averaged off the YRD, and on the conventional geographical coordinate system. As shown in the Fig. 8c, strong wind (more than 12 m/s) began in the morning of April 13 with directions moved from northwest to the northeast on April 13 and moved the northwest again on April 14. The northeasterly wind speeds shown two acceleration processes, in the morning and the end of April 13, respectively. The results from Run 2 showed that the wave height of approximately 2 m along the Gudong coast under the maximum wind speed, and the wave height of more than 1.2 m along the northern YRD coast (Fig. 8b). The time series of significant wave height, direction and period of site N3 is presented in Fig. 8d to show the changes at temporal scales of wave features. It can be seen that the significant wave height and period were generally accordant with wind speed, and the wave directions changed with wind directions. The significant wave height reached its maximum, more than 2 m, at site N3, during the first wind acceleration process of northeasterly wind, and reached more than 1.5 mduring the second wind acceleration process.

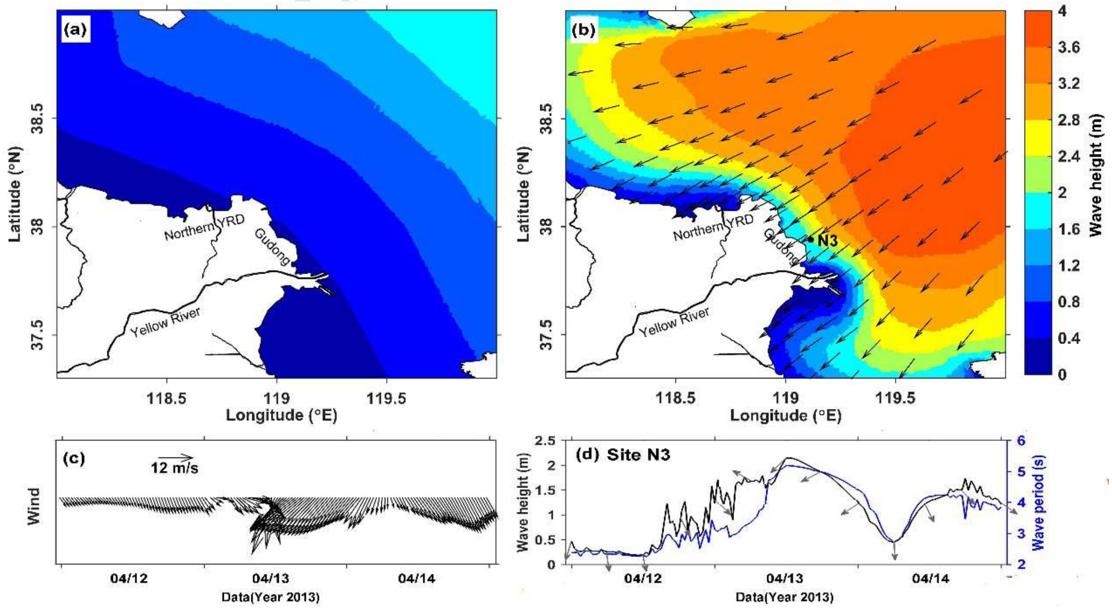

Fig. 8. (a) Significant wave height during calm condition forcing for Run 1. (b-d) Wave features during the examined storm: (b) significant wave height and direction with the maximum wind speed; (c) time series of surface area averaged wind vector off the YRD (118-120°E, 37.3-38°N);

(d) significant wave height (black line), direction (gray arrow) and period (blue line) at site N3.

4.2 Currents

4.2.1 Water mass transport

Storm-induced seaward coastal sediment transport can be key for to the inner shelf (Goff et al., 2010). To investigate the impacts of storm-surge flood and ebb on sediment transport, we first examined storm-induced current fields. The model runs were either forced by calm wind (Run 1), or strong northerly wind (Run 2). Fig. 9a shows the current was reciprocated with southeastern flood and northwestern ebb in normal conditions, with areas of high current velocity locating off the northern YRD coast and the active river mouth. Reciprocated current was predominant in shallow area (roughtly within the 15m isobaths), while it gradually turned into rotated current with the increase of water depth. In storm conditions, not only the current velocities increased, especially the flood velocity, but the directions were also changed: rotated current was predominant (Fig. 9b). Special attention should be paid to the feathers in the shallow area: most of these current vectors were along the flood-ebb axis or directed to the right side of the ebb direction. Nonlinear interaction between the tide, wind-driven current, and the Coriolis force should be responsible for this phenomenon. Huang et al. (1996) and Cao and Lou (2011) suggested that on the surface, the wind-driven current flows along the wind direction. During flood tide, wind-driven current added to tide current, the water mass could flow to southeast with higher velocity. During ebb, when the sea surface elevation decreases, the tidal water returned to the outlets hard and flowed north-northwestward, opposing with wind-driven current, and the water mass could turn into right-neighbored outlets.

Wind intensity and direction can generate changes in residual currents in the shallow areas, which are also found in the shore of the Tagus Estuary (Vaz and Dias, 2014).

In order to quantitatively reveal the contributions of the storm to water mass transport, the residual transport of water (Tr_w) through a unit width was calculated, which can be defined as follows:

$$Tr_w = \frac{1}{T}\int_0^T \int_{-H}^{\eta} \vec{V}(x,y,z,t)\mathrm{d}t \qquad (11)$$

where η is the surface elevation, H is the still water depth, and $\vec{V}$ is the horizontal velocity vector, and T is the time period. Previous studies (Wu et al., 2014, 2018) showed that residual transport velocity is a more reasonable method than the Eulerian residual current to index the subtidal transport in the shallow coastal water. In this study, 3 d (from 0:00 on April 13 to 16 April), were used as an statistical time window to obtain the Tr_w in normal and storm conditions, respectively, as shown in Fig. 10.

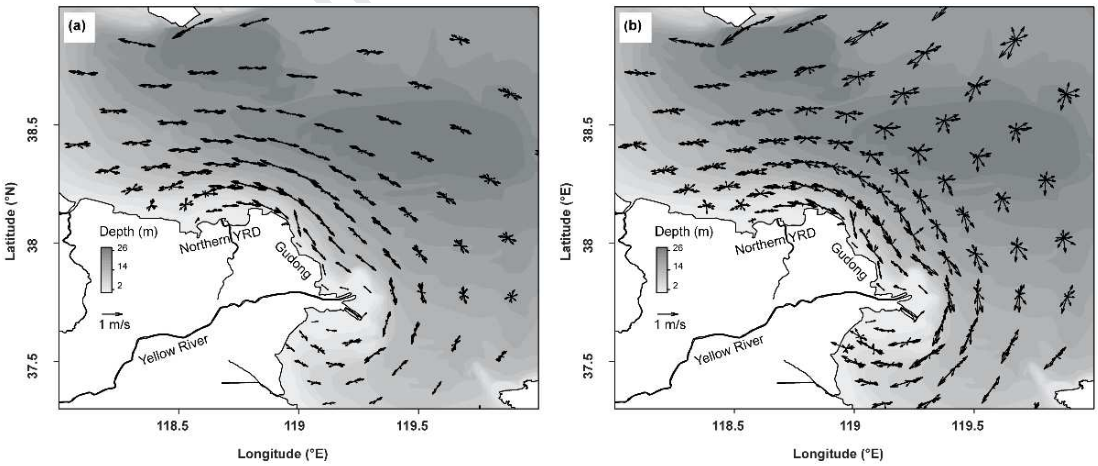

Fig. 9. Tide velocity vectors of depth-averaged current during an ebb-flood process in (a) normal conditions and (b) storm conditions.

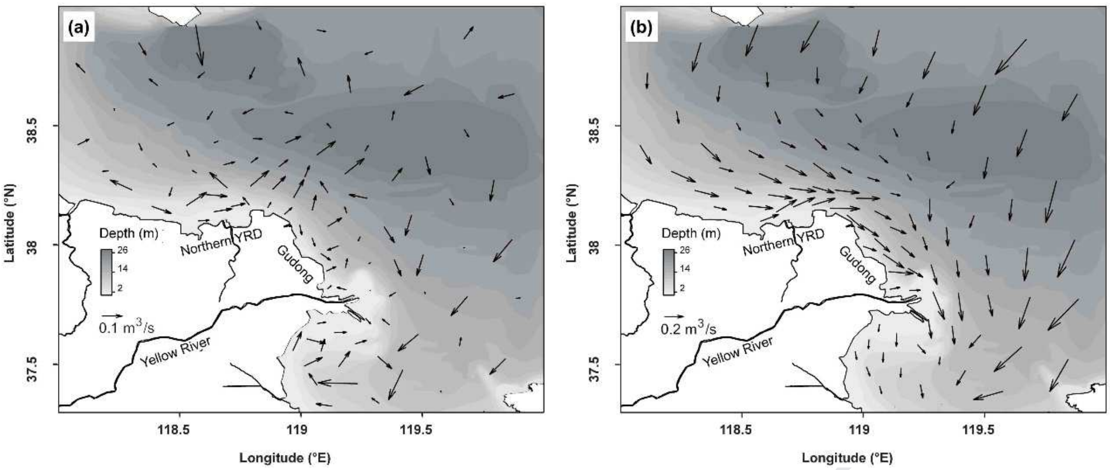

Fig. 10. Residual water mass transport in (a) normal and (b) storm conditions.

In normal conditions, the influence of wind was weak, and the residual currents were greatly affected by tidal current. In the shallow area, the Tr_w was generally less than 0.1 m^3/s. Affected by the northerly strong wind, the residual transport of water was transported southward in storm conditions, and the Tr_w was generally greater than 0.2 m^3/s, which was 2 to 4 times as large as that in normal conditions. Deep water mass transports southwest as a whole, while it begins to transports southeast gradually after reaching the central part of the Bohai Bay. Off the northern YRD, the residual currents flow eastward along the E-W coast. The direction of residual current along the Gudong coast was southeast in storm conditions, basically consistent with it in normal conditions. While, converging the water masses from the shallow area of the Bohai Bay and the northern YRD, and supported by the water mass from deep area, water mass in this area performs a notable transport rate, which was 4 times larger than it in normal conditions. The water transport rate off the river mouth also significantly increase, and massive water was transported to the central area of the Laizhou Bay with the northward inflow. This water transport model also explains why high water level always occurs in the Laizhou Bay and the Bohai Bay during storms

(Li et al., 2016).

4.2.2 Tidal shear front

Tidal shear front is an interface between two water bodies with opposing flow directions and significant low velocity zone, which are instantaneous extraordinary gradients closely related to sediment dynamics and morphological variabilities (Wang et al., 2007). Tidal shear front in the littoral area of the YRD has been observed and modeled in the previous studies (Qiao et al., 2008; Wang et al., 2017). The front was first reported by Li et al. (1994) who concluded that the shear front, occurring twice during a tidal cycle, could be classified into two types: inner-flood-outer-ebb (IFOE) and inner-ebb-outer-flood (IEOF).

From Run 1, both types of tidal shear front were observed in normal conditions, and shown in Fig. 11a and Fig. 11c, respectively. The IEOF type was closer to land and grows to the northern YRD with larger range than the IFOE type. While, strong winds had a predominant impact on tidal shear front. Under the pressure of northerly wind, both the IFOE type (Fig. 11b) and the IEOF type (Fig. 11d) have been weakened with smaller ranges of tidal shear front than in the normal conditions. Besides, the trends of tidal shear front changed to be perpendicular to the coasts comparing with the parallel trends in normal conditions, and the low velocity zones along the YRD coast disappeared, especially at the IFOE type happens (Fig. 11b). These changes of tidal shear front were because of the formation of rotated currents in deep area in strong wind circumstance: tides through rotated currents complete phase changes, not entirely form oppose-direction flow in shallow area. The changes such as weakened shear front, disappearance of low velocity zone, were benefit for the sediment resuspension and dispersal.

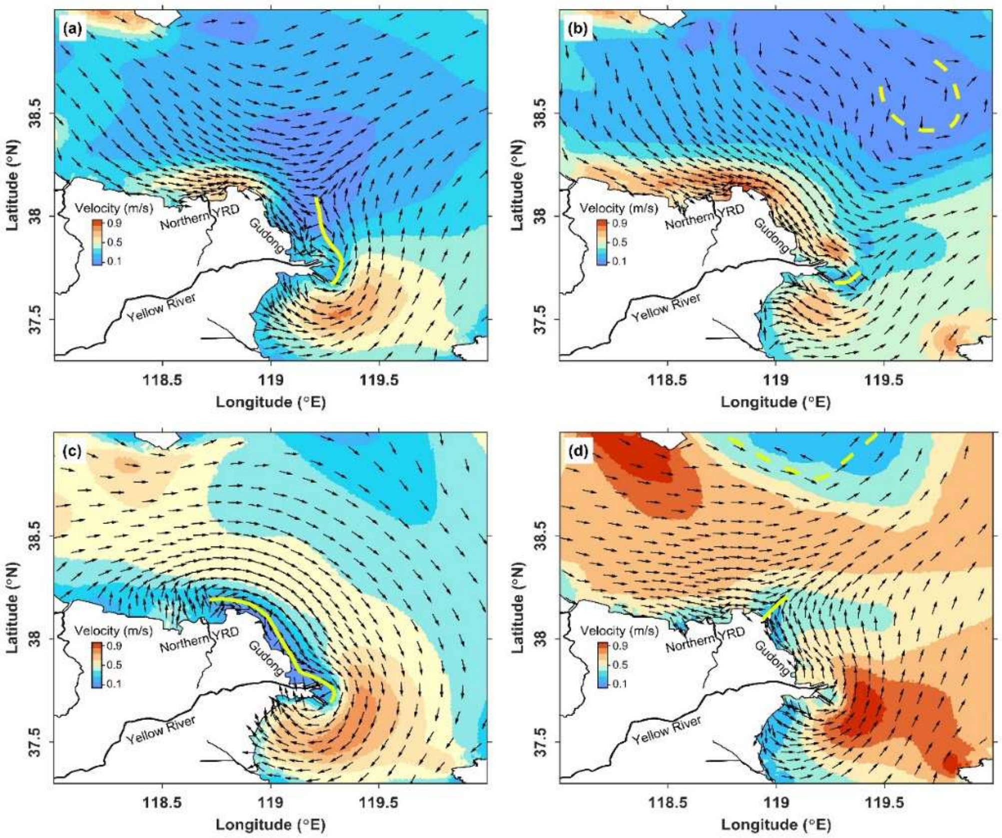

Fig. 11. Locations of tidal shear front of (a) and (b) IFOE type in Runs 1 and 2; and (c) and (d) IEOF type in Runs 1 and 2. The yellow solid lines represent the fronts, and the dashed lines represent the ranges of rotated currents.

4.3 Sediment process

4.3.1 SSC

The suspended sediment off the YRD is either introduced by river sources or resuspended from the seabed in response to various forcing conditions. We first performed process study to examine suspended sediment distributions. The simulated distribution of depth-averaged SSC from Run 1 and Run 2 are shown in Fig. 12a and Fig. 12b, respectively. When using Landsat data to create sediment color images, we can estimate the simulated results. For example, we chose the Landsat ETM+ data for

22 March 2014 (3.6 m/s average wind speed at S1-S4 and N1-N4) and 27 November 2012 (10.2 m/s average wind speed at S1-S4 and N1-N4) to show the turbid water distribution in normal and storm conditions, respectively. The model reproduced distribution of SSC matches well with the satellite images in Fig. 13, and compared well with the observed data (Yang et al., 2011b; Wang et al., 2014) and the satellite ocean color data (Zhang et al., 2014).

Bottom shear stress is an important dynamic factor for sediment erosion and deposition. When the bottom shear stress is greater than the critical bottom shear stress, the bottom sediment will be suspended. The total bottom shear stress (τ_{cw}) is composed of current-induced bottom shear stresses (τ_c) and wave-induced bottom shear stresses (τ_w) under wave-current interaction. The τ_c and τ_{cw} could be obtained from the Run 1 and Run 2, by Formula (7). To further understand the effect of τ_w on the formation of the sediment plume, a numerical Run 3 was conducted in which only wave and strong wind were included. Fig. 14a, 14b and Fig. 14c show the 3-day average τ_c, τ_w and τ_{cw} in the storm conditions, respectively.

High SSC values were observed in two regions under normal conditions (Fig. 12a) and formed two substantial sediment plumes, one nearshore the northern YRD and the other at the active river mouth, with a value about 1.5 kg/m^3. The sediment plume of the river mouth diffuses to the south, which results in the higher SSC in the northern area of Laizhou Bay. Off the Gudong coast, the SSC was relatively low, less than 0.5 kg/m^3. The distribution of high and low SSC is consistent with that of τ_c (Fig. 14a), which indicates that the τ_c is strong enough to stir the bottom sediment, and formed the sediment plumes off the northern YRD and the river mouth.

Compared with the normal conditions, the ranges of high SSC area enlarge significantly under storm conditions (Fig. 12b). The maximum SSC off the northern YRD and the active river mouth was more than 2.6 kg/m^3. High SSC was profound off the Gudong coast, which was 3 times as large as that in normal conditions, with a maximum value of 2.5 kg/m^3, appearing at the most prominent point of Gudong dyke toward the sea. Off the river mouth, the weakened shear front and disappearance of low velocity zone were benefit for the sediment dispersal. Thus, the sediment plume of the river mouth diffuses to the central area of the Laizhou Bay, which causes high SSC appearing at this area.

The characteristics of SSC distribution were related to the τ_w and τ_{cw} under storm conditions. The τ_w was higher along the Gudong coast due to larger wave height, where its value reached approximately 1.0 N/m^2 (Fig. 14b). The high value of τ_w at the river mouth was attributed to the shallow water of the mouth bar. In the most of the littoral area of YRD, the τ_{cw} reached approximately 1.1 N/m^2 (Fig. 14c), and the Gudong coast with larger values which was attributed to the higher τ_w (Fig. 14b). This fact indicates that the high SSC along the Gudong coast is generated by local sediment resuspension in storm conditions. During storms, researchers found that the waves as an important agent in the reworking and retreat at the mud-rich deltas that are generally considered as either'river-dominated', such as the Mississippi (Anthony, 2015) or 'tide-dominated', such as the Chao Phraya (Uehara et al., 2010).

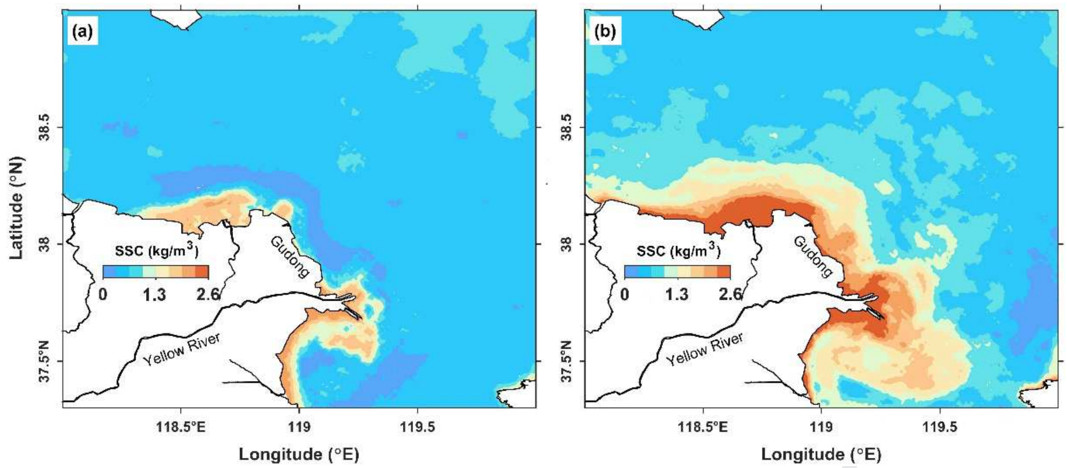

Fig. 12. The depth-averaged SSC: (a) in normal conditions; and (b) in storm conditions.

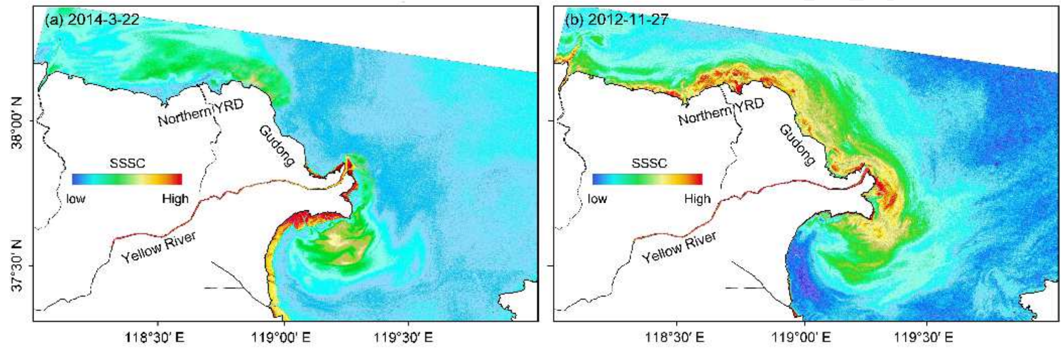

Fig. 13. Surface SSC (SSSC) retrieved from Landsat in the YRD region under: (a) in normal condition; and (b) under strong wind conditions.

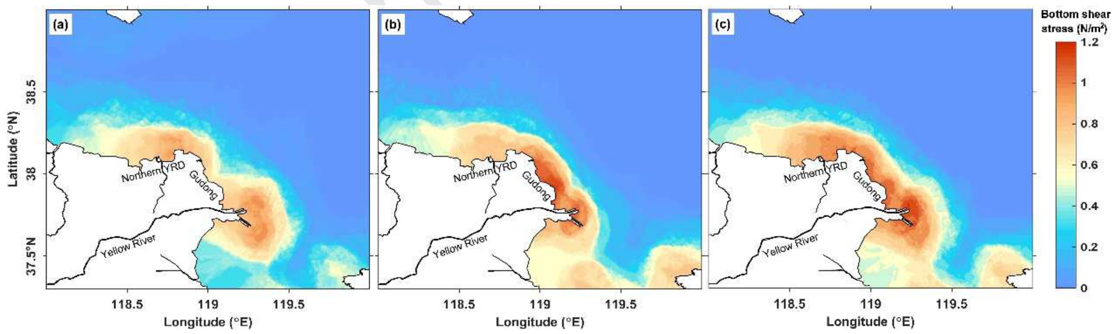

Fig.14. Bottom shear stress (units: N/m^2) in the littoral area of YRD: (a) current-induced; (b) wave-induced; and (c) total.

4.3.2 Sediment transport

In this section, the sediment transport characteristics were analyzed by calculating the residual transport of sediment (Tr_{sed}) through a unit width, which can be defined as follows:

$$Tr_{sed}=\frac{1}{T}\int_0^T \int_{-H}^{\eta} \vec{V}(x,y,z,t)\cdot C(x,y,z,t)\mathrm{d}t \qquad (12)$$

where η is the surface elevation, H is the still water depth, and $\vec{V}$ is the horizontal velocity vector, C is the sediment concentration, and T is the time period. As shown in Fig. 7, the whole process of the repeated storm lasted for nearly 50 hours. During the whole process, a wind turn occurred, forming two strong wind periods with different directions, i.e. the northeasterly wind period (NEP) and the northwesterly wind period (NWP). The dividing time of these two periods was approximately the middle time of the whole storm process, thus we can take 25 h as T to calculate Tr_{sed} of these two periods. The average SSC and residual of sediment transport rate are shown in Fig. 15.

From Fig. 15, we can see that the NEP was the growth and duration of storm process with larger average wind speed, while the NWP showed a downward trend. Therefore, the NEP appeared a larger maximum value of than the NWP. Although the wind speed was weakening as a whole during the NWP, there was also a process of wind acceleration with a maximum wind speed of 18.0 m/s. During the process of offshore and southward transportation of sediment, a large amount of suspended sediment diffuses to the sea and Laizhou Bay. Therefore, during the NWP the area of high SSC was more widely distributed, and the area larger than 1.5 kg/m^3 increased by nearly 50% compared with the NEP.

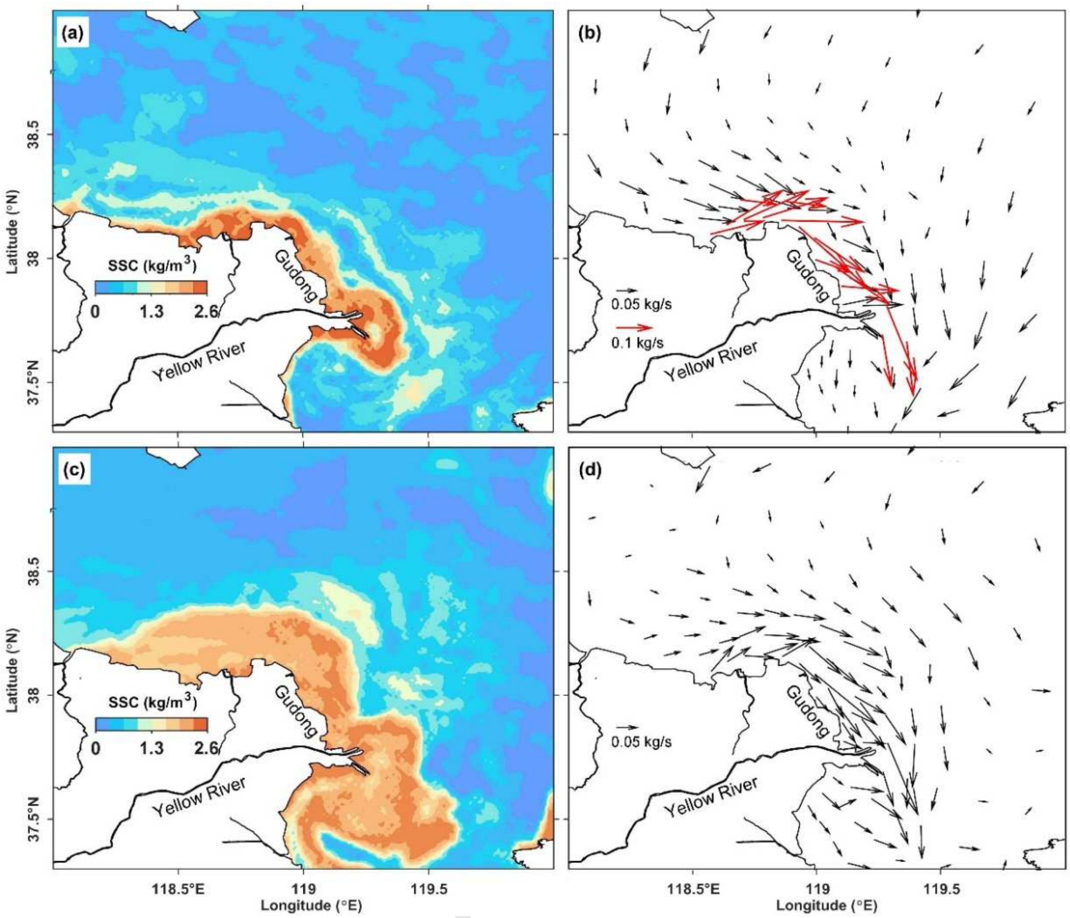

Fig. 15. The sediment transport features: (a) the suspended sediment concentrations and (b) residual sediment mass transport during northeasterly wind; (c) the suspended sediment concentrations and (d) residual sediment mass transport during northwesterly wind.

During the NEP, the residual transport of sediment increased with the decrease of water depth. The larger value appeared off the Gudong coast, with the value of 0.23 kg/s. Although the residual transport of sediment during the NWP was less than that during the NEP, it also showed a trend of increasing with the decrease of water depth, with a high value of more than 0.18 kg/s off the Gudong coast and river mouth. The directions of sediment transport were similar during these two periods, and basically consistent with the direction of water transport. The main difference of them occurred in the deep area, but the rates were mostly less than 0.05 kg/s. In both periods, the sediment was transported offshore and southward as a whole. Specifically, the sediment along the northern YRD coast was mainly transported eastward. After arriving at the Gudong coast, sediment was transported southeast, and continued to transport to the central area of the Laizhou Bay after passing the river mouth.

Different from the offshore transport in the littoral area of YRD during storm surge, the sediment is transported landward by the storm surge in the Yangtze River submerged delta (Dai et al. 2015). Coastal geometry may account for this difference: compared with Bohai Bay and Laizhou Bay, the main coastline of the Yellow River Delta protrude toward the sea, which makes the storm energy easier to gather in its near shore; while the Yangtze River Delta is characterized as a channel-shoal system with multiple outlets and shallow shoals, and the sediment can be transported to the shore along the channel. Similarly, along the Ebro Delta coast (Spain) whose geometry is cusp, researchers found that future trends in sea level rise produce exacerbated cross-shore sediment transport by storm forcing (Grases et al. 2020).

4.4 Seabed erosion

Having identified the main directions and magnitudes of sediment transport, the resulting morphological changes due to the storm are investigated. The final bathymetric changes, obtained from Runs 1 and 2, are shown in Fig. 16a and Fig. 16b, respectively. Positive values hereafter represent accretion and negative values represent erosion. It can be seen that in most parts of the littoral area the bed level changed within the confines of -0.05 m to 0.05 m in normal conditions (Fig. 16a). The seabed erosion off Gudong was also slight due to its insignificant sediment transport. Whereas in storm conditions, the changing hydrodynamics and sediment transport induced significant nearshore erosion. Fig. 16b shows that the seabed erosion of the

Gudong and the northern YRD reached 0.1 m to 0.15 m, even more than 0.2 m near the dike area. While, the main siltation occurred in the central area of Laizhou Bay. Overall, the area (off the YRD, 118°E -120°E, 37.3°N -38°N) of seabed erosion in storm conditions was 362.67 km^2, nearly 3 times as large as that in normal conditions, and the erosion volume is 0.0543 km^3, about 20 times as large as that in normal conditions. Therefore, the seabed erosion caused by the changes of hydrodynamics and sediment transport under storm surge is an important factor in the coastal seabed erosion of the YRD.

In order to explore the seabed changes after the storm, the bathymetric changes during the recovery period after the storm were calculated. The time range of recovery period was determined according to the wind speed and direction observed in P2 site. As shown in Fig. 17, the end of this strong wind at 3:00 on April 15, indicating the recovery period began at this time. At the time of 22:00 on April 18, strong wind occurred again, indicating the recovery period began at this time and it lasted totaling 91 hours. Similar to the SSC calculated in the normal conditions in experiment 1, the SSC off the north YRD and the active river mouth area was about 1.5 kg/m^3, while in other areas it was less than 0.5 kg/m^3 (Fig. 18a). The residual transport of sediment through a unit width was also similar to that calculated in Experiment 1 in light wind conditions. There was no strong deposition or erosion area, and it was basically in the equilibrium state during recovery period (Fig.18b). Along Guong coast, which had been severely eroded during storm period, the bathymetry did not change significantly. It can be seen that it was difficult to recover the seabed erosion in the short term after the storm, due to the insignificant sediment transport and deposition.

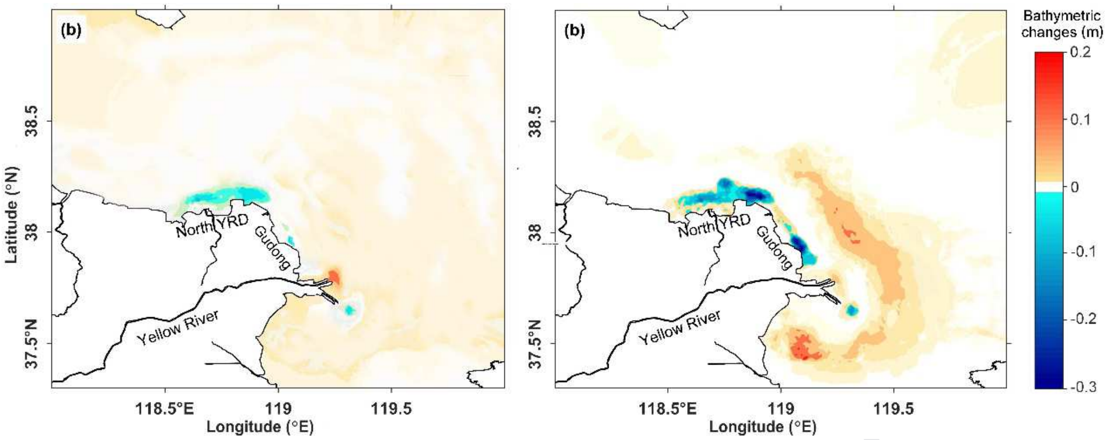

Fig. 16. Computed bathymetric changes (a) in normal conditions, and (b) in storm conditions. Positive values represent accretion and negative values represent erosion.

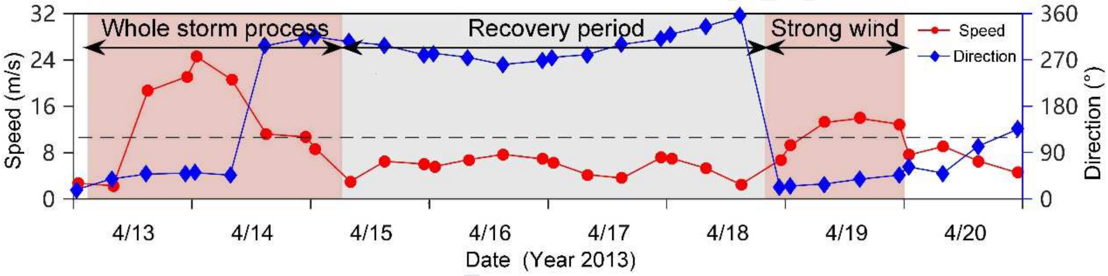

Fig. 17. The changes of wind speed and direction during and after the storm.

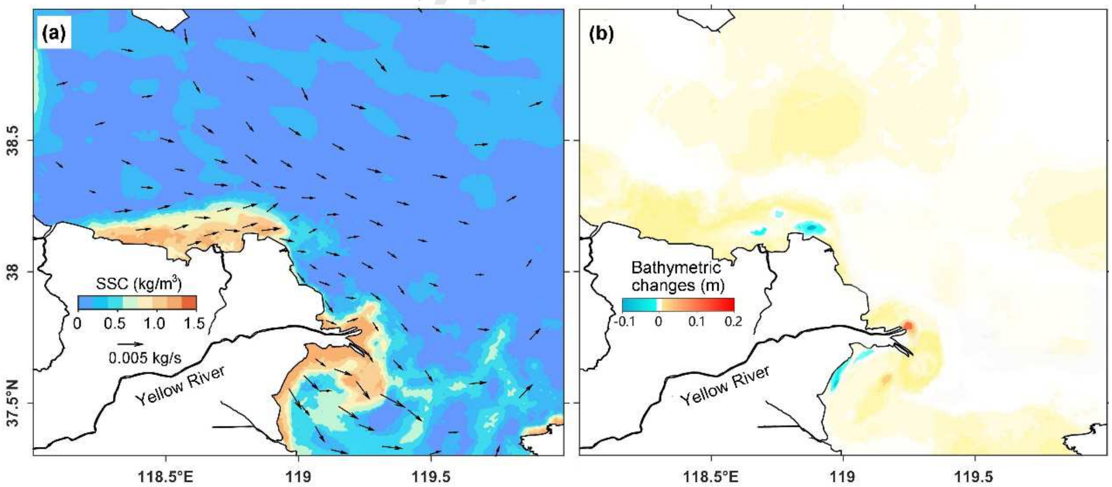

Fig. 18. (a) Suspended sediment concentrations and residual sediment mass transport after the storm; (b) erosion and accretion pattern after the storm.

4.5 Frequency of strong wind

The northern YRD and the Gudong coast are abandoned delta lobes, which underwent erosion after the river channel shifted southward. Despite of the coastal defenses (dikes) being built, the overall coastal area continued to be in the state of erosion and coastal managers were obliged to build protection works constantly, for example the pipe pile projects outside the destroyed dikes in 2004 and in 2016. Previous studies attributed the long term erosion to the avulsion of Yellow River and subsequent lack of sediment supply (Li et al., 2000; Xing et al., 2016), while this short timescale event hardly explain the long-term eroded states.

Although the winter storm surge is an extreme event, the storm-induced coast erosion plays an important role in the coastal geomorphological changes of the YRD. On the one hand, the effects of a storm give a distinguished interpretation for the seabed erosion, and on the other hand, storms occur at a higher frequency. Based on the hourly wind field data of P2 site from 2005 to 2014, the time series variation process of wind speed is analyzed. As shown in Fig. 19, the wind speed series has obvious seasonal variation characteristics. In winter and spring, the wind speeds are larger, while in summer, the wind speed is smaller. From the monthly scale change process of wind speed, the average probability of strong wind (speed more than 10.8 m/s) for 7 consecutive months from October to May of next year is 10.28%, the maximum is 22.14%, which appears in February of 2009.

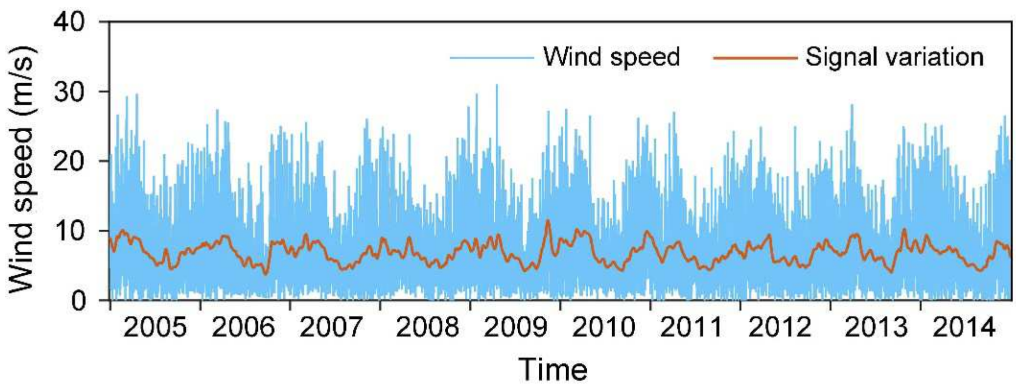

Fig. 19. Time series of observed wind speed and the signal variations in a monthly scale.

Using the ECMWF wind data, the frequency and interval time of strong wind in autumn-winter-spring (October 15 to April 15 of next year) since 1976 can be calculated. The results are shown in Fig. 20. Statistics show that the average number of strong wind occurred 39 times per period, 31 times at least, from October 1981 to May 1982, and 48 times at most, from October 2016 to May 2017. Since 1976, the number of strong winds has fluctuated slightly upward, while the average time interval of strong wind has fluctuated slightly downward. Thus, in the past 40 years, the YRD has seen more frequent strong winds. This fact indicates that the erosion state is mainly due to the accumulative effect of scour during storms, not merely attributable to the frequent avulsion.

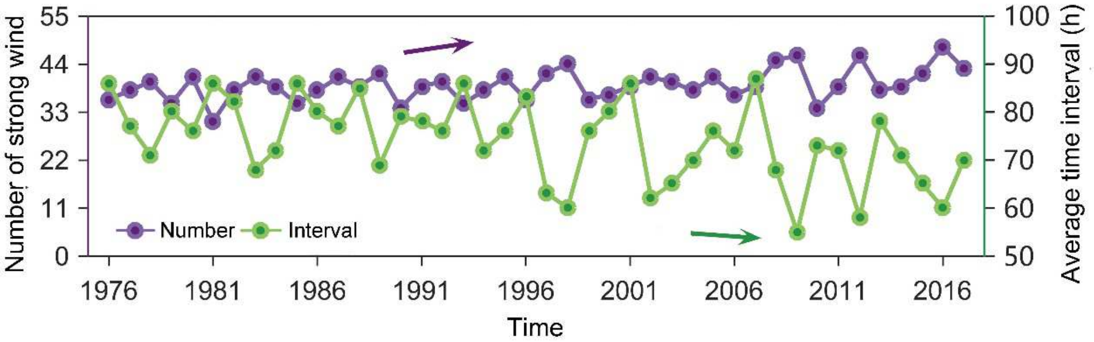

Fig. 20. Variation of the number of strong winds in autumn-winter-spring and the mean time between two strong winds since 1976.

5 Conclusions

In this study, the effect of storms on the hydrodynamics and sediment transport off the YRD were examined using a coupled modelling system including tides, waves, and sediment processes. Verifications of flow field, wave heights, tides, sediment concentrations demonstrated that the model can reproduce the hydrodynamic and sediment processes and indicated storm erosion occurring in nearshore zones of the northern YRD and Gudong.

The results of numerical experiments show that the interactions between the tide and wind-driven current during a storm period strengthen the residual currents and weaken the tidal shear front in the shallow areas. In addition to hydrodynamic changes, the strong northerly wind used in this numerical model causes the maximum wave heights of more than 2 m appearing at the Gudong coast. Under the influence of changing hydrodynamics during the storm, resuspension and sediment transport occurs, which leads to higher sediment concentration, with the maximum SSC exceeding 2.5 kg/m^3 nearshore the northern YRD. The local resuspension due to greater wave-induced bottom stress promotes the sediment plume to shift to the Gudong coast. Besides, the sediment transported offshore and southward. The dynamic and sediment transport changes under storm conditions caused significant changes in seabed erosion and siltation. The area of seabed erosion area was nearly three times as large as that under normal conditions, and the erosion volume was nearly 20 times as large as that under normal conditions. No significant recovery after a storm and frequent strong winds have an accumulative effect on the seabed erosion. The results from this study improve our understanding of the formation mechanism of the eroded coast in the YRD: the accumulated storm erosion is more likely to dominate the long-term erosive coastal states, not just the frequent avulsion and of Yellow River and subsequent discontinuity of sediment supply.

Acknowledgements

The Landsat data used in this study are available at https://glovis.usgs.gov. Sea surface wind and atmospheric pressure data obtained from ECMWF are available at http://apps.ecmwf.int/datasets/. Open ocean boundary tidal information included the major tide harmonic constituents is provided by the TPXO 7.2 Global Tidal Solution, at http://volkov.oce.orst.edu/tides/tpxo8_atlas.html. The source code of the Delft3D model is freely available at https://oss.deltares.nl/web/delft3d/source-code. The field observation data and input files which are necessary to reproduce the experiments used in this study are available upon formal request to the correspondence author (slchen@sklec.ecnu.edu.cn). This study was financially supported by the National Key Research and Development Program of China (No. 2017YFC0405503), the National Natural Science Foundation of China (No. U1706214) and the Open Research Fund of SKLEC (SKLEC-PGKF201903). The authors appreciate the two reviewers for their excellent comments and suggestions that improved this paper. We also acknowledge the editors for their assistance in editing the manuscript.

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Highlights

- Storm-induced energetic hydrodynamic forces intensify sediment resuspension and dispersal significantly.
- Wave-induced bottom stress promotes sediment plume and enhances local resuspension.
- Storms increase suspended sediment concentration and offshore sediment transport.
- Storm-induced accumulative effect on seabed scour tends to cause long-term erosion.

Conflict of interest

The authors declared that they have no conflicts of interest to this work. We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.