Acta Oceanologica Sinica 2010, Vol. 29, No. 2, P. 98-106
DOI: 10.1007/s13131-010-0028-9
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Simulation of three-dimensional cohesive sediment transport in Hangzhou Bay, China

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Received 11 December 2008; accepted 7 April 2009

Abstract

Sediment transport in the Hangzhou Bay is extremely complicated due to its bathymetry and hydrodynamic conditions. The ECOMSED model is employed to simulate three-dimensional (3-D) cohesive sediment transport in Hangzhou Bay. Dynamical factors such as Coriolis force, tides, salinity, river discharges, and waves are considered in the model. The wave parameters, including the significant wave height, period, and direction, are calculated with the SWAN model. The Grant-Madsen model is introduced for the bed shear stress due to the combined effect of waves and currents. The formulation of bed shear stress used to calculate the sink/source terms is modified based on previous research that sufficiently validated the formulation with measurement data. The integrated model of the above-mentioned models is applied to simulate sediment transport in Hangzhou Bay. The results of the simulation agree well with field observations concerning the distribution of suspended sediment, indicating that the sediments are remarkably suspended in Hangzhou Bay under the action of waves and currents.

Key words: waves, currents, suspended sediment, deposition, erosion, Grant-Madsen Model

1 Introduction

A better understanding of cohesive sediment transport processes is essential not only for port construction and seabed changes, but also for the study of chemical and biological processes in estuaries and coastal areas. The objective of this paper is to use the ECOMSED model to simulate three-dimensional cohesive sediment transport processes in Hangzhou Bay.

Hangzhou Bay (shown in Fig. 1), located on the east coast of China, is the largest macro-tidal bay in China. The width of the bay varies from 100 km at the mouth to 25 km at the head, and the total length from the mouth to the head is about 95 km. In the southeast part of the bay, there are lots of islands and deep channels. Hangzhou Bay abuts on the Changjiang (Yangtze) Estuary, where water and sediment exchange frequently. The results of various studies have indicated that fresh water and sediment from the Changjiang Estuary are transferred in significant amounts into Hangzhou Bay, and especially into its northern part (Chen et al., 1988; Su et al., 1989; Hu et al., 2000; Chen et al., 2001). Furthermore, winds, waves, and a mix of saline water and fresh water also affect the bay. Under such topographic and hydrodynamic conditions, sediment transport in Hangzhou Bay is extremely complicated.

Some basic characteristics of tide and sediment movement in Hangzhou Bay have been discussed through numerous observations and analyses for hydrograph and sediment transport (Chen et al., 1988; Li, 1990; Chen et al., 2001). Suspended sediment is transported into the bay through the north end by the secondary Changjiang plume. There are two high sediment concentration areas, one in the Nanhui Flat and the other one in the Andong Flat (Su et al., 1989; Chen et al., 1988; Li, 1990; Chen et al., 2001). The sediment in Hangzhou Bay mainly comes from the Changjiang Estuary (Chen, 2001), and obvious seasonal and tidal cycles of sediment concentration have been observed (Li et al., 1992; Kong et al., 2006). Furthermore, numerical simulation has been also applied to the study of sediment in Hangzhou Bay. For example, a two-dimensional sediment transport model has been used to simulate sediment transport and deposition in the YangShan Deep-Water Harbor of Hangzhou Bay

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Foundation item: the Funds for Creative Research Groups of China under contract No. 40721004 and the Sino-Dutch Program for Strategic Scientific Alliance Project under contract No. 2008DFB90240.

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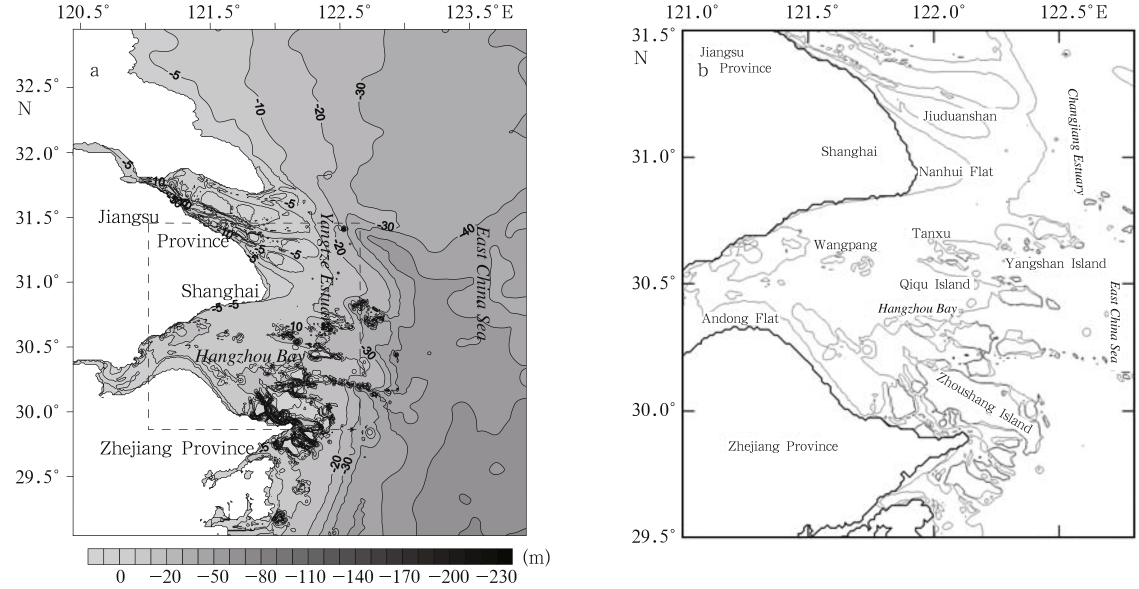

Fig.1. Hangzhou Bay and Changjiang Estuary.

(Zhang et al., 1998; Dou et al., 1999; Wang et al., 2004; Yang et al., 2006). These studies provide the basic characteristics of sediment transport in Hangzhou Bay, however, the distribution of sediment concentration in the Hangzhou Bay has not been revealed yet. For this reason, three dimensional models of sediment transport seem particularly appropriate due to the complex bathymetries and hydrodynamics of Hangzhou Bay.

Based on the previous studies, the ECOMSED model developed by Blumberg (2002) has been revised and employed to Hangzhou Bay. By coupling a wave module and a bed layer module, the ECOMSED model is capable of simulating sediment transport under the combined waves and currents. The hydrodynamic module includes multiple dynamical factors, such as four main tidal constituents (M_2, S_2, K_1, and O_1) at the open boundaries, salinity, river discharges, and waves, and it thus can reproduce the complicated current field in Hangzhou Bay well. Waves are calculated by the SWAN model, and the bed shear stress under waves and currents is calculated with the Grant and Madsen module. According to Ding et al. (2003), the critical shear velocity and erosion coefficient have a strong relationship with the characteristics of the bed properties. Thus, the local coefficients, with spatial variation in Hangzhou Bay, are used in the formulation of critical erosion shear velocity. Furthermore, the flocculation of sediment grains under the mixture of saline water and fresh water is considered in the sediment settling velocity formulation. The application of this generated model can preferably reproduce the sediment process in Hangzhou Bay and describe the characteristics of the sediment transport.

2 Model description

2.1 *Hydrodynamic module*

The 3-D Estuarine and Coastal Ocean Model (ECOM) (Blumberg and Mellor, 1987) is adopted for the simulations of current and salinity in Hangzhou Bay. A turbulence closure model is incorporated to provide a realistic parameterization of the vertical mixing process. The propagation of salinity fronts is very important to the flocculation of sediment grains in the bay, and thus in our calculation an improvement method (MPDATA) (Smolarkiewicz, 1990) that is a better choice when factoring in upwind and central differences is used to simulate salinity fields. For the wave simulation, the third generation spectral wave model SWAN (Booij et al., 2004) is adopted.

2.2 *Suspended sediment transport module*

Concepts of cohesive sediment resuspension, settling, and consolidation were incorporated within the circulation model to develop the ECOMSED model (Blumberg et al., 1998; 2002). Sediments in Hangzhou Bay, which are mostly fine-grained sediments with particle diameters less than 75 um (clay-silt range), can be regarded as cohesive sediments. The 3-D advectiondispersion equation for cohesive sediment is expressed in Eq (1):

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\frac{\partial (w-w_s)C}{\partial z}= \frac{\partial}{\partial x}(A_H\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(A_H\frac{\partial C}{\partial y})+\frac{\partial}{\partial z}(K_H\frac{\partial C}{\partial z}) \qquad (1)$$

Boundary conditions:

$$w_sC+K_H\frac{\partial C}{\partial z}=0, z\rightarrow \eta \qquad (2)$$

$$w_sC+K_H\frac{\partial C}{\partial z}=E-D, z\rightarrow -H \qquad (3)$$

Where C is suspended sediment concentration, and A_H and K_H are the horizontal diffusivity and vertical eddy diffusivity of sediment under waves and currents, respectively. H is the bathymetric depth below the datum. E and D are erosion and deposition flux of sediment at seabed, respectively, and can be expressed as follows (Gailani et al., 1991):

$$E=\frac{a_0}{T_d^m}(\frac{u_b^2-u_c^2}{u_c^2})^n/3600, u_b^2\geqslant u_c^2; E=0, u_b^2<u_c^2$$
$$D=W_sCP_d, P_d=1-u_b^2/u_d^2; u_b^2\leqslant u_c^2;$$
$$P_d=0, u_b^2>u_d^2 \qquad (4)$$

where E is erosion potential (mg·cm^{-2}); a_0, m, and n are constants depending upon the bed properties; T_d is time after deposition; u_b is the corresponding velocity of real bed shear stress under waves and currents, which is calculated by the Grant-Madsen Model (Grand and Madsen, 1987).

The determination of two critical velocities, i.e., critical erosion velocity u_d and critical deposition velocity u_c, is the critical to the modeling of suspended sediment transport. Constant values with no spatial variation are used in the original ECOMSED model. However, the fact that the sediment properties are not uniform spatially does not allow such assumption. These velocities are strongly related to the bed boundaries and material properties of the surface sediment, which depend on specific factors such as grain size and compaction. In this study, based on previous work (Ding et al., 2003), an improved formula is introduced to estimate critical erosion velocity, as follows,

$$u_c=K_e(\frac{H}{D_{b50}})^{0.14}(17.6\frac{\gamma_s-\gamma}{\gamma}D_{b50}+0.000\,000\,605\frac{10+H}{D_{b50}^{0.72}})^{0.5} \qquad (5)$$

where γ is the water specific weight, 1 000 kg/m^3; and γ_s is the sediment specific weight, 2 650 kg/m^3. D_{b50} is the median grain size of the bed material. K_e is the spatially varying coefficient depending on the local situation. Furthermore, an empirical formulation (Sha, 1965) is adopted to determine the critical deposition velocity,

$$u_d=0.812D_{s50}^{0.4}(w_sH)^{0.2} \qquad (6)$$

Where D_{s50} is the median grain size of the suspended sediment with an unit of mm. The formulation of the settling velocity in the ECOMSED Model,$W_s=\alpha(C_1G)^{\beta}$, is not best choice for the simulation of sediment transport in Hangzhou Bay. The works of the Wuhan University of Hydraulic and Electric Engineering (Wuhee, 1960) and Peng (1987), which have been validated by much measurement data and are widely used in Hangzhou Bay and the Changjiang Estuary, are thus introduced. When there is no flocculation, the settling velocity can be expressed as follows (Wuhee, 1960),

$$\omega_s=\omega_0=-4\frac{k_2}{k_1}\frac{v}{D_{s50}}+\sqrt{(4\frac{k_2}{k_1}\frac{v}{D_{s50}})^2+\frac{4}{3k_1}\frac{\gamma_s-\gamma}{\gamma}gD_{s50}} \qquad (7)$$

where k_1=1.22, k_2= 4.27, and v is the kinematic viscosity coefficient. In addition, when suspended sediment flocculates, Peng's (1987) experimental formula, which is related to salinity, SSC (Suspended Sediment Concentration), and velocity, is used,

$$\omega_f=\omega_0\times 0.274S^{0.48}S_a^{0.03}G^{0.22}/D_{s50}^{0.58} \qquad (8)$$

in which ω_f is the floc settling velocity and its unit is mm/s, S_a is the salinity, G is the current turbulence intensity, $G=\sqrt{g\sqrt{u^2+v^2}J_E/v}$, J_E is the energy gradient, $J_E=m_f^2(u^2+v^2)/R^{4/3}$, m_f is the manning coefficient, and R is the hydraulic radius, using water depth in the calculation.

3 Model settings

3.1 *Model domain and grids*

The model is applied to Hanghzou Bay and validated by comparing the simulated results with observation data. The annual average river runoff discharging into the bay from the Qiantang River is 29×10^9 m^3, and the annual average sediment discharge is approximately 66.8×10^5 t, whereas the runoff and sediment discharge of the Changjiang River are 889×10^9

m^3 and 459×10^6 t, respectively. Because of the frequent exchange of water and materials between them, the model domain covers the entire Hangzhou Bay and Changjiang Estuary, extending from 120.25°E to 123°E in longitude and from 29.1°N to 33.5°N in latitude. The horizontal grid alignment of Hangzhou Bay is shown in Fig. 2. Totally of 160×97 horizontal cells and 10 vertical σ-layers are defined in the model domain.

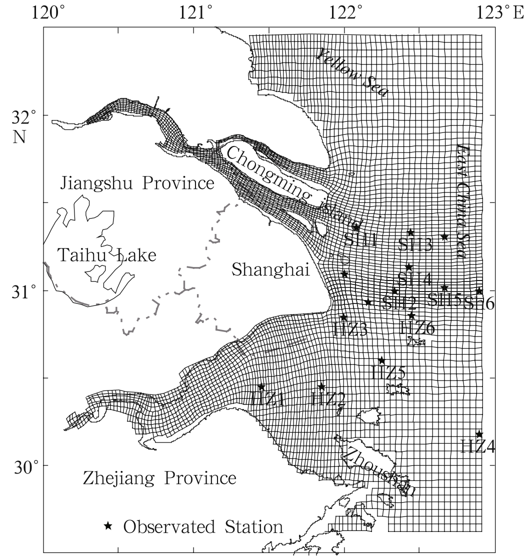

Fig.2. Grids and observation stations of Hangzhou Bay and Changjiang Estuary.

3.2 *Initial and boundary conditions*

The initial conditions are related with the initial distributions of surface elevation, velocity, salinity, and sediment concentration. The surface elevation and velocity are taken as zero at the initial state. The distributions of initial salinity and sediment concentration are derived from interpolation of the observed data. Furthermore, the distribution of the characteristics of the surface sediment (Fig. 3) is also acquired from the observations.

The boundary conditions include river runoff at the river boundaries, tide in the offshore sea boundaries, salinity and sediment concentration at the open boundaries, and wind and wave fields in the whole domain. Four major tidal constituents (M_2, S_2, K_1, and O_1) are used in this model at the open sea boundary. The river boundary forcing at the Jiangyin and Qiatntang rivers is specified by using multi-year monthly-averaged river runoff in July, i.e., 49 500 m^3/s and 1 200 m^3/s, respectively, and the sediment concentration is 0.6 and 1.69 kg/m^3. At the outer sea boundaries, the SSC is 0.2 kg/m^3. The surface wind fields are obtained from the observation data of NASA's Quick Scatterometer and NCEP blended wind data (http://dss.ucar.edu/datasets/ds744.4/), with a grid step of 0.25^0 and a time interval of 6 hours.

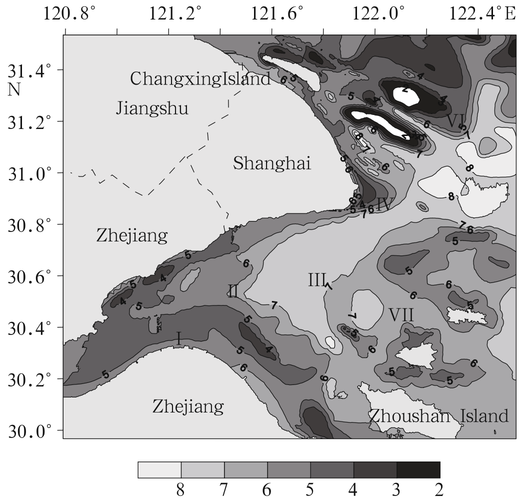

Fig.3. Different sub-areas of the coefficients of deposition and erosion, showing the distribution of median grain size diameter.

3.3 *Other Parameters*

The internal time step of the simulation is 60 s, and the Manning's roughness of bed friction is about 0.012, which needs to be adjusted according to the different surface sediments in different areas. The median grain size of suspended sediment adopts the average values of the area, which is between 0.004 and 0.032 mm. To rationally select the sediment parameters of bed boundaries is proved to be a major difficulty to the simulation of sediment transport. In this paper, referring to the distribution of the median grain diameter of bed material (Fig. 3), and through numerical tests, the coefficient of deposition and erosion are determined in different areas, as shown in Table 1.

Table 1. K_e in different areas, as Fig. 4 shows through numerical tests

Region	Andong Flat	Wangpang	Tanxu	Nanhui Flat	Jiuduansha	Qiqu Island	Other
	(I)	(II)	(III)	(IV)	(VI)	(VII)	
K_e	0.2	0.8	0.6	0.2	0.5	0.9	0.4

3.4 *A numerical test in Station HZ1*

Figure 4a shows the variation of wind observed at station HZ1 in July, 2005. In the summer, the direction of the wind is generally south or southeast. Further, because these winds blow towards the coast they will often generate stronger waves. The wave parameters observed at Station HZ1 in July are shown in Fig. 4b. To determine the influence of wave-current interactions, a numerical test is done. The current is calculated both with waves and without waves in July. By comparing the current simulations between the actual with and without wave-current interactions observed at HZ1 station, it could be concluded that the influence of the wave-current on the near bottom current is significant, as shown in Fig. 4d. The higher turbulence intensities near the bottom lead to a lower current velocity. These results also indicate that more energy was used to suspend sediment, resulting in the generation of a high concentration sediment zone.

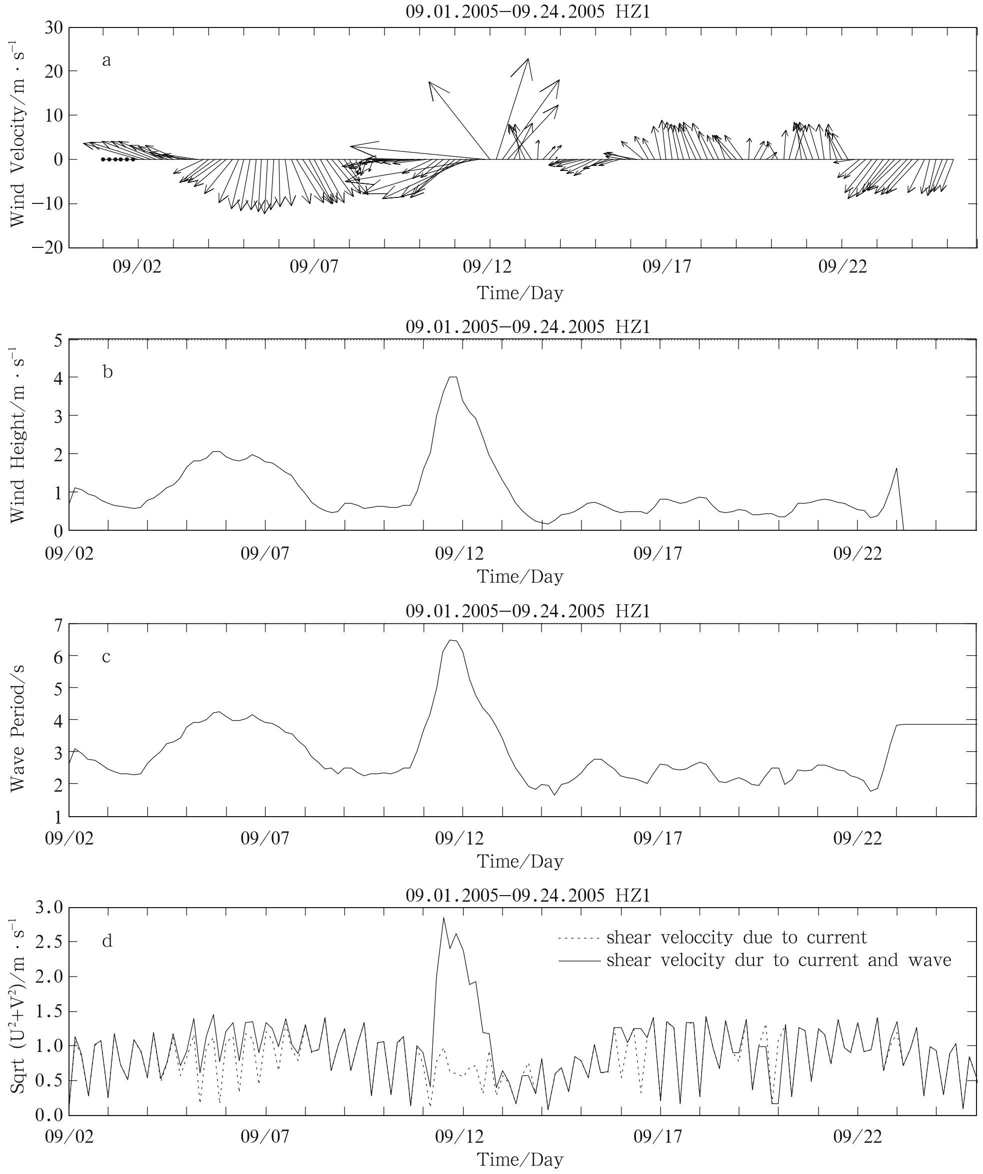

Fig.4. (a) Variation of wind at station HZ1 in September (b) Wave height (c) Wave period (d) Comparison of shear velocity from 1 September to 24 September at HZ1 station.

4 Verification

4.1 *Hydrodynamics*

A hydrodynamic model of Hangzhou Bay is developed on the basis of the ECOMSED Model. Further, the wave parameters, including the significant wave height, period, and direction, are calculated by the SWAN model, and they are introduced into the

Grant-Madsen Model to get the bottom shear velocity under the influence of wave-current interaction. The model is verified by the direct comparisons of numerical results and observation data. From September 2002 to October 2005, large-scale hydrology and sediment field observations were carried out at more than 15 stations distributed along Hangzhou Bay and the Changjiang Estuary both in spring tide and in neap tide (locations of stations are shown in Fig. 2). The model was verified based on the observation data of salinity and current, and detailed information on the model verifications can be reviewed from Du et al. (2007).

4.2 *Sediment Process*

Based on the rational simulation of currents, waves, and salinity fields, the transport of suspended sediments is simulated, and the results at four stations are presented in Fig. 5, indicating that the model results are consistent with the observations. The distribution of SSC within the model domain presents prominent variations on different time scales, i.e. the neap-spring cycle. There is also a pronounced correspondence relationship between the shear velocity and SSC, and between the fortnightly variations of tidal currents and the neap-spring cycle of the SSC. The bottom shear velocities gradually decrease from Hangzhou Bay to the Changjiang Estuary, in agreement with the decreased trend of the SSC. From Fig. 5, it is further suggested that the variations of the SSC mainly depend on the bottom sediment resuspension. In addition, at station HZ1 in the middle bay, the vertical difference of SSC is less than that at the upper bay and the Changjiang River Estuary, which suggests that the vertical turbulence in the Hangzhou Bay, a macro-tide estuary is evident. Furthermore, though Hangzhou Bay abuts on the Changjiang Estuary, their characteristics of current are discrepant.

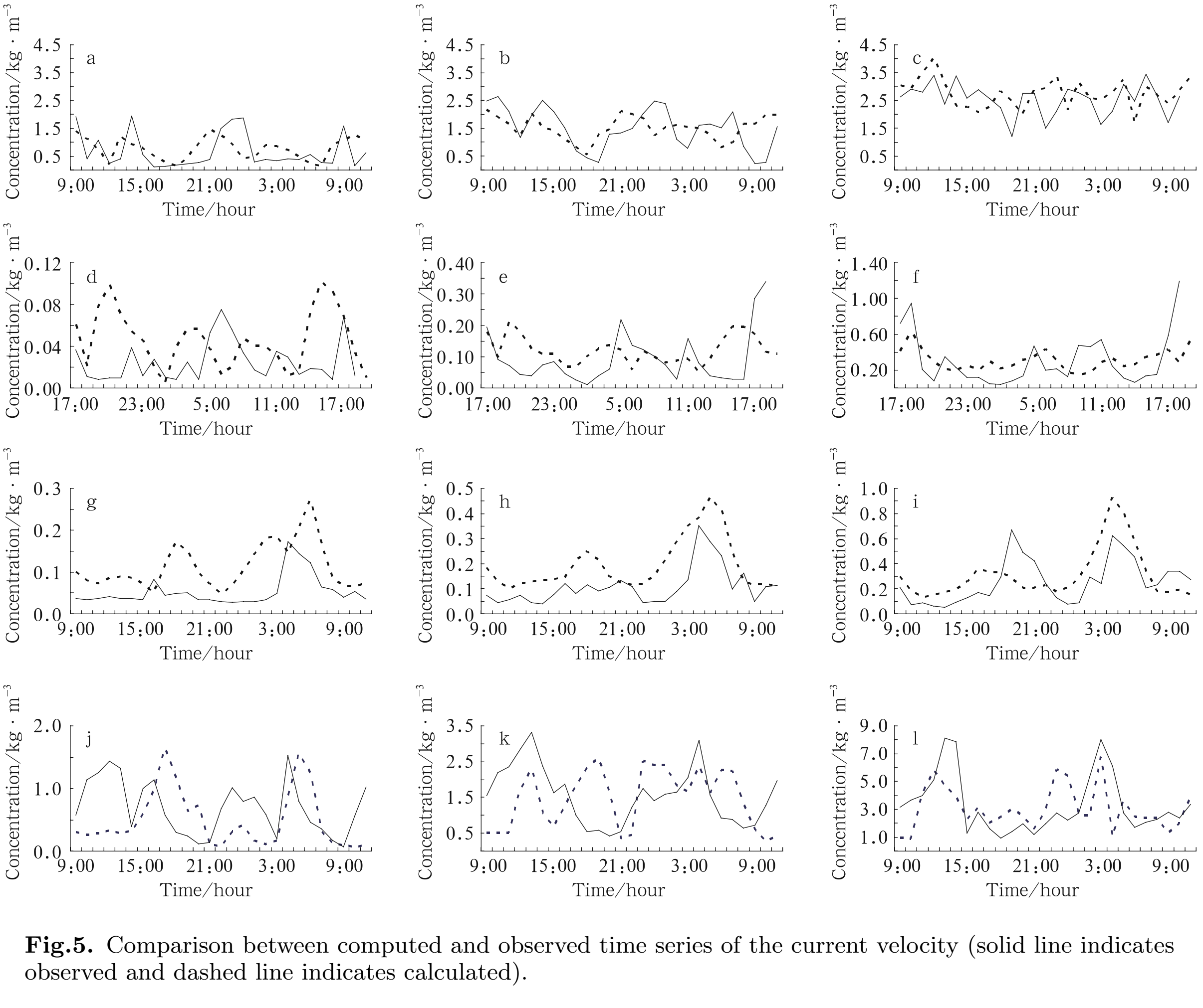

Fig.5. Comparison between computed and observed time series of the current velocity (solid line indicates observed and dashed line indicates calculated).

5 Results

The simulated SSC distributions in the study area during the flood season in July are shown in Fig. 6. According to spring-neap variations of SSC distribution, three high sediment concentration regions in the Changjiang Estuary and Hangzhou Bay are identified, which is in agreement with the results from remote sensing (Li et al., 1992). In the Hangzhou Bay, a high sediment concentration zone appears in the Andong Flat, which forms the north mouth and upper area of Hangzhou Bay. In addition, in the mouth-bar region of the Changjiang Estuary, the SSC is generally higher than those in the upstream and downstream reaches, indicating turbidity maximum (TM) of the Changjiang River Estuary is produced there, given the presence of flats and sands in the area the effects of waves on sediment resuspension are prominent. The SSC on the flats are higher than that in the channels. The SSC in the Nanhui Flat, Andong Flat, and the South Channel are the highest among the flats and channels, respectively. These results are consistent with the results of field measurements (Chen, 2001). The Hangzhou Bay is characterized by strong tides, rapid water flow, high sediment discharge, violent sediment transport, and distinct seabed deformation. The SSC in Hangzhou Bay is higher than that of the Changjiang Estuary during the same tidal period. However, the turbidity maximum zone of the Changjiang Estuary plays an important role in the sediment budgets north of Hangzhou Bay, acting as a sink of the suspended cohesive sediments under the

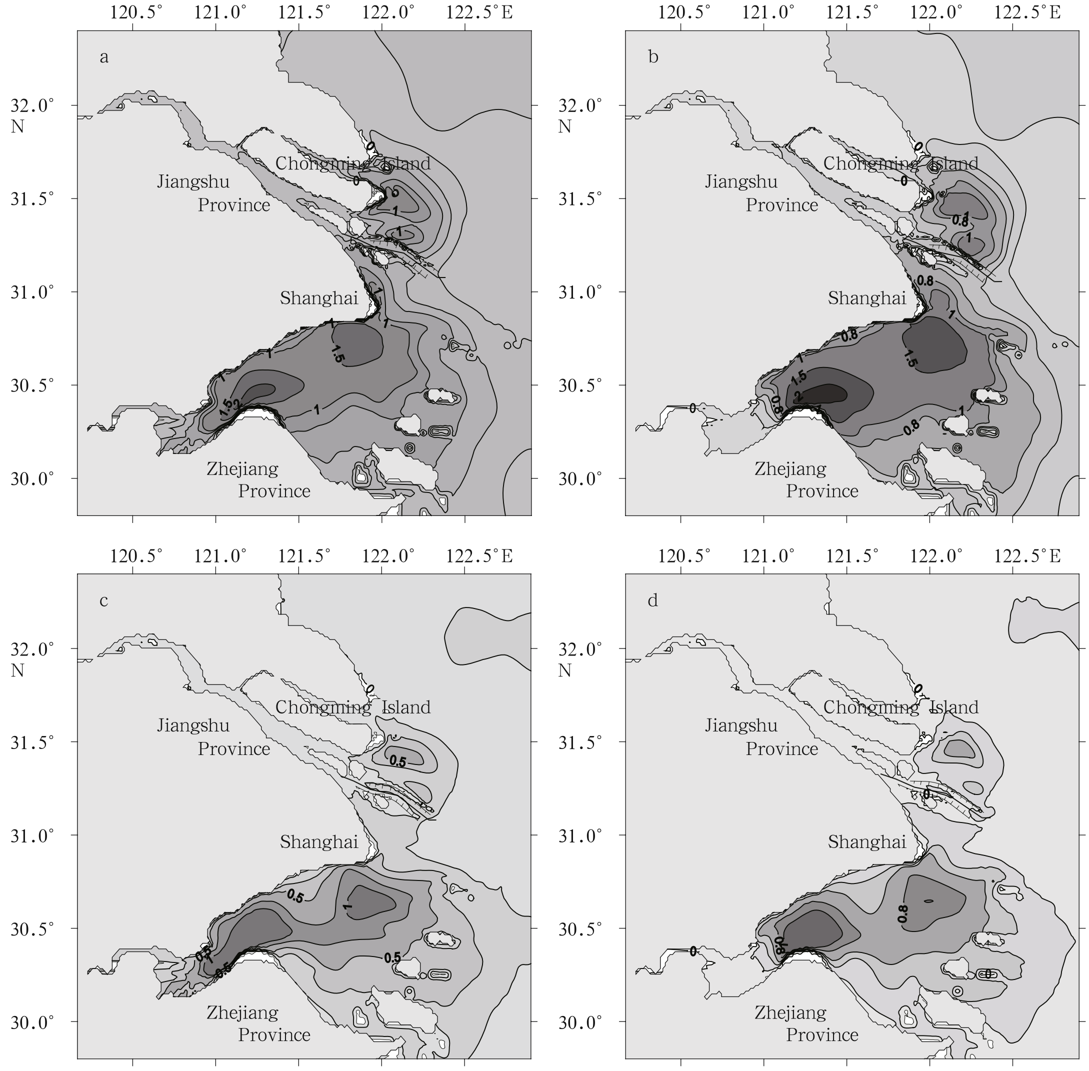

Fig.6. Distributions of surface SSC (a) in the flood period of spring tide, (b) in the period of neap tide, (c) in the flood period of neap tide and (d) in the ebb period of neap tide.

action of the tidal current and waves. Based on the extended orientation of the accumulation body, it also may be concluded that there exists an underwater sediment flow running from the north to the south to the east of Nanhui Flat, indicating that in the process of transport of sediment into the sea along the Southern Trough in the Changjiang Estuary, one branch of sediment flow enters Hangzhou Bay directly along the frontal margin of Nanhui Flat (Wang et al., 2004).

Over one tidal cycle, the position of the high sediment concentration zones varies with flood and ebb tides. The SSC in Hangzhou Bay has a close relationship with the spring and neap tides. In the flood period, the two zones are connected; whereas in the ebb period, they are detached. The SSC during spring tide is much higher than that during neap tide because the mean velocity during spring tide is much larger.

6 Conclusions

The ECOMSED model coupled with the SWAN wave model was applied to Hangzhou Bay to simulate the transport of cohesive sediment under combined waves and currents. The preliminary verification of the model output shows that it is sufficiently robust to capture the main features of the sediment transport processes in the estuary. The model outputs were compared to the observed results and shown to exhibit good agreement. The simulated results indicated that sediments are remarkably suspended in the northeast and west region of Hangzhou Bay. The SSC within the study area shows pronounced temporal variations over different time scales, i.e. the neap-spring cycle. Furthermore, there are two high concentration zones in Hangzhou Bay due to waves and a strong tidal currents. For future research, in order to better understand the sediment transport processes and to calibrate the model, field observations should be enhanced with respect to high spatial-temporal resolutions that are helpful to building a more accurate predictive model for the Hangzhou Bay.

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