

Modeling of storm surge in the coastal waters of Yangtze Estuary and Hangzhou Bay, China

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ABSTRACT

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The region of Yangtze Estuary and Hangzhou Bay (YE-HB) is subjected to tropical cyclone (TC) impacts during summer almost every year, resulting in extensive loss of life and property. An integrated model system, which includes a storm-induced wind model, wave model and hydrodynamic model, was developed for storm surge simulation in this area. Nesting computation was adopted for considering the effect of a remote wind field. Wave effects were included by considering radiation stress and enhanced bottom shear stress. Taking Typhoons Agnes (8114) and Matsa (0509) as examples, the model system was applied to the waters of the YE-HB. The calculated results of winds, waves and storm surges agree well with the observed data, which means there is good applicability of the model system for the study area. The distributions of the surge setup were analyzed. Finally, the effects of waves and remote winds on storm surge were probed by numerical experiments.

ADDITIONAL INDEX WORDS: *Storm-induced wind, Wind-waves, Nesting, Tide simulation, Surge setup.*

INTRODUCTION

Predictions of storm surge in coastal areas are of great importance for coastal structure design, coastal management and the safety of human life and property. Many studies have been conducted on simulating storm surges (MADSEN and JAKOBSEN, 2004; SHEN et al., 2006). For instance, the famous SLOSH model (JELESNIANSKI et al., 1992) was widely used for two-dimensional (2-D) application. With the fast developments of computer science and numerical technology, some three-dimensional (3-D) models were developed (PENG et al., 2004) that can consider the hydrodynamic processes more realistically and precisely. Furthermore, wave effects were introduced by including radiation stress and enhanced bottom shear stress (JONES and DAVIES, 1998), which can improve the results nearshore. Considering storm surge is a 2-D variable and 2-D calculation has an advantage for computational speed or time, 2-D models are still irreplaceable, especially in some cases, where a rapid prediction is required.

Whether the models are 2-D or 3-D, the accuracy of the input wind field during a tropical cyclone (TC) is crucial for the results of modeling storm surge. Some classic parametric pressure or wind models (FUJITA, 1952; HOLLAND, 1980) are frequently used to conveniently generate symmetric wind fields. These models have similar formulae, and the accurate choice of TC parameters is the key point. Both local wind and remote wind can cause storm surge, as studied by WONG and MOSES-HALL (1998) with a conceptual method. Their studies show that the computational region should be large enough to include the effects of remote winds, or the nesting technique should be applied.

The region of Yangtze Estuary and Hangzhou Bay (YE-HB, see Figure 1), located on the east coast of China facing to the open sea, the East China Sea (ECS), is subjected to TC impacts almost every year during summer. These TCs are mainly generated at the

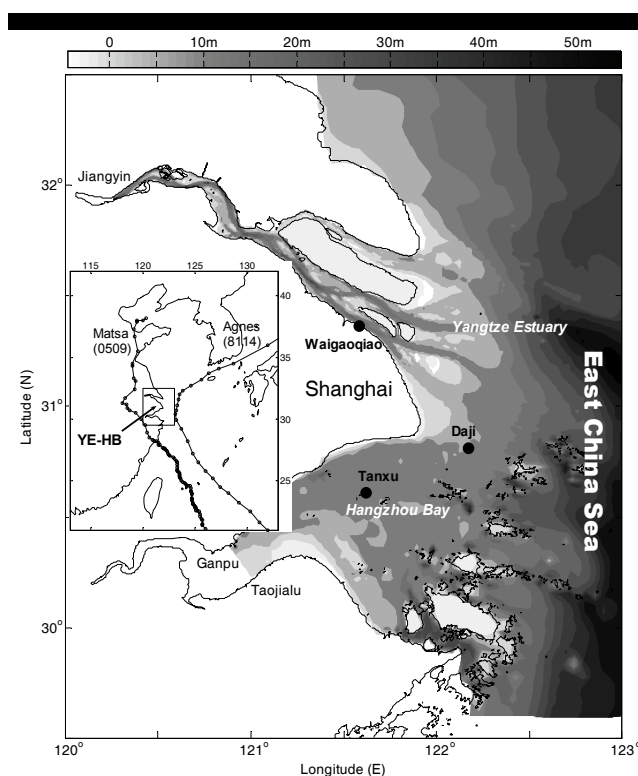


Figure 1. Region of the YE-HB, survey stations (black points) and typhoon paths (sub-figure).

ocean surface either east of the Philippine islands or near Guam. The TCs that affect this region can be divided into two main groups according to the different tracks of their low-pressure center (see sub-figure of Figure 1), namely the turning type and the landfalling type. The latter type can sometimes turn and move into the sea again.

In this study, an integrated model system is developed for storm surge simulation. Nesting computation is adopted for considering the effect of remote wind fields. The shallow depth in the YE-HB makes wave effects on storm surge important. Wave effects are included through radiation stress and bottom shear stress in the hydrodynamic model. Taking two strong TCs, in the turning and landfalling categories, respectively, the model system is applied to the YE-HB for the simulation of storm surge. The characteristics and mechanics of storm surge in this region are analyzed. The effects of waves and remote winds are also discussed.

MODEL SYSTEM DESCRIPTION

The numerical model system consists of a wind model, a nearshore wave model and a hydrodynamic model. The wind model provides storm-induced wind fields for both the wave model and the hydrodynamic model. Wave elements provided by wave model can be input into the hydrodynamic model for calculating radiation stress and bottom shear stress under waves and currents. The hydrodynamic model includes the dynamic factors of river runoff, astronomical tides, and winds and waves.

Model Grid Settings

Yangtze Estuary (YE) and Hangzhou Bay (HB) are considered as one research system because of the substantial exchange of water and sediment between them. In order to resolve the complicated topographies and coastal shapes in the YE-HB, it is necessary to use curvilinear grids with high resolution in the area of interest. Figure 2 shows the calculation grids for the YE-HB. The grids are 147×131 ; the average grid spacing is about 2 km; the maximum is about 6 km offshore; the minimum is about 300 m inside the Estuary.

The nesting method is used for considering the remote wind effect during storm events. The region of ECS is chosen for the larger calculation domain, in which the wind- or storm-induced water level change is computed. This level change can be added into the boundaries of the small domain of YE-HB by interpolation. The grids for the ECS are generated by de-refining the grids for the YE-HB and expanding to the whole domain (sub-figure of Figure 2). The grids are 151×207 ; the average grid spacing is about 8 km.

Wind and Wave Models

A symmetrical storm-induced wind model with a background wind is adopted in this study. The 6-hourly background wind data at 10 m above sea level on a T62 Gaussian grid (approximately 2°) are obtained from NCEP/NCAR Reanalysis. The parametric wind model uses Fujita's formula (FUJITA, 1952) for the atmospheric pressure field due to storms (Refer to HU et al., 2005, for details).

The SWAN wave model developed by TU Delft was introduced for simulation of storm-induced wind-waves. The spectral wave model based on the wave action balance equation is made suitable for nearshore applications by incorporating some specific treatments of nearshore wave processes. Detailed descriptions can be found in the SWAN user manual (BOUJ et al., 2004). Driven by the wind from the wind model introduced above, the SWAN model was applied to the YE-HB for simulation of storm-induced waves with reasonable results obtained by HU et al. (2005), using

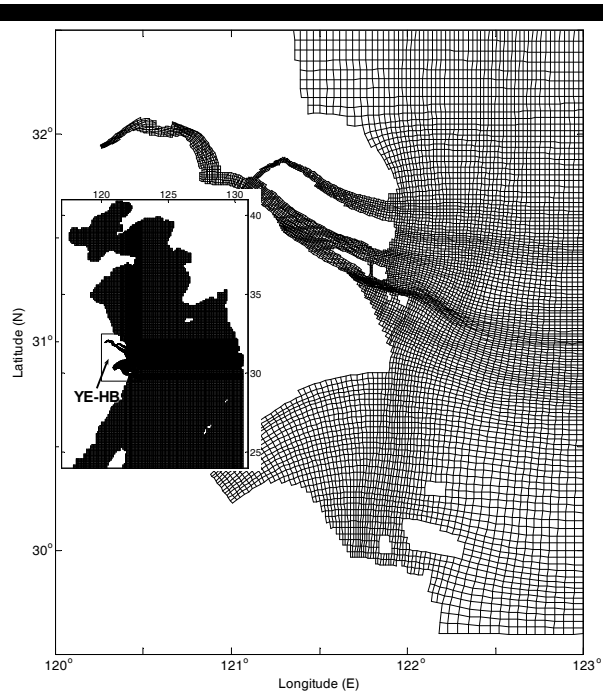


Figure 2. Curvilinear model grids for the regions of the YE-HB and ECS (sub-figure).

the method on which this study is based.

Hydrodynamic Model

A 2-D hydrodynamic model for storm surge calculation was developed from the model by SHI et al. (1997) using the wet-dry grid point method. This model was applied to the YE-HB for simulation of astronomical tides and currents (HU et al., 2000). In this study, the original model was revised by adding the water level change due to the atmospheric pressure field and considering the effect of waves. The governing equations in Cartesian coordinates are as follows:

$$\frac{\partial H}{\partial t} + \frac{\partial Hu}{\partial x} + \frac{\partial Hv}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - f v = -g \frac{\partial \zeta}{\partial x} - \frac{1}{\rho} \frac{\partial P_{atm}}{\partial x} \\ + \frac{1}{\rho H} (\tau_{ax} - \tau_{bx}) - \frac{1}{\rho H} \left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \right) \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + f u = -g \frac{\partial \zeta}{\partial y} - \frac{1}{\rho} \frac{\partial P_{atm}}{\partial y} \\ + \frac{1}{\rho H} (\tau_{ay} - \tau_{by}) - \frac{1}{\rho H} \left(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \right) \end{aligned} \quad (3)$$

in which Eq. 1 is the continuity equation, Eqs. 2 and 3 are momentum equations in x- and y-direction; (u, v) are the components of depth-averaged velocity \bar{U} ; g is the gravity acceleration; $H = h + \zeta$ is the total depth, h is the depth under the mean water level, ζ is the water elevation; f is the Coriolis parameter; ρ is the water density; P_{atm} is the atmospheric pressure; $(S_{xx}, S_{xy}, S_{yx}, S_{yy})$ are the components of radiation stress induced by waves.

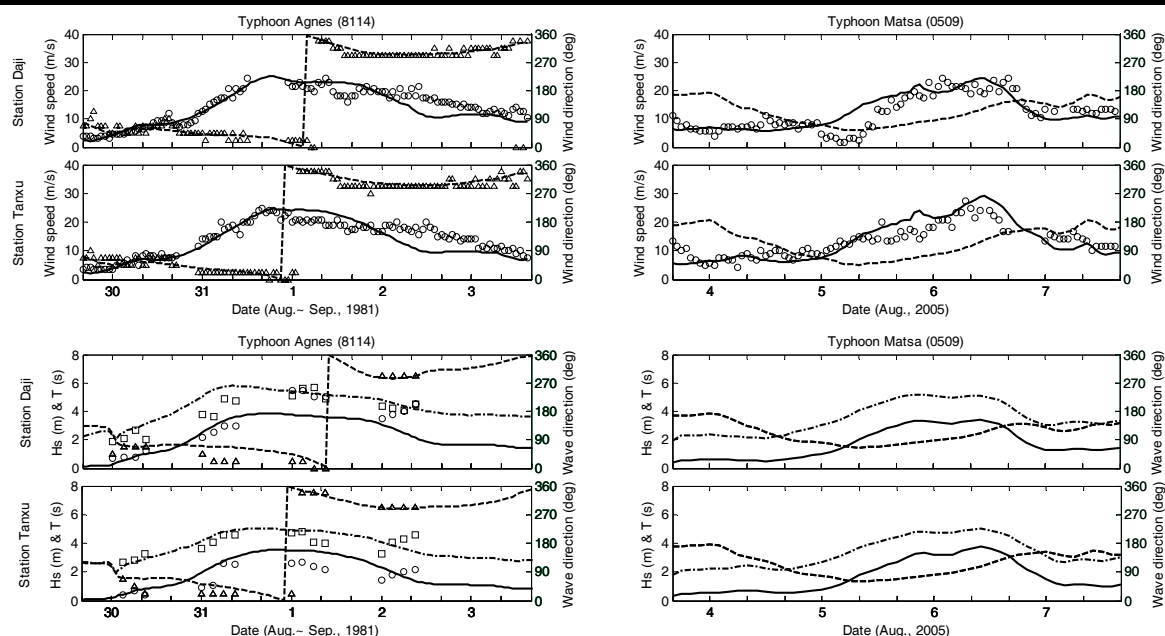


Figure 3. Comparisons of wind speed (solid line for the modeled; circles for the observed), wind direction (dashed line for the modeled; triangles for the observed), significant wave height (solid line for the modeled; circles for the observed), wave direction (dashed line for the modeled; triangles for the observed) and average wave period (dash-dotted line for the modeled; squares for the observed) at two stations (Daji and Tanxu) during Typhoons Agnes and Matsa.

(τ_{ax}, τ_{ay}) are the components of surface wind stresses $\bar{\tau}_a$, parameterized by the quadratic law, that is:

$$\bar{\tau}_a = \rho_a C_D |\bar{W}| \bar{W} \quad (4)$$

where ρ_a is the air density, \bar{W} is the vector of wind speed, C_D is the drag coefficient based on the following equation (SMITH, 1980):

$$C_D = (0.73 + 0.069 |\bar{W}|) \times 10^{-3} \quad (5)$$

(τ_{bx}, τ_{by}) are the components of bed shear stresses (bottom friction) $\bar{\tau}_b$. A wave-current boundary layer sub-model, Grant-Madsen (GM) model (GRANT and MADSEN, 1986) is adopted for calculating bed shear stress due to waves and currents. For pure astronomical tide simulation with no wave effects, $\bar{\tau}_b$ is represented by the Manning's friction relationship,

$$\bar{\tau}_b = \rho g n^2 H^{-1/3} |\bar{U}| \bar{U} \quad (6)$$

where n is the Manning parameter.

TYPHOONS AND OBSERVED DATA

A typhoon is a super strong TC that originates on the North-West Pacific Ocean. Two typhoons (see sub-figure of Figure 1), Agnes, a very strong one historically, and Matsa, a recent one, which greatly affected the YE-HB, were selected for the simulation of storm surge.

TC Agnes (No. 8114) formed near Guam on August 25, 1981. On August 29, it became a typhoon and then entered the ECS. On August 31, Agnes developed into its strongest stage with 949 hpa center air pressure and 45 m/s near-center maximum wind velocity at 6:00 UTC. After 36 hours of slow northward movement, it moved north-east. Agnes impacted greatly on the YE-HB because it was very close to the area and lasted for a long period.

TC Matsa (No. 0509) originated at 900 km east of the Philippines, on July 31, 2005. Increasing gradually in intensity, it became a typhoon on August 3. During the time from August 4 to August 5, Matsa reached its strongest stage with 950 hpa center air pressure and 45 m/s near-center maximum wind velocity. At 19:40 UTC on August 5, it made landfall to the south of the YE-HB. At 18:00 UTC on August 6, it weakened to a TC. After 2 days, it moved into the sea again and finally diminished.

Both typhoons coincided with spring tides, which caused extremely high water levels during their passage. During typhoon events, wind and wave data were collected at two stations, Daji and Tanxu. Wave data were rare (4 times a day) compared to wind data (every hour). Unfortunately, the data for wind direction and waves during Typhoon Matsa are not available. Water levels were observed at three stations, Daji, Tanxu and Waigaoqiao. For verification of astronomical tides, observed harmonic constants are available at more than 20 stations (Refer to HU et al., 2000 for details) throughout the region of YE-HB, and the predicted tide data can be obtained from the tide tables.

WIND AND WAVE SIMULATIONS

Winds and waves due to typhoons were modeled and compared with observations before simulation of storm surge, as shown in Figure 3. For Agnes, the agreement of wind direction was very good, while for wind speed, the result was underestimated a little at both stations on September 2. The reason for the discrepancy may be that the symmetrical wind model cannot account for the asymmetry of winds, caused by, for instance, the effect of land and the resolution of background wind is relatively low. For Matsa, the agreement for wind speed was good. The result for wind direction differs from that of Agnes because of their different TC categories. In general, the modeled wind reproduced the observed winds fairly well and can be used in the wave model and hydrodynamic model.

The non-stationary mode in spherical coordinates was used in SWAN. The nesting computation was set up between the YE-HB domain and the ECS domain. Twenty-two exponentially spaced frequencies from 0.125 Hz to 1 Hz with 60 evenly spaced directions (of 6° resolution) and a time step of 15 minutes were adopted. Other parameters took the default values given in the SWAN model.

Wave direction here is defined as the direction where waves come from, which, for easy comparison, is similar to wind direction. During Agnes, wave direction and period agreed well with the observations except that the modeled wave height did not reach the huge measurements observed (about 5.5 m) at Daji, and at the same time, it overestimated the wave height a little at Tanxu. There are many islands located in the south part of HB, the effect of which cannot be fully considered by a wave spectral model. Overall, the wave results are reasonable and suitable for consideration of the wave effect in the hydrodynamic model.

STORM SURGE SIMULATION

Astronomical Tide Simulation

The astronomical tides in the YE-HB should be first verified before the calculation of storm surge. This work has been done by HU et al. (2000) using a similar hydrodynamic model. As shown in Figure 1, the boundary of the YE is at Jiangyin, the upper limit of the tidal current, where the river runoff enters. The boundary of the HB is at the line between Ganpu and Taojialu. There are three offshore boundaries (shown in Figure 2). Water level conditions were used to force the model. Seven main constituents were considered at these boundaries, namely M_2 , S_2 , K_1 , O_1 , N_2 , K_2 and P_1 . Harmonic constants of M_2 , S_2 , K_1 and O_1 were derived by interpolation from observed distributions in the ECS. Harmonic constants of N_2 , K_2 and P_1 were derived from the values of M_2 , S_2 and K_1 , respectively, by the statistical relationship resulting from the observed data. The time step is 60 s and the Manning parameter is about 0.013. The model runs 10 days for spinning-up, and then starts to output results for verification.

The modeled harmonic constants gained by using 30 days of calculated water levels for harmonic analysis were compared with the observed constants. At most stations, the relative error of the local tidal amplitude and the absolute error of the local phase were less than 10% and 10°, respectively, which means the astronomical tide simulation in this model is successful.

Furthermore, the astronomical tides during Typhoons Agnes and Matsa were calculated with the month-average river runoff, that is, 41500 m³/s and 40000 m³/s, respectively, and no wind input. The calculated results of water level agreed quite well with the predicted data of tide tables at three tidal stations, Daji, Tanxu and Waigaoqiao (Figures were omitted here due to limitations on space).

Storm Tide Simulation

Storm surge during two TCs was simulated by using the nesting method. There are two steps in the calculation. Firstly, driven by the modeled storm-induced winds, the water level due to TCs in the larger domain, the ECS, was calculated and interpolated (every hour) to the open boundaries of the small domain, the YE-HB. Secondly, the storm surge in the YE-HB was simulated. Water level boundaries were the combination of the astronomical tide from harmonic constants and the water level change from the larger domain, through which the effect of remote winds can be considered. The monthly-average river runoff was added.

Figure 4 shows the comparisons of the modeled water levels

against the observed data. It can be seen that the agreements between the modeled and the observed data were fairly good. The effects of storms can be clearly shown by the time series of surge setup. The modeled surge setup is the difference between the results in the storm tide simulation and those in the pure astronomical tide simulation. The observed setup is the difference between the observed water level and the predicted level from tide tables. During Agnes, the surge setup was obvious during two days, from August 31 to September 1, due to strong typhoon intensity and the short distance of the low-pressure center from the region. The modeled maximum setup accorded well with the observed one, about 1 m both at Daji and Tanxu, and 1.5 m at Waigaoqiao. During Matsa, the pattern of the surge process was similar, but with lower value (mainly due to different wind directions between the two categories), about 0.5 m at Daji and Tanxu, and 1.0 m at Waigaoqiao. There was some discrepancy during the last 8 hours of August 6, which may have been caused by some other weather processes that were not considered here. Overall, the good agreements between the modeled and the observed data showed that the simulation of storm surge was successful.

The distributions of the surge setup during two typhoons at the time when maximum setup occurred are shown in Figure 5. At 23:00 UTC on August 31, the low-pressure center (pentagram in sub-figure) of Typhoon Agnes was very close to the YE-HB. The wind direction was counter-clockwise near the region, that is, easterly in the north and westerly in the south, which caused surge set up in the north (0.3 m) and set down in the south (-0.2 m). The maximum setup appeared at two places. One was the mouth bar region of YE, where storm surge offshore was converged by the gradually shallow depth under the east wind. The other place is the south part of HB, where storm surge induced by south-west winds was blocked by the islands. Both setups reached 1.6 m. At 10:00 UTC, August 6, the center of Matsa was very close to the south coast of HB. Winds were easterly and southeasterly throughout the region, which caused a high surge setup in the north part of HB and the upstream of YE. These setups reached 1.6 m and 1.2 m, respectively. In addition, it should be pointed out that winds in the north part of the larger domain (ECS) were mainly caused by background winds, not by typhoon-induced winds, because the center of Matsa was far away.

DISCUSSION

There are several factors that affect the accuracy of storm surge calculations, which include storm-induced wind, wind-waves, astronomical tide and the setting of the computational domain. In this study, the effects of waves and remote winds were probed by conducting numerical experiments. Remote wind was considered by a nesting computation. The normal simulation with waves and nesting is defined as Case 0; the test simulation with no wave effects (with nesting) is defined as Case 1; the test simulation with no nesting (with waves) is defined as Case 2. For the legibility of figures, the results of Cases 1 and 2 are not directly added to Figure 4b. The surge differences between Cases 1, 2 and 0 are shown in Figure 6. Their differences can also be viewed as wave-induced setup and remote-wind-induced setup, respectively.

The solid line in Figure 6 represents the surge difference due to waves. During Agnes, the biggest difference appeared from August 31 to September 1, when there were huge waves. This difference was about 0.2 m, which was about 20% of the total surge setup. During Matsa, the wave-induced setup was less than those during Agnes, about 0.1 m. It should be pointed out that some stations, like Daji and Tanxu, are not located in the surf zone, where wave effects will be more important. So for extreme storms

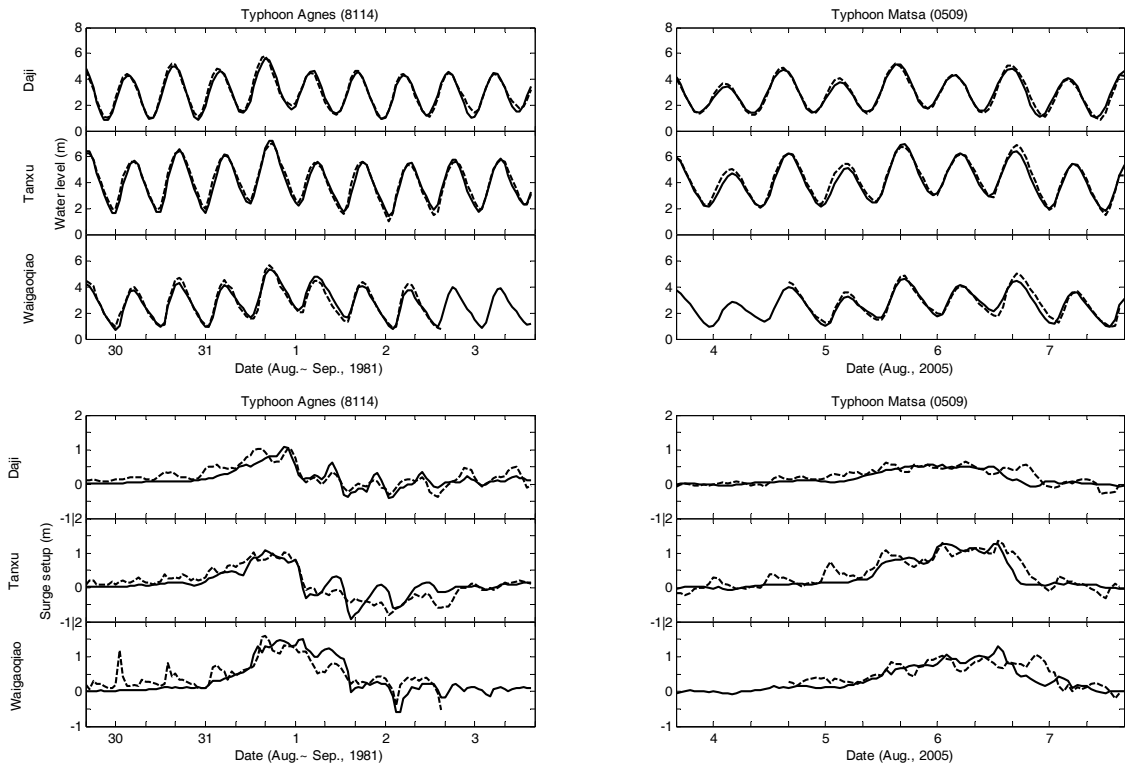


Figure 4. Comparisons of water level and surge setup at three stations (Daji, Tanxu and Waigaoqiao) during Typhoons Agnes and Matsa (solid line for the modeled; dashed line for the observed).

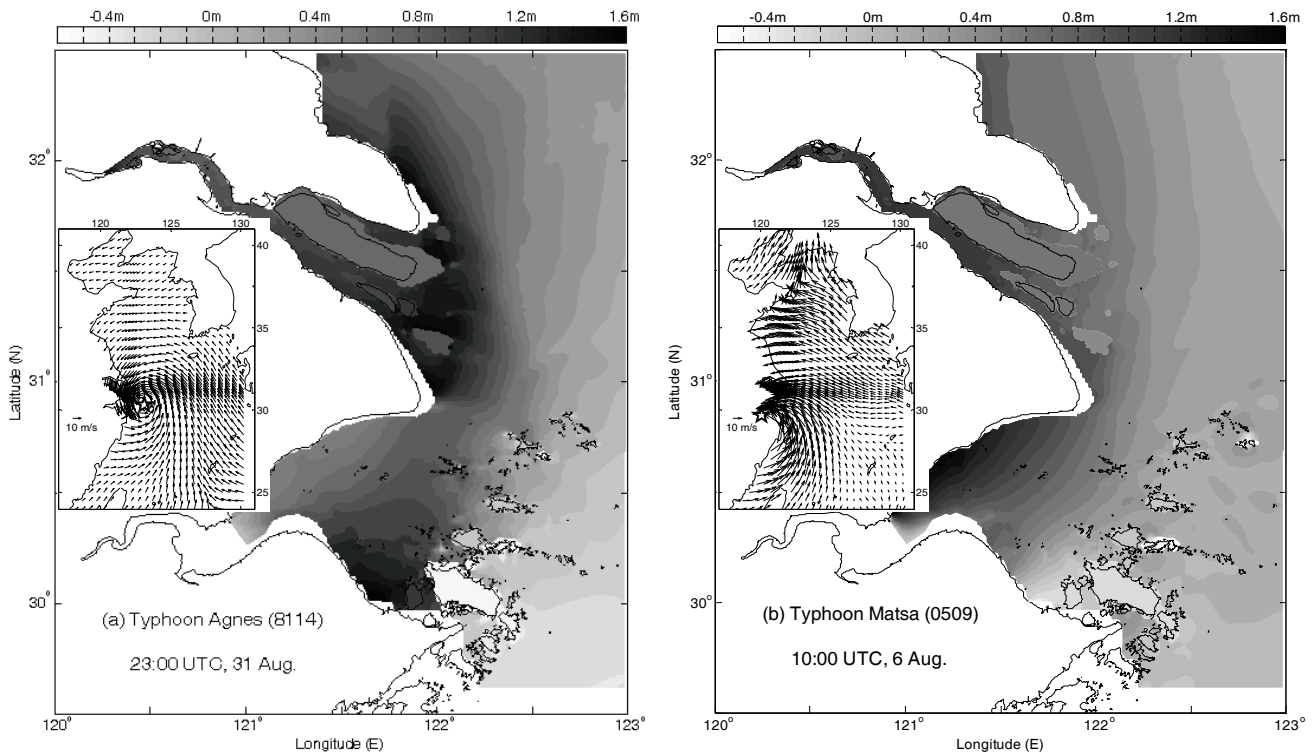


Figure 5. Distributions of the surge setup in the YE-HB and wind field in the ECS (sub-figure) during Typhoons Agnes and Matsa.

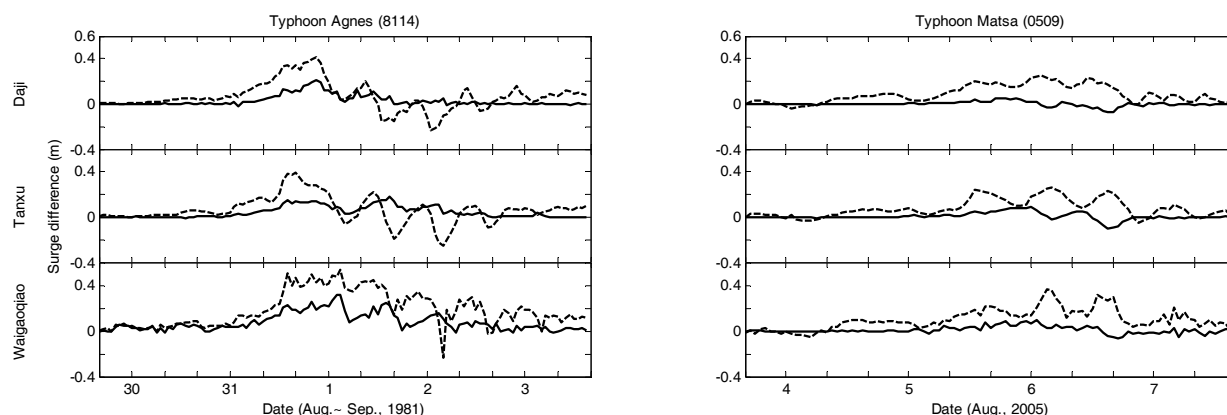


Figure 6. Surge difference with different model conditions at three stations (Daji, Tanxu and Waigaoqiao) during Typhoons Agnes and Matsa (solid line for the difference between Case 0 and Case 1; dashed line for the difference between Case 0 and Case 2).

with huge waves, wave effect should be accounted for to produce an accurate simulation of storm surge, especially in shallow places.

The dashed line in Figure 6 represents the difference in surge due to remote winds. It can be seen that the nesting computation is essential for both typhoons. The difference in surge was about 0.4 m for Agnes and 0.2 m for Matsa. If the effect of remote winds were excluded, the final results would be a lot less accurate.

CONCLUSIONS

Taking Typhoons Agnes and Matsa as examples, an integrated model system was applied to the waters of the YE-HB for the simulation of storm surge. The effects of waves and remote winds were considered. The results of modeling winds, waves, astronomical tides and storm tides were compared with observed data. Good agreements between the observed and modeled data showed that this model system is suitable for storm surge calculation in the YE-HB. Through numerical experiments, it was found that waves should be considered in the case of strong storms, and nesting computation should be adopted if the calculation domain is not large enough to include the effect of remote wind.

Many factors, such as winds, waves, astronomical tides and the setting of the calculation domain, affect the final accuracy of storm surge modeling. The wind model can be improved by using an asymmetric pressure distribution and the method of data assimilation. The spectral wave model SWAN cannot fully account for the effect of wave diffraction. Therefore, the coupling of SWAN with momentum-based wave models, such as mild-slope or Boussinesq models, is desirable for some local places. 3-D simulation can reflect more realistically the processes in nature. These will be our future work.

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