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Research of the Influential Factors on the Simulation of Storm Surge in the Bohai Sea

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Abstract: A hindcast of typical extratropical storm surge occurring in the Bohai Sea in Oct. 2003 is performed using a three-dimensional storm surge model system based on Finite-Volume Coastal Ocean Model (FVCOM). The surface winds are obtained from the WRF data set. Some preliminary sensitivity studies of the influential factors affecting the storm surge simulation in the Bohai Sea are conducted with the high revolution numerical model of storm surge. The factors of tide-surge interaction, the wind stress, the water depth, the bottom drag coefficient and the critical depth in the model are studied. After considering the tide-wind interaction and the severe wind, the most important influential factor affecting the storm surge in the Bohai Sea is the bottom drag coefficient. These sensitivity studies indicate that the storm surge simulations depend critically on the parameterizations. Hence additional experimental guidance is required on the bottom drag coefficient. This study is useful for the storm surge simulation in order to select the proper parameter to make possible a good conservation behavior of the storm surge model.

Keywords: FVCOM, influential factors, numerical simulation, storm surge, surge level, the Bohai Sea.

1. INTRODUCTION

Storm surge is defined as the abnormal change in sea level that may accompany either extratropical or tropical storm [1]. Storm surges have a hazardous impact on coastal regions, threatening infrastructures, ecosystems and even human lives. The investigation of the processes related to the generation of storm surge and their temporal variability has become a major issue in climate research. The risks of flooding of storm surge increase in many regions, enhancing the effects and possible damages caused by extreme high water levels. Extreme sea level events are commonly driven by the combination of tidal elevation and storm surges. While tidal oscillations are deterministic, the storm surge component depends on the forcing of atmospheric pressure and wind. In areas of large tidal amplitudes and shallow water regions the tide-surge interaction may become significant. In such areas, storm surges represent a problem when they occur at the time of high water level [2].

China is the most severe region for suffering storm surges in the world. Storm surge is the most dangerous disaster among the sea damage. The frequency and the intensity of storm surge has increased in the recent years. The most frequent and severe regions affected by the extratropical storm surge in China are Laizhou Bay, Bohai Bay and Haizhou Bay. According to the statistics from 1950 to 1998, there are 3383 days in a typical extratropical storm surge at Tianjin Tanggu Port in 49 years where the water level fluctuations exceed 50 centimeters. There are about 78 days every year. During these days, there are 495 days for the water level fluctuation exceeding 100 centimeters, and there are about 9.3 days every year [3].

The Bohai Sea located in 37° 07′ N-41° N and 117° 35′ E-121° 10′ E. Its total area is 77,000 km^2 and its average depth is 18 m. The Bohai Sea is one of China's marginal seas and usually harmed by storm surge. Unlike the other marginal seas, the Bohai Sea is less susceptible to storm surges associated with tropical cyclones, and its latitudes are so high that only a few tropical cyclones are able to move northward far enough to generate storm surges along the coastal regions. The Bohai Sea faces frequent threats from extratropical storm surge and suffers a massive damage from its resulting storm surge. In the Bohai Sea, storm surges caused by extratropical cyclones are very important compared to those induced by tropical cyclones [4].

The study of storm surge has routinely been undertaken by the combination of tide and surge [5, 6] or by the output of hindcasts of simulations of storm surge [7], for reducing the loss of the storm surge. Storm surges have been studied intensively by numerical method. But few of these studies take the different influential factors on the storm surge model into consideration. This study will focus on the different factors on the storm surge simulation of the local coastline geometry in the Bohai Sea and investigate its

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effects on storm surges simulation induced by extratropical cyclone, aiming to estimate the important factors on the storm surge simulation and make possible a good conservation behavior of the storm surge model.

A hindcast of typical extratropical storm surge occurring in the Bohai Sea in Oct. 2003 is performed using a 3D FVCOM nonlinear barotropic model forced by 10-m winds. The surface winds are obtained from the WRF data set. Some preliminary sensitivity studies of the influential factors on storm surge simulations in the coast area of the Bohai Sea are studied and simulated with the high revolution numerical model. The factors of tide-surge interaction, the wind stress, the water depth, the critical depth in the model, and the bottom drag coefficient to that of the water level fluctuations of storm surge are compared. The output of this model is used to identify the important factors on the storm surge simulation.

This paper is organized as follows: the numerical models and the verification, with their corresponding forcing and outputs are described in section 2. In section 3, the different influential factors are considered for affecting storm surges simulation and the outputs of the simulation are performed. Section 4 is devoted to present the results leading to the best model for the storm surge of the Bohai Sea. The conclusions are outlined.

2. THE MODEL FORMULATION

2.1. The Primitive Equations

FVCOM is an unstructured-grid, finite-volume, free-surface, three-dimensional primitive equations ocean model developed originally by Chen *et al*. [8]. The original version of FVCOM consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using the Mellor and Yamada level 2.5 turbulent closure scheme for vertical mixing and the Smagorinsky turbulent closure scheme for horizontal mixing. The merits of FVCOM are mainly associated with the triangular grids suiting well the complex geometry and with the finite volume approach making possible a good conservation behavior of the model. Mode splitting technique is applied to internal mode, allowing the use of large time step. 2D external mode is numerically integrated using a modified fourth-order Runge-Kutta time-stepping scheme, while 3D internal mode is integrated using second-order Runge-Kutta time-stepping scheme. The point wetting/drying treatment technique is included to predict the water covering and uncovering progress in the inter tide zone [8].

2.2. The Model Set

The geometry and bathymetry of the Bohai Sea are shown in Fig. (**1**), which are similar to the geometry [9], which were provided by the National Geophysical Data Center of the National Oceanic and Atmospheric Administration in 1976.

The model domains the whole Bohai Sea, with the open boundary arching outside of the Bohai Strait. The grid resolution remains at 1 km near shoreline of Bohai Bay and gradually increases to about 3-5 km in the central Bohai Sea, at last remains about 10 km in the open boundary to fit for the complicated coastline (Fig. **2**). The horizontal triangular grid has 12824 nodes and 24656 elements. The initial field of water velocity is set to zero in this study. Six sigma levels are used in the vertical. The external time step is 3 s. The ratio of internal time step to eternal time step is 10.

In this work, the ocean model has been forced 3-hourly by 10-m winds provided by the WRF data set, with a spatial

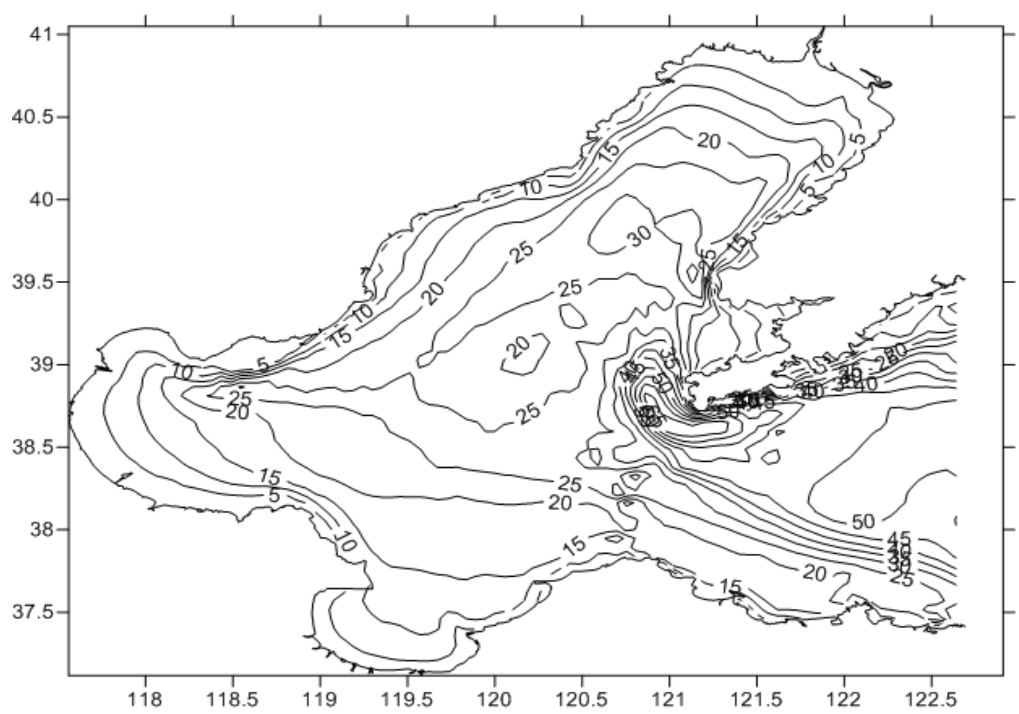

Fig. (1). Geometry and bathymetry of the Bohai Sea.

resolution of 0.1° and 0.1° in latitude and longitude, respectively. The elevation clamped open boundary condition is provided along the open boundary where the water depth is generally about 70 m. The time-dependent water elevations consist of both the main astronomical tides M2, S2, N2, K2, K1, O1, P1 and Q1 calculated from OTPS (OSU Tidal Prediction Software). Hourly model outputs have been stored for the whole domain.

2.3. Model Verification

Prior to simulating the storm surges, we tested the model simulations of tides. The tide model runs have been carried out, and the detailed validation of the hindcast against observation is presented in Figs. (**3**, **4**). The Co-amplitude

Fig. (2). The grids used for the simulations.

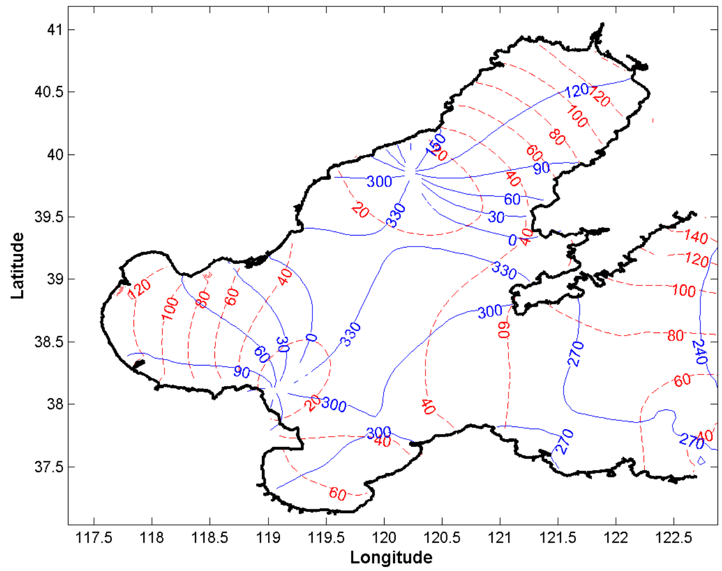

Fig. (3). Co-amp and Co-pha of M2 constituent in the Bohai Sea.

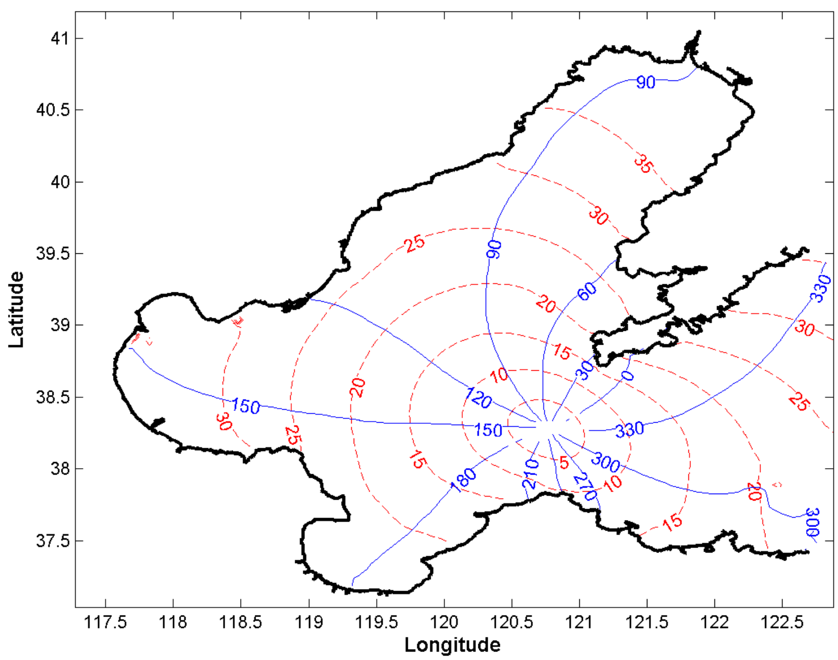

Fig. (4). Co-amp and Co-pha of K1 constituent in the Bohai Sea.

and Co-phase of M2 constituent in the Bohai Sea are in accordance with the references, the Co-amplitude and Co-phase of K1 constituent in the Bohai Sea are similar to the references too. These tidal constituent results are generally found to be good, particularly for the semidiurnal species.

For the storm surge simulations, the model is driven by the wind stress, plus tides with elevations at the open boundaries. The model with runs had begun at 00 GMT on 1 Oct. 2003, and ended at 23 GMT on 31 Oct. 2003. To test the modeling ability, the model system was initially applied to reproduce the storm surge generated at 10 Oct. to 13 Oct. in 2003 during which the field observations were carried out.

We select Tanggu port located in the north west of the Bohai Sea. A detailed validation of the hindcast against observation is presented as follows (Fig. **5**), which finds correlations with water level fluctuations lower than 9 cm in Tanggu port. The simulation accounts for the observed surge levels. Even though this validation does not focus on the extreme events, this is not a major problem here, as far as we are interested in the change of the factors of the surge model and not the absolute values.

3. RESULTS AND DISCUSSION

Five group baseline runs were performed for the storm surge occurring in Oct. 2003 in order to study the influential factors on the storm surge simulation in the Bohai Sea.

3.1. The Nonlinear Interaction Between Storm Surges and Astronomical Tides

For these storm surge simulations, two baseline runs are performed: (a) The model forced by tide and wind (called model-A); (b) The model forced only by wind (called model-B). The surge levels are the sea elevation from the output of model-A minus the sea elevation from the output of the model driven only by tide. As shown in Fig. (**6**), the model-A simulation is in good agreement with the observation, both in storm surge amplitude and phase, it captures the initial rapid increase of surge level very closely, whereas the model-B does not respond so well. The model-A simulation peaks at 1 o'clock on 11 Oct. 2003 with a storm surge level of 1.52 m, about 0.09 m lower than observed. Then the simulation and the observation show the surge levels decreasing in 48 hours, followed by a lower decrease along with tidal oscillations. In comparison with the model-A simulation, the model-B simulation underestimates the peak with the storm surge level of 1.40 m, about 0.21 m lower and 4 hours later than observed.

As shown in Fig. (**6**), the model-B simulations account for the observed surge levels reasonable well at the initial phase and the mature phase. Thus, the important factor which affected the storm surge level is wind stress. But the model-B does not simulate the whole storm surge. It is concluded that the nonlinear effects play important roles in the nonlinear interaction between storm surges and astronomical tides.

3.2. The Effect of the Wind Stress on the Storm Surge

For these storm surge simulations, two baseline runs are performed as follows: (a) The model forced by tide and wind, and the wind provided by the ERA40 data (called model-A); (b) The model forced by tide and wind, and the wind velocity was increased by 10% with the similar other situations (called model-B). In comparsion with the model-A, the model-B simulation overestimates the surge level peak about 0.4 m higher than the model-A simulation.

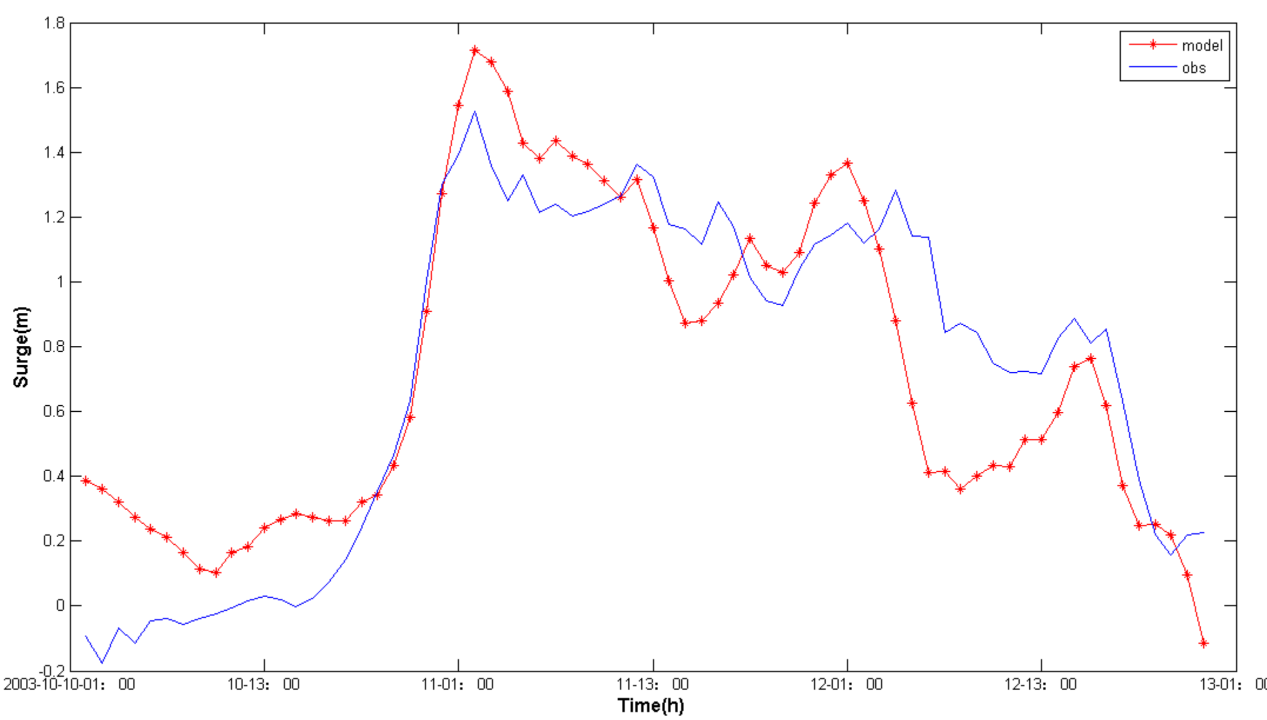

Fig. (5). Calculated and observed water level fluctuations.

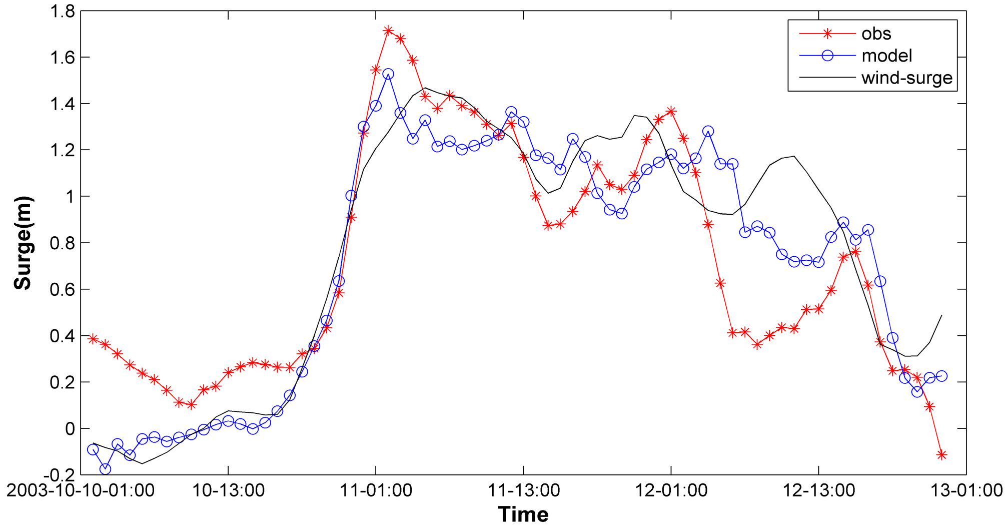

Fig. (6). Comparison of the calculated and observed surge levels.

The storm surge derives primarily from the slope of the sea surface, which sets up to balance the Coriolis force and the difference between the wind stress on the sea surface and the bottom stress. It is concluded that the storm surge's magnitude depended on the wind stress. The surge level is proportional to the wind velocity, and the north west direction is the main direction on the storm surge in the Bohai Sea.

3.3. The Effect of the Depth on the Storm Surge

The effect of shallow water is significant for the Bohai Sea. To investigate the contribution made by the water depth on the storm surge simulation, two baseline runs are performed as examples for comparison with the simulations: (a) For the first model run, the minimum water depth of the Bohai Sea was held at 1 m (called model-A). (b) For the second model run, the minimum water depth was held at 3 m (called model-B). The model simulation shows that the storm surge level is opposite proportion to the water depth. The shallower the water is, the higher the storm surge level. At Tanggu port, the model-B simulation agrees better with the peak surge, the model-A while overestimating the observed peak surge 0.09 m.

3.4. The Effect of the Bottom Drag Coefficient on the Storm Surge

The bottom drag coefficient is particularly important in shallow water for the storm simulation. This attributes to different bottom drag coefficient for the present study we strive to investigate. In this simulation, the constant bottom drag coefficient is held in the Bohai Sea.

For these simulations, two baseline runs are performed as follows: (a) The model forced by the tide and wind, in which the constant bottom drag coefficient is held at 0.001 (called model-A); (b) The model forced by the tide and wind, in which the constant bottom drag coefficient is held at 0.01 (called model-B). Compared to the model-A, the model-B simulation underestimates surge level 0.10 m lower than the model-A. The magnitude of the bottom stress is also explained. The model-B simulation generates a larger bottom stress than the model-A simulation. As a result, the simulated surface slope is smaller for the model-B simulation, and its spatially integrated values and the storm surges are therefore smaller.

These sensitivity studies indicate that storm surges depend critically upon the parameter values used for specifying bottom stress.

3.5. The Effect of the Critical Depth Parameter on the Storm Surge

Considering the effect of the storm surge inundation, the wet/dry grid method is used in FVCOM. Thus the critical depth is an important parameterization in the simulation. For these simulations, two baseline runs are conformed: (a) For the first model run, the critical depth is held at 0.05 (called model-A); (b) For the second model run, the critical depth is held at 0.5 (called model-B). The model simulation shows that the model-A simulation is good account for the observation surge level. In comparison with the model-A, the model-B simulation underestimates the peak surge 0.27 m and 12 hours later than the model-A.

These sensitivity studies indicate that storm surge levels also depend on the critical depth parameter. The simulation with small critical depth will account good for the observed storm surge along the coast area.

CONCLUSION

A three-dimensional storm surge model is applied to investigate the hydrodynamic response in the Bohai Sea. The simulated surge levels and tidal elevations reproduced during the extratropical storm surge agree with the field observations and the references. Based on this validated model system, a series of experimental cases has been carried out to study the effects of the parameters of the model simulations. The results show that the storm surge is the interaction of the tides and the surge. The wind stress on water surface, the parameters of the bottom drag coefficient and the critical depth are important on peak surge for the simulation in the

Bohai Sea. These sensitivity studies indicate that the storm surge simulations depend critically on the parameterizations. After considering the tide-wind interaction and the severe wind, the most important influential factor affecting the storm surge in the Bohai Sea is the bottom drag coefficient. Hence additional experimental guidance is required on the bottom drag coefficient. This study is useful for the storm surge simulation in order to select the proper parameter to make possible a good conservation behavior of the storm surge model.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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