Numerical Simulation of Typhoon Storm Surge in Wenzhou Coastal Areas

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Abstract. Focusing on the numerical simulation of storm surge in the coastal waters of Wenzhou, this paper uses the atmospheric Mesoscale Model5 (MM5) model to provide the wind field of typhoons, and the advanced circulation (ADCIRC) model for oceanic, coastal, and estuarine waters to simulate the process of storm surges, which adopts the finite element method with a dry-wet grid. The simulated results agree well with the observed data from marine observation stations (Longwan, Aojiang, Ruian), indicating that the simulation of storm surge is accurate. The good agreement between the simulated and observed results of four typhoons (Nos. 200216, 200414, 200509, 200608) shows that the combination of the two numerical models has the capacity to calculate storm surge elevations along the coast of Wenzhou. Using this method to simulate the 23 typhoon storm surge processes of the Wenzhou sea area of the last 23 years, we find that the majority of storm surge is between 0.5 to 2.5 m, and about one-fifth have an extreme value of more than 2 m. The maximum storm surge value recorded in Wenzhou coastal waters is 3.02 m, which occurred during Typhoon Wipha (No. 200713) at 03:00 on September 19, 2007 when landed. Water decreasing processes occurred 10 h after the main water increasing process with the maximum negative storm surge of -0.5 m. This paper can be used as a reference for storm surge forecasting, coastal engineering design and damage minimization in the future.

Keywords: Storm surge; Numerical simulation; ADCIRC model; Wenzhou.

1. Introduction
Coastal regions are important interface zones, involving the interaction between land, water, and atmosphere in a dynamic balance. Their physical features provide excellent conditions for biological production, supporting consequently many valuable populations of species. Storm surge can have significant damaging impacts on any coastal zone. This paper focuses on the numerical simulation of storm surges in the coastal waters of Wenzhou, using the MM5 model to provide the wind field of typhoons, and using the ADCIRC model to simulate the process of storm surge. Verification is performed to ensure that the simulation results are sufficiently accurate. Credible features of storm surges in the Wenzhou sea areas are obtained from simulation results (from 1988 to 2010). There are mainly four parts in this study. Section 2 presents a brief description of study area. A description of the simulation method and data verification of the wind field are set out in Section 3. Section 4 concerns the numerical modeling using ADCIRC to calculate the storm surge and verification. And finally, Section 5 completes the paper with the main conclusions.
2. Study Area
Wenzhou is located on the southeast coast of Zhejiang province. On average, there are about four typhoons influencing or landing in this area every year. Generally, typhoon storm surge processes occur from April through to November and most processes occur in July, August, and September. Storm surges of more than 1 m usually appear in July to September, and elevations of more than 2 or 3 m mainly appear in August and September. About one-fifth of storm surges that occur in August and September are larger than 2 m.

Considering the scale of typhoons, to improve the precision of storm surge models, the computational domains must be sufficiently large. Here, the computational domain is bounded by 116°–125°E, 21°–30°N with high resolution (the minimum distance between nodes is about 500 m) in the Wenzhou coastal sea areas (Figure 1). The ADCIRC-2DDI model adopts the finite element (FE) method using triangular mesh, because it can better describe the complex coastal and island boundaries.

3. Storm Surge Model
The advanced circulation (ADCIRC) model for oceanic, coastal, and estuarine waters is a highly developed computer program for solving the equations of motion for a moving fluid on a rotating earth. These equations have been formulated on the basis of the traditional hydrostatic pressure and Boussinesq approximations, and have been discretized in time using the finite difference (FD) method, in space using the finite element (FE) method.

3.1. Governing Equations
The two-dimensional governing equations for storm surge in Cartesian coordinates are the Primitive continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U H}{\partial x} + \frac{\partial V H}{\partial y} = 0$$

(1)

and the Primitive momentum equations:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} - fV = -\frac{\partial}{\partial x} \left[ \frac{p_\rho + g \zeta - g (\eta + \gamma)}{\rho_\rho} \right] + \frac{\tau_{\mu x}}{\rho_\rho H} - \frac{\tau_{\rho x}}{\rho_\rho H} + D_x - B_x$$

(2)

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + fU = -\frac{\partial}{\partial y} \left[ \frac{p_\rho + g \zeta - g (\eta + \gamma)}{\rho_\rho} \right] + \frac{\tau_{\mu y}}{\rho_\rho H} - \frac{\tau_{\rho y}}{\rho_\rho H} + D_y - B_y$$

(3)
where \( H \) is the total water depth (m); \( U \) and \( V \) are the depth-integrated currents in the \( x \)- and \( y \)-directions, respectively; \( f \) is the Coriolis parameter; \( g \) is the gravitational acceleration (ms\(^{-2}\)); \( p_a \) is the atmospheric pressure at the surface (Nm\(^{-2}\)); \( \rho_0 \) is the reference density of water (kgm\(^{-3}\)); \( \eta \) is the Newtonian equilibrium tidal potential; \( \tau_s \) is the surface stresses (Nm\(^{-2}\)); \( \tau_b \) is the bottom stress (Nm\(^{-2}\)); \( D \) is a momentum dispersion term (Nm\(^{-2}\) per m); and \( r_0 \) is a numerical parameter that optimizes the phase-propagation properties (unitless).

3.2. Initial and Boundary Conditions

The initial conditions state that currents and surface elevation are zero, \( \zeta = U = V = 0 \).

Lateral boundary conditions are assumed to be zero for normal flow to the solid boundary, and along the open boundary the model is driven by the K1, O1, S2, and M2 four main astronomical tidal constituents.

In addition, the dry and wet method is adopted to treat the moving boundary; therefore, it can simulate the process of storm surge across floodplains veritably.

3.3. Wind Field

In this paper, the modeling domain is bounded by about 113°–130°E, 14°–33°N and the domain is divided into 36,000 grids (180 × 200), with each grid having an interval of 10 km. The vertical height is partitioned into 34 layers. To better reflect the features of the boundary layer, the resolution of the lower layer is much finer than that of those layers above. This paper takes advantage of the west Pacific typhoon information of UNISYS and the Japan Meteorological Agency to form the typhoon’s initial field, using four-dimensional assimilative technology (FDDA) to assimilate the typhoon information provided by UNISYS.

One of the verifications about track and maximum wind speed in the center of Typhoon FEIYAN (No. 200102) are shown in Figure 2 and the results are satisfactory.

![Figure 2](image)

**Figure 2.** Comparison of track of Typhoon FEIYAN (No. 200102) and maximum wind speed in the center of the typhoon between simulation and observation provided by UNISYS. a) track of Typhoon FEIYAN, and b) maximum wind speed of typhoon center.

4. Results and Discussions

4.1. Validation

Twenty-three typhoon storm surge processes that occurred in Wenzhou coastal waters between 1988 and 2010 were simulated. Four typhoon (Nos. 200216, 200414, 200509, 200608) storm surge processes were selected for comparison with observed data from Longwan, Aojiang and Ruian stations. Table 1 shows the locations of these three stations and Figure 3 gives the verification results.
Table 1. Longitude and latitude of the three stations

| Station | longitude(°E) | Latitude(°N) |
|---------|--------------|--------------|
| Longwan | 120°48’      | 27°58’       |
| Aojiang | 120°38’      | 27°47’       |
| Ruian   | 120°34’      | 27°36’       |

Typhoon Saomai (No. 200608) originated from a tropical disturbance over the west Pacific (146.4°E, 11.9°N) on August 5, 2006, and moved steadily northwestward after its generation and then gradually strengthened. It was classified as a typhoon at 14:00 on August 7, and landed at 05:00 on August 10 at Cangnan with a minimum central atmospheric pressure of 915 hPa and a maximum wind speed of 60 m/s. At the same time, the extreme storm surge value caused by Saomai reached 2.5 m at the Ruian station. The whole process, during which the storm surge elevation was greater than 0.5 m, lasted about 8 h (Figure 3a).

Typhoon Matsa (200509) originated from a tropical disturbance over the west Pacific to the east of the Philippines (134.0°E, 11.7°N) on July 31, 2005, and moved steadily northwestward after its generation and then gradually strengthened. At 02:00 on August 3, it was classified as a typhoon with a minimum central atmospheric pressure of 950 hPa and a maximum wind speed of 45 m/s. The fluctuant storm surge process during Matsa was clearly simulated by the model, as shown in Figure 3b. Both the simulated and measured extreme storm surge value was about 1.2 m at the Longwan station.

Typhoon Rananim (200414) originated over the west Pacific to the east of the Philippines (130.0°E, 16.1°N) on August 8, 2004, and moved steadily northwestward after its generation and then gradually strengthened. At 02:00 on August 11, it was classified as a typhoon. The minimum central atmospheric pressure was 950 hPa and the maximum wind speed was more than 45 m/s. Rananim landed at Wenling at 20:00 on August 12, at the same time the extreme storm surge value reached about 1.8 m at the Ruian station, as shown in Figure 3c.

Typhoon Sinlaku (200216) originated over the west Pacific to the east of Guam (155.7°E, 16.4°N) on August 8, 2004, and it moved steadily northward after its generation and then gradually strengthened. At 12:00 on August 30, it was classified as a typhoon and then turned west. At 06:00 on August 31, it was classified as a super typhoon and its minimum central atmospheric pressure dropped to 933 hPAl, and the maximum wind speed was about 53 m/s. The fluctuant storm surge process with three obvious peaks was also clearly simulated by the model, as shown in Figure 3d. Both the simulated and measured extreme storm surge values were about 1.4 m at the Aojiang station.

From the above validations, the simulated results agree well with the observed data, both in terms of the extreme value and the time of occurrence. From Figure 3a and 3c, it can be seen that the peak of...
the curve occurred in conjunction with the landfall of the typhoons. Figure 3b and 3d clearly shows the fluctuant storm surge processes.

### 4.2. Analysis

To determine the characteristics, we selected three points for analysis: marked 4, 5, and 6 (see Table 2 and Figure 1b).

**Table 2.** Longitude and latitude of three engineering points.

| Point | Longitude(°E) | Latitude(°N) |
|-------|---------------|--------------|
| 4     | 120.91743     | 27.90422     |
| 5     | 120.85688     | 27.77821     |
| 6     | 120.70387     | 27.69611     |

The extreme values of storm surge during the 23 typhoons processes are given in Table 3. Most of the extreme values are between 0.5 and 2.5 m, and about one-fifth of the extreme values are greater than 2 m. The maximum storm surge elevation value is 3.02 m, which occurred at point 6 during Typhoon Wipha (No. 200713), as shown in Figure 4. Three points were considerably influenced by Typhoon Wipha, which landed at 03:00 on September 19 and caused a 3.02 m storm surge elevation at point 6. It is also shown that water decreasing processes occurred 10 h after the main water increasing process, with the maximum negative storm surge of -0.5 m.

![Figure 4. Simulation of the storm surge caused by Typhoon Wipha (200713) at point 4, 5, and 6.](image)

According to the simulation results shown in Table 3 and relevant research, the storm surge processes in the Wenzhou coastal sea areas are mainly between 0.5 and 2.5 m, but can reach about 4 m if the influence of the typhoon is sufficiently strong. Comparatively, the negative storm surge is much smaller than the storm surge.

### 5. Conclusion

The agreement between the simulated and observed data shows that the ADCIRC-2DDI model has the capacity of simulating storm surge along the coastal waters. A good wind field is very important for storm surge simulation, including the track, landing location, and wind speed. At the same time, the landing location relative to the study area has an important influence on the storm surge process. In this paper, through the simulated results of 23 typhoon storm surges, we give the main characteristics of storm surge in the Wenzhou coastal waters. This research can be used as a reference for storm surge forecasting, coastal engineering design, and damage minimization in the future.
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