

Typhoon Storm Surge Simulation for Typhoon Haiyan

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Abstract

Typhoon Haiyan (local name, Yolanda) in November 2013 brought record-breaking meteorological forcing, surface winds of 65 m/s and surface pressure of 895hPa at its maximum intensity, and made landfall over Samar Island, causing unprecedented disasters in the center of Philippines.

In this note, the numerical simulations for storm surge and wind waves, using unstructured mesh system are conducted. The atmospheric input is computed by Holland wind model. The radius of maximum wind is estimated by the other informations by JMA. The storm surge and wind waves are simulated with ADCIRC and SWAN. Large domain including the whole track of Typhoon Haiyan is constructed with triangular unstructured meshes, and results show the calculated storm surges of nearly 4 m in the San Pedro and San Pablo Bay.

Key words: Typhoon Haiyan; Philippians; storm surge; coupled wave-tide-surge model

1. Introduction

Typhoon Haiyan, also known as Yolanda in Philippines, struck the central Philippines on November 8, 2013. Typhoon Haiyan was one of the strongest typhoons to strike land on record. It was an exceptionally powerful tropical cyclone as “super typhoon” with a force equivalent to a Category 5 hurricane and sustained winds of up to 87 m/s over 16 hour period. It devastated six provinces and affected over 10% of the nation’s population in the Philippines.

For the storm surge simulation, the pressure and wind information during the passage of the typhoon is the most important data. Outside of that the topographic data for numerical model is another enhancement factor. Although the development of survey technology for the topography and bathymetry using variable instruments including remote sensing technics is increasing, the enhancement of typhoon prediction is not entirely satisfactory.

Several institutes or agencies are operating the tropical cyclone prediction system. In case of the Typhoon Haiyan, the Joint Typhoon Warning Centre (JTWC), Japan Meteorological Agency (JMA), the Hong Kong Observatory, the China Meteorological Administration and the Korea Meteorological Administration were announced own prediction data with some differences. Typhoon informations produced by JTWC and JMA are commonly used for the prediction of pressure and wind fields and the comparison with the numerical model results. The typhoon information of JTWC is intended for use by U.S. government agencies, but is accessible from the general public. However the maximum sustained wind is expressed only, while central pressure is not.

The value of maximum sustained wind is different between JTWC and JMA. Usually the value of JTWC is higher than that of JMA, because of the definition of maximum sustained wind and the different method used for estimating maximum sustained wind from observation. JTWC use the 1 minute averaged wind speed and JMA use the 10 minute. In general, the 10 minute averaged wind speed is 0.88 times of 1 minute. In this research, the typhoon information of JMA is used.

For estimating storm surge in Philippine coasts, the integrally coupled wave-tide-surge model based on unstructured mesh, which does not require nesting or overlapping of structured wave meshes and interpolation is used. The problem of wave reflection in the nesting boundary for the uncompleted feedback to mother’s domain also was not needed to consider. The waves and storm surge were allowed to develop on the continental shelf and interact with the complex nearshore environment. The coupled system consists of unstructured-mesh SWAN wave and ADCIRC based on the same unstructured mesh. This identical and homogeneous mesh allows the physics of wave-circulation interactions to be correctly resolved in both models. The hydrodynamic model (ADCIRC) is driven partly by radiation stress gradients that are computed using information from spectral wind wave model (SWAN) which uses the water levels and currents computed in the hydrodynamic model. The basic structure of the coupling

system (ADCIRC+SWAN) was developed by Dietrich et al. (2010), and applied to another study for wave and storm surges during Typhoon Maemi (Choi et al., 2014)

2. Typhoon Haiyan

The typhoon Haiyan, the Category 5-equivalent super typhoon on the Saffir-Simpson hurricane wind scale, occurred on Nov. 4 and decayed on Nov. 11, 2013. A death and missing toll of 7200 due to the typhoon was reported on Nov. 27 by Philippine National Disaster Risk Reduction and Management Council. The lowest pressure by JTWC is 895 hPa and the maximum sustained wind speed (1 minute average) is 195 mph (87 m/s). Also the maximum sustained wind speed averaged in 10 minute by JMA is 125 kt (64 m/s). The information of JMA is updated every three hours under normal operation, but it is updated every hour when typhoons approach to Japan (usually within 300km).

For the typhoon model, these informations are necessary; the location of center of typhoon, the minimum (mean sea level) pressure, P_{min} , the maximum wind speed, V_{max} , and the radius of maximum wind, R_{max} . The radius of maximum wind is not provided from JMA and JTWC. It can be estimated by Rankin equation (Eq. 1) and the radiuses of storm wind, $R50$, and gale wind, $R30$.

$$W = V_{max} \times \left(\frac{R}{R_{max}} \right)^{\alpha}, \quad (1)$$

$$\alpha = \log \left(\frac{V50}{V30} \right) / \log \left(\frac{R50}{R30} \right), \quad (2)$$

$$R_{max} = R50 / \left(\frac{V50}{V_{max}} \right)^{1/\alpha}, \quad (3)$$

here W is the wind speed for out of R_{max} , R is the distance from the center of typhoon, $V50$ is the wind speed of 50 knot (=25.7 m/s) and $V30$ is 15.4 m/s. Table 1 shows the estimated the radius of maximum wind and the Rankin vortex factor, α , for Holland wind model (Holland, 1980).

Table 1. Typhoon Information for Holland model

| Date (yyyy-mmdd hh) | Latitude (°N) | Longitude (°E) | P_{min} (hPa) | V_{max} (m/s) | R_{max} (km) | α |
|---------------------|---------------|----------------|-----------------|-----------------|----------------|----------|
| 2013-1105 00 | 6.5 | 145.9 | 985 | 28.3 | 42.9 | -0.369 |
| 2013-1105 06 | 6.5 | 144.6 | 980 | 30.9 | 50.1 | -0.465 |
| 2013-1105 12 | 6.9 | 142.9 | 975 | 33.4 | 52.7 | -0.465 |
| 2013-1105 18 | 7.1 | 141.3 | 965 | 38.6 | 53.7 | -0.558 |
| 2013-1106 00 | 7.3 | 139.7 | 950 | 43.7 | 42.9 | -0.558 |
| 2013-1106 06 | 7.6 | 138 | 930 | 48.9 | 35.1 | -0.558 |
| 2013-1106 12 | 7.9 | 136.2 | 920 | 54 | 42.9 | -0.670 |
| 2013-1106 18 | 8.2 | 134.4 | 905 | 59.2 | 37.4 | -0.670 |
| 2013-1107 00 | 8.7 | 132.8 | 905 | 59.2 | 37.4 | -0.670 |
| 2013-1107 06 | 9.3 | 131.1 | 905 | 59.2 | 37.4 | -0.670 |
| 2013-1107 12 | 10.2 | 129.1 | 895 | 64.3 | 34.6 | -0.630 |
| 2013-1107 18 | 10.6 | 126.9 | 895 | 64.3 | 34.6 | -0.630 |
| 2013-1108 00 | 11 | 124.8 | 910 | 56.6 | 30.2 | -0.541 |
| 2013-1108 06 | 11.4 | 122.5 | 940 | 46.3 | 43.7 | -0.541 |
| 2013-1108 12 | 11.9 | 120.5 | 940 | 46.3 | 43.7 | -0.541 |
| 2013-1108 18 | 12.2 | 118 | 940 | 46.3 | 58.3 | -0.630 |
| 2013-1109 00 | 12.3 | 116.6 | 940 | 46.3 | 58.3 | -0.630 |
| 2013-1109 06 | 13.5 | 114.8 | 940 | 46.3 | 58.3 | -0.630 |
| 2013-1109 12 | 14.4 | 113.1 | 945 | 43.7 | 63.8 | -0.630 |
| 2013-1109 18 | 15.4 | 111.4 | 950 | 41.2 | 70.3 | -0.630 |
| 2013-1110 00 | 16.5 | 110.3 | 955 | 38.6 | 77.8 | -0.630 |
| 2013-1110 06 | 17.9 | 109 | 960 | 36 | 86.8 | -0.630 |
| 2013-1110 12 | 19.4 | 108 | 965 | 33.4 | 107.3 | -0.813 |
| 2013-1110 18 | 20.4 | 107.5 | 975 | 30.9 | 62.6 | -0.465 |
| 2013-1111 00 | 21.5 | 107.1 | 990 | 20.6 | 135.7 | -0.584 |

3. Typhoon Pressure and Wind Calculation using Symmetric Typhoon Model

The Holland wind model (Holland, 1980) is used for estimating the typhoon pressure and wind fields by determines the wind velocity induced by the typhoon pressure gradient under cyclostrophic balance. Also temporal interpolation in 1 hour interval along the typhoon track was also performed. Figure 1 shows the computed results of pressure and wind vector fields for the typhoon Haiyan at 12:00 07 Nov. 2013 with the ASCAT wind speed data (Verhoef and Stoffelen, 2010) which is observed from 12:30 to 13:30. The contours show the atmospheric pressure and the shade image shows the computed wind speed. The wind speed on right side is stronger than left side because of the movement of typhoon. The white dots with the dashed line indicate the typhoon track with 6 hour time interval. Figure 2 shows the scatter comparison between ASCAT and Holland wind speed at valid time. The wind speed observed by satellite could not reach to the modeled wind speed. These differences are also shown in the comparison research using dropwindsonde observation data (Chou et al., 2013).

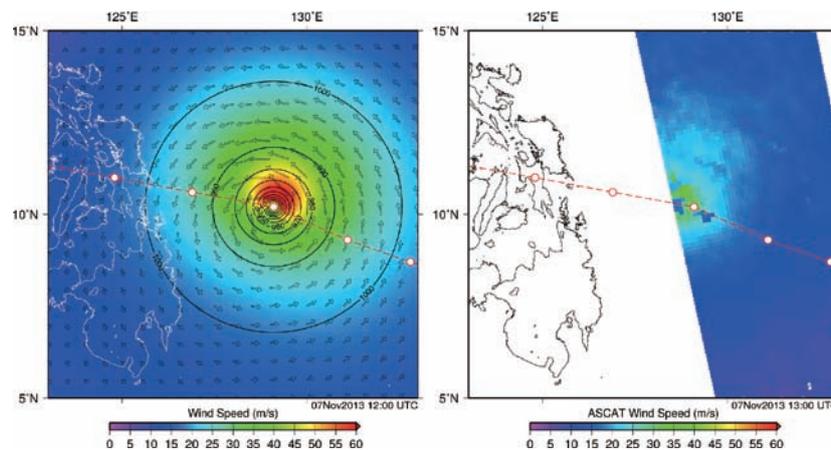


Figure 1. The computed pressure and wind vector fields by Holland wind model (left) and the ASCAT wind speed data (right)

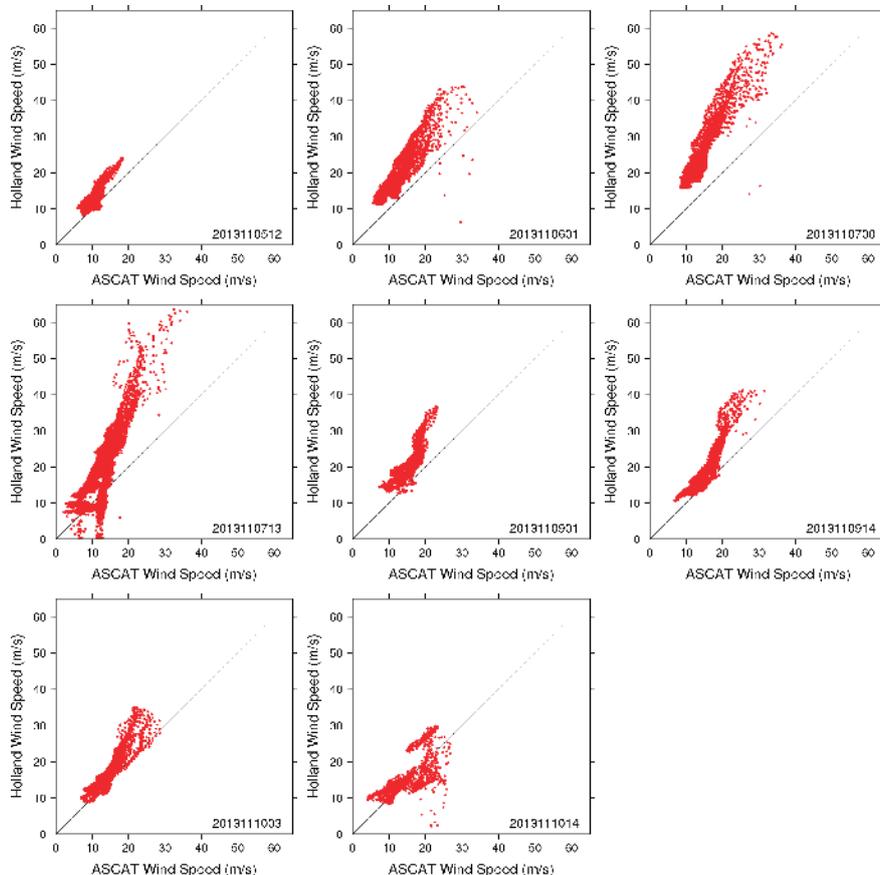


Figure 2. Scatter comparison between ASCAT and Holland wind speed

Figure 3(a) shows the wind and pressure fields of NCEP FNL (<http://rda.ucar.edu/datasets/ds083.2/>) at 12:00 07 Nov. 2013. The central pressure of NCEP is approximately 100 hPa higher (week intensity) than JMA data when the typhoon passed Tacloban. The meteorological data of NCEP is not appropriate for the hindcast of the typhoon Haiyan unless correct the strength typhoon using downscale model in the finer mesh system and bogus scheme. Therefore, the blending scheme was introduced by composing the wind velocity and atmospheric pressure calculated at storm area using the Dynamic Holland model, and the ambient wind and pressure fields computed by the NCEP data removing the Rankin vortex storm (Davis and Low-Nam, 2001). The blending factor (f) is introduced by linear weighting relative on the distance from the typhoon center. If the distance to the center of typhoon (R) is smaller than $R50$, the Holland results are used only. And the ambient atmospheric fields are used the outer area ($R > R30$).

$$W = f \cdot W_{holland} + (1 - f) \cdot W_{ambient}, \quad (4)$$

$$f = (R - R30) / (R50 - R30), \quad 0 \leq f \leq 1. \quad (5)$$

The wind and pressure fields removing the vortex are shown in Figure 3(b), and the blending fields with Holland data are shown in Figure 3(c).

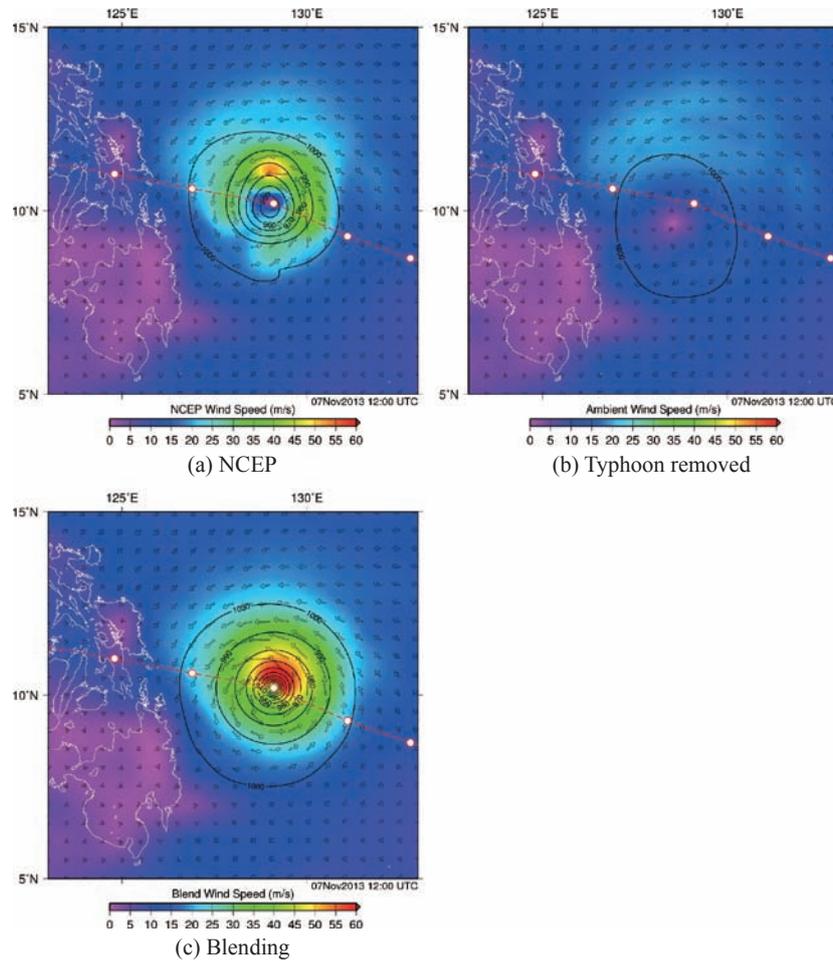


Figure 3. The wind and pressure fields of (a) NCEP, (b) typhoon removed and (c) blending with typhoon removed and Holland data (Figure 1).

4. Storm Surge Simulation using Unstructured Tide-Surge-Wave Coupled Model

SWAN (Simulating WAVes Nearshore) predicts the evolution in geographical space and time of the wave action density spectrum, with the relative frequency and the wave direction, as governed by the action balance equation (Booij et al., 1999). The unstructured-mesh version of SWAN implements an analog to the four-direction Gauss-Seidel iteration technique employed in the structured version, and it maintains SWAN's unconditional stability (Zijlema, 2010). SWAN computes the wave action density

spectrum at the vertices of an unstructured triangular mesh, and it orders the mesh vertices so it can sweep through them and update the action density using information from neighboring vertices.

ADCIRC (the ADvanced CIRCulation model) is a continuous-Galerkin, finite-element, shallow-water model that solves for water levels and currents at a range of scales (Westerink et al., 2008; Luetlich and Westerink, 2004; Atkinson et al., 2004; Dawson et al., 2006). The details of this solution have been published widely (<http://www.nd.edu/~adcirc/manual.htm> to see Users Manual and Theory Report) and will not be stated here.

SWAN is driven by wind speeds, water levels and currents computed at the vertices by ADCIRC. Marine winds can be input to ADCIRC in a variety of formats, and these winds are adjusted directionally to account for surface roughness (Bunya et al., 2010). ADCIRC interpolates spatially and temporally to project these winds to the computational vertices, and then it passes them to SWAN. The water levels and ambient currents are computed in ADCIRC before being passed to SWAN, where they are used to recalculate the water depth and all related wave processes (wave propagation, depth-induced breaking, etc.). The ADCIRC model is driven partly by radiation stress gradients that are computed using information from SWAN.

ADCIRC and SWAN run in series on the same local mesh and core. The two models “leap frog” through time, each being forced with information from the other model. Because of the sweeping method used by SWAN to update the wave information at the computational vertices, it can take much larger time steps than ADCIRC, which is diffusion- and also Courant timestep limited due to its semi-explicit formulation and its wetting and drying algorithm. For that reason, the coupling interval is taken to be the same as the SWAN’s time step. On each coupling interval, ADCIRC is run first, because we assume that, in the nearshore and the coastal floodplain, wave properties are more dependent on circulation. At the beginning of a coupling interval, ADCIRC can access the radiation stress gradients computed by SWAN at times corresponding to the beginning and end of the previous interval. ADCIRC uses that information to extrapolate the gradients at all of its time steps in the current interval. These extrapolated gradients are used to force the ADCIRC solution as described previously. Once the ADCIRC stage is finished, SWAN is run for one time step, to bring it to the same moment in time as ADCIRC. SWAN can access the wind speeds, water levels and currents computed at the mesh vertices by ADCIRC, at times corresponding to the beginning and end of the current interval. SWAN applies the mean of those values to force its solution on its time step. In this way, the radiation stress gradients used by ADCIRC are always extrapolated forward in time, while the wind speeds, water levels and currents used by SWAN are always averaged over each of its time steps. The basic structure of this coupling system (ADCIRC+SWAN) was developed by Dietrich et al. (2010). A schematic of the communication is shown in Figure 4.

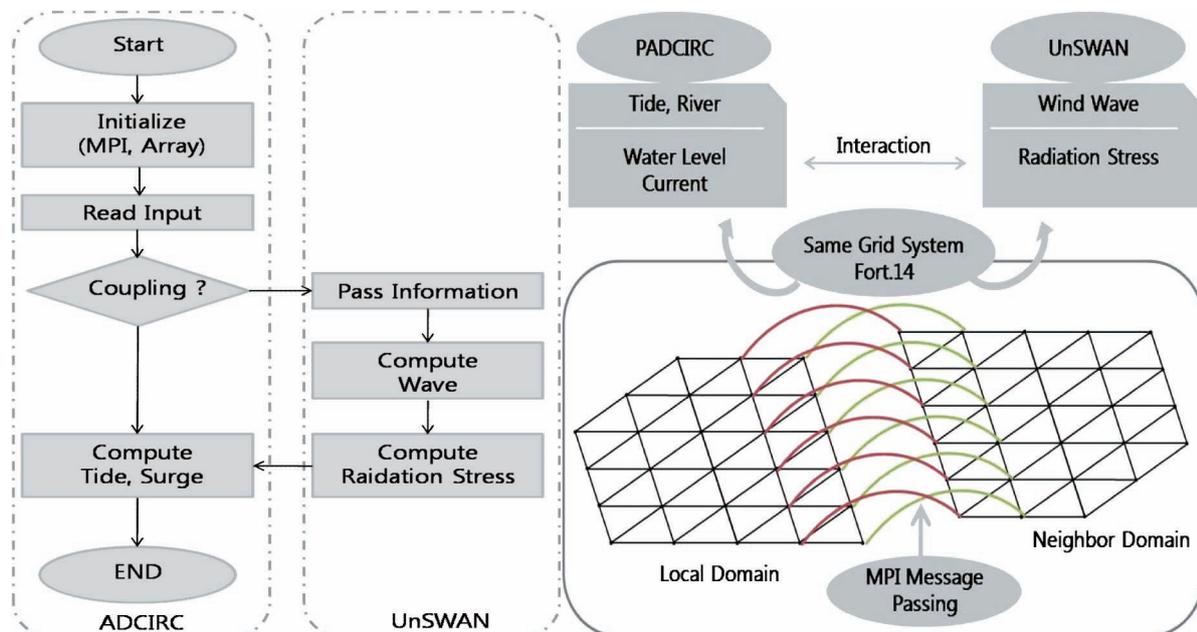


Figure 4. Schematic of parallel communication between models and cores. Solid lines indicate communication for the edge-layer-based nodes between sub-meshes, and are intra-model and inter-core

5. Storm Surge Model Setup

The total model domain covers the South China Sea and the North West Pacific Ocean. The coupled model use the Spherical Coordinate but the meshes are composed by consideration of water depth and geometry gradient. Semi-automatic mesh generation was performed in UTM Caresian Coordinate, then convert to Spherical Coordinate. We used GEBCO 30 seconds from BODC focusing on Leyte Gulf and Tacloban City, Philippines. We made the fine mesh for Leyte Gulf and neighboring seas of Tacloban City, Philippines. The refined mesh near Tacloban City was carried out. The mesh size of outer area is 2 km to 30 km, and minimum mesh size is 50 meter for the Tacloban region. Figure 5 shows the mesh system with complex mesh resolutions and bathymetry. The meshes consist of 197,934 vertices and 387,476 triangular elements. Figure 6 shows the water depth of South Philippines damaged by Typhoon Haiyan and major surge observation points by American Red Cross (<https://github.com/AmericanRedCross/response/tree/master/data>).

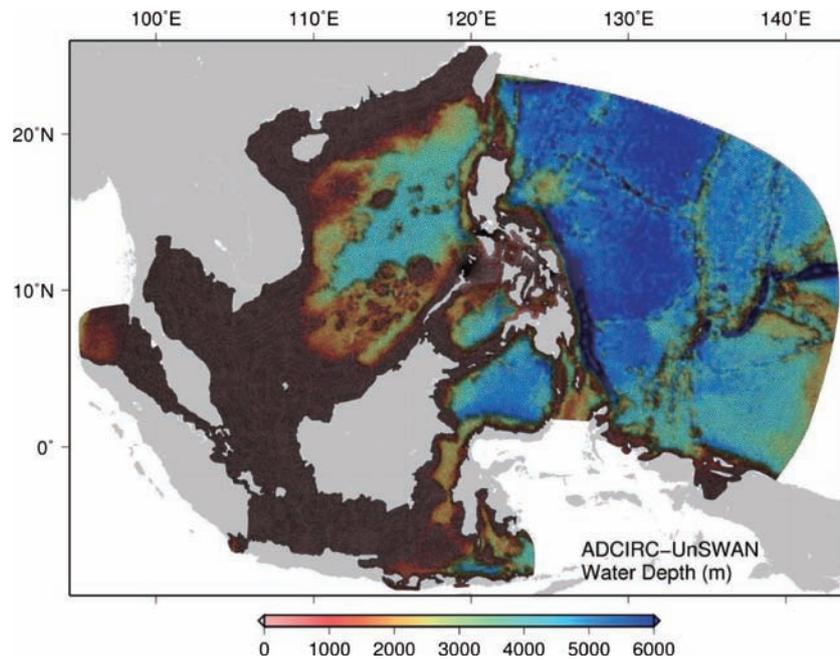


Figure 5. Overall meshes of the model domain and the detailed meshes near Tacloban City, Philippines with the water depth

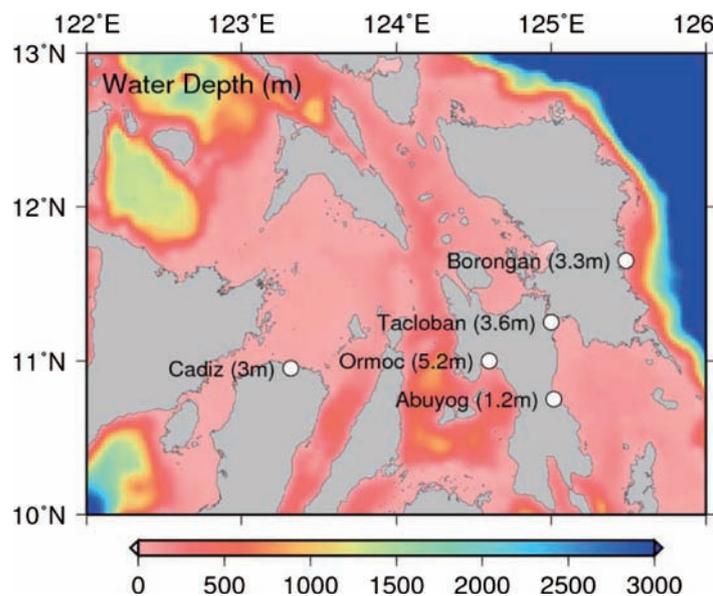


Figure 6. Water depth of South Philippines and major surge observation points by American Red Cross

Open boundary forcing was applied in the form of specifications based on NAO's (National Astronomical Observatory) tidal predictions (Matsumoto et al., 2000) along the model's open water boundary. NAO's tidal prediction is the ocean tidal height at given time and location using ocean tide model developed by assimilating TOPEX/Poseidon altimeter data. The short-period tide value is from 16 major constituents and 33 minor constituents which are inferred from major ones by interpolating or extrapolating the admittance. The long-period tide value is from 7 major constituents and 5 nodal modulations. 18.6-year period equilibrium tide is added to the 12 terms. Totally 62 tidal constituents are considered in this estimation of water elevation at the open boundary.

The time steps for tide and storm surge is 2 seconds in ADCIRC model, and 600 seconds for wave in SWAN model. The wave frequency range is from 0.031 to 0.548 Hz discretized into 30 bins on a logarithmic scale of 0.1. The wave directions are discretized into 36 sectors, each sector representing 10 degree. The total run time is 4.5 days from 12:00 5th November 2013 to 10th November. The 1 day for spinup was skipped for analysis. Using 128 cores (CPUs), this tide-surge-wave coupled simulation takes approximately 2 hours wall time.

6. Simulation Results

Figure 7 shows the simulated maximum water elevation and the maximum significant wave height in the entire model domain and near Tacloban City. The maximum water elevation over 4 m is computed including tide. The significant wave height in the outer area of West Pacific is computed over 30 m by strong typhoon wind. Figure 8 shows the comparison of water elevations observed by American Red Cross and calculated by the tide-surge model (TS) and the coupled tide-surge-wave model (TSW). Generally, the water elevations calculated by two models are lower than observations. The observation data is not verified. Figure 9 shows the surge height and water elevation at 5 stations located in South Philippines marked in Figure 6. The upper comparison charts indicate the surge heights by subtracting the tide elevation from the coupled tide-surge-wave model (TSW-T) and the tide-surge model (TS-T). The lower comparison charts indicate the water elevation calculated by the coupled model (TSW), tide-surge model (TS) and tide model (T), with observation of the American Red Cross, but it is not clear whether the elevation data include the tide or not, and it is not clear how the data were obtained. If the observation data is assumed to be water elevation, the water elevation was underestimated in Ormoc and Borongan Stations. The water elevations are reasonably calculated in the other 3 stations.

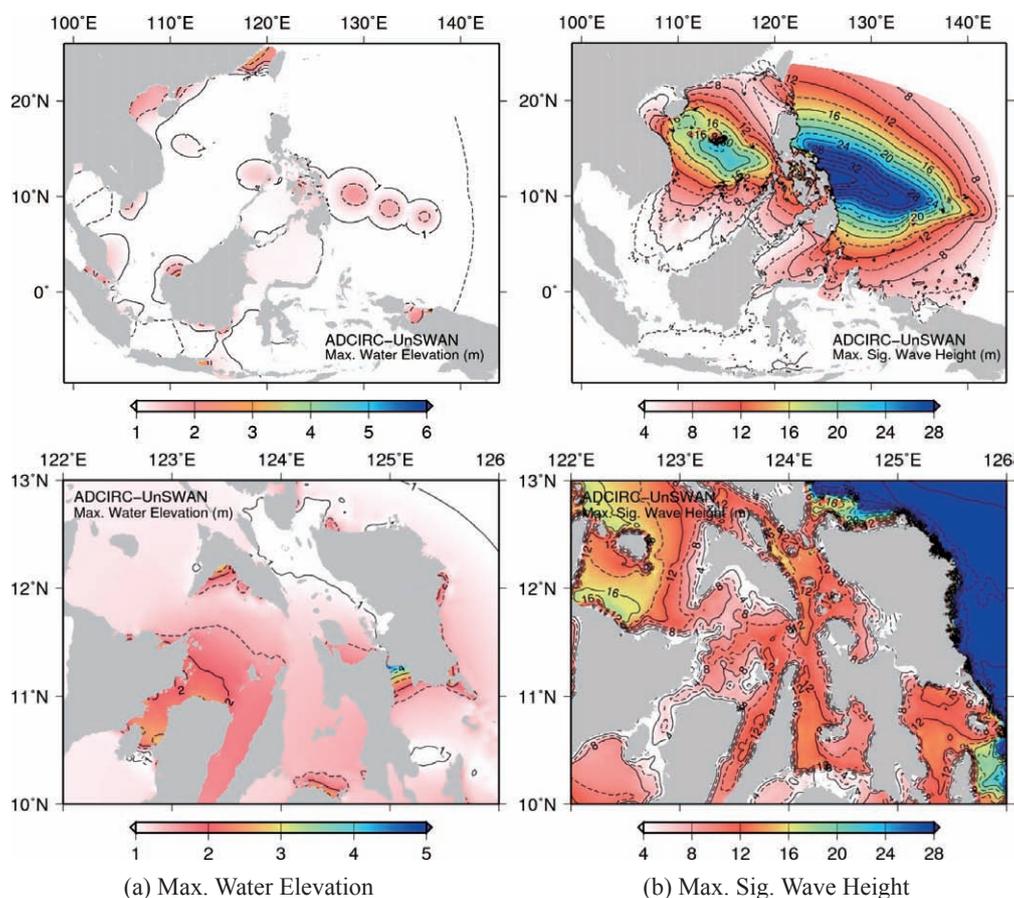


Figure 7. Maximum water elevation and maximum significant wave height

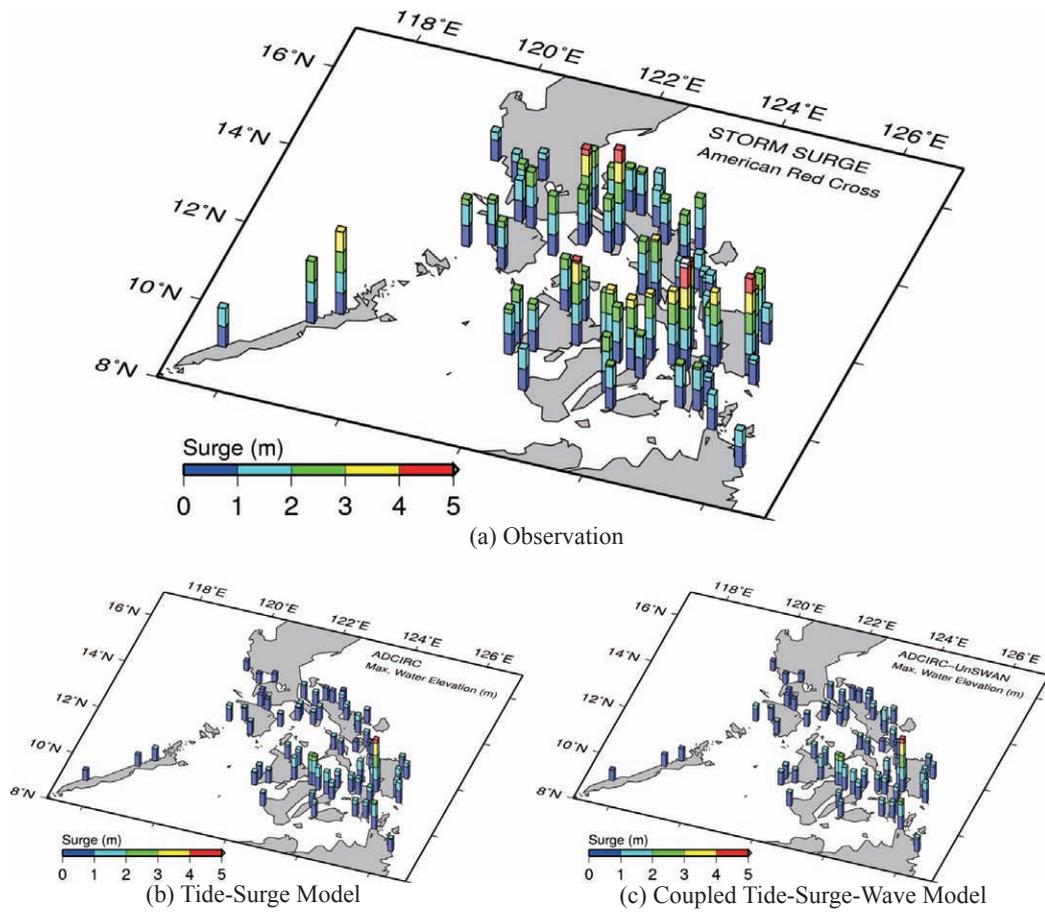


Figure 8. Comparison of water elevations near Tacloban

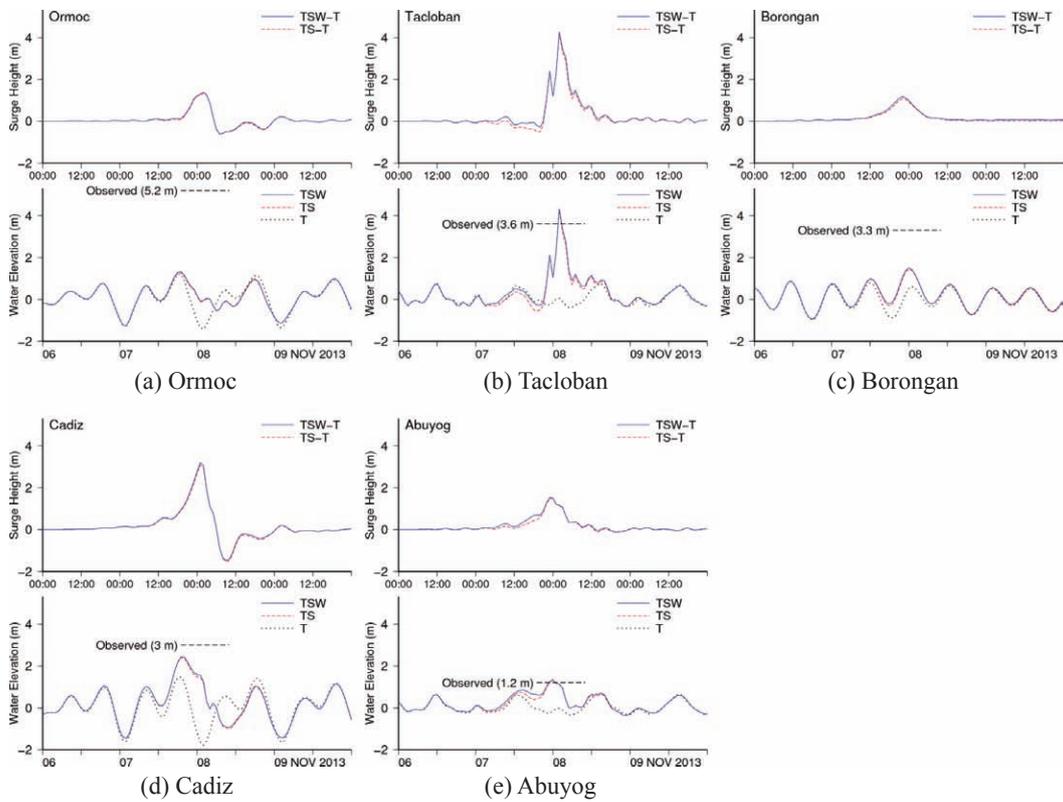


Figure 9. Comparison of surge height and water elevation

7. Conclusions

The numerical simulations for typhoon, storm surge and wind waves using unstructured mesh system are conducted to simulate Typhoon Haiyan caused unprecedented disasters in the center of Philippines in November 2013. The typhoon wind and pressure fields are estimated using the Symmetric Typhoon Model with the typhoon informations by JMA. The storm surge and wave was simulated using unstructured Tide-Surge-Wave Coupled Model. This research simulated the storm surge damaging Philippine coasts well, however the limitation of observation data made poor verification. The results show the calculated storm surges over 4 m near Tacloban. All materials for numerical modeling are downloadable and linked in <http://sites.google.com/site/kyeongokkim/typhoonhaiyan>.

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