Simulation of storm surge and wave due to Typhoon Lekima in 2019

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Abstract: Zhejiang province is located at the southeast coast of China and vulnerable to typhoons generated in the northwest Pacific Ocean. An integrally coupled surge-wave model is developed and applied to the simulation of storm surge and wave induced by typhoon Lekima occurred in 2019. When considering wave-induced forces and using identical unstructured grid in coupled model, the model shows high accuracy and reproduces the typhoon process well. The distribution of maximum surge level shows great spatial differences along Zhejiang coast. Due to shelf geometry and shallow water effect, peak surge level rises significantly near Zhejiang coast. In addition, the peak surge levels on the right side of typhoon track are much higher than that on the left side. Contrary to characteristics of storm surge levels, significant wave height decreases rapidly near the Zhejiang coast due to shoaling, blocking of islands, and wave breaking.

1. Introduction

Storm surge and wave induced by typhoon can cause devastating damage to low-lying coastal zones, particular coinciding with high tides. Typhoon disasters are more severe due to climate change in recent years. Thus, study on storm surge and wave is essential and helpful to mitigate disaster losses. In the earlier study, the effect of waves is usually not considered in storm surge calculation. With the deepening of research, it is realized that inclusion of wave-induced surge can improve storm surge level prediction significantly in near shore zones [1]. Radiation stress theory shows how wave-induced forces act on currents though the gradient of radiation stress. Wave setup produced by the divergence of radiation stress is particularly significant in in shallow water area [2]. In fact, there is complicated interaction between storm surge and wave except induced wave setup. Water levels and currents from storm surge affect the propagation of waves and location of wave-breaking zones. Meanwhile, waves influence the vertical momentum mixing and bottom friction to change the water levels and currents [3, 4]. For example, wave-induced setup caused tens of centimeters in the total level and accounts for thirty-five percent of the total water level in some areas [5]. Many studies have shown that including wave-enhanced surface drag coefficient and wave-enhanced bottom stress improved storm surge simulation results, more consistent with the observations [6].

Storm surge and waves were investigated using numerical models since fifty years ago. With the development of computational ability, more ocean physical processes are considered in models [7]. Various models have been developed for tide and storm surge simulations, such as FVCOM (Finite
Volume Coastal Ocean model), CH3D (Curvilinear-grid Hydrodynamics in 3D), ADCIRC (Advanced CIRCulation model). The effect of waves is included by one-way coupling or two-way coupling between storm surge model and wave model such as SWAN (Simulating Waves Near shore) and STWAVE, which has been widely used. In recent years, more attention is paid to the two-way coupling because it describes the real physical process between wave and storm surge [8].

Zhejiang province is located at southeast coast of China and influenced frequently by typhoons generated in the northwest Pacific Ocean. In August 2019, typhoon Lekima hit Zhejiang coast and made landfall in central coastal area of Zhejiang province, resulting in extensive casualties and property losses. Typhoon Lekima is the third strongest typhoon that landed in Zhejiang province since 1949 and its path is highly representative. Therefore, typhoon Lekima is selected for the simulation of storm surge and waves of Zhejiang coast. In present study, the coupled process between storm surge and wave is described in detail. Then the storm surges and waves induced by typhoon Lekima are simulated using fully coupled wave-tide-surge model to investigate the distribution of extreme surge level and wave heights along Zhejiang coast.

2. Data and Method

2.1. Storm surge model description
The coupled surge-wave model is established by integrating SWAN and ADCIRC through coupling system [9]. Firstly, the governing equations of two models are introduced in detail, respectively. ADCIRC solves the primitive equations with the finite element method in space and with the finite difference method in time. Primitive equations are formulated using traditional hydrostatic pressure and Boussinesq approximations. The governing equations of ADCIRC are written as follows:

$$
\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(UH) + \frac{\partial}{\partial y}(VH) = 0
$$

(1)

$$
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -g \left[ \frac{\partial \zeta}{\partial x} + \frac{p_s}{g \rho_0} \right] + \frac{\tau_{sx,\text{wind}} + \tau_{sx,\text{waves}} - \tau_{sx}}{H \rho_0} - \frac{D_x}{H}
$$

(2)

$$
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -g \left[ \frac{\partial \zeta}{\partial y} + \frac{p_s}{g \rho_0} \right] + \frac{\tau_{sy,\text{wind}} + \tau_{sy,\text{waves}} - \tau_{sy}}{H \rho_0} - \frac{D_y}{H}
$$

(3)

where $(U, V)$ are the $x$ and $y$ depth-averaged velocity components, $\zeta$ is free surface elevation, $h$ is the still water depth, $H = h + \zeta$ is the total water level, $f$ is the Coriolis force parameter, $g$ is gravitational acceleration, $p_s$ is sea surface atmospheric pressure, $\rho_0$ is sea water density, $(\tau_{sx,\text{wind}}, \tau_{sy,\text{wind}})$ are the $x$ and $y$ components of surface wind stress, $(\tau_{sx,\text{waves}}, \tau_{sy,\text{waves}})$ are the $x$ and $y$ components of wave radiation stress gradients, $(\tau_{sx}, \tau_{sy})$ are the $x$ and $y$ components of bottom stress, $(D_x, D_y)$ are the horizontal momentum diffusion terms.

2.2. Wave model description
The SWAN model is usually used for numerical simulations of waves [10]. Basic action balance equation of SWAN is given by:

$$
\frac{\partial N}{\partial t} + \frac{\partial C_s N}{\partial x} + \frac{\partial C_s N}{\partial y} + \frac{\partial C_\sigma N}{\partial \sigma} + \frac{\partial C_\theta N}{\partial \theta} = \frac{S}{\sigma}
$$

(4)

Where $N$ is the wave action spectrum, defined as $N=E/\sigma$, $E$ is the energy density, $\sigma$ is the relative frequency, $\theta$ is the wave direction, $C_s$ and $C_\sigma$ are velocities in $x$ and $y$ direction, respectively, $C_s$ and $C_\sigma$ are propagation velocities in $\sigma$-space and $\theta$-space. The first term in the left-hand of equation represents the local change of action density in time, the second and third terms represent propagation of action in $x$ and $y$ directions. The fourth term represents shifting of the relative frequency due to variations in depths and currents with the propagation speed $C_s$. The fifth term represents depth-induced and current-induced refraction. The term $S$ at the right hand side of equation (4) is the source term representing the effects of wind energy input, dissipation and nonlinear wave-wave interaction. It
includes the linear and exponential growth of wind input, energy dissipation by white capping, bottom friction and depth-induced breaking, quadruplet wave-wave interactions and triad wave-wave interactions.

2.3. Wind model introduction
The analytical wind model from Holland (1980) is applied in reconstructing the wind field for storm surge calculation [11]. The pressure and wind profile are calculated as follows

\[ P_s(r) = P_c + (P_n - P_c) \cdot \left( \frac{R_{\text{max}}}{r} \right)^8 \]

\[ W_g(r) = \left( P_n - P_c \right) \frac{B R_{\text{max}}}{\rho_c} \exp\left( - \frac{R_{\text{max}}}{r} \right)^8 + \frac{rf}{2} \]

Where \( r \) is the distance from the typhoon center; \( P_n \) is the ambient pressure; \( P_c \) is the central pressure; \( R_{\text{max}} \) is the maximum wind radius; \( W_g \) is wind speed. The \( B \) parameter is defined by

\[ B = 1.5 + \frac{980 - P_c}{120} \]

The \( R_{\text{max}} \) is calculated by the following formula [12]

\[ R_{\text{max}} = 51.6 \times \exp\left(-0.0223V_{\text{max}} + 0.0281\phi\right) \]

\( V_{\text{max}} \) is the maximum wind and \( \phi \) is latitude.

As \( B \) increases, the maximum wind speed increases while the wind speed distal from the center of the typhoon decreases. The inflow angle caused by friction contributes to wind field asymmetry, and a constant angle of 25° is used in this study. The central pressure and position data are retrieved from the China Meteorological Administration tropical cyclone database [13].

2.4. Coupling process description
According to the above introduction, wind data generated by Holland wind model is imported into ADCIRC and SWAN separately. Water levels and ambient currents are computed by ADCIRC and transmitted to SWAN model. Then SWAN model uses water levels and ambient currents to calculate the water depth and related wave processes. Moreover, as seen from equation 2 and equation 3, the ADCIRC model is also forced by radiation stress gradients computed by SWAN. These radiation stress gradients are computed by

\[ \tau_{xx, \text{wave}} = -(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{yx}}{\partial y}) \]

\[ \tau_{xy, \text{wave}} = -(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y}) \]

Where \( S_{xx}, S_{yx} \) and \( S_{yy} \) are the wave radiation stress, proportional to the wave energy density and derived straightforward from SWAN model. The wave radiation stresses are expressed by

\[ S_{xx} = \rho g \iint \left( \frac{C_g \cos^2 \theta}{C} + \frac{C_g}{C} - \frac{1}{2} \right) E d\theta d\phi \]

\[ S_{sy} = S_{yx} = \rho g \iint (\sin \theta \cos \theta) E d\theta d\phi \]
\[ S_{xy} = \rho_0 g \int_0^{\theta_y} \left( \frac{C_g}{C} \sin^2 \theta + \frac{C_g}{C} - \frac{1}{2} \right) Ed \theta \]  

(13)

When considering the wave-induced forces in the momentum equation, the coupling process is more comprehensive and accurate [14, 15].

2.5. model setup
In present study, the model domain is extended to the Bohai Sea, Yellow Sea and East China Sea, with a range of 114-130°E in longitude and 20-41°N in latitude (Figure 1). The mesh resolution ranges from 25 km at open boundary to 200 m in Zhejiang coast. The domain space is discretized into 260079 triangular cells with 142200 nodes. The bathymetry data used for model are composed by GEBCO dataset (https://www.gebco.net/data_and_products/gridded_bathymetry_data/) and sea charts of Zhejiang coast. The model is forced at open boundary by 9 tidal constituents extracted from the global tidal model TPXO7.2, including M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1 and M_4 tidal constituents. The typhoon wind field is generated by Holland wind model and imposed through surface boundary condition. The model is run with a cold start when the currents and water level at the initial time are set to zero. Both SWAN and ADCIRC model apply the same unstructured mesh, because it can reduce the error of interpolation between different meshes and resolves the physics of surge-wave interaction correctly.

3. Result and Discussion

3.1. Model validation
Typhoon Lekima, the ninth named typhoon of 2019, formed in the western North Pacific Ocean on 4 August 2019 and began to move westward rapidly. The center of Typhoon Lekima made landfall in the city of Wenling in Zhejiang Province, with a maximum wind speed of 52m/s and a minimum sea level pressure of 930 hPa. Then, Lekima continued to move through Zhejiang and Jiangsu provinces, making its second landfall in Qingdao. Lekima was characterized by its high intensity, heavy rainfall, and long duration. A total of 30 people died and 18 remained missing due to Lekima, along with a
A large amount of property loss. Figure 2 shows the track of Typhoon Lekima. Data from three observation stations are used to verify the model. The location of observation stations is also shown in Figure 2. Among the three stations, Kanmen station provides tidal observation data only while Nanji station just provides wave observation data. Both tidal and wave data are available at Dachen station. The time series of observed surge level were obtained by subtracting astronomical tide from total level. Figure 3 shows the comparison between the observed and model storm surge.

As seen from Figure 3, the storm surge level and phase are in good agreement with observations for Dachen and Kanmen station, indicating that our model succeeds to reproduce the storm surge induced by Typhoon Lekima. The maximum surge level of Dachen station exceeded 1.2m, much higher than Kanmen. The occurrence of peak surge level at Dachen station is consistent with the landing time of typhoon. However, peak surge level of Kanmen station is four hours earlier before landfall of Typhoon Lekima.

Figure 2 shows the comparison between modeled and observed significant heights. Because of the destructive typhoon, wave observation instrument was damaged and did not work properly, and only part of the data was recorded. Despite this, our model verification results are good and especially the model captures the maximum wave height well at Dachen and Nanji station. Overall, our coupled surge-wave model shows high computational accuracy and reproduces the typhoon process well.
Figure 3. Modeled (solid line) against observed (scatter point) storm surge at (a) Dachen station and (b) Kanmen station

Figure 4. Modeled (solid line) against observed (scatter point) significant wave heights at (a) Dachen station and (b) Nanji station
3.2. Simulation of storm surge and wave

From operational perspective, peak surge level is more important and needs to be focused on. The peak surge level combined with tide level is more likely to cause flooding and inundation. According to this, the distribution of maximum storm surge level from model result is shown in Figure 5. In the open ocean, the storm surge level is not high, no more than 1 m along the track of Typhoon Likema. The pressure effect is most obvious in deep oceans, which is known as inverse barometer effect. When the typhoon approached Zhejiang coast, the surge level started to increase, because the wind forcing was the dominant factor that generates the storm surge in coastal areas. In addition to the wind forcing, shelf geometry also plays an important role in storm surge level. When the storm surge propagated through the continental shelf, the surge level raised significantly due to the cumulative effect. The relationship of factors affecting the surge level can be illustrated with a linear expression [16]:

$$\eta = \frac{LCW^2}{H}$$  (14)

Where $L$ is shelf width, $W$ is wind speed, $H$ is depth, and $C$ combines gravity, density and drag.

The East China Sea continental shelf is located along the coast of Zhejiang. As one of the broadest continental shelves in the world, the widest part reaches 550 km. Moreover, the water depth is the denominator, so wind forcing is more effective in shallow waters. It can be seen from Figure 5 that water depth along the coast of Zhejiang does not exceed 20 m. Therefore, two factors above determine that storm surge along the coast of Zhejiang induced by Typhoon Likema is more serious.

From Figure 5, the peak surge levels at most area of northern Zhejiang coast exceed 1.5 m. In some bays such as Sanmen Bay and Hangzhou Bay, maximum surge levels are more than 2.5 m due to funnel effect. However, the effect of storm surge on southern area of Zhejiang coast is much smaller, peak surge level is generally less than 1 m. This phenomenon can be explained by typhoon track and wind direction. According to the typhoon track, northern coastal area of Zhejiang is in the right side and strong onshore easterly winds push water to the north coast of Zhejiang to generate high storm surge level. On the contrary, offshore westerly winds cause lower surge level to the south of Zhejiang coast.

The significant wave heights are calculated from the coupled surge-wave model and depicted in Figure 6. Contrary to the distribution characteristics of storm surge level, the maximum significant wave heights are very high and exceed 12 m off the coast. When the typhoon Likema moved near the shore, the significant wave height decreased rapidly. The decrease in wave heights is caused by shoaling, blocking due to islands, and wave breaking. The significant wave heights are about 3 to 5m along the Zhejiang coast. And the distribution is relatively similar in both north and south sides of typhoon track.
Figure 5. Computed maximum storm surge level induced by Typhoon Lekima, dotted line indicates the track of Typhoon Lekima.

Figure 6. Computed maximum significant wave heights induced by Typhoon Lekima, dotted line indicates the track of Typhoon Lekima.
4. Conclusions

In current study, a coupled surge-wave model considering the wave-induced forces has been established based on ADCIRC and SWAN. This coupled surge-wave model shows high accuracy and is applied to simulate the storm surge and wave of Zhejiang coast induced by typhoon Lekima in 2019.

The distribution of maximum surge level shows spatial differences along Zhejiang coast. Storm surge level is relatively lower in the open sea. Due to shelf geometry and shallow water effect, peak surge level rises significantly near Zhejiang coast. In addition, the surge level on the right side of typhoon track is much higher than that on the left side. Contrary to characteristics of storm surge level, the maximum significant wave heights are very large off the coast. Significant wave height decreases rapidly along the Zhejiang coast due to shoaling, blocking due to islands, and wave breaking. The contribution of waves to the storm surge and its physical process needs further study.

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