COUPLING OF HYDRODYNAMIC AND WAVE MODELS CASE STUDY FOR WINTER STROM SURGE IN BOHAI SEA

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A hydrodynamic and wave coupled model, ADCIRC+SWAN, is used to simulate winter storm during 8th, Oct 2003 to 14th, Oct 2003 in Bohai Sea. Effect of wave radiation Stress on the current and the elevation is studied through numerical test. The sea surface elevation can increase over 2.0m in the Bohai Bay and Laizhou Bay, and decrease in the same order in Liaodong Bay under the effect of strong north wind. The currents change in a wide range and large scale counterclockwise circulations occur in the area. The evaluation induced by wave radiation stress can reach 0.10m to 0.20m and the current can reach 0.20m/s to 0.40m/s near the coastline during the winter storm.

Keywords: winter storm; ADCIRC+SWAN; wave-current interaction; Bohai Sea

INTRODUCTION

The Bohai Sea, a quasi-closed sea connected to the Yellow Sea with the Bohai Strait, is surrounded by the mainland except for east mouth (Fig. 1). It includes three bays: Laizhou Bay in the south, the Liaodong Bay in the north, and the Bohai Bay in the west, and covers about 77,000 km2. It is a rather shallow sea with mean depth about 18 m, and the maximum depth in the center is about 30m. The deepest area of it is the Bohai Strait where the depth exceeds 80m.

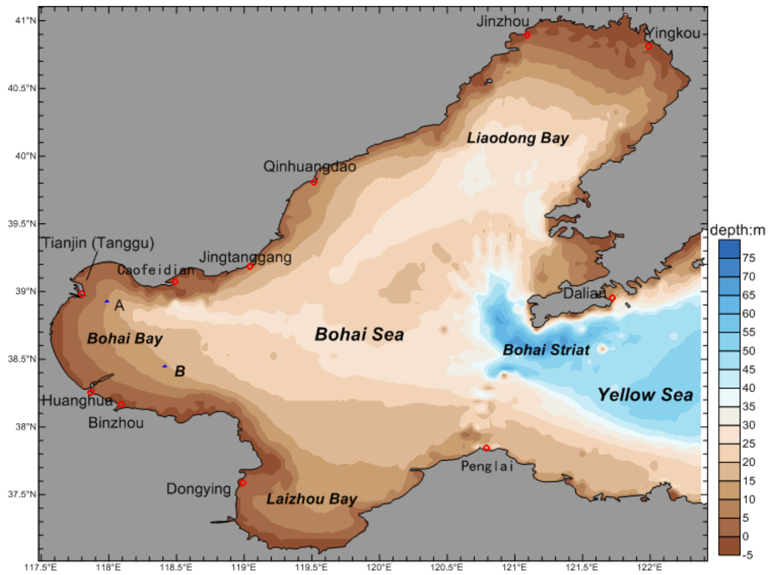

Figure1. Topography of the Bohai Sea

The Bohai Sea is frequently invaded by winter storms induced by strong wind in winter or spring. For developed industry and numerous ports along the coast, it is a big threat of prolonged high water level, huge wave and strong current in winter storm. So, recently series of numerical modeling has been applied to simulate such environmental factors. Yet few of the models used to this region take into account the interaction between wave, current and tide.

Since the theory of wave-current interaction developed by Longuet-Higgins and Stewart (1960; 1961; 1962), many study researchers try to take the wave-current interaction into simulation by a coupled model. Yet there are different views about the effects of wave-current interaction during storm. By tested for three recent storm periods, Mastenbroek (1993) conclude the radiation stress increased the surge some 5% during one storm, but the effect was negligible during the other two storms. Zhang (1996) use coupled wave and storm surge model to hindcast two storm events in the northern South

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China Sea, and find the inclusion of the radiation stress improves the accuracy of the computed results slightly by 2%, while introduction of a wave-dependent surface drag gives a significant improvement. On the contrary, Lin (2002) views that the radiation stress can increase sea level by up to 40cm in Bohai Sea in two cases of winter storm, and the effect of radiation stress is more significant. Based on a coupled wave-tide-surge interaction numerical model, Sun (2006) concludes that after long time wave effect, the wave radiation stresses have little effect on tidal elevation, but they have a significant effect on tidal current, especially when waves break.

The reason of inconsistent views about effect of wave-current interaction is obviously related to the model they used. In the past, most of the coupling of wave and circulation models has been implemented typically with relatively rough structured meshes or heterogeneous meshes. It can bring considerable errors when rough structured meshes are used in near shore area with complex coastline and topography. And the models with heterogeneous meshes is also creates problems with respect to both accuracy in the process of spatial interpolation.

In this paper, the interactions of wave, current and tide in the Bohai Sea during a winter storm are examined with ADCIRC+SWAN coupled model with same unstructured triangular meshes. A brief description of the coupled model is given in the following section. Then the numerical simulated results are discussed in the next, and the main conclusions are summarized at the end.

METHODS

SWAN model

SWAN is a third-generation wave model for predicting wave propagation in coastal areas, lakes and estuaries from given wind, bottom and current conditions. It is governed by action balance equation (Booij et al., 1999):

$$\frac{\partial N}{\partial t}+\nabla_{\vec{x}}\cdot\left[\left(\overrightarrow{c_g}+\vec{U}\right)N\right]+\frac{\partial c_\theta N}{\partial\theta}+\frac{\partial c_\sigma N}{\partial\sigma}=\frac{S_{tot}}{\sigma} \quad (1)$$

where, $N\left(\vec{x},t,\sigma,\theta\right)$ is wave action function of geographical space $\vec{x}$, time t, the relative frequency σ and wave direction θ. $\nabla_{\vec{x}}$ is the gradient operator in geographic space, $\overrightarrow{c_g}$ is the wave group velocity $\vec{U}$ is the ambient current vector, c_θ, c_σ is propagation velocity in θ and σ domain, and S_{tot} is the source term include wind, whitecapping, surf breaking and bottom friction; action exchanged between spectral components in deep and shallow water due to nonlinear effects.

The 40.91A version of SWAN with unstructured-mesh implements is used in the coupled model. The input data and other parameters description are shown in the user manual.

ADICIRC model

ADCIRC is a shallow-water circulation model, which solves for water levels and currents with continuous-Galerkin, finite-element at a range of scales (Westerink et al., 2008; Luettich and Westerink, 2004). Govern equation of water levels is the Generalized Wave Continuity Equation:

$$\frac{\partial^2\zeta}{\partial t^2}+\tau_\theta\frac{\partial\zeta}{\partial t}+\frac{\partial\widetilde{J_x}}{\partial x}+\frac{\partial\widetilde{J_y}}{\partial y}-UH\frac{\partial\tau_0}{\partial x}-VH\frac{\partial\tau_0}{\partial y}=0 \quad (2)$$

where,

$$\begin{aligned}\widetilde{J_x}=&-Q_x\frac{\partial U}{\partial x}-Q_y\frac{\partial U}{\partial y}+fQ_y-\frac{g}{2}\frac{\partial\zeta^2}{\partial x}-gH\frac{\partial}{\partial x}\left[\frac{P_s}{g\rho_0}-\alpha\eta\right]\\&+\frac{\tau_{sx,winds}+\tau_{sx,waves}-\tau_{bx}}{\rho_0}+\left(M_x-D_x\right)+U\frac{\partial\zeta}{\partial t}+\tau_0Q_x-gH\frac{\partial\zeta}{\partial x}\end{aligned} \quad (3)$$

$$\begin{aligned}\widetilde{J_y}=&-Q_x\frac{\partial V}{\partial x}-Q_y\frac{\partial V}{\partial y}-fQ_x-\frac{g}{2}\frac{\partial\zeta^2}{\partial y}-gH\frac{\partial}{\partial y}\left[\frac{P_s}{g\rho_0}-\alpha\eta\right]\\&+\frac{\tau_{sy,winds}+\tau_{sy,waves}-\tau_{by}}{\rho_0}+\left(M_y-D_y\right)+V\frac{\partial\zeta}{\partial t}+\tau_0Q_y-gH\frac{\partial\zeta}{\partial y}\end{aligned} \quad (4)$$

and equation for currents in vertically-integrated momentum equations：

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}-fV=-g\frac{\partial}{\partial x}\left[\zeta+\frac{P_s}{g\rho_0}-\alpha\eta\right] +\frac{\tau_{sx,winds}-\tau_{bx}}{\rho_0 H}+\frac{M_x-D_x}{H} \tag{5}$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+fU=-g\frac{\partial}{\partial y}\left[\zeta+\frac{P_s}{g\rho_0}-\alpha\eta\right] +\frac{\tau_{sy,winds}-\tau_{by}}{\rho_0 H}+\frac{M_y-D_y}{H} \tag{6}$$

Here, H (=ζ+h,ζ is the deviation of the water surface from the datum level; h is the bathymetric depth under datum level) is the total water depth; U and V are depth-averaged currents in the x- and y-directions, respectively; Q_x (=UH) and Q_y (=VH) are fluxes per unit width; f is the Coriolis parameter; g is the gravitational acceleration; P_s is the atmospheric pressure at the sea surface; ρ_0 is the reference density of water; η is the Newtonian equilibrium tidal potential and α is the effective earth elasticity factor; $\tau_{s,winds}$ and $\tau_{s,waves}$ are surface stresses induced by winds and waves, respectively; τ_b is the bottom stress; M are lateral stress gradients and D are momentum dispersion term; τ_0 is a numerical parameter that optimizes the phase propagation properties (Atkinson et al., 2004; Kolar et al., 1994).

The ADCIRC model is driven partly by radiation stress gradients that are computed using information from SWAN, which are computed by:

$$\tau_{sx,waves}=-\frac{\partial S_{xx}}{\partial x}-\frac{\partial S_{xy}}{\partial y} \tag{7}$$

$$\tau_{sy,waves}=-\frac{\partial S_{xy}}{\partial x}-\frac{\partial S_{yy}}{\partial y} \tag{8}$$

where S_{xx}, S_{xx} and S_{xy} are the wave radiation stresses (Longuet-higgins and Stewart,1964)

$$S_{xx}=\rho_0 g\iint\left(n\cos^2\theta+n-\frac{1}{2}\right)\sigma N d\sigma d\theta \tag{9}$$

$$S_{xy}=\rho_0 g\iint n\sin\theta\cos\theta\sigma N d\sigma d\theta \tag{10}$$

$$S_{yy}=\rho_0 g\iint\left(n\sin^2\theta+n-\frac{1}{2}\right)\sigma N d\sigma d\theta \tag{11}$$

where n is the ratio of group velocity to phase velocity.

Model Setting

The wind drag coefficient C_D is calculated by

$$C_D=0.001\times\left(0.75+0.067W_{10}\right) \tag{12}$$

where, W_{10} is the wind speed at 10m height. According to Powell (2003), there is a cap of wind drag coefficient with $C_D\le 0.0035$.

Bottom friction is parameterized using a Manning's n formulation as

$$\vec{\tau}_{b2d}=C_{db2d}\rho_w\vec{U}\left|\vec{U}\right| \tag{13}$$

where C_{db2d} is bottom friction coefficient, and：

$$C_{db2d}=C_{f\min}\cdot\left[1+\left(\frac{H_{BREAK}}{H}\right)^{\theta_f}\right]^{\frac{\gamma_f}{\theta_f}} \tag{14}$$

Where, $C_{f\min}$ is minimum bottom friction, H_{BREAK} is break depth， θ_f 、 γ_f are coeffcients. As recommended by the model, $C_{f\min} = 0.003$， $H_{BREAK} = 1.0$m， θ_f =10 and γ_f = 4/3.

The computational mesh is uniform for both the ADCIRC and SWAN (Fig. 2), the horizontal grid is between 100 to 5000 m. the total number of element and node are 36997and 18964, respectively.

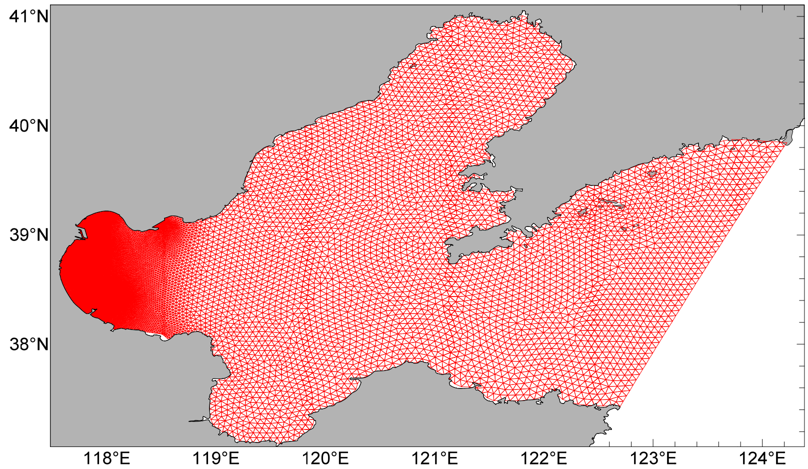


Figure 2. Triangular mesh

The time step used in the SWAN model is 600 s; the time step in the ADCIRC is 1 s. The simulating time lasted from 0:00, 8th October to 00:00,14th October, 2003.The open boundary conditions are obtained by northwest Pacifica model, with scope of 90°E to 161°10′, 0°N to 61°N, and resolution is 2′×2′.Because the open boundary is far away from the area concerned, the open boundary conditions for the northwest Pacifica model are just given by tidal level. Yet the wind effect is also take into consider in the model.

The wind data obtained the mesoscale meteorological model MM5 (Dudhia, 1993). Wind velocity is interpolated spatially and temporarily from the meteorology to the model grid in process of simulation. The wind speed varied with time at the station A, B (Fig.1), and the simulation result of the model is shown in Fig. 3. The wind reached the maximum during 10th to 11th Oct, which is over 25m/s in direction of N. The wind field at 08:00, 10th Oct and 08:00, 11th Oct are shown in Fig.4.

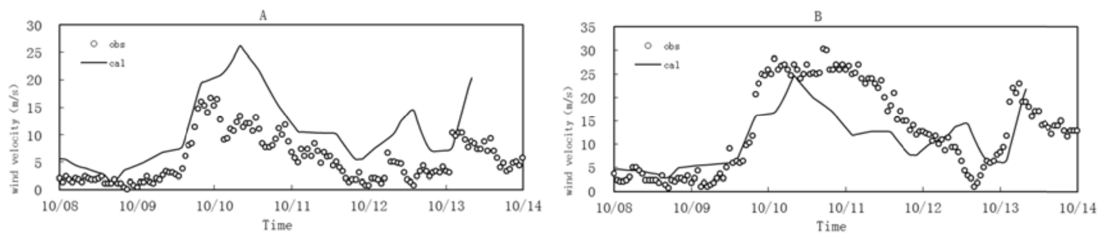


Figure 3. The wind velocity of observed data and the results from the models in the station

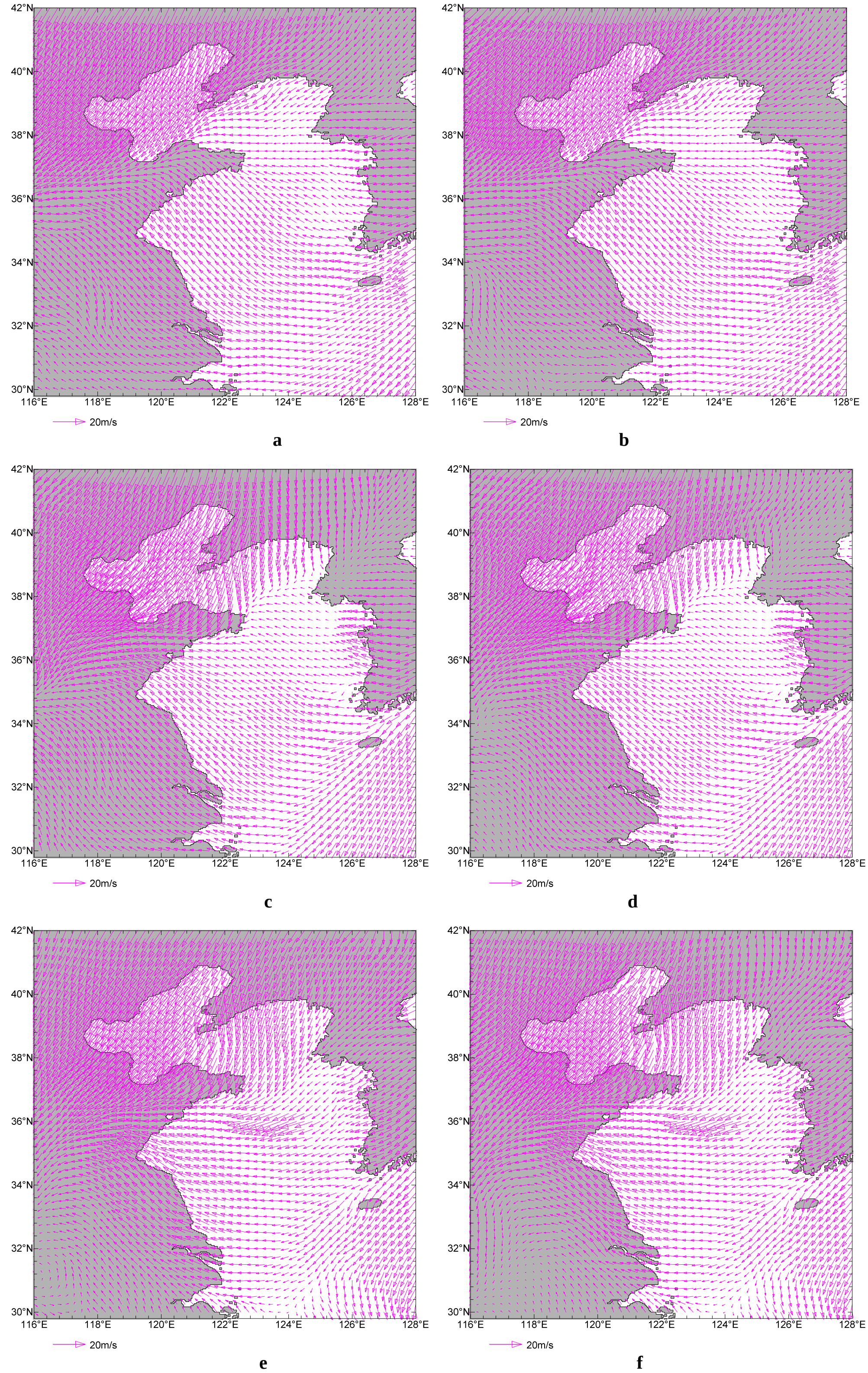


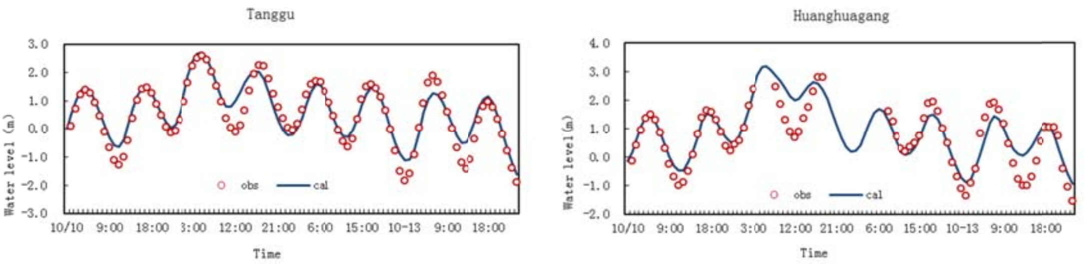
Figure 4. Wind field at a)00:00, 11th, Oct 2003; b) 06:00, 11th, Oct 2003;c) 12:00, 11th, Oct 2003; d) 18:00, 11th, Oct 2003; e) 00:00, 12th, Oct 2003; and f) 06:00, 12th, Oct 2003; in GMT +8

NUMERICAL RESULT

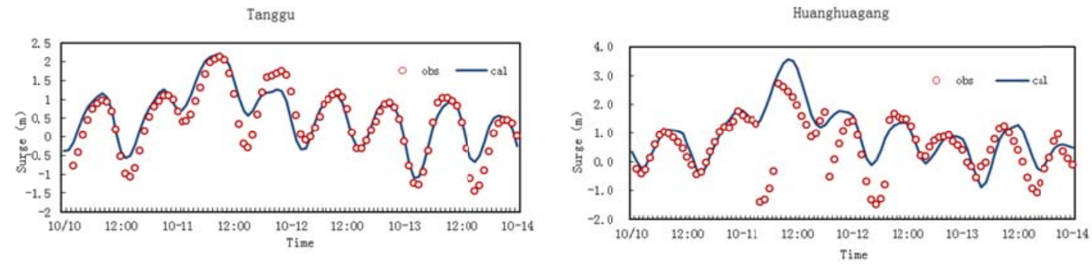
Water level and current

The water level and residuals at the station Tanggu, Huanghua (Fig. 1) of observed and results from the models are shown in Fig. 5. The model matches the magnitude and timing of the peaks at two stations, and the difference between of observed and calculated is no more than 0.20m at most time. As shown in the figure, the highest water level of Tanggu is 2.67m (National Height Datum 1985 of China), which occurs at 04:00, 11th Oct. The maximum residual of Tanggu is 2.05m, which occurs at 08:00, 11th Oct. The maximum residual of Huanghua from the model is some larger than the observed is probably induced by the errors of wind data.

It can be find that residuals of both observed and calculated by the model are periodic waveform, like tidal wave. There are several peaks during the storm, which can be interpreted as lasting action by strong wind.



a



b

Figure 5. Water level (a) and residuals (b) of observed data and the results from the models in the station

Fig.6 are the water level and currents during the storm surge. One can find that, influence by strong north wind, flood current in North of the Liaodong Bay turns to South at the middle of the bay. That causes a larger amount of water enters Bohai Bay and Laizhou Bay and leads to surge in the area. Also, the ebb current of Liaodong Bay move to Bohai Bay and Laizhou Bay along west coastline instead of recreating to Bohai Strait as tidal current movement. As a consequence, negative residual as larger as 2.0m generated in Liaodong Bay. Moreover, large scale counterclockwise circulation occurs in the center of Bohai Sea. Under the action, water exchanges among the three bays. That is different with the result of tidal current.

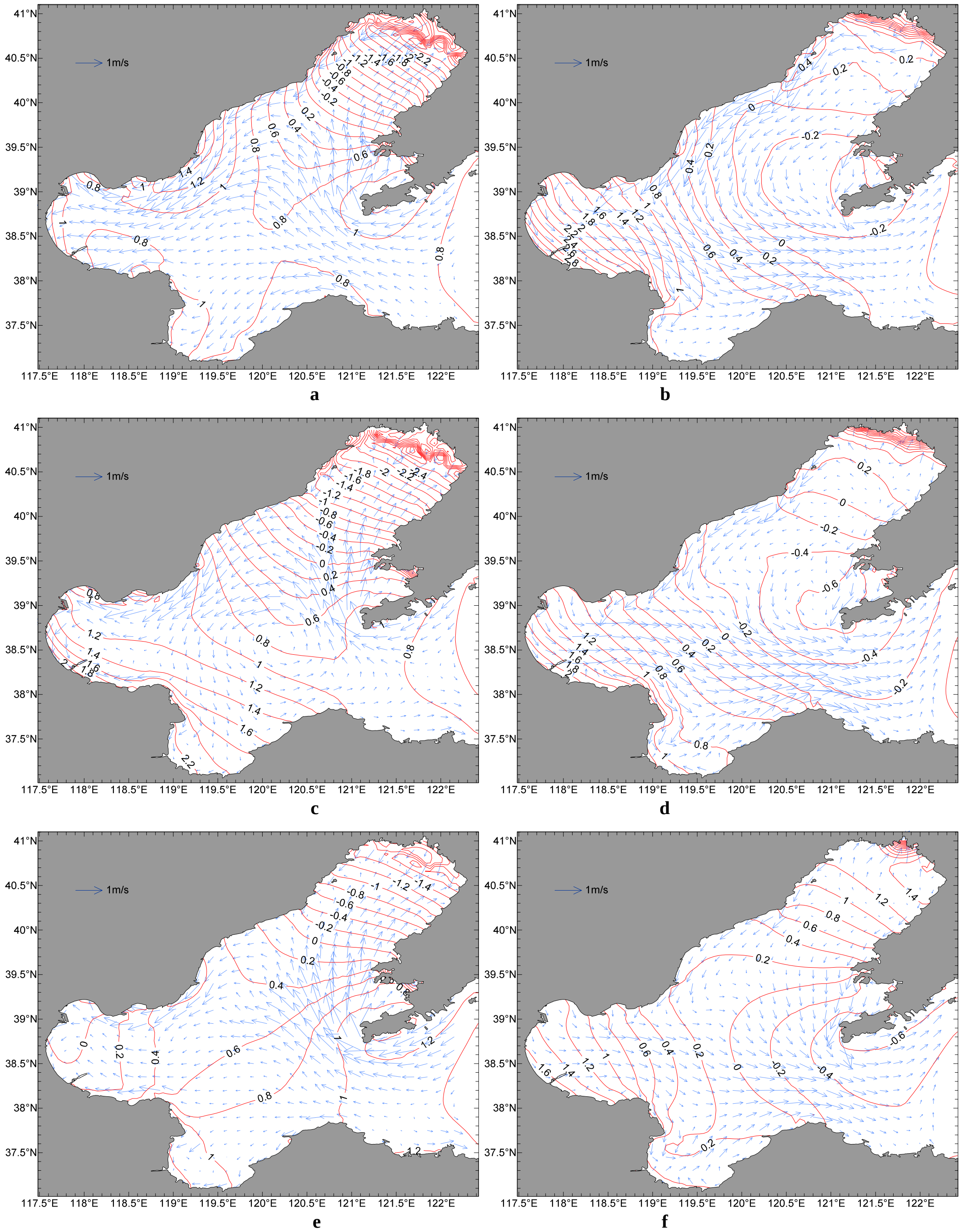


Figure 6. The same as Fig. 4 for water level (in meters) and current

Wave

Fig. 7 are wave height and vectors during the storm. The wave was generated as soon as the wind affects and reached the maximum at 0:00,12th Dec. The maximum effective wave height is over 6m in the center of Bohai Sea. And it reaches 4m or so in the mouth of Bohai Bay and Liazhou Bay. Wave height is about 1 to 2m near the coastline due to water depth limited. Then, it decreased slowly with the wind after 12:00, 13th Dec.

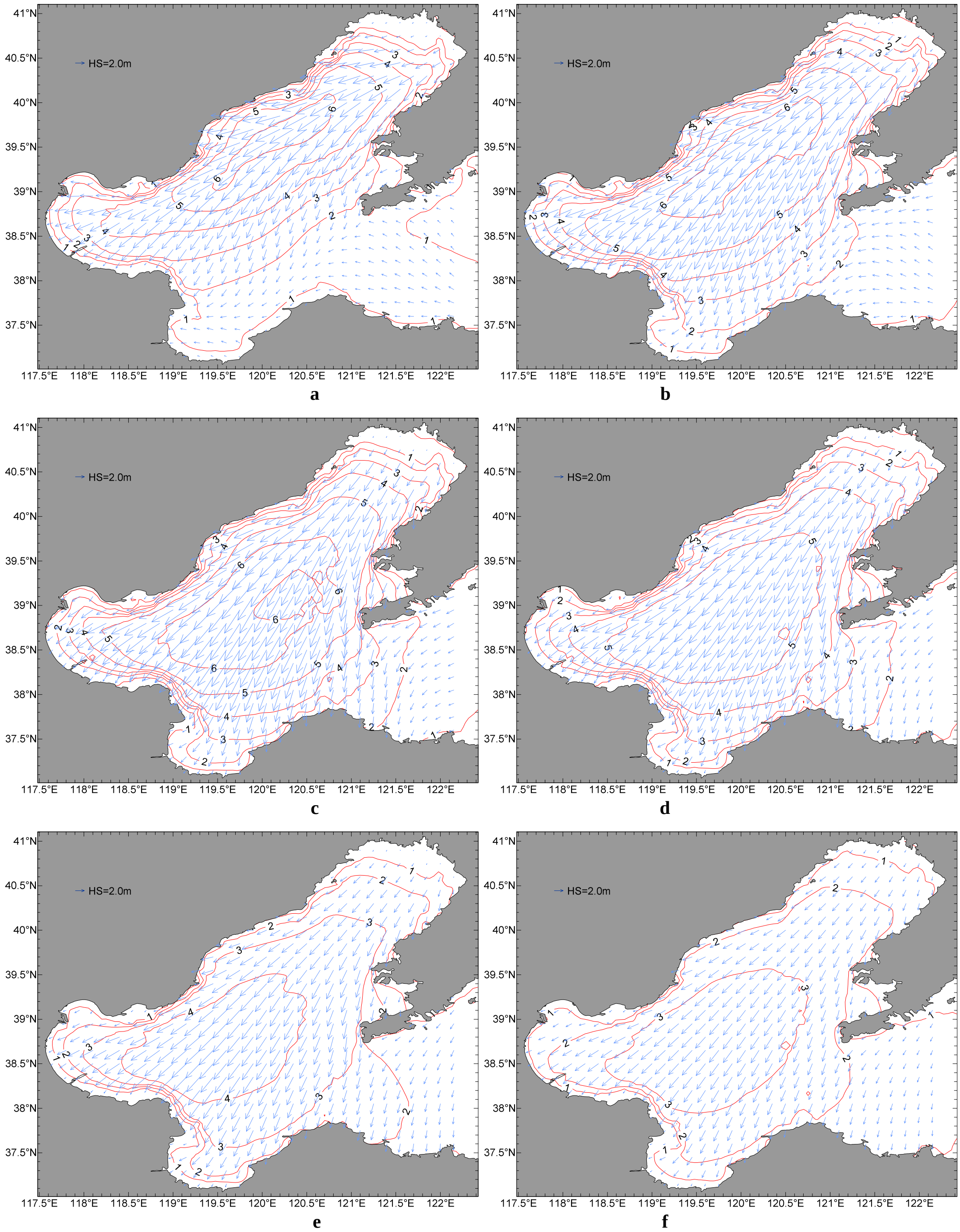


Figure 7. The same as Fig. 4 for effective wave height Hs (in meters) and vectors

Effect of Radiation Stress on the Current and the Elevation Fields

Two cases of numerical simulations are considered to investigate the effect of radiation stress on the surface current and the elevation fields. Case 1 assumes no wave action, and the ADCIRC runs forced by the wind stress and the tide. Case 2 assumes there are interactions between wave, current and tide.

Figs. 8 describe the distribution of surface current and the elevation induced by wave radiation stress s in the coupled model. The wave set-up can reach 0.10m in the bottom of Liaodong Bay, and about 0.05m near coastline of Bohai Bay and Laizhou Bay at 00:00, 11th Oct. With wave height increase, it exceeds 0.10m at the nearshore of Dongying at 12:00, 11th Oct. For long distance wave affect, it is about 0.02 to 0.20 m in the whole Liaodong Bay at that time. It is slight in the center of Bohai Sea, because of deep-water in the area. As the wave height decrease at the following times, it reduces to below 0.10m in the most area.

Meanwhile, the current induced by wave radiation stress is also considerable under the wave action. The typical currents move from Liaodong Bay to Bohai Bay and Laizhou Bay near the west coastline. The compensation currents move in the opposite direction in the offshore. And there are several counterclockwise circulations in the middle region of them. The map is consistent with description of current induced by wave action. The maximum velocity of wave-induced current is about 0.40m/s near the coastline, and 0.20m/s offshore area.

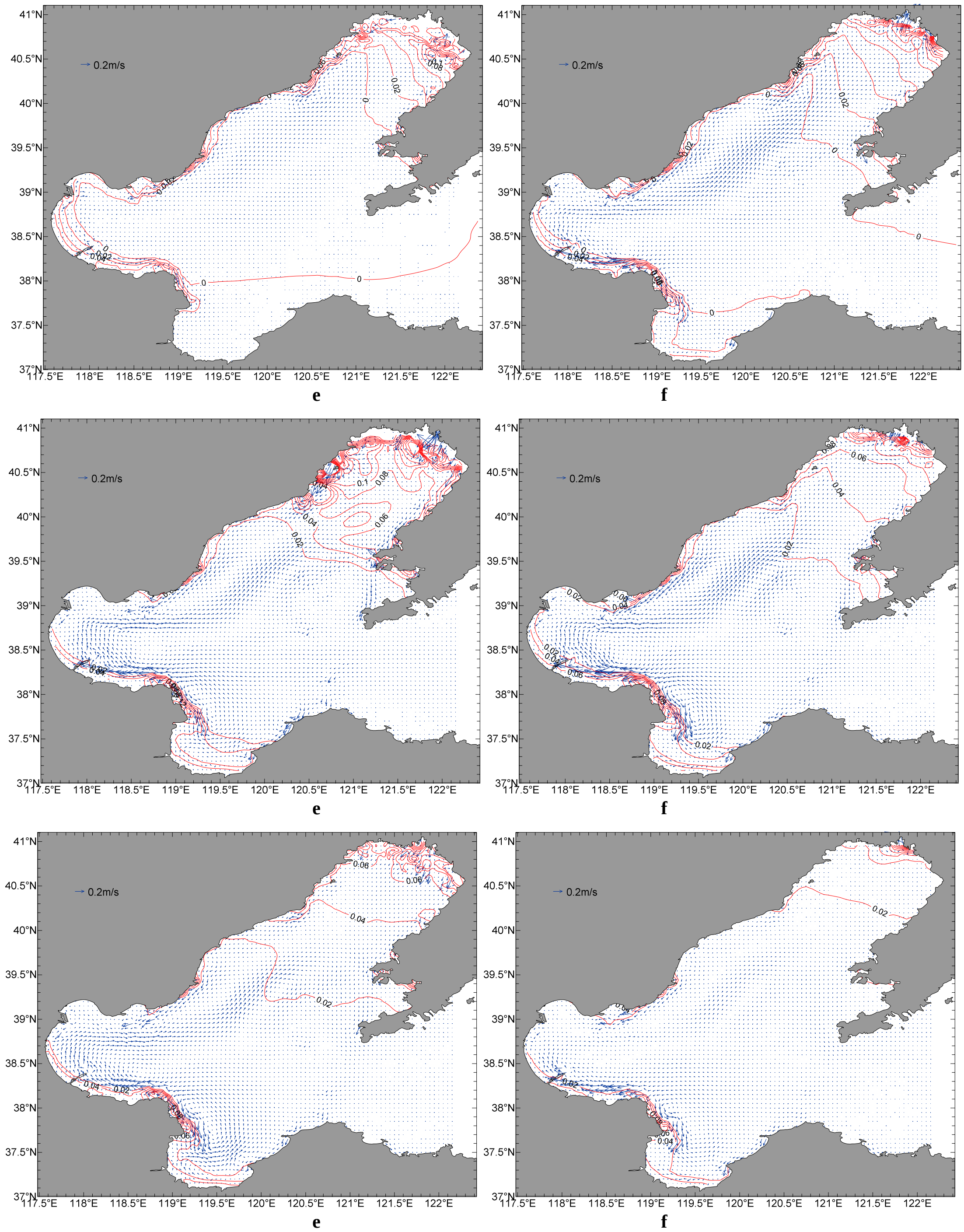


Figure 8. The same as Fig. 4 for wave setup (in meters) and wave-induced current

REMARKS

The storm surge in a certain waters can be decomposed into two sources, remote and effects of local wind stress (Wong et al. 1998). In this case, the oscillation of both water level and current is almost directed by local strong wind but not remote wind effects. So the water level as well as current change in large scale in the sea. The counterclockwise circulation and strong current among the three bays are apparent different from the case driven by tidal wave. Meanwhile, huge waves are also induced by the surface wind stress. So there is intensive wave-current interaction between the two fields during the storm, as shown in the numerical results. For this reason, it can be draw conclusion that, wave-current interaction is almost inevitable for storm surge induced by local wind stress in the shallow seas. Yet if induced by remote wind stress, the wave condition may not be consistent with the surge for different propagating behavior. So whether the effects of wave radiation stress is significant for current and elevation would depend on the circumstances.

CONCLUSIONS

ADCIRC+SWAN coupled model is applied to hindcast wave, current and surge of winter storm during 8th, Oct 2003 to 14th, Oct 2003 in Bohai Sea. Effect of radiation Stress on the current and the elevation is studied through numerical test. Numerical results show that water level increases over 2m in Bohai Bay, while it reduces in same order in Liaodong Bay. The currents are change in a wide range and large scale counterclockwise circulations appear in the area. The wave height can reach 6.0 meters in centurial region of Bohai Sea. Furthermore, the wave set-up can reach 0.10m to 0.20m and the current induced by wave radiation stress is also considerable with maximum about 0.20m/s to 0.40m/s near the coastline during the winter storm.So it is necessary to simulate the storm surge by coupled model.

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