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RESEARCH ARTICLE

Influence of bathymetry evolution on position of tidal shear front and hydrodynamic characteristics around the Yellow River estuary

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Abstract A three dimensional numerical model based on the hydrodynamic module of finite-volume coastal ocean (FVCOM) was established for the Yellow River estuary. The model has been calibrated by observed data and proved to be suitable to reflect the hydrodynamic force in the research area. We employed the model to simulate the tidal shear front off the Yellow River estuary and analyzed the formation, spread and duration of two different types of shear front. To examine the effect of bathymetry evolution on the position of tidal shear front, subaqueous bathymetry of the Yellow River estuary was changed according to the changing patterns obtained from the past few years. Tidal shear front was modeled on both the original and the changed bathymetry. The results show that the position of shear front moved from a shallow to a deep area due to the deposition of bathymetry. The influence of bathymetry evolution on hydrodynamic characteristics including the distribution of salinity and the movement of particles was studied. We found the dispersion areas of low salinity became larger after changing bathymetry and the particles on the surface, middle and bottom layer are able to move further both north and west of Laizhou Bay on the changed bathymetry.

Keywords Yellow River estuary, shear front, hydrodynamic force, bathymetry evolution, salinity

1 Introduction

The Yellow River, the second largest river in China with average runoff of 33.21×10^9 m^3, is best known for large sediment transportation and frequently shifting course in its lower reaches (Milliman and Meade, 1983). Approximately 0.84×10^9 t of sediment are delivered annually to the Bohai Sea. The Yellow River, stretching from south-west to north-east, was shifted from the Qingshuigou course to the Q_8 course manually in August 1996 (Zhong and Liu, 2003). The Yellow River estuary is in the place where the Laizhou Bay and Bohai Bay meet and is dominated by an irregular semi-diurnal tide. The tide elevation varies from 0.6 to 0.8 m around the estuary, but increases to 1.5–2.0 m in the south of Laizhou Bay (Zhang et al., 1990). There is an amphidromic point of M_2 tidal constituent located in the north-west coastal area of Wuhaozhuang station (Shi and Zhao, 1985). Since the major tidal constituent in this area is M_2 and its ellipse's long axis is much longer than the short axis, reciprocating tidal currents paralleling with coastline flow south during flood tide and north during ebb tide. The Yellow River delta is formed and developed by the large amount of sediment from the Yellow River, so the subaqueous bathymetry of the Yellow River estuary changes rapidly, which exerts significant influence on the hydrodynamic characteristics around the adjacent waters. Hu et al. (1996) reported that the amphidromic point for M_2 moved 5 km to the south-east because of the changes of bathymetry in the past few years (1976–1994). Zhou et al. (1996) indicated a strong tidal current zone was formed in front of the Yellow River delta owing to the accumulation of sediment around the estuary. Tidal shear front, as a kind of special hydrodynamic phenomenon off the Yellow River estuary, has drawn attention from many scholars.

A shear front is defined as an interface between two water bodies with opposing flow directions or significantly different velocities. The shear front is usually a transient and local dynamic process with particular geometry and hydrodynamics regime (Shen and Kuo, 1999). It is often found at the estuaries and interface between two oceans. According to the observed data of Saint Lawrence estuary,

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Ingram (1976) introduced the concept of shear front for the first time. Huzzey and Brubaker (1988) studied the shear front of York River. Tidal shear front off the Yellow River was first discovered by Li et al. (1994), in which they described the basic characteristic of the shearing zone and discussed reasons for its formation. Li et al. (1998, 2001) concluded that tidal shear front off the Yellow River estuary is the result of river-sea interaction. The perpendicular angle between river outflow and main axis of tidal current is the main environment to generate tidal shear front. Each shear front lasts for about 2–3 h with landward propagation. In contrast, Wang et al. (2007) argued that the shear front propagates seaward with similar duration. Qiao et al. (2008) simulated tidal shear front off the Yellow River using ECOMSED (Estuarine, Coastal and Ocean Modeling System with Sediments), discussed the reasons for the generation and pointed out that bathymetry performs an important role in the formation of tidal shear front. In addition, Bi et al. (2010) analyzed the causes and mechanisms of tidal shear front off the Yellow River estuary.

Most previous publications studied tidal shear front off the Yellow River estuary by in situ observations (Li et al., 1994, 1998, 2001; Wang et al., 2007; Bi et al., 2010). Less attention has been paid to study the formation, spread, and duration of tidal shear front numerically. No studies have yet demonstrated the influence of bathymetry evolution on the salinity and the movement of particles via numerical simulations.

In this paper we built a three dimensional model of the Yellow River estuary based on the hydrodynamic module of FVCOM (3D unstructured grid, finite-volume coastal ocean model), employed the model to simulate tidal shear front off the Yellow River estuary, and studied the influence of bathymetry evolution on the position of shear front, distribution of salinity, and the movement of particles around the Yellow River estuary.

2 Numerical model and setup

2.1 Model description

An unstructured grid, finite-volume coastal ocean model (FVCOM), which was developed by Chen et al. (2003a), has been adopted in this study. The model contains continuity, momentum, temperature, and salinity equations and is closed physically and mathematically using the Mellor and Yamada level 2.5 turbulent closure schemes (Mellor and Yamada, 1982). Unstructured mesh is employed in the horizontal by FVCOM to fit complicated coastal boundaries. A terrain-following sigma coordinate system is used in the vertical to represent the irregular bottom bathymetry.

The governing equations are listed below:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv =-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)+F_u, \quad (1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu =-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}\left(K_m\frac{\partial v}{\partial z}\right)+F_v, \quad (2)$$

$$\frac{\partial P}{\partial z}=-\rho g, \quad (3)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \quad (4)$$

where x, y, and z are the east, north, and vertical axes in the Cartesian coordinate system; u, v, and w are the x, y, and z velocity components; K_m is the vertical eddy viscosity coefficient; ρ is the density; P is the pressure; g is the gravitational acceleration; f is the Coriolis parameter; F_u, F_v represent the horizontal momentum terms on the x,y direction, respectively.

The equations for temperature and salinity are solved in the FVCOM:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial T}{\partial z}\right)+F_T, \quad (5)$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial S}{\partial z}\right)+F_S, \quad (6)$$

where T is the temperature; S is the salinity; K_h is the thermal vertical eddy diffusion coefficient; and F_T and F_S represent thermal and salt diffusion terms, respectively.

FVCOM has been proved to be suitable to study oceans and estuaries. Chen et al. (2003a) used FVCOM to simulate hydrodynamic forces in the Bohai Sea successfully; Guo et al. (2009) adopted FVCOM to simulate the typhoon-induced storm surge in the Hangzhou Bay; Ma et al. (2011) applied the model to reproduce the hydrodynamic characteristics of the Yangtze River estuary.

2.2 Model configuration

The computational area covers 118.80°–120.47° E, 37.15°–38.19° N, which spans the Laizhou Bay containing the Yellow River estuary (Fig. 1). Figure 2 shows the computational unstructured grid. To fit the irregular coastline well, the minimal horizontal resolution in the study area is about 85 m around the Yellow River estuary, while the maximal resolution is 3200 m. The domain includes 19590 triangular meshes and 10106 nodes. For the vertical resolution, 10 uniform sigma layers were specified. The bathymetry data used in the paper was provided by the Navigation Guarantee Department of the Chinese Navy Headquarters and interpolated to the nodes by inverse distance weighting (Fig. 1).

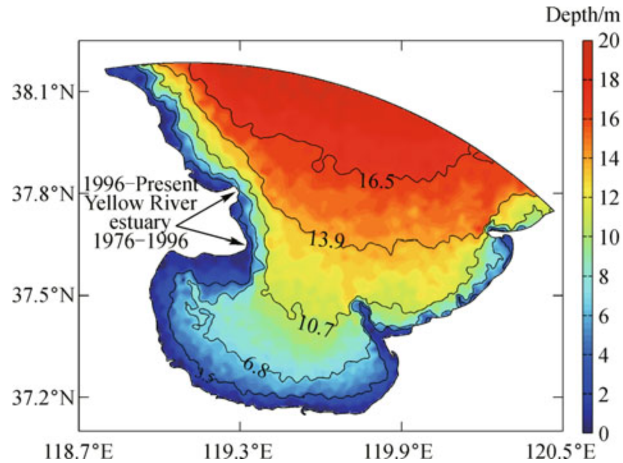

Fig. 1 Bathymetry of Laizhou Bay

The harmonic constants of M_2, S_2, K_1, O_1, K_2, N_2, P_1, and Q_1, obtained from OTPS (OSU Tidal Prediction Software), which was developed by Oregon State University, were interpolated to the open boundary which is set at the north of Laizhou Bay. Monthly temperature and salinity data derived from the data set of National Oceanographic Data Center (NODC) were interpolated to the open boundary. The initial salinity and temperature were set to zero and 20°C at the river boundary, respectively. The Yellow River runoff was derived from River Sediment Bulletin of China published by the Ministry of Hydrology of China. The bottom roughness z_0 was set to 0.0025 m. The meteorological parameters, including wind at 10 m above the sea level, air temperature, cloudy cover, precipitation rate, and evaporation rate, were extracted from the data set of NODC. Heat forcing at the air-sea interface was calculated by the method presented by Rosati and Miyakoda (1988). According to the CFL (Courant-Friedrich Levy) stability criterion, the internal time step was 10 s while the external time step was 1 s. The model was driven by cold start. To obtain stable prediction results, the simulation lasted for three years, spanning from January 1, 2001 to December 31, 2003. The results of summer of 2003 were analyzed in this paper. The model was run on a Linux system on the Lenovo DeepComp 6800 High Performance Computer System.

3 Numerical model validation

To validate the model's capability in the study area, the results of tidal elevation, current, and salinity obtained from the model were compared with observed data. The observed station locations are shown in Fig. 3.

3.1 Tides and currents

The data of two observed stations and two tidal gaging stations derived from the Tide Tables. (National Marine Data and Information Service, 2003), were chosen to validate the tidal elevation in the computational area (Fig. 4). In Fig. 4, the numerical results were in good agreement with the observed data. The model could reflect well the variation of tide in the study area.

Comparisons of current velocity and direction at ten observed stations (A1, A2, A3, A4, B1, B2, B3, B4, C1, and C2) between the model results and observed data were shown in Fig. 5. The comparisons showed that the model predicted the current direction well in Laizhou Bay. Some

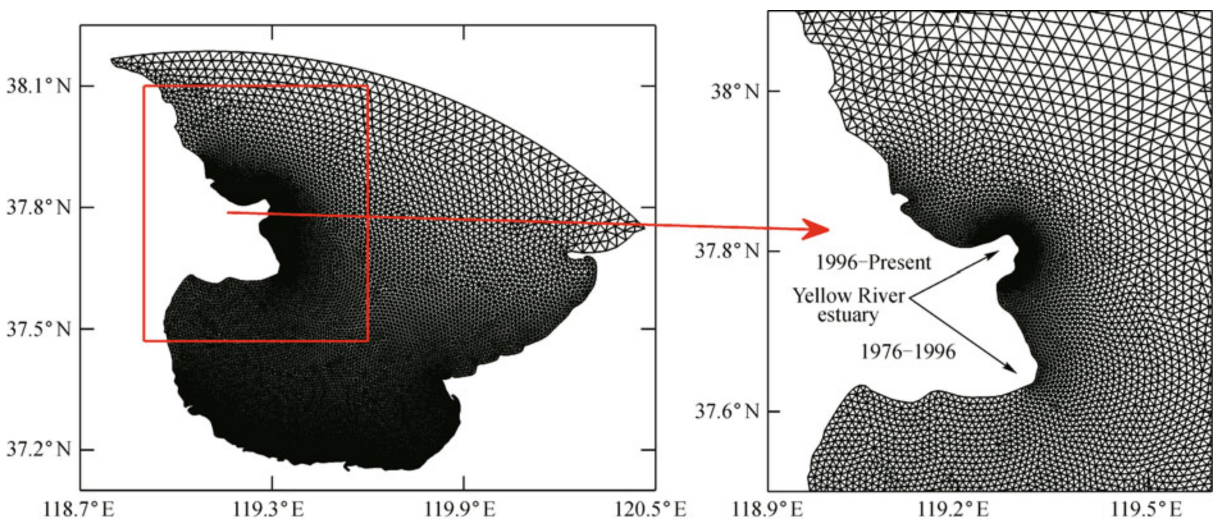

Fig. 2 Computational unstructured grid of Laizhou Bay

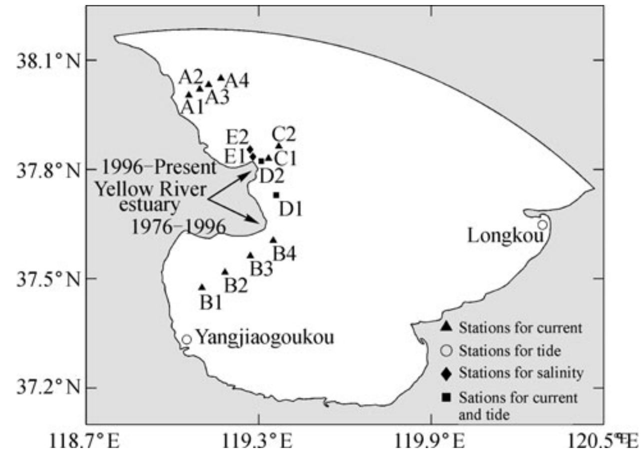

Fig. 3 Locations of observed stations

small discrepancies were found in the comparisons of current velocity, which could be due to the fact that the current inflow at the open boundary was omitted because of the lack of data.

The tidal constituents M_2, S_2, O_1, and K_1 were analyzed in this study. The co-amplitude and co-phase of each tidal constituent are shown in Fig. 6. The modeled results have been confirmed to be in good agreement with the observed data (Editorial Board for Marine Atlas, 1992). It is clearly seen that the predicted amphidromic point of M_2 was near the Wuhaozhuang station which was located at the north-west of Laizhou Bay (Shi and Zhao, 1985).

3.2 Salinity

As shown in Fig. 7, salinity simulated by the model was compared with the observed data at stations E1 and E2, respectively. The numerical results fitted well with measurements. Although it was difficult for the model to capture the sudden change of the observations due to insufficient data, the trend of simulations was consistent with the observed data in general.

The numerical result of salinity distribution on the surface around the Yellow River estuary was compared with observed data as well (Fig. 8). Deviations were detected between observed data and numerical results at the south of the Yellow River estuary, which was induced by the coarse wind data. Nonetheless, the simulated results showed overall qualitative agreement with the observed data.

In addition, at transect T1-T2-T3 (the position of this transect is shown in Fig. 9), the observed longitudinal distribution of mean salinity and the corresponding numerical results were compared (shown in Fig. 10). The simulation showed obvious stratification around station T3 between 0 and 7 m below sea level where the salinity is about 27–31 psu. Similar phenomena were also found from the observation data shown in the right panel of Fig. 10. Consequently, the model predicts the general trend of longitudinal salinity distribution successfully and is consistent with observation.

After validation of tidal elevation, current, and salinity, the model built in this paper was proven to be able to accurately reproduce hydrodynamic force and salinity in the study area.

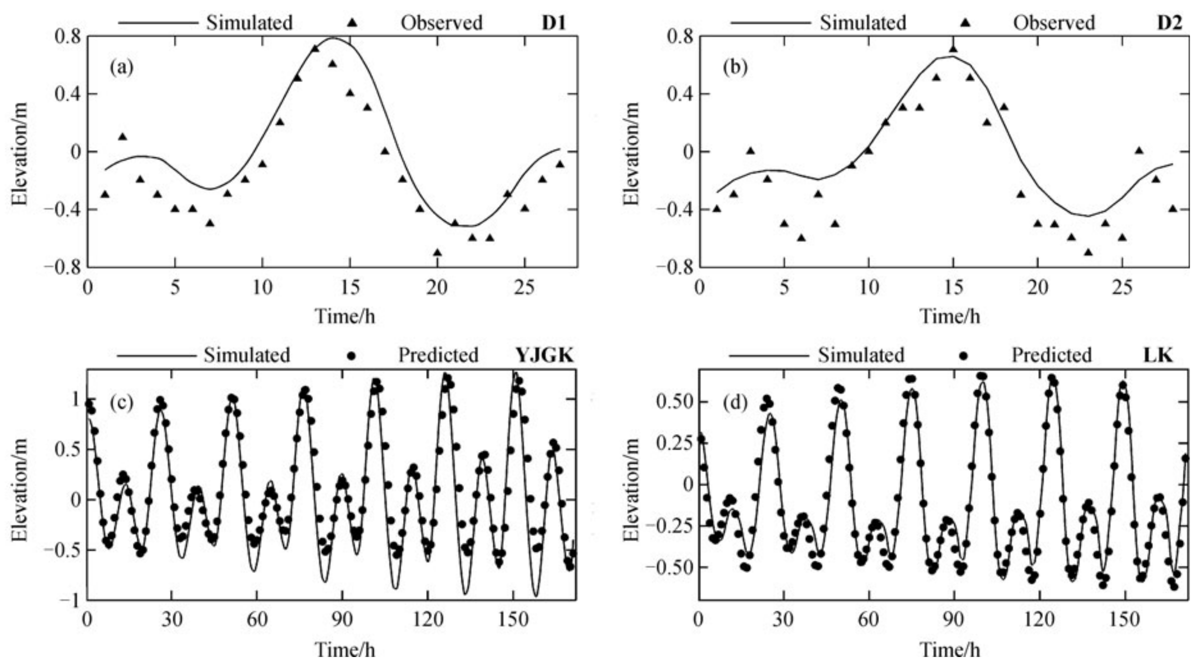

Fig. 4 Comparisons of observed and modeled tidal elevation ((a) and (b) are for D1 and D2, (c) and (d) are for Yangjiaogoukou (YJGK) and Longkou (LK))

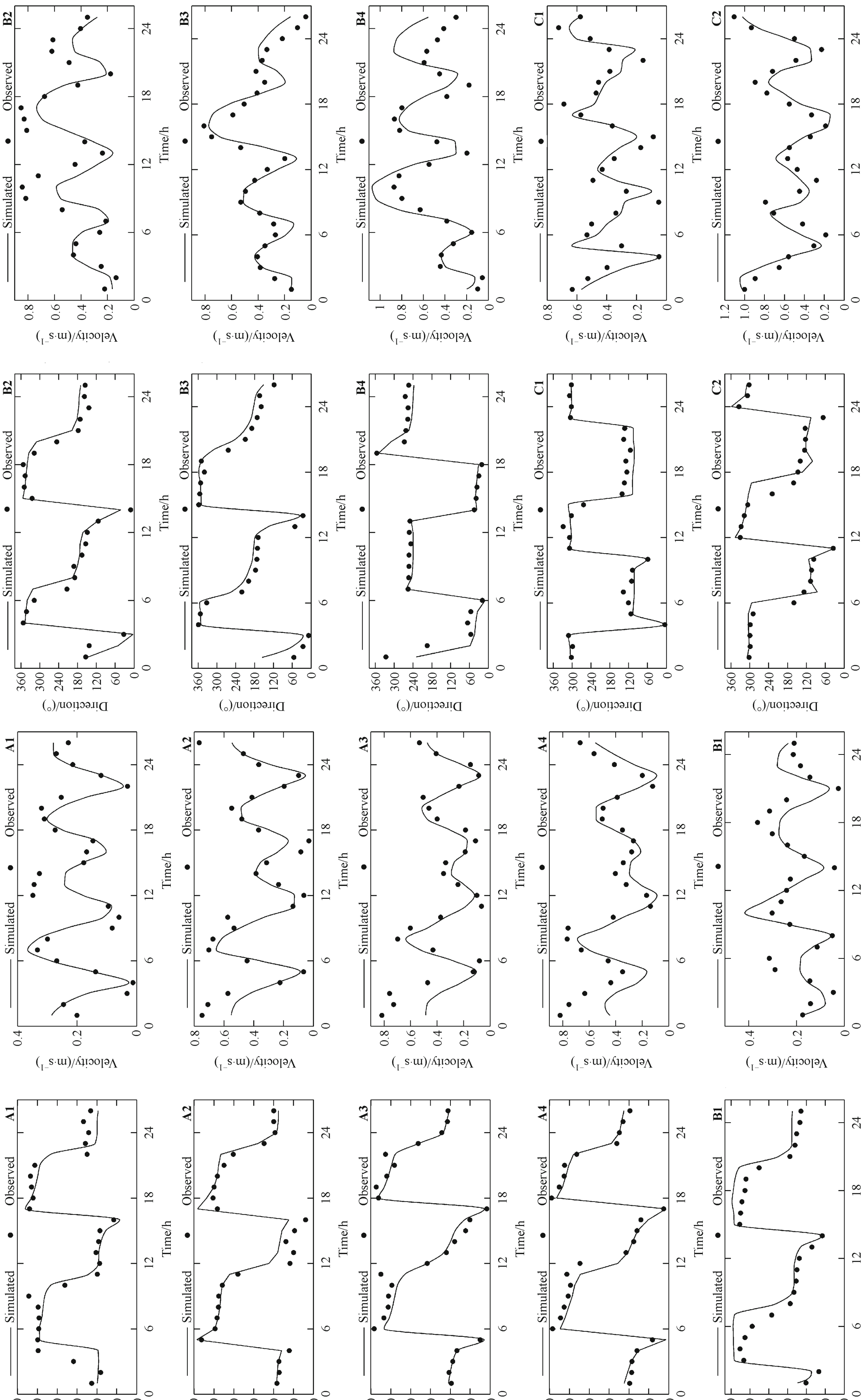

Fig. 5 Comparisons of observed and modeled current velocity and direction(A1, A2, A3, A4, B1, B2, B3, B4, C1, C2)

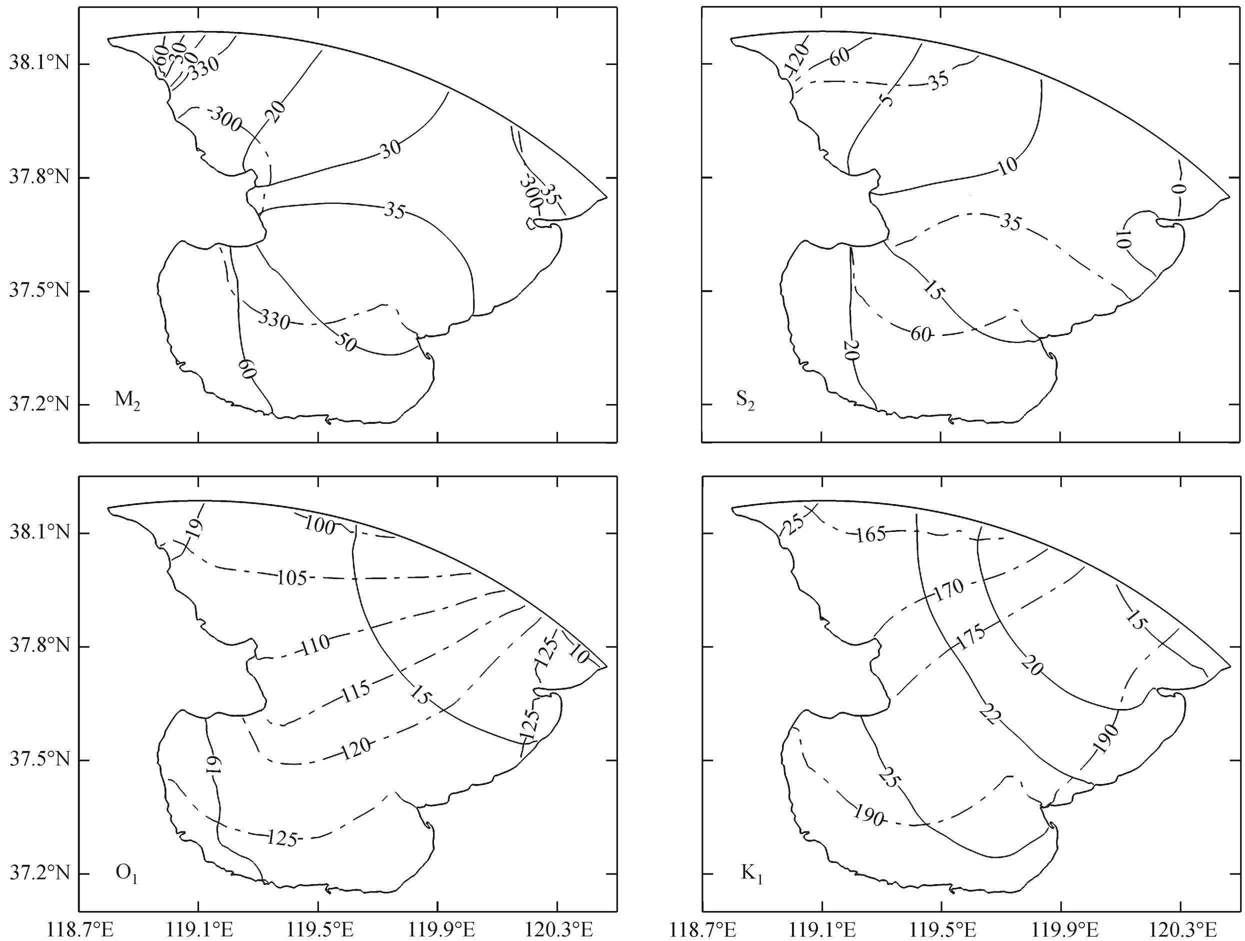

Fig. 6 Co-amplitude line (solid line, in cm) and co-phase line (dashed line, in degree) of M_2, S_2, O_1 and K_1

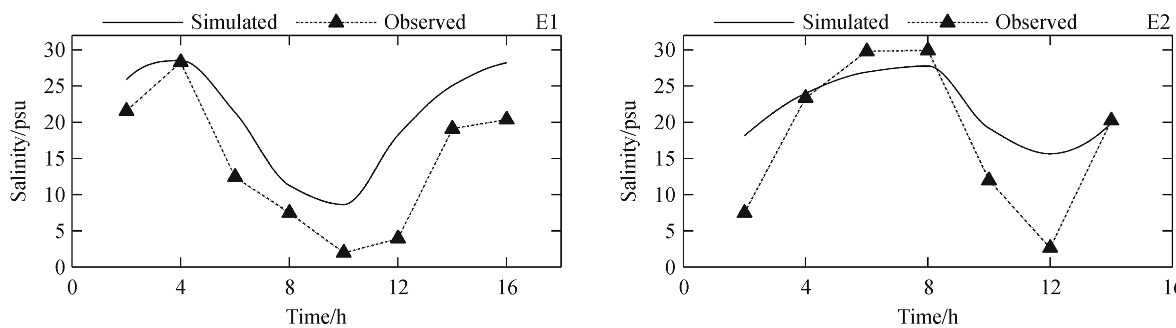

Fig. 7 Comparison of surface salinity between simulation and observation at two observed stations

4 Influence of bathymetry evolution on position of tidal shear front around the Yellow River estuary

4.1 Tidal shear front off Yellow River estuary

The tidal shear front off the Yellow River estuary has been simulated based on the numerical model described above. The result showed that the shear front is classified into two types: I-F-O-E (inner-flood-outer-ebb) and I-E-O-F (inner-ebb-outer-flood) as shown in Figs. 11(a) and 11(b), respectively. Tidal shear front was found at transect 2 (F1-F2-F3-F4) near the modern Yellow River estuary. The modeled tidal current in the surface layer was used to show the propagation of shear front along transect 2 (Fig. 12(a)). As shown in Fig. 12(a), the tidal shear front occurred four times a day with mean 6 h interval. At the very beginning, currents at station F1 changed from ebb (flowing north-west) to flood (flowing south-east), but those at station F2 were still ebbing, so shear front formed between F1 and F2.

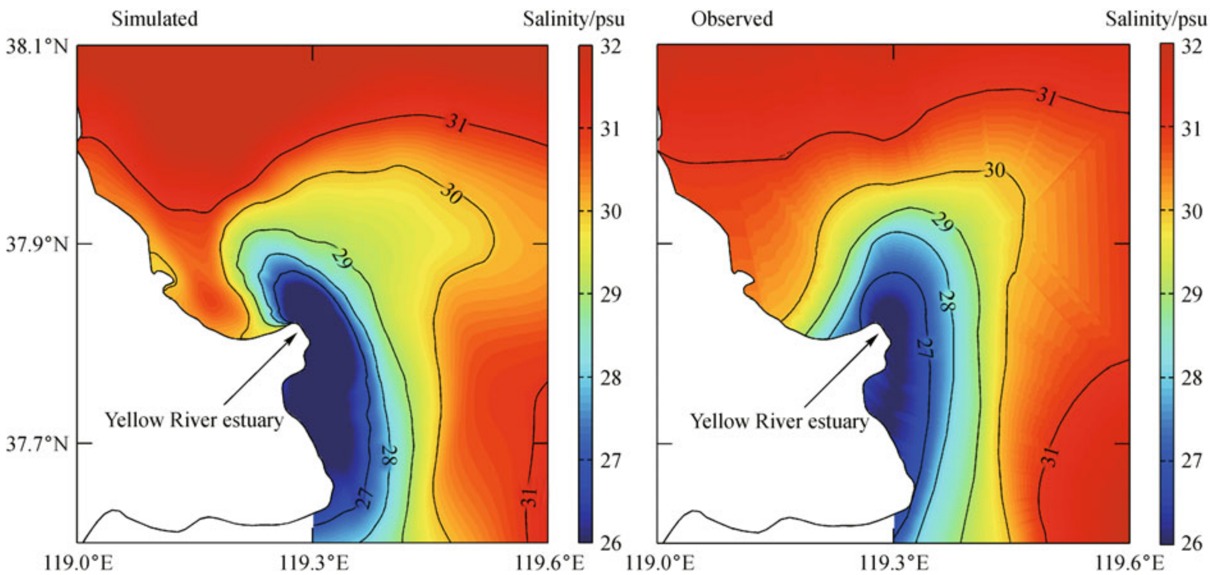

Fig. 8 Comparison of simulated and observed salinity distribution on the surface around the Yellow River estuary

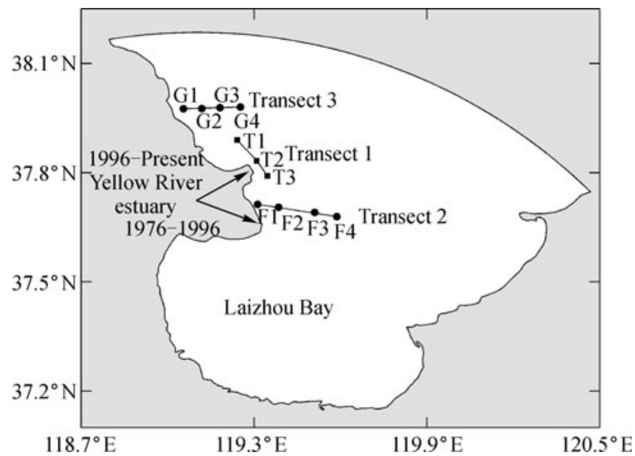

Fig. 9 Locations of transects

In the next hour, shear front moved seaward and was found between F2 (flood) and F3 (ebb). There was no shear front found between F3 and F4. This was a complete process about formation, propagation, and disappearance of an I-F-O-E type shear front. About six hours later, an I-E-O-F type shear front was generated when currents at station F1 were ebbing and currents at station F2 were flooding. The shear front appeared between F2 (ebb) and F3 (flood) one hour later, then disappeared later on. I-F-O-E and I-E-O-F types of shear front were detected again in the next 12 h alternately. Apart from the modern Yellow River estuary, tidal shear front was also found along transect 3 (G1-G2-G3-G4), which was located off the abandoned Qingshuigou River mouth. Propagation of shear front along transect 3 (Fig. 12(b)) was similar to that along transect 2. Thus, this prediction fits well with previous study (Bi et al., 2010).

As shown in Fig. 12, time intervals marked by shadows clearly indicated that two types of shear fronts occurred 4 times a day alternatively and lasted 2 h every time. The land side stations changed their direction earlier than did sea side stations, indicating that tidal shear front formed near shore and moved to a deep area. This prediction is consistent with the findings of Wang et al. (2007), but differs from the study by Li et al. (2001), in which they noted that tidal shear front may exist for 2 – 3 h with a landward propagation from the analysis of a sedimentary dynamics survey of the Yellow River estuary conducted by a single ship in 1991. The survey was carried out along six transects repeatedly, so the measurements at different stations along the same transect cannot be conducted simultaneously. This might lead to inaccuracy about the propagation of tidal shear front off the Yellow River estuary.

4.2 Effect of bathymetry evolution on position of tidal shear front off the Yellow River estuary

Qiao et al. (2008) found that bathymetry plays a significant role in the tidal shear front off the Yellow River estuary. The relationship between bathymetry and position of the tidal shear front was further examined by changing the subaqueous bathymetry of the Yellow River estuary in this study. We simulated tidal shear front on the original bathymetry and the changed bathymetry respectively, then compared the numerical results.

Based on the previous study of bathymetry evolution of Yellow River estuary (Chen and Gao, 2006a, 2006b; Chen et al., 2003b, 2004), we adopted a method of evolving isobaths to change the bathymetry. The moving distance of each isobaths for 15 years was calculated according to the changing patterns of 2, 4, 6, 8, 10, 12,

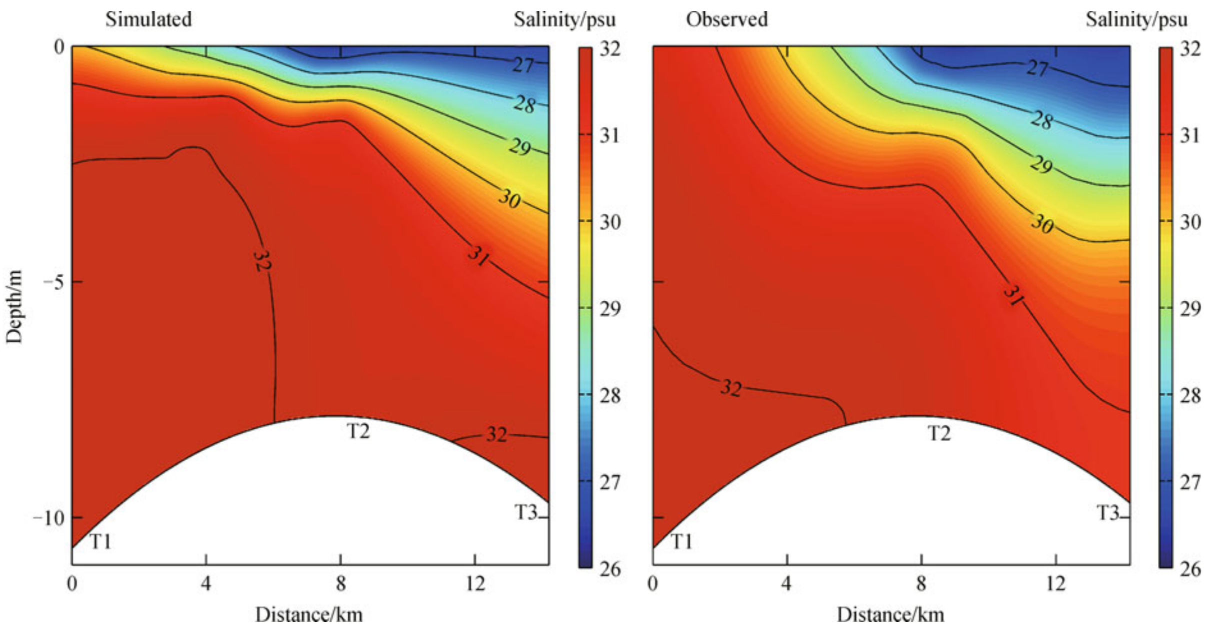

Fig. 10 Comparison of simulated and observed longitudinal salinity distribution along transect 1 (T1-T2-T3)

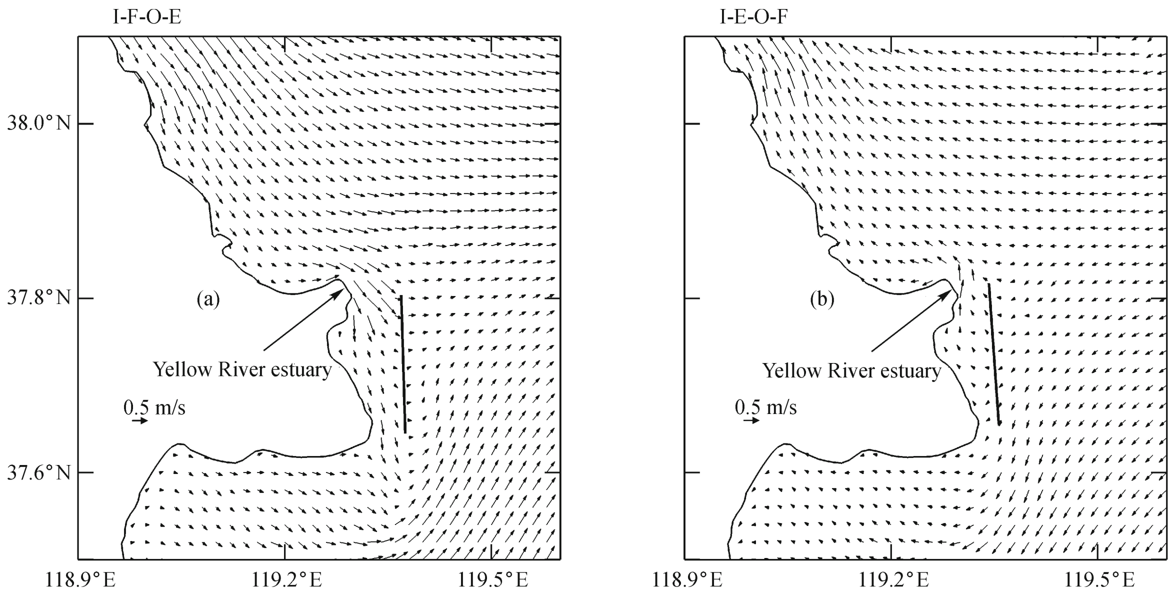

Fig. 11 Two types of tidal shear front off the Yellow River estuary

14, 16 and 18 m isobaths. The details are illustrated in Table 1.

The deformation of bathymetry around the Yellow River estuary is shown in Fig. 13. By comparing with the original bathymetry, it is obvious that 6 – 16 m isobaths were in a silting-up state, while erosion was found at 2 and 4 m isobaths. There was no change on 18 m isobaths, because the influence of sediment coming from Yellow River on it can be ignored.

The tidal shear front was simulated on two sorts of bathymetry with the same conditions, including open boundary, current, tide, initial salinity, temperature field data, wind field, heat forcing, and so on. As shown in Fig. 14, the tidal shear front moved seaside apparently after evolving bathymetry. Figures 14(a) and 14(b) showed that the comparisons of numerical simulation of positions of I-E-O-F type of shear front on original bathymetry and changed bathymetry. It indicated that shear front moved further on the east side of Yellow River estuary on the changed bathymetry. Figures 14(c) and 14(d) showed comparison of the positions of I-F-O-E type shear front on the two different sorts of bathymetry. The outcome

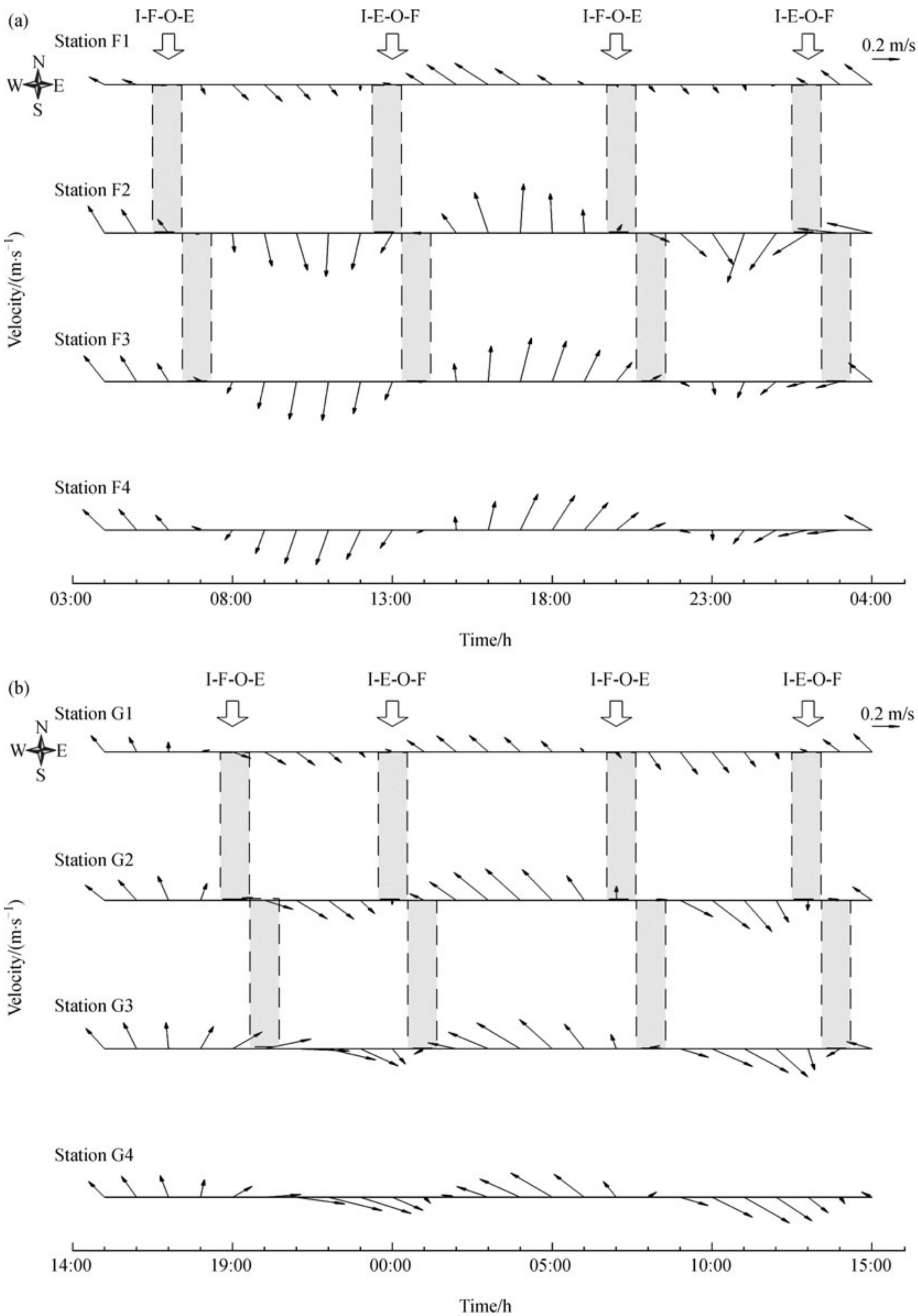

Fig. 12 Current vectors of tidal currents along transects 2 (a) and 3 (b)

illustrated that on the east side of the Yellow River estuary, shear front moved further on the changed bathymetry. In the vertical, Fig. 15 clearly showed that the position of tidal shear front moved seaward due to the deposition of bathymetry.

Qiao et al. (2008) suggested that a steep slope was the dominant factor causing the formation of the tidal shear front off the Yellow River estuary. Bathymetry evolution may change the position of steep slope. Hence, tidal shear front is able to move seaward.

Table 1 Moving distance of isobaths

Isobaths	Moving distance per year/m	Total moving distance for 15 years/m
2 m	−20.8	−312
4 m	−5	−75
6 m	120	1800
8 m	163	2445
10 m	200	3000
12 m	230	3450
14 m	230	3450
16 m	340	5100
18 m	0	0

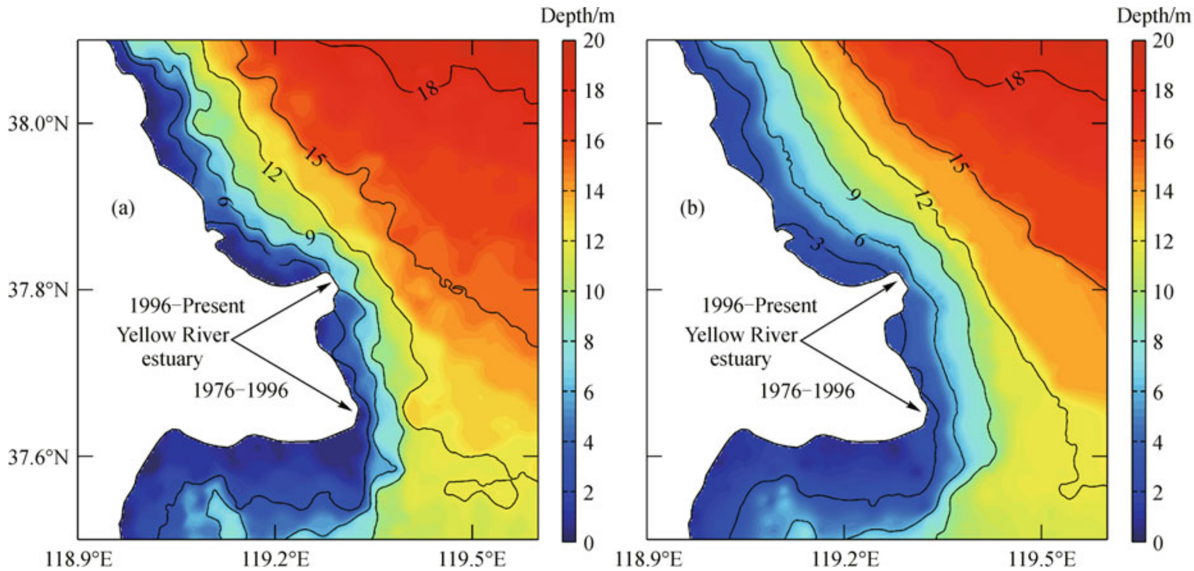

Fig. 13 Original bathymetry (a) and changed bathymetry (b)

5 Influence of bathymetry evolution on hydrodynamic characteristics around the Yellow River estuary

5.1 Effect of bathymetry evolution on distribution of salinity around the Yellow River estuary

To examine the impact of bathymetry on the distribution of salinity, numerical simulation of salinity on the original bathymetry and the changed bathymetry was conducted. The comparisons are shown in Fig. 14. After changing the bathymetry, the dispersion region of low salinity water was much larger than that on the original bathymetry. The 27 psu salinity isolines moved seaward on the east and southeast side of the Yellow River estuary (Fig. 14(b)).

Figure 15 shows the comparison between the longitudinal distribution of salinity along transect 2 (F1-F2-F3-F4) on the original bathymetry (Fig. 15(a)) and the corresponding distribution on the changed bathymetry (Fig. 15(b)). Compared with the salinity isolines of 27 – 30 psu on the original bathymetry (Fig. 15(a)), those on the changed bathymetry moved seaward (Fig. 15(b)), indicating that the low salinity water spread further away from the Yellow River estuary.

Two possible reasons account for this phenomenon. First, due to the deposition of bathymetry, the cross section becomes narrow which induces an increase of current velocity, thus low salinity water is able to propagate further. In addition, according to the conclusion of Bi et al. (2010), tidal shear front applies a barrier effect on diluted water. After the deformation of bathymetry, the position of shear front moves seaward, indicating that the barrier also moves seaward. Consequently, the low salinity water spreads to a deeper area.

5.2 Effect of bathymetry evolution on movement of particles around the Yellow River estuary

To study the influence of bathymetry variation on the displacement of particles around the Yellow River estuary, a total of 10800 particles were released in box areas located at Laizhou Bay and the initial positions are shown in Fig.

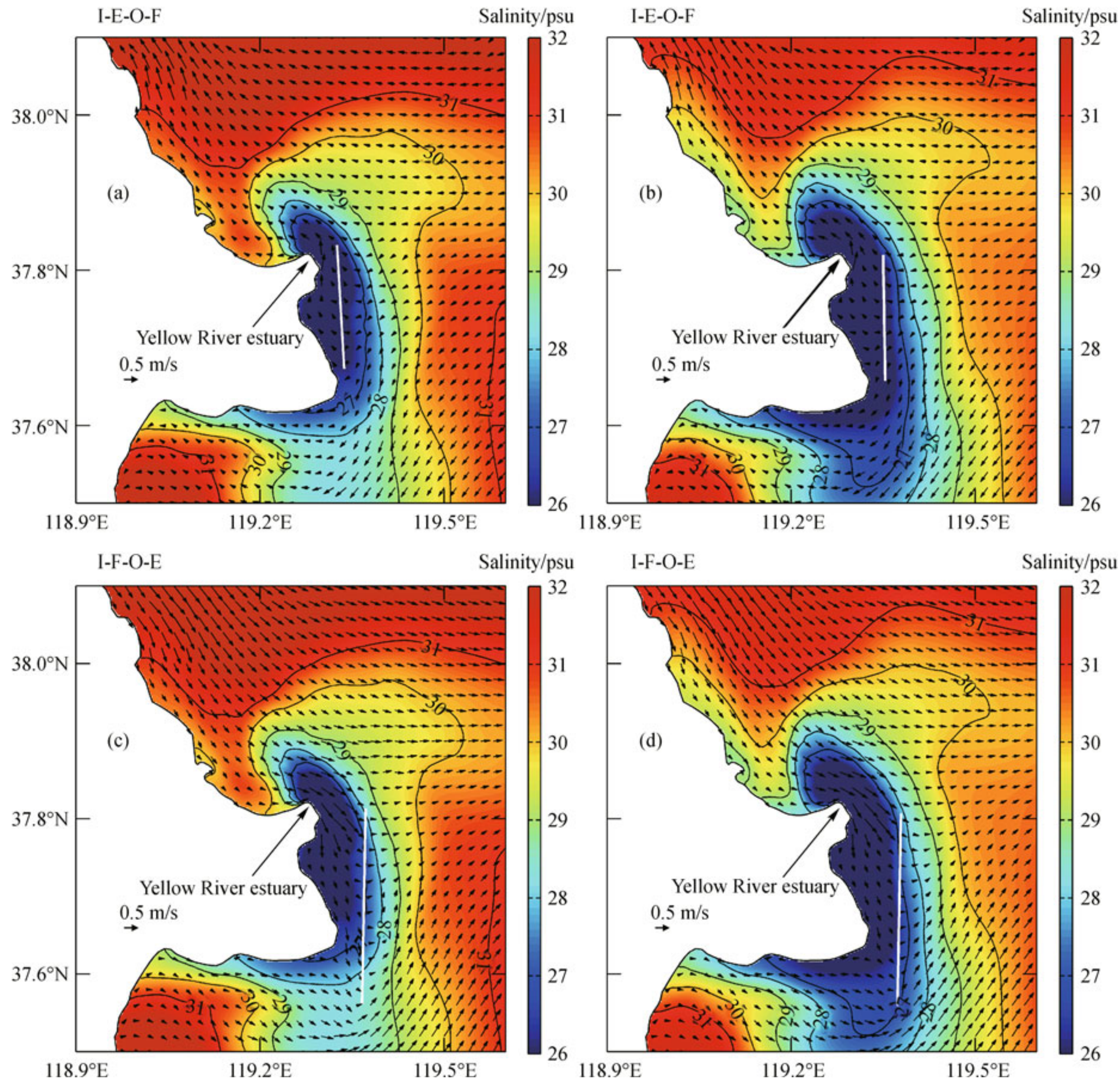

Fig. 14 Comparison of position of tidal shear front and salinity distribution of the surface layer on the original bathymetry ((a),(c)) and changed bathymetry ((b),(d))

16. We modeled the movement of particles for 30 days on the original bathymetry and the changed one, and then compared the results (Fig. 17).

After a period of 10 days, as shown in Fig. 17(a), on the original bathymetry, most of the particles near the surface moved toward the north of Laizhou Bay, while a small part of them moved eastward. Some particles can also be detected along the coastline near the Yellow River estuary. This may be the effect of reciprocating flow. As for most of the particles which are in the middle and bottom layers, the movements were not obvious. A possible explanation is that 10 days are too short for particles to react. On the changed bathymetry, shown in Fig. 17(b), the result showed that the movement of surface particles was almost the same as the ones on the original bathymetry.

Twenty days later, shown in Figs. 17(c) and 17(d), on the original bathymetry, it is clearly seen that most of the particles on the surface, middle and bottom layer moved north-east, while the other small part of particles moved toward the south of Laizhou Bay. The distributions of surface particles were relatively disperse: at the north of Laizhou Bay, the majority of particles can be found, while there was a small amount of particles located to the south. On the changed bathymetry (Fig. 17(d)), most of particles on the surface, which were located at the east-middle and north-middle of Laizhou Bay, moved toward the Laizhou Bay inlet. Other surface particles moved to the south-west and formed an arc. Similar to the movement of on the unchanged bathymetry, particles located on the middle and

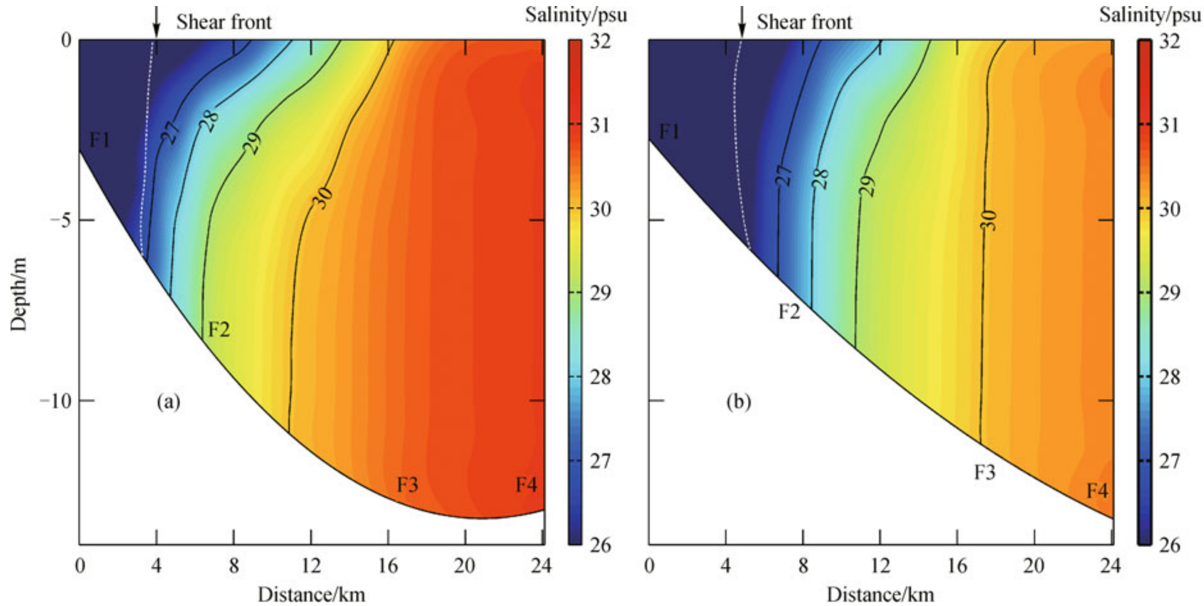

Fig. 15 Comparison of longitudinal salinity distribution along transect 2 (F1-F2-F3-F4) on the original bathymetry (a) and changed bathymetry (b)

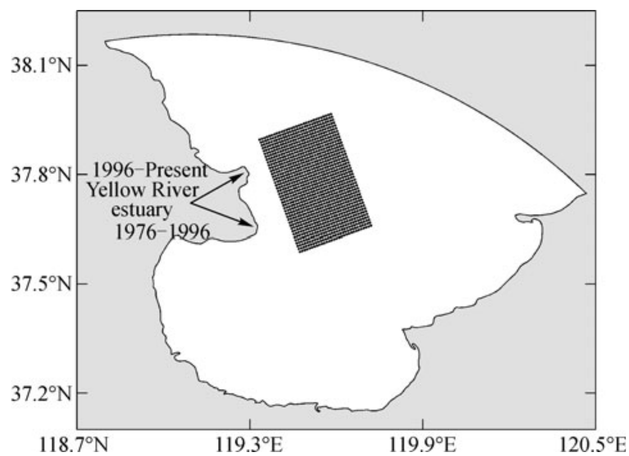

Fig. 16 Initial positions of tracers around Yellow River estuary

bottom layers moved northward and a very small amount of them can be detected near the Yellow River estuary.

After a period of 30 days, as shown in Fig. 17(e), on the unchanged bathymetry, the dominated directions of surface particle movement were to the north-east and south-east. Compared with the surface particles distributions 10 days before, these distributions were more concentrated. A portion of surface particles moved to the south-east in a line. This may be induced by the inflow of the Yellow River in the summer. Some of the particles on the bottom layer moved to the north-east of Laizhou Bay. In comparison with the surface particles, they were further away from the coastline, which was caused by the strong density current from the Yellow River. The density of diluted water from the Yellow River was relatively high because of high sediment concentration, so most diluted water enters into the bottom layer of ocean when flowing into Laizhou Bay. Hence, inflow of the Yellow River plays an important role in the bottom particles. Most of the particles in the middle layer still stayed at the center of Laizhou Bay. On the changed bathymetry (Fig. 17(f)), it is clearly seen that some surface particles moved to the south and formed a clockwise movement. A part of surface particles moved to the inlet of Laizhou Bay, and the distributions were relatively dispersed. The possible reason is that the structure of water flow has been changed due to the bathymetry evolution. In the comparison of the movement of middle and bottom particles on the unchanged bathymetry, the particles on the changed bathymetry transport further on the north. This may be caused by Yellow River inflow. Because of bathymetry evolution, the cross section becomes narrow and this induces the increases of current velocity, thus particles are able to move to a further location.

6 Conclusions

A three dimensional hydrodynamic model of the Yellow River estuary was established based on FVCOM. We demonstrated that this model was suitable to simulate water level, current velocity and direction, and salinity by comparing with observed data. Tidal shear front was successfully reproduced by the model. The influence of bathymetry evolution on the position of tidal shear front, salinity distribution, and the movement of particles around the Yellow River estuary was studied by the model as well, and the conclusions are listed below:

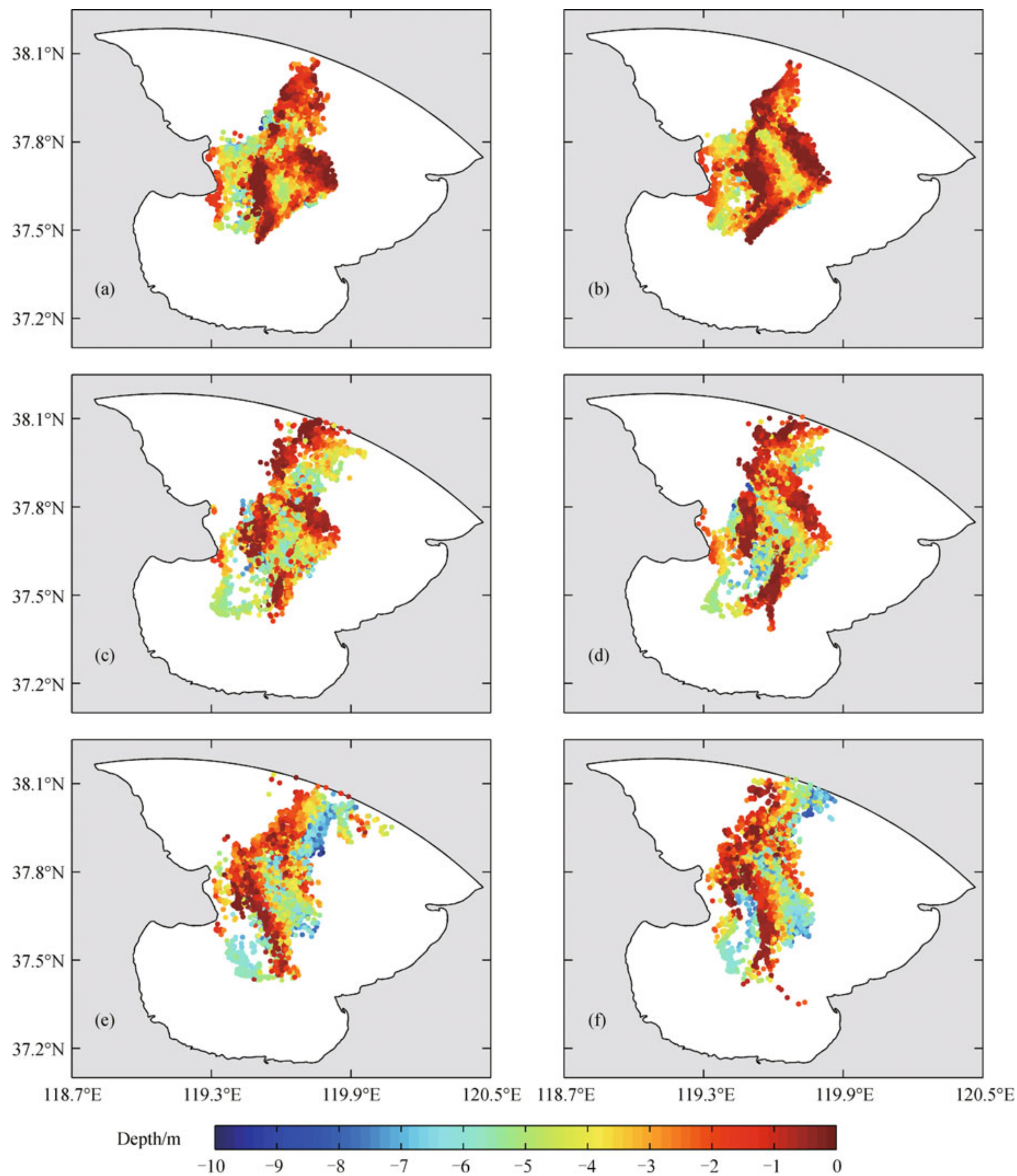

Fig. 17 Positions of the tracers on the original bathymetry and the changed one, (a) and (b) are the snapshots for 10 days, (c) and (d) are the snapshots for 20 days, (e) and (f) are the snapshots for 30days. (a), (c), (e) represent for the positions on the original bathymetry, while (b), (d), (f) represent for the positions on the changed bathymetry

1) Tidal shear front off the Yellow River estuary formed during the transition between flood and ebb, being classified into two types: inner-ebb-outer-flood and inner-flood-outer-ebb. Tidal shear front occurs four times a day and lasts for about 2 h every time, propagating from a shallow to a deep area. It not only can be detected off the modern Yellow River estuary, but also can be found at the abandoned Qingshuigou estuary.

2) Subaqueous bathymetry around the Yellow River estuary was evolved according to its changing patterns concluded from the past few years. Tidal shear front was simulated on both the original bathymetry and the changed bathymetry. The results showed that the position of tidal shear front moved seaward after the deformation of bathymetry.

3) Subaqueous bathymetry plays an important role in

salinity distribution around the Yellow River estuary. On the changed bathymetry, the dispersion range of low salinity water is much larger than that on the original bathymetry.

4) Bathymetry evolution exerts significant function on particle movement in Laizhou Bay, and the influences intensify with time. On the changed bathymetry, the particles on the surface, middle and bottom layer are able to move further to north and west of Laizhou Bay. This is caused by the inflow of the Yellow River after changing bathymetry.

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