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

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13 **Highlights**

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

22 Abstract

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

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

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

51 **1 Introduction**

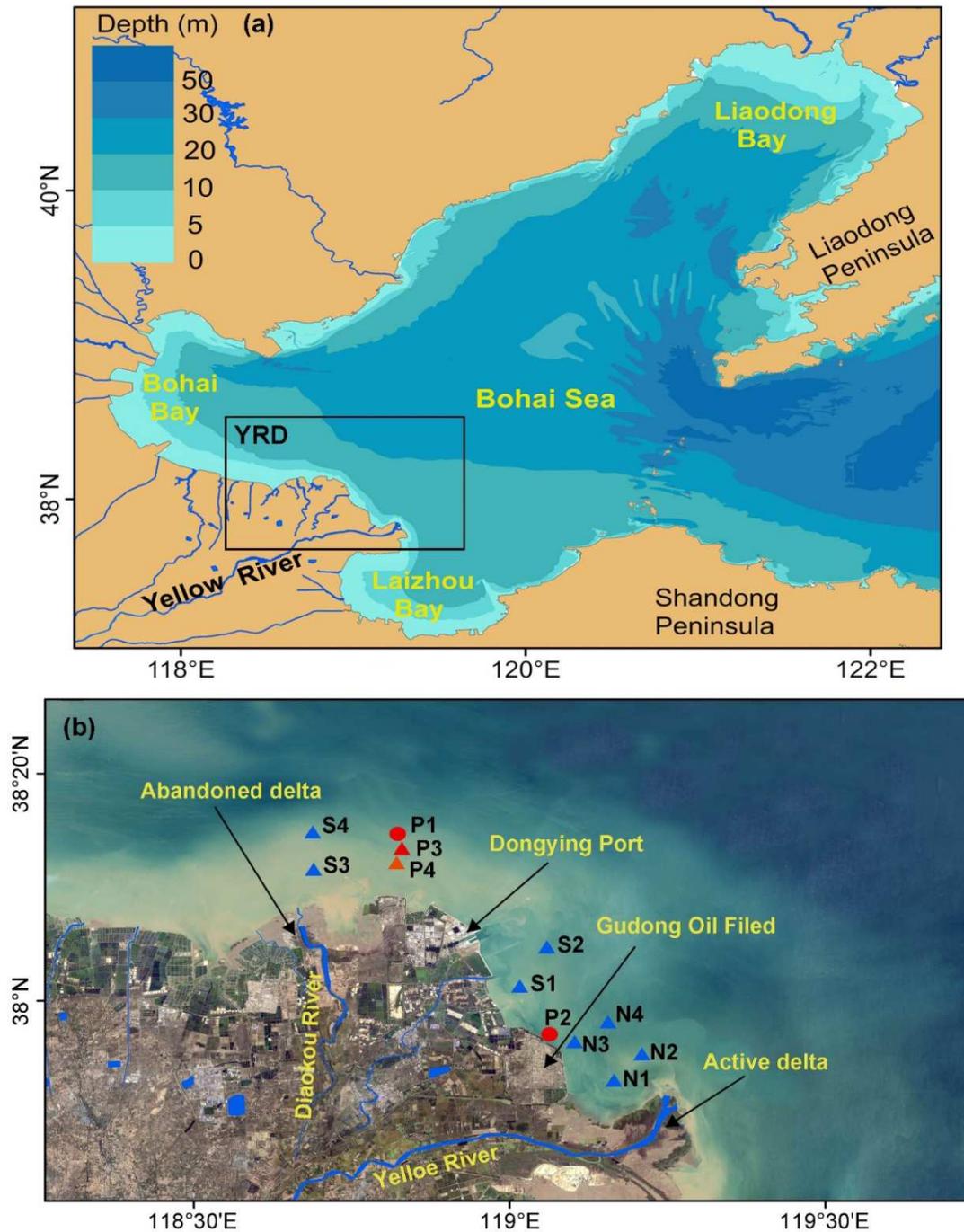
52 Fluvial discharge, wave energy and tidal range are critical in determining
53 morphological evolutions of most deltas worldwide. Sediment input to deltas has been
54 reduced or eliminated (Syvitski and Kettner, 2011; Wang et al., 2011; Dai et al., 2016;
55 Liu et al., 2019), which causes delta erosion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

63 As we known, hydrodynamic changes and sediment transport control
64 morphological evolution of deltas (Gong et al., 2014; Wu et al., 2015). These control
65 impacts varied at different time scales. Wherein, hydrodynamic changes and sediment

66 transport in storm event can belong to a short-term effect (Ralston et al., 2013;
67 Anthony, 2015; Florin et al., 2017). However, it is difficult to observe them during the
68 storm event. Therefore, the numerical model, which integrate hydrodynamics, wave
69 propagation, sediment transport and morphological changes numerical model, has
70 provided new indispensable tools to examine the effects of storm events. Numerous
71 numerical models have been developed with enhanced capability of simulating the
72 processes of currents, waves, salinities and sediments in delta areas, such as ECOM-si,
73 and FVCOM for estuarine circulations; ECOMSED for sediment transport; SWAN for
74 nearshore wave climates; and many other modelling systems, such as ROMS, MIKE 3
75 (DHI Water and Environment), and Delft3D for regional hydrodynamics and
76 morphodynamics.

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

88 Kuenzer et al., 2014; Fan et al., 2018), morphological changes (Kong et al., 2015; Xu
 89 et al., 2016; Jiang et al., 2017; Wu et al., 2017) and sediment dispersals (Wang et al.,
 90 2010; Bi et al., 2014; Wu et al., 2015).



91
 92 **Fig. 1.** (a) Computational domain and topography of the Bohai Sea; (b) Detailed study area, where
 93 blue triangles mark the locations of the vertical hydrological and sediment measurements and
 94 other marks represent the locations of continuous survey during the storm event in April 2013.
 95 Two alongshore sections are also indicated for detailed comparisons.

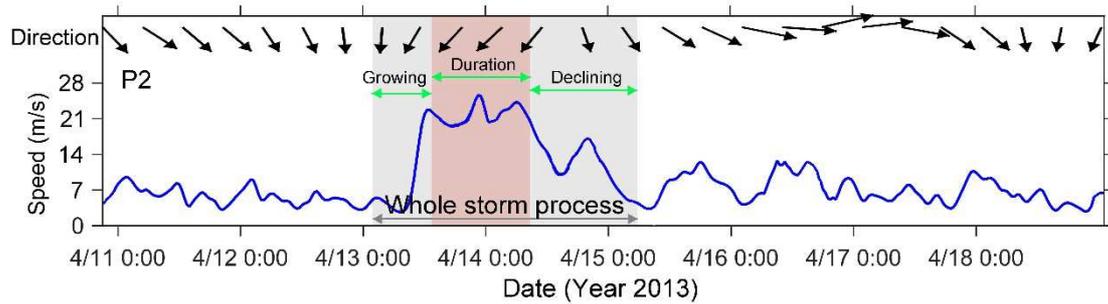
96 However, little research has been focused on the storm-induced hydrodynamic
97 and morphological processes, especially in relation to the mechanism of coastal
98 erosion. Therefore, this study focuses on exploring the hydrodynamic and sediment
99 characteristics in the YRD during storms using the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

102 **2 Model description**

103 **2.1 Study area and model grid**

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

118 m/s for 20 hours, from 12:00 on the 13th to 8:00 on the 14th (Fig. 2).

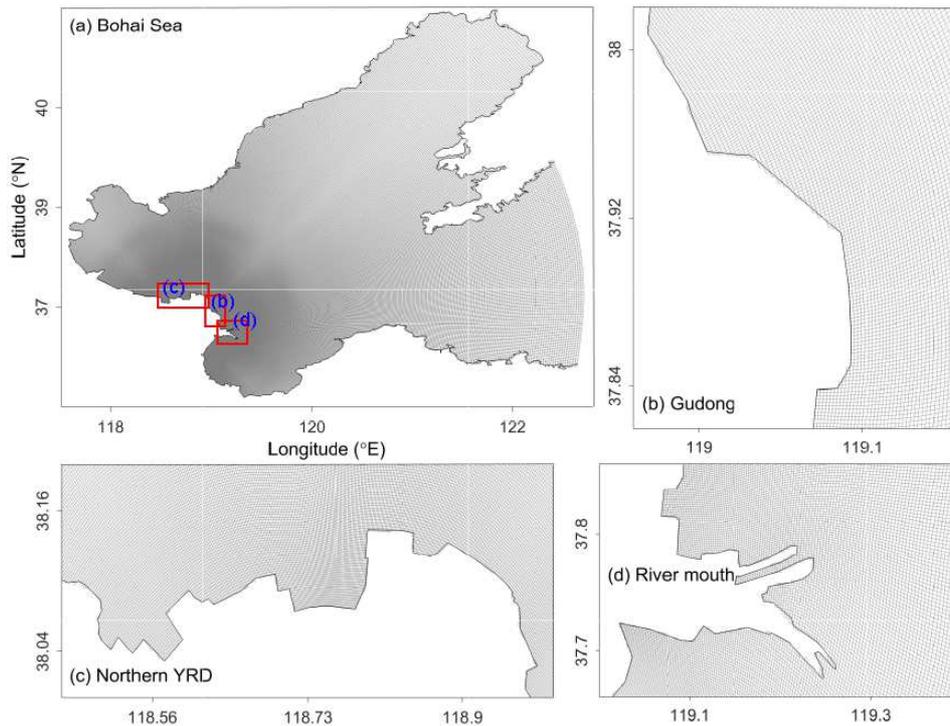


119

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

121 Since the Bohai Sea is a semi-enclosed sea, and cold-air outbreaks mostly occur
 122 northerly in this region, the model domain was set to cover the entire Bohai Sea, with
 123 an open boundary in the north Yellow Sea near the Bohai Strait. Curvilinear grid cells
 124 that cover this domain were generated by Delft3D-RGFGRID with a refined high grid
 125 resolution used in the areas of interest at the Yellow River subaqueous delta. The total
 126 number of grid cells was 771×432 (Fig. 3 a). The average grid cell spacing was about
 127 1 km; varying from the maximum mesh size of nearly 2 km at the open boundaries to
 128 the minimum mesh size of approximately 150 m along the YRD coast (Fig. 3 b-d).
 129 The topography data were based on the YRD surveys carried out in 2012 for the
 130 subaqueous delta, with a spatial resolution of 300-500 m, and coastal surveys carried
 131 out in 2009 for the other part of the Bohai Sea, with a spatial resolution of 1000-5000
 132 m, respectively (Fig. 3 a). In winter, due to the prevalence of strong northerly wind
 133 and concomitant high waves (Bi et al., 2011), the distribution of salinity, temperature
 134 and sediment in the littoral area of YRD is found to be vertically homogeneous,
 135 indicating a well-mixed water column (Yang et al., 2011). Thus, the model adopted
 136 seven layers in the vertical direction, and from the bottom layer to surface layer, the

137 values of σ were set to 0.1, 0.1, 0.2, 0.2, 0.2, 0.1, and 0.1.



138

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

142 2.2 Initial and boundary conditions

143 Using the modelling system above described, simulations started initially with a
 144 static state from the mean sea level, and zero flow velocity and sediment
 145 concentration in the domain. The coastline boundaries were determined from the
 146 high-water lines with a spatial resolution of 15 m, which were extracted from the false
 147 color composite images of Landsat OLI data. The model was driven by the tide
 148 forcing along the open boundary, consisting of 8 main tidal constituents, i.e. M2, S2,
 149 N2, K2, K1, O1, P1 and Q1, as well as surface forcing from the ECMWF (European
 150 Centre for Medium-Range Weather Forecasts) wind and atmospheric pressure data
 151 with a spatial resolution of $0.25^\circ \times 0.25^\circ$ (latitude \times longitude). Compared with the

152 storm scale in the Bohai Sea, this resolution is sufficient for modeling land-ocean
153 gradients (Lv et al, 2014).

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

163 **2.3 Parameter settings**

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

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

166 where h is the water depth (m). The bottom roughness for regions water depth below
167 1 m is prescribed by a uniform Manning coefficient of 0.025, which is the result of
168 verification of the coupled model. It should be noted that the Manning coefficient was
169 defined differently in Delft3D as $M_n=1/n$. The horizontal eddy viscosity and
170 diffusivity are calculated with the Horizontal Large Eddy Simulation (HLES) sub-grid
171 model.

172 According to Ren et al. (2012), the seabed composition off the YRD is highly

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

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

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

185 where ρ_s is the specific sediment density, 2650 kg m^{-3} ; ρ is the fresh water density,
 186 1000 kg m^{-3} ; g is gravity acceleration, and D_{50} is median size of sediment; ε_0 is
 187 comprehensive cohesion coefficient, 1.75 cm^3/s^2 ; k is a coefficient of different status
 188 of incipient motion, 0.128; δ is the thickness of pellicular water, and $\delta = 2.31 \times 10^{-5}$
 189 cm. In this study, $d' = 0.5$ mm when $D_{50} < 0.5$ mm, and $d^* = 10$ mm accordingly.
 190 Initial dry bulk density γ_0 is:

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

191 and steady dry bulk density γ_0^* is:

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

192 where e_0 is the maximum porosity, and we used $e_0 = 0.625$. For all the mud
 193 fractions, the erosion parameter M is 5.0×10^{-5} kg/m²/s, the specific density is 2650
 194 kg/m³, and the dry bed density is 500 kg/m³.

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

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

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

197 where E_i , D_i and M_i are the erosion flux, deposition flux and erosion parameter of
 198 the i th mud fraction (kg/m²/s), respectively; $w_{s,i}$ is the settling velocity of the i th mud
 199 fraction (m/s); $c_{b,i}$ is the depth-averaged concentration of the i th mud fraction
 200 (kg/m³); τ_b is the combined bed shear stress due to currents and waves (N/m); and
 201 $\tau_{b,i}$ is the critical shear stress for erosion of the i th mud fraction (N/m²). For 2D
 202 depth-averaged flow bed shear stress induced by a turbulent flow is assumed to be
 203 given by a quadratic friction law:

$$\tau_b = \frac{\rho_0 g \bar{U} |\bar{U}|}{C_{2D}} \quad (7)$$

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

210 **Table 1**

211 Sediment and mud fractions considered in the morphological model

Type	Fraction	D_{50} (μm)	τ_{ce} (N/m^2)	w_s (mm/s)	M ($\text{kg/m}^2/\text{s}$)
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	–	–	–

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

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

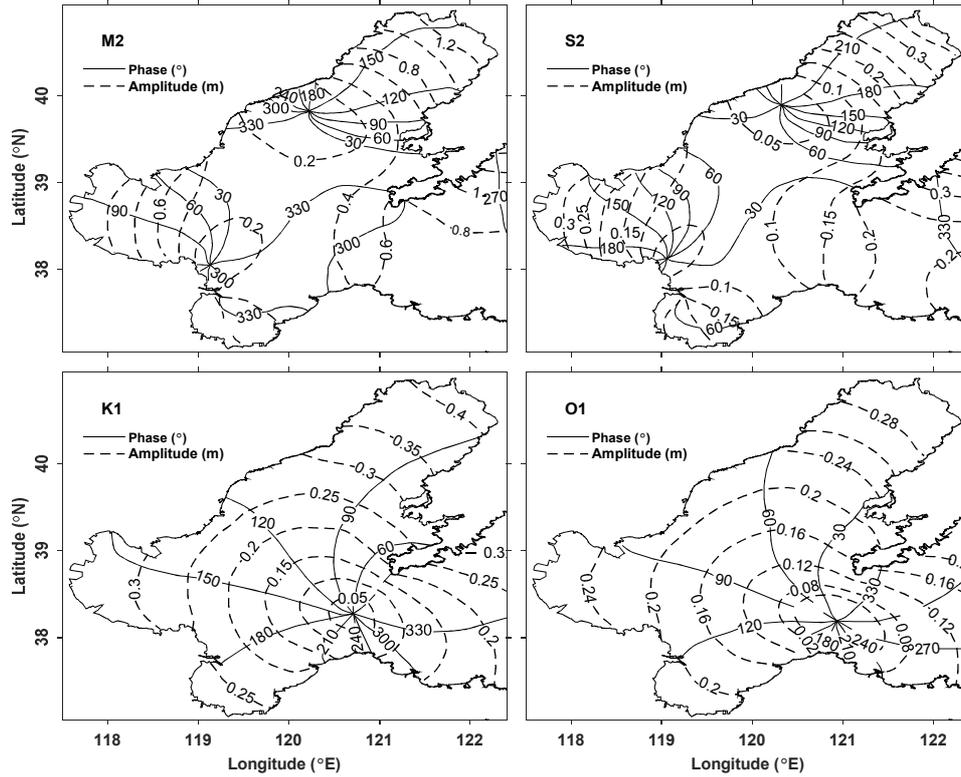
219 where c_i is the sediment concentration of the i th sediment fraction (kg/m^3), u and v
 220 are horizontal velocity components (m/s), ε_h is horizontal eddy diffusivity (m^2/s),
 221 and S_i is the source and sink term of the i th sediment fraction representing the
 222 exchange between the water column and the bed. For non-cohesive sediment transport
 223 ($\geq 64 \mu\text{m}$), we follow the approach of Van Rijn (1993).

224 **3 Model validations**

225 **3.1 Tidal regime**

226 The tides in the Bohai Sea are relatively small and fall into the
 227 micro-tidal/mixed-semidiurnal categories. Tides from the northwest Pacific

228 propagates into the Bohai Sea through the Bohai Strait. There are two amphidromic
229 points for semidiurnal tidal constituents (M2 and S2) in the Bohai Sea: one at the
230 offshore area of Qinhuangdao and the other near the Yellow River mouth. One
231 amphidromic point for diurnal tidal constituents (K1 and O1) appears in the Bohai
232 Strait. The tidal model ran 30 days in order to obtain tidal constituents harmonic
233 constants. Harmonic constants of tidal elevation of each constituent are obtained by
234 applying harmonic analysis to modeled time series of sea level at each model grid.
235 The results showed that our model successfully simulated tide systems. The co-tidal
236 and co-range lines for M2, S2, K1, O1 constituents (Fig. 4) fitted well with
237 observations (Chen et al., 1992) and the results of Huang (1995). The changes of the
238 YRD influenced its surrounding tidal wave and obstructed tidal energy (Pelling et al.,
239 2013), and the amphidromic points here calculated using new coastlines were farther
240 to land than previous studies. Also, this result agreed well with other publications
241 (Hao et al., 2010).



242

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

245 3.2 Tide velocity

246 The accurate prediction of flow velocity and direction was a crucial step for the

247 simulations of sediment transport which strongly depends on the shear stress,

248 deposition criterion, and turbulence characteristics in the bottom boundary layer. The

249 time series of currents and SSCs measured along the YRD coast were used to validate

250 the model in normal conditions. The observations were taken at eight sites, as shown

251 in Fig. 1b, at N1, N2, N3 and N4 in July 2009, and S1, S2, S3 and S4 in October 2009.

252 The correlation coefficient (CC), the skill score (SS), and the root mean square errors

253 (RMSE) were calculated to evaluate the quality of the model performance:

$$CC = \frac{\sum (X_{mod} - \bar{X}_{mod})(X_{obs} - \bar{X}_{obs})}{[\sum (X_{mod} - \bar{X}_{mod})^2 \sum (X_{obs} - \bar{X}_{obs})^2]^{1/2}} \quad (8)$$

$$SS = 1 - \frac{\sum (X_{mod} - X_{obs})^2}{\sum (X_{mod} - \bar{X}_{obs})^2} \quad (9)$$

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

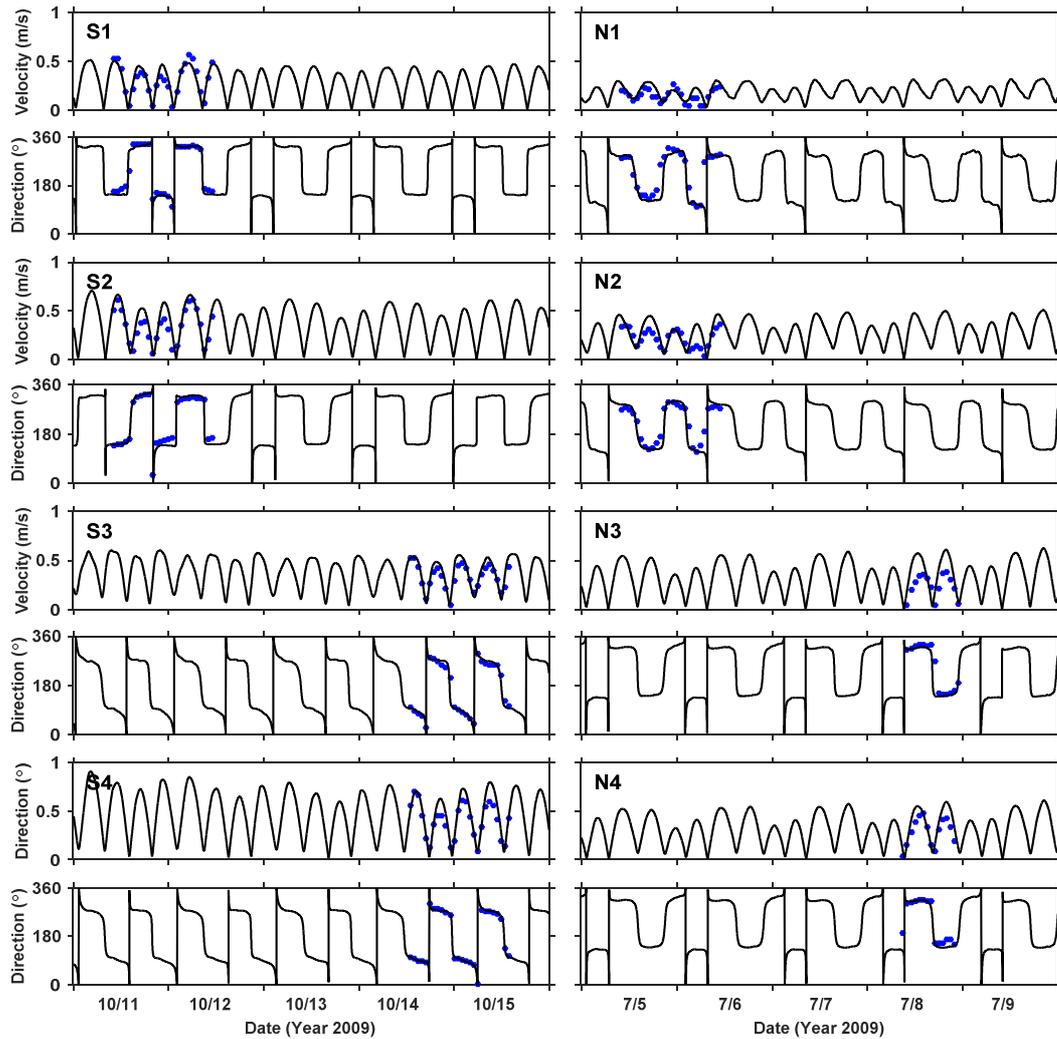
254 where X_{mod} is the modeled result and X_{obs} is the observed data. The performance of
 255 model is classified as suggested by Allen et al., 2007; Ralston et al., 2010; Luo et al.,
 256 2017 as show in Table 2.

257 **Table 2**

258 Classification of model performance

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

259 We first validated the simulations with the normal conditions. The model
 260 simulation began June 15, 2009. After running for half a year with the observed runoff
 261 and 6-hourly ECMWF re-analyzed wind, the model results were output for
 262 comparison. Comparisons of the depth-averaged flow velocity and direction with the
 263 model results and the observation data are shown in Fig. 5. The type of tidal current
 264 was semidiurnal and rectilinear, and the velocity curve showed four peaks and four
 265 valleys within one day. Statistical assessments of validation are shown in Table 3. It is
 266 clear that the average CC of flow velocity at N1-N4 was 0.78, which was lower than
 267 those at S1-S4, 0.89, because those sites locate at the river mouth, the estuarine
 268 circulation is rather complicated. The average SS at S1-S4 and N1-N4 was 0.62 and
 269 0.49 (Table 3), respectively, ranking “very good” and “good” according to the
 270 categories described above. The $RMSE$ were also reasonable.



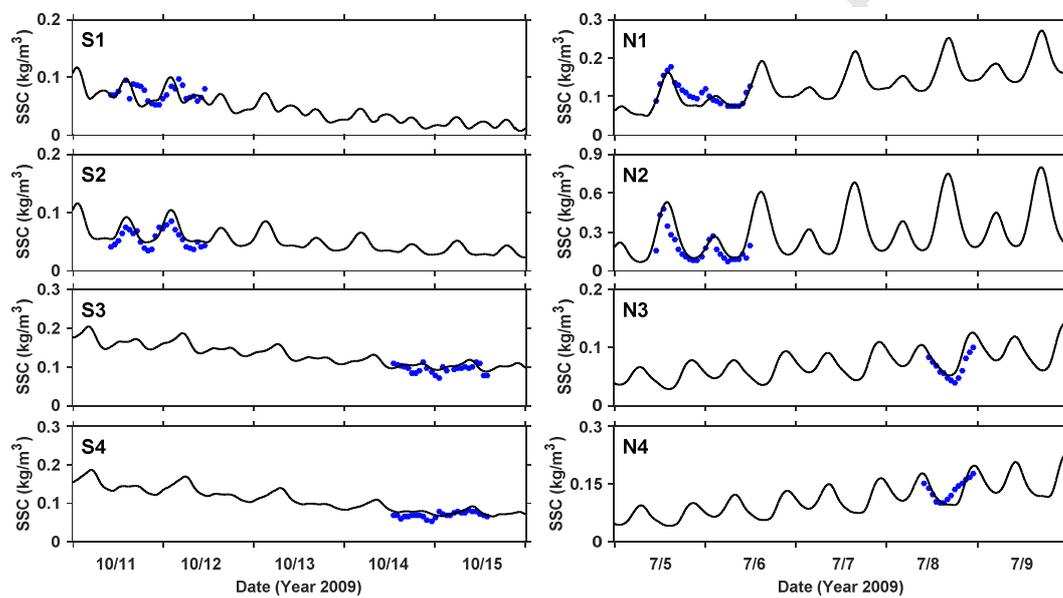
271

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

274 3.3 Suspended sediment concentration

275 The computed SSCs were compared with the observed SSCs at Sites S1-S4 and
 276 N1-N4 (Fig. 6). The computed SSC was well reproduced with tidal variation. For
 277 example, the tide had a transition from spring tides to neap tide during Oct 11 to Oct
 278 15, 2009, so the modeled SSCs of sites S1-S4 during the period had decrease trends.
 279 The modeled SSC had the same order of magnitude as the measurements. The
 280 relatively large errors between the modeled and observed data appearing at sites S3
 281 and S4 were mainly due to the erosion caused by waves, which was difficult to

282 estimate during neap tides. The average *SS* of SSC at sites S1-S4 and N1-N2 (not with
 283 N3 and N4 because of less samples) were 0.24 and 0.26 (Table 3), indicating that the
 284 model performed satisfactory. The *CC* and *RMSE* in Table 2 also illustrated the good
 285 performance of the model. The results clearly indicate that the model was properly set
 286 up and can be used to study the dynamics of sediment process off the YRD coast
 287 during normal conditions.



288
 289 **Fig. 6.** Comparison of depth-average flow velocity and flow direction between the simulated
 290 (solid line) and the observed (blue dots) at eight sites.

291 **Table 3**

292 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

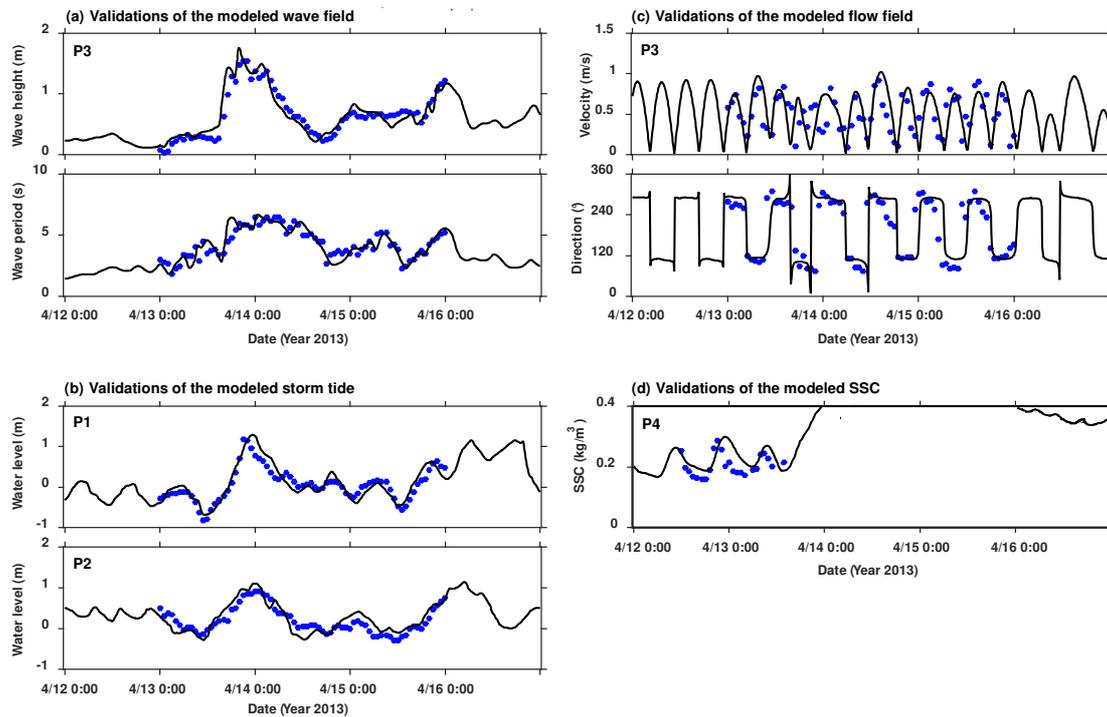
293 3.4 Storm validations

294 The measured data during a storm in April 2013 were employed for storm
 295 verification of hydrodynamic and sediment characteristics. More details of this survey
 296 can be seen in the work by Quan (2014) and Bian et al (2016). The water levels data

297 were provided by Central Platform of Shengli Oil Field (P1, locations are labeled in
298 Fig. 1b) and Gudong gauge station (P2). The flow and wave data were collected with
299 an ADCP (Acoustic Doppler Current Profilers) at P3, and the SSC data were collected
300 with a turbidity meter (OBS-3D) at P4.

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

319 model were quite consistent with the observations at these sites.



320

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

323 **Table 4**

324 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

325 4 Results and discussion

326 In total, three runs were considered in this study to examine the impacts of storm
 327 conditions on hydrodynamics and sediment transport over the nearshore seabed of
 328 YRD, as shown in Table 5. Run 1 (control run) was embedded into a
 329 wave-tide-circulation coupled model and driven by climatological daily mean river
 330 discharge and calm wind (speed below 3 m/s) as well as water flux and salinity in
 331 open ocean boundary. We can understand the characteristics of hydrodynamics and

332 sediment in normal conditions from the control run. In Run 2, the calm wind and
 333 normal atmospheric pressure conditions used in Run 1 were replaced by strong wind
 334 and low atmospheric pressure conditions (data from ECMWF) for setting storm
 335 conditions. By comparing the results of these two runs, we can quantitatively identify
 336 storm impacts. In addition, Run 3 was conducted with storm conditions without tides.
 337 The impacts of storm-induced wave on the seabed erosion were examined by
 338 comparing the results of three runs.. All the numerical experiments were run over a
 339 period of one month, beginning on April 1, 2013, and the data calculated by the model
 340 from April 13 to April 15 were used to analyze the hydrodynamic processes and
 341 sediment transport.

342 **Table 5**

343 Three different conditions for model simulations

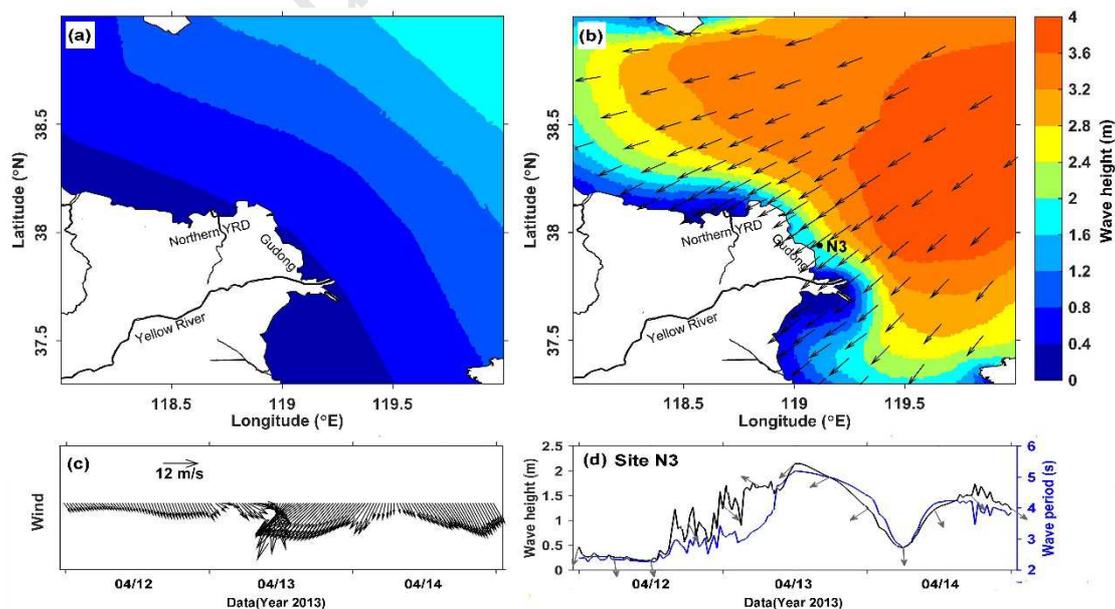
Simulation	Tide	Wind	Waves
Run 1 (control run)	Yes	No (normal condition)	Yes
Run 2	Yes	Strong	Yes
Run 3	No	Strong	Yes

344 **4.1 Waves**

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

350 The time series of wind stress for Run 2 are shown in Fig. 8c from April 12 to 14,
 351 2013. The wind vectors were surface area averaged off the YRD, and on the
 352 conventional geographical coordinate system. As shown in the Fig. 8c, strong wind

353 (more than 12 m/s) began in the morning of April 13 with directions moved from
 354 northwest to the northeast on April 13 and moved the northwest again on April 14.
 355 The northeasterly wind speeds shown two acceleration processes, in the morning and
 356 the end of April 13, respectively. The results from Run 2 showed that the wave height
 357 of approximately 2 m along the Gudong coast under the maximum wind speed, and
 358 the wave height of more than 1.2 m along the northern YRD coast (Fig. 8b). The time
 359 series of significant wave height, direction and period of site N3 is presented in Fig.
 360 8d to show the changes at temporal scales of wave features. It can be seen that the
 361 significant wave height and period were generally accordant with wind speed, and the
 362 wave directions changed with wind directions. The significant wave height reached its
 363 maximum, more than 2 m, at site N3, during the first wind acceleration process of
 364 northeasterly wind, and reached more than 1.5 m during the second wind acceleration
 365 process.



366
 367 **Fig. 8.** (a) Significant wave height during calm condition forcing for Run 1. (b-d) Wave features
 368 during the examined storm: (b) significant wave height and direction with the maximum wind
 369 speed; (c) time series of surface area averaged wind vector off the YRD (118-120°E, 37.3-38°N);

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

371 **4.2 Currents**

372 *4.2.1 Water mass transport*

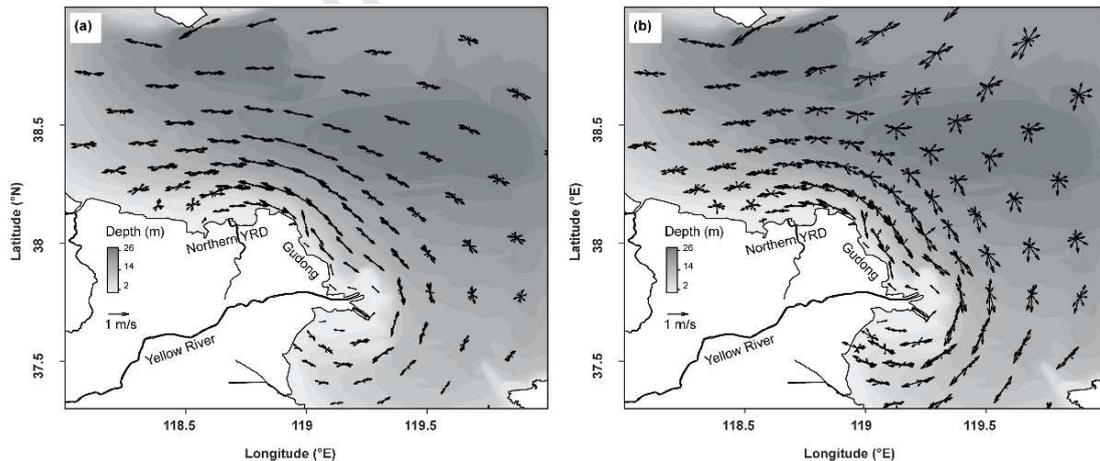
373 Storm-induced seaward coastal sediment transport can be key for to the inner
374 shelf (Goff et al., 2010). To investigate the impacts of storm-surge flood and ebb on
375 sediment transport, we first examined storm-induced current fields. The model runs
376 were either forced by calm wind (Run 1),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

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

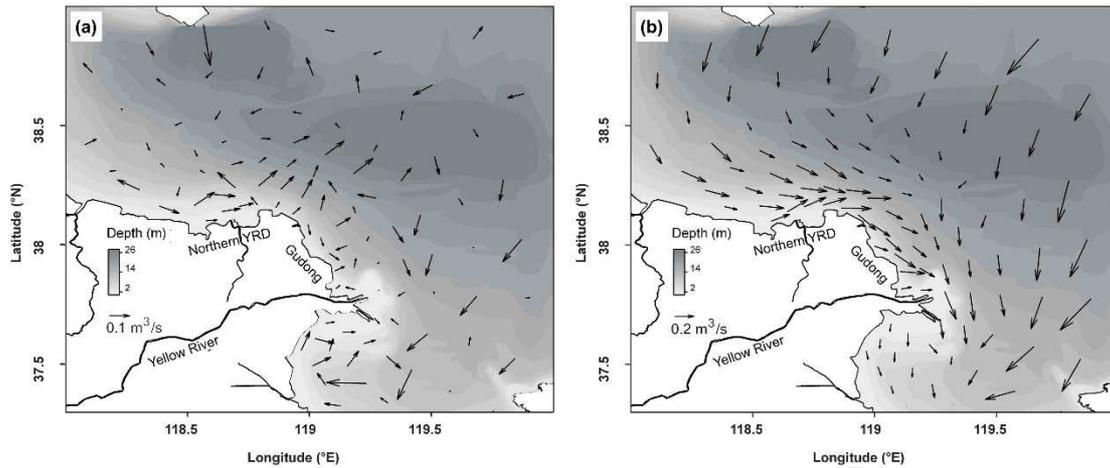
395 In order to quantitatively reveal the contributions of the storm to water mass
 396 transport, the residual transport of water (Tr_w) through a unit width was calculated,
 397 which can be defined as follows:

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

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



404
 405 **Fig. 9.** Tide velocity vectors of depth-averaged current during an ebb-flood process in (a) normal
 406 conditions and (b) storm conditions.



407

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

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

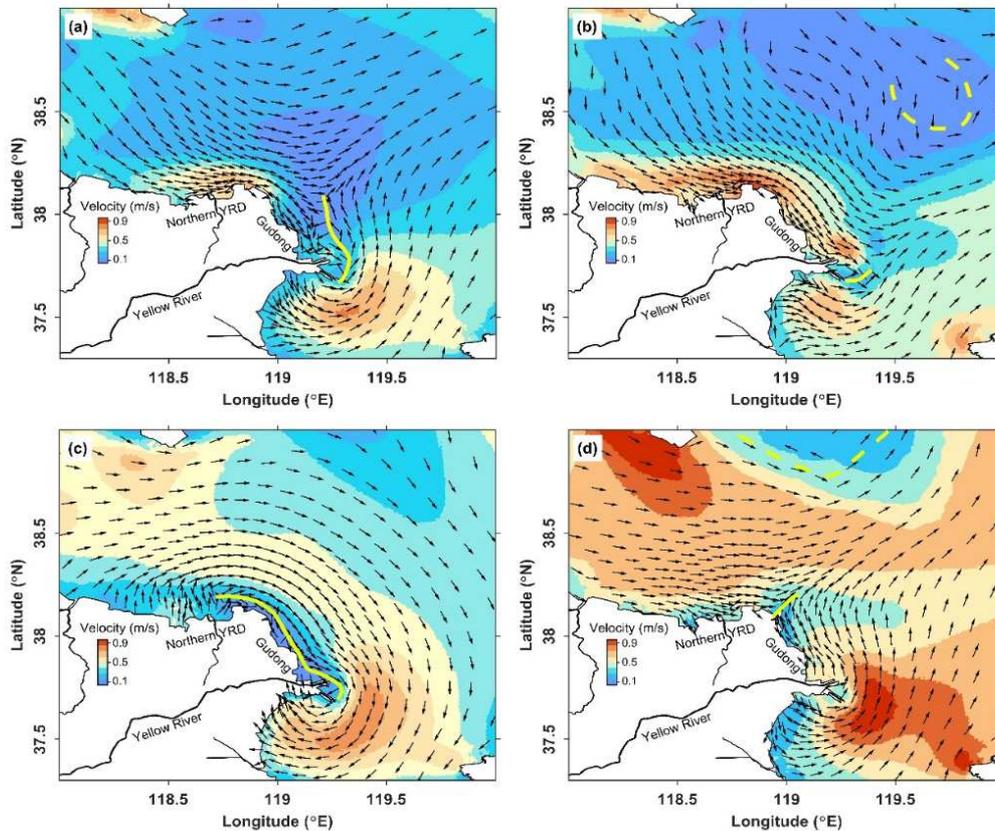
425 (Li et al., 2016).

426 *4.2.2 Tidal shear front*

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

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

447 weakened shear front, disappearance of low velocity zone, were benefit for the
 448 sediment resuspension and dispersal.



449
 450 **Fig. 11.** Locations of tidal shear front of (a) and (b) IFOE type in Runs 1 and 2; and (c) and (d)
 451 IEOF type in Runs 1 and 2. The yellow solid lines represent the fronts, and the dashed lines
 452 represent the ranges of rotated currents.

453 4.3 Sediment process

454 4.3.1 SSC

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

461 22 March 2014 (3.6 m/s average wind speed at S1-S4 and N1-N4) and 27 November
462 2012 (10.2 m/s average wind speed at S1-S4 and N1-N4) to show the turbid water
463 distribution in normal and storm conditions, respectively. The model reproduced
464 distribution of SSC matches well with the satellite images in Fig. 13, and compared
465 well with the observed data (Yang et al., 2011b; Wang et al., 2014) and the satellite
466 ocean color data (Zhang et al., 2014).

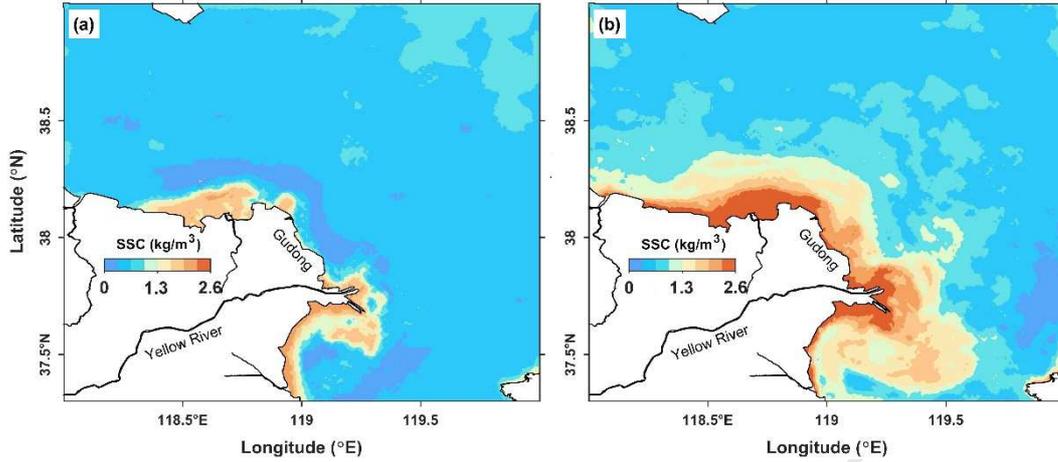
467 Bottom shear stress is an important dynamic factor for sediment erosion and
468 deposition. When the bottom shear stress is greater than the critical bottom shear
469 stress, the bottom sediment will be suspended. The total bottom shear stress (τ_{cw}) is
470 composed of current-induced bottom shear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

476 High SSC values were observed in two regions under normal conditions (Fig.
477 12a) and formed two substantial sediment plumes, one nearshore the northern YRD
478 and the other at the active river mouth, with a value about 1.5 kg/m^3 . The sediment
479 plume of the river mouth diffuses to the south, which results in the higher SSC in the
480 northern area of Laizhou Bay. Off the Gudong coast, the SSC was relatively low, less
481 than 0.5 kg/m^3 . The distribution of high and low SSC is consistent with that of τ_c
482 (Fig. 14a), which indicates that the τ_c is strong enough to stir the bottom sediment,

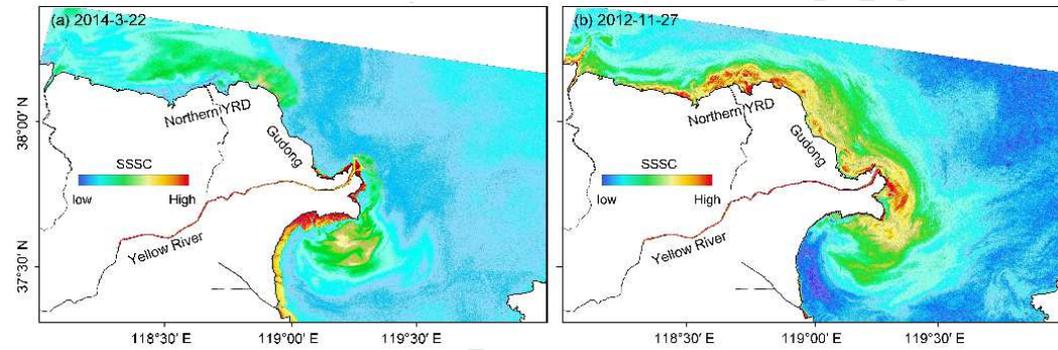
483 and formed the sediment plumes off the northern YRD and the river mouth.

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

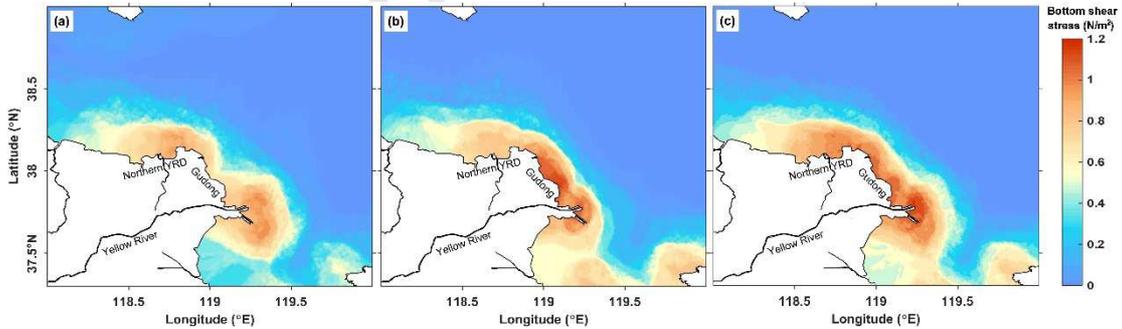
493 The characteristics of SSC distribution were related to the τ_w and τ_{cw} under
494 storm conditions. The τ_w was higher along the Gudong coast due to larger wave
495 height, where its value reached approximately 1.0 N/m^2 (Fig. 14b). The high value of
496 τ_w at the river mouth was attributed to the shallow water of the mouth bar. In the most
497 of the littoral area of YRD, the τ_{cw} reached approximately 1.1 N/m^2 (Fig. 14c), and
498 the Gudong coast with larger values which was attributed to the higher τ_w (Fig. 14b).
499 This fact indicates that the high SSC along the Gudong coast is generated by local
500 sediment resuspension in storm conditions. During storms, researchers found that the
501 waves as an important agent in the reworking and retreat at the mud-rich deltas that
502 are generally considered as either ‘river-dominated’, such as the Mississippi (Anthony,
503 2015) or ‘tide-dominated’, such as the Chao Phraya (Uehara et al., 2010).



504

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

506

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

509

510 **Fig.14.** Bottom shear stress (units: N/m^2) in the littoral area of YRD: (a) current-induced; (b)
511 wave-induced; and (c) total.512

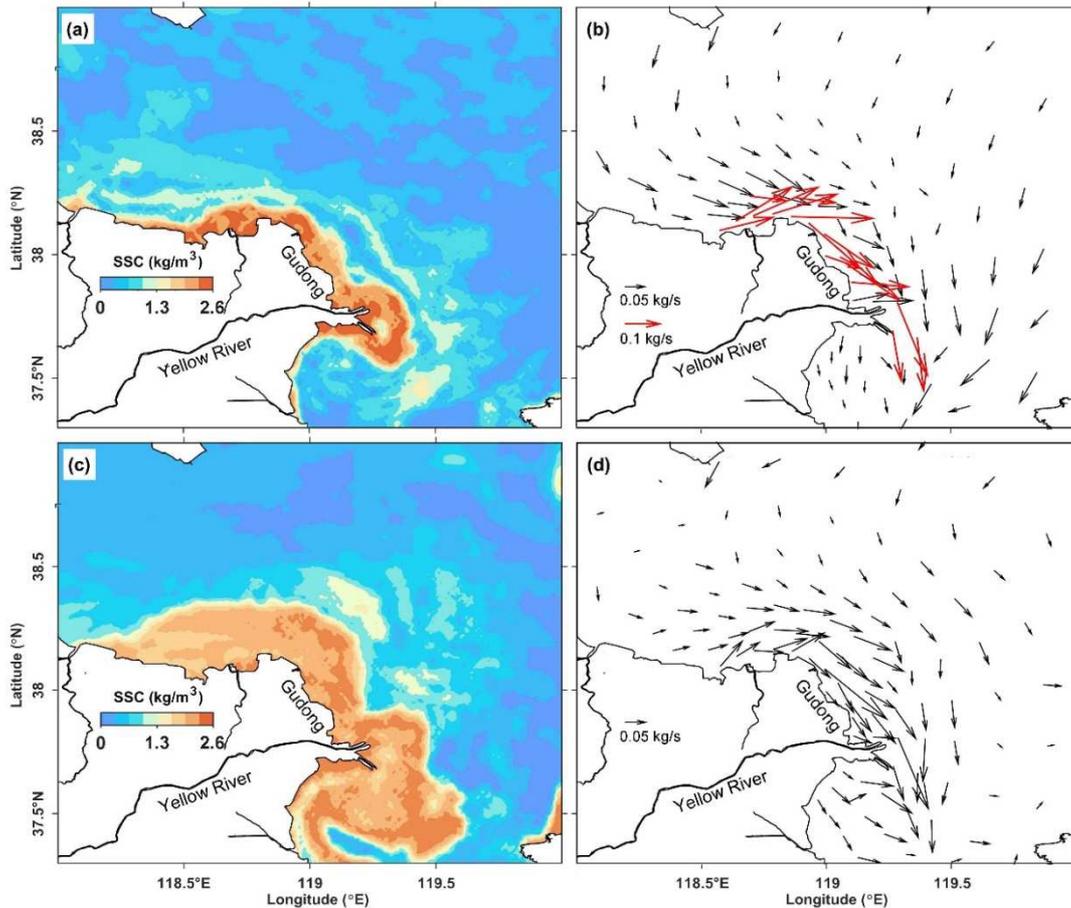
4.3.2 Sediment transport

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

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

516 where η is the surface elevation, H is the still water depth, and \vec{V} is the horizontal
517 velocity vector, C is the sediment concentration, and T is the time period. As shown in
518 Fig. 7, the whole process of the repeated storm lasted for nearly 50 hours. During the
519 whole process, a wind turn occurred, forming two strong wind periods with different
520 directions, i.e. the northeasterly wind period (NEP) and the northwesterly wind period
521 (NWP). The dividing time of these two periods was approximately the middle time of
522 the whole storm process, thus we can take 25 h as T to calculate Tr_{sed} of these two
523 periods. The average SSC and residual of sediment transport rate are shown in Fig.
524 15.

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



534
 535 **Fig. 15.** The sediment transport features: (a) the suspended sediment concentrations and (b)
 536 residual sediment mass transport during northeasterly wind; (c) the suspended sediment
 537 concentrations and (d) residual sediment mass transport during northwesterly wind.

538 During the NEP, the residual transport of sediment increased with the decrease of
 539 water depth. The larger value appeared off the Gudong coast, with the value of 0.23
 540 kg/s. Although the residual transport of sediment during the NWP was less than that
 541 during the NEP, it also showed a trend of increasing with the decrease of water depth,
 542 with a high value of more than 0.18 kg/s off the Gudong coast and river mouth. The
 543 directions of sediment transport were similar during these two periods, and basically
 544 consistent with the direction of water transport. The main difference of them occurred
 545 in the deep area, but the rates were mostly less than 0.05 kg/s. In both periods, the
 546 sediment was transported offshore and southward as a whole. Specifically, the
 547 sediment along the northern YRD coast was mainly transported eastward. After

548 arriving at the Gudong coast, sediment was transported southeast, and continued to
549 transport to the central area of the Laizhou Bay after passing the river mouth.

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

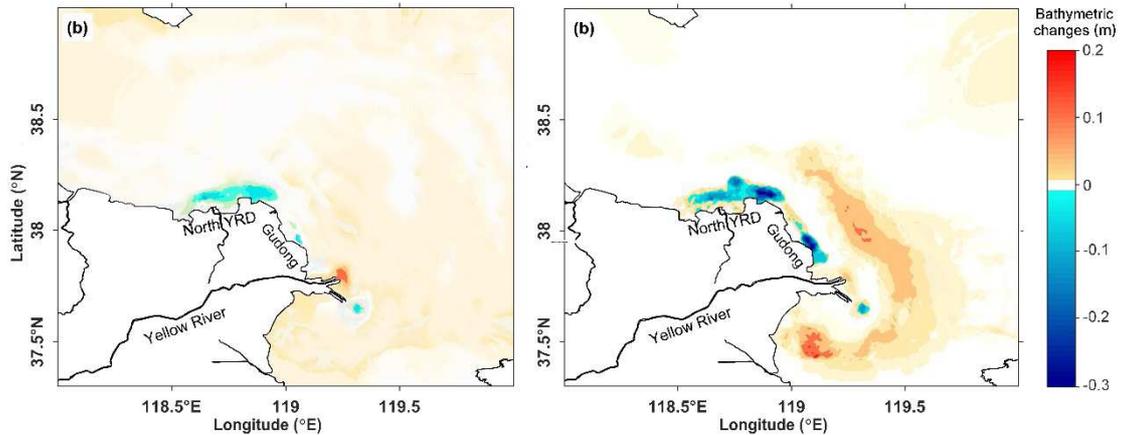
560 **4.4 Seabed erosion**

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

570 Gudong and the northern YRD reached 0.1 m to 0.15 m, even more than 0.2 m near
571 the dike area. While, the main siltation occurred in the central area of Laizhou Bay.
572 Overall, the area (off the YRD, 118°E -120°E, 37.3°N -38°N) of seabed erosion in
573 storm conditions was 362.67 km², nearly 3 times as large as that in normal conditions,
574 and the erosion volume is 0.0543 km³, about 20 times as large as that in normal
575 conditions. Therefore, the seabed erosion caused by the changes of hydrodynamics
576 and sediment transport under storm surge is an important factor in the coastal seabed
577 erosion of the YRD.

578 In order to explore the seabed changes after the storm, the bathymetric changes
579 during the recovery period after the storm were calculated. The time range of recovery
580 period was determined according to the wind speed and direction observed in P2 site.
581 As shown in Fig. 17, the end of this strong wind at 3:00 on April 15, indicating the
582 recovery period began at this time. At the time of 22:00 on April 18, strong wind
583 occurred again, indicating the recovery period began at this time and it lasted totaling
584 91 hours. Similar to the SSC calculated in the normal conditions in experiment 1, the
585 SSC off the north YRD and the active river mouth area was about 1.5 kg/m³, while in
586 other areas it was less than 0.5 kg/m³ (Fig. 18a). The residual transport of sediment
587 through a unit width was also similar to that calculated in Experiment 1 in light wind
588 conditions. There was no strong deposition or erosion area, and it was basically in the
589 equilibrium state during recovery period (Fig.18b). Along Guong coast, which had
590 been severely eroded during storm period, the bathymetry did not change significantly.
591 It can be seen that it was difficult to recover the seabed erosion in the short term after

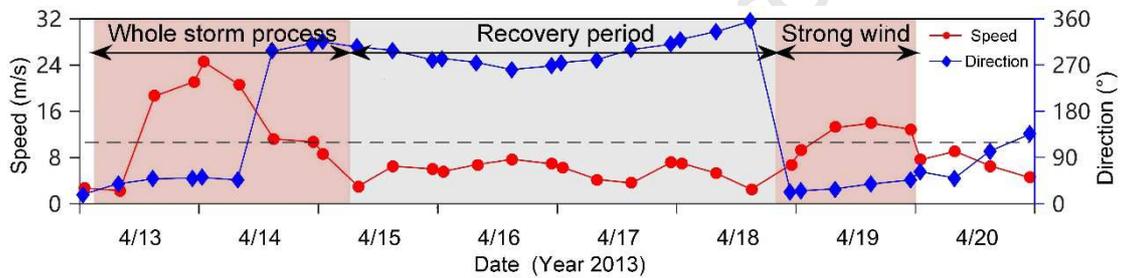
592 the storm, due to the insignificant sediment transport and deposition.



593

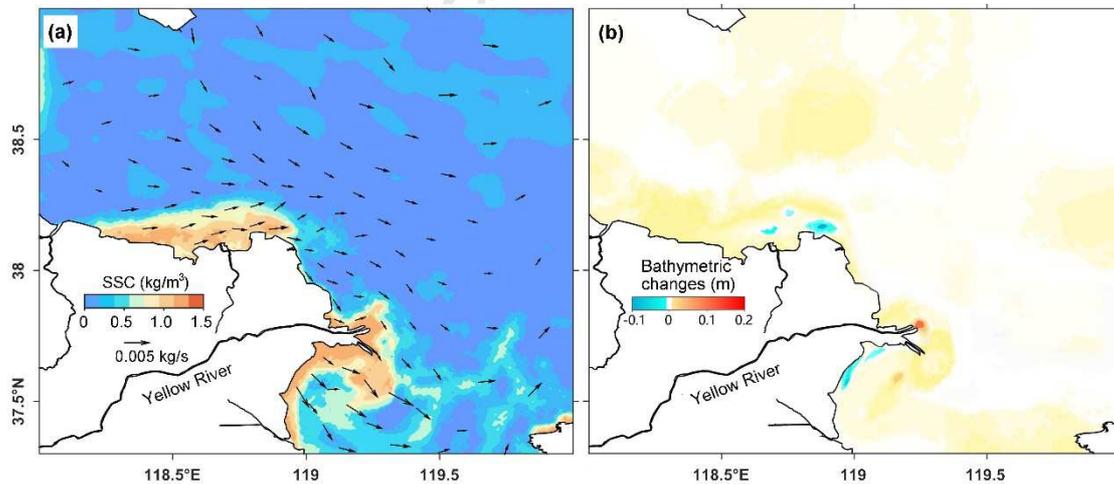
594 **Fig. 16.** Computed bathymetric changes (a) in normal conditions, and (b) in storm conditions.

595 Positive values represent accretion and negative values represent erosion.



596

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



598

599 **Fig. 18.** (a) Suspended sediment concentrations and residual sediment mass transport after the

600 storm; (b) erosion and accretion pattern after the storm.

601 4.5 Frequency of strong wind

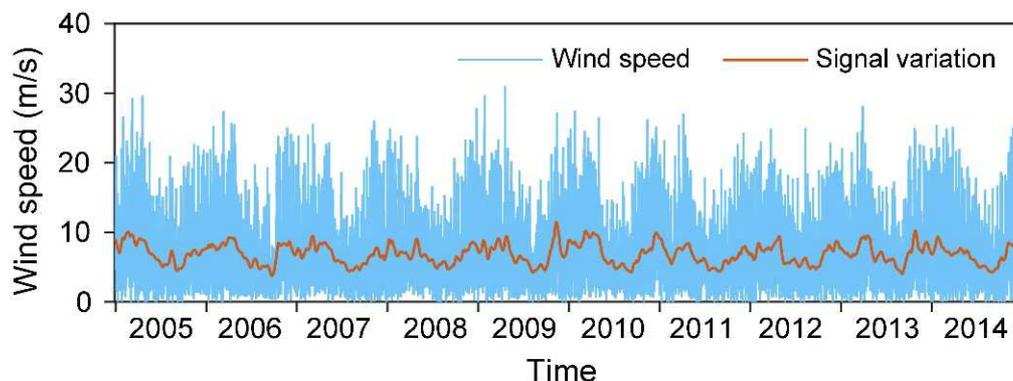
602 The northern YRD and the Gudong coast are abandoned delta lobes, which

603 underwent erosion after the river channel shifted southward. Despite of the coastal

604 defenses (dikes) being built, the overall coastal area continued to be in the state of

605 erosion and coastal managers were obliged to build protection works constantly, for
 606 example the pipe pile projects outside the destroyed dikes in 2004 and in 2016.
 607 Previous studies attributed the long term erosion to the avulsion of Yellow River and
 608 subsequent lack of sediment supply (Li et al., 2000; Xing et al., 2016), while this short
 609 timescale event hardly explain the long-term eroded states.

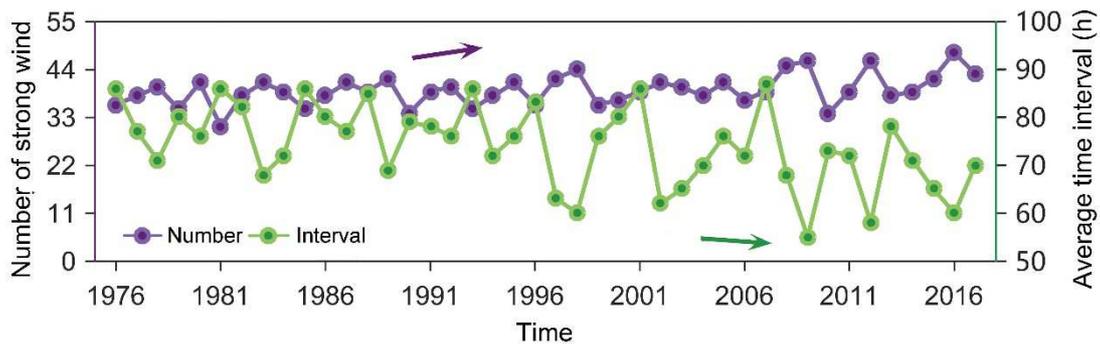
610 Although the winter storm surge is an extreme event, the storm-induced coast
 611 erosion plays an important role in the coastal geomorphological changes of the YRD.
 612 On the one hand, the effects of a storm give a distinguished interpretation for the
 613 seabed erosion, and on the other hand,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



621
 622 **Fig. 19.** Time series of observed wind speed and the signal variations in a monthly scale.

623 Using the ECMWF wind data, the frequency and interval time of strong wind in

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



633
 634 **Fig. 20.** Variation of the number of strong winds in autumn-winter-spring and the mean time
 635 between two strong winds since 1976.

636 5 Conclusions

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

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

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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.

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