STORM SURGE SIMULATION IN NAGASAKI DURING THE PASSAGE OF 2012 TYPHOON SANBA

D. P. C. Laknath[1], Kazunori Ito[1], Takahide Honda[1] and Tomoyuki Takabatake[1]

As a result of global warming effect, storm surges generated by extreme weather events such as tropical cyclones, typhoons and hurricanes, significantly impact to the life and property in storm-surge prone coastal low-lying areas. Therefore, numerical modeling systems, comprising meteorological, hydrodynamic and wave simulation capabilities are essential for the storm surge hindcasting and forecasting phases in disaster mitigation and management processes. Accordingly, we assessed the applicability of two meteorological simulation methods; (1) Mesoscale Meteorological Model MM5 and (2) Delft Dashboard (DDB) Tropical Cyclone Tool, together with Delft3D FLOW-WAVE coupled modeling system to simulate the storm surges in Nagasaki coast during the passage of 2012 typhoon SANBA. Storm surge generated by MM5-Delft3D and DDB-Delft3D systems in Nagasaki area were reasonably agreed with the observations. Thus, applicability of both meteorological simulation techniques together with Delft3D FLOW-WAVE coupled modeling system to simulate the storm surge was validated with a reasonable level of accuracy. Further, compared to the MM5-Delft3D system, fast and easy simulation capability of DDB-Delft3D system was identified. However, in terms of accuracy, MM5-Delft3D system demonstrated much better performance in outer regions of the typhoon than the DDB-Delft3D system.

Keywords: MM5; Delft3D; typhoon bogus; Delft Dashboard; Wind Enhancement Scheme

INTRODUCTION

Sea surface temperature (SST) rise, induced by the global warming might increase the intensity and recurrence frequency of the extreme weather phenomenon such as tropical cyclones, torrential rainfall and flooding in future (Nordhaus 2006). Hurricane Katrina (2005), Hurricane Ike (2008), Cyclone Nargis (2008) and Typhoon Jangmi (2008) are a few foretastes of destructive extreme weather events in this global warming era. It has been identified that there is an increasing trend of occurrence of tropical cyclones and typhoons in the western Pacific and Atlantic Oceans due to the global warming effects (Emanuel 2005; Webster et al. 2005). Storm surges are generated primarily by the extreme winds from low pressure atmospheric systems (e.g. cyclone, typhoon and hurricane) (Dean and Dalrymple 2002). Further, secondary factors such as atmospheric pressure drops, earth's rotation (Coriolis effects), surface waves and associated wave setup also influence the intensity of the storm surge. Thus, a storm surge is a rise of sea water level above the predicted astronomical tide level, due to the combined effects of strong winds, reduced atmospheric pressure over a shallow water body and other secondary factors.

Since storm surges are often the greatest threat to life and property in storm-surge prone coastal low-lying areas, storm surge simulation is an important task for disaster mitigation and management processes. Generally, storm surge simulating systems comprise meteorological, hydrodynamic and wave simulation capabilities. Accurate depiction of the simulated storm surge heights highly depends on the imposed wind and pressure fields. These forcing could be computed by using either empirical typhoon models or numerical weather prediction (NWP) models. In this study, two different approaches; (i) 5th generation PSU/NCAR Mesoscale NWP Model called as MM5 (Grell et al. 1994) with typhoon bogus and (ii) Tropical Cyclone Tool included in Delft Dashboard (hereafter DDB) developed by Deltares (Delft Dashboard Team 2013) were used for the reproduction of atmospheric conditions during the extreme weather event. In order to simulate the coastal hydrodynamic characteristics (mainly tide, wind driven surge and pressure surge) and wind induced wave effects, the Delft3D FLOW-WAVE coupled modeling system (Deltaers 2010) was used.

Thus, an applicability of two meteorological modeling methods (MM5 and DDB) to simulate the storm surge heights together with Delft3D FLOW-WAVE coupled modeling system was assessed as the main objective of this study. By using both approaches, we attempted to reproduce and compare the storm surge induced by 2012 Typhoon SANBA (ID: 1216) in Nagasaki coast in Japan.

[1] Hydraulic and Environmental Engineering Research Section, Civil Engineering Research Institute, Technology Center, Taisei Corporation, 344-1, Nase-cho, Totsuka-ku,Yokohama, 245-0051, Japan

TYPHOON SANBA

A typhoon is a large low pressure atmospheric system, originating over the northwest Pacific basin. Typhoon SANBA was the strongest tropical typhoon in the western North Pacific Ocean after the Typhoon Megi in 2010. On September 9th 2012, a low pressure atmospheric system was originated east of the Palau in Pacific Ocean. On September13th, it intensified into a category 5 super typhoon by attaining its peak intensity with maximum sustained wind speed of 56.94 m/s and minimum barometric pressure of 900 mbar. On September 15th, the system started to weaken into a category 3 typhoon. Then it headed towards South Korea after passing over Okinawa Island and then western part of the Japan. In Nagasaki coast, it elevated maximum surge level up to 2.16 m. Finally, on September 17th, it made landfall on South Korea (Wikipedia contributors 2013). JMA (Japan Meteorological Agency) observed typhoon track and its development stages are illustrated in Fig. 1.

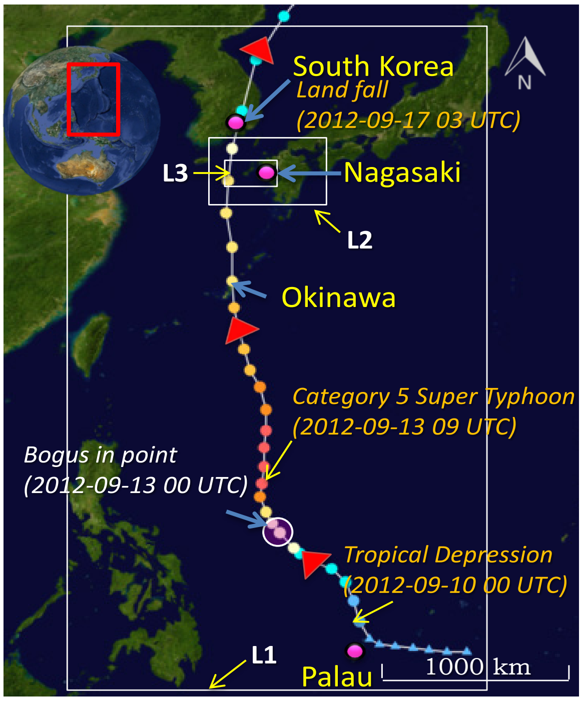

Figure 1. Best track of typhoon SANBA (JMA Observation)

MODEL DETAILS

In this study, two different approaches; (i) MM5 Mesoscale Model and (ii) DDB Tropical Cyclone Tool were used for the reproduction of wind and pressure fields for the period from 13th to 18th September, 2012.

The high resolution MM5 weather prediction model is a non-hydrostatic model, designed to simulate the atmospheric circulation. Initial conditions, lateral and lower boundary conditions for the nested L1, L2 and L3 domains (Fig. 1) are taken from NCEP (National Centers for Environmental Prediction) Operational Global Analysis data at every 6 hour interval. The grid resolution of L1, L2 and L3 domains of MM5 model are 15 km, 5 km and 1.67 km respectively. USGS (U.S. Geological Survey) terrain elevation data was provided with 56 km, 9 km and 4 km grid resolution for L1, L2 and L3 domains respectively. The model was run with 34 sigma levels in the vertical direction. Further, bogus typhoon parameters were included into the MM5 model to enhance the accuracy of the results (Low-Nam and Davis 2001). As recommended by MM5 manual, model physics (e.g. PBL Schemes, Explicit Moisture Schemes and Cumulus Parameterizations) were selected based on the grid spacing of the MM5 model. Thus, surface wind and pressure fields were generated at 1 hour interval and output data structure was changed in to the Delft3D readable format to use as the input for the FLOW and WAVE model of the Delft3D modeling system.

As the 2nd approach, spatially varying wind and pressure fields of Typhoon SANBA were reproduced by using DDB Tropical Cyclone Tool. Time series of spiderweb parameters such as maximum sustained wind speed and coordinates of the center of typhoon were provided as the input of

DDB (UNISYS 2013). DDB Tropical Cyclone Tool generates the surface wind and pressure fields on a moving circular spider web grid for the given track information data, based on the Wind Enhancement Scheme (WES) following Holland (Holland 1980). As shown in Fig. 2, the center of spider web grid has high grid resolution to resolve the higher wind and pressure gradient in the center region of the typhoon.

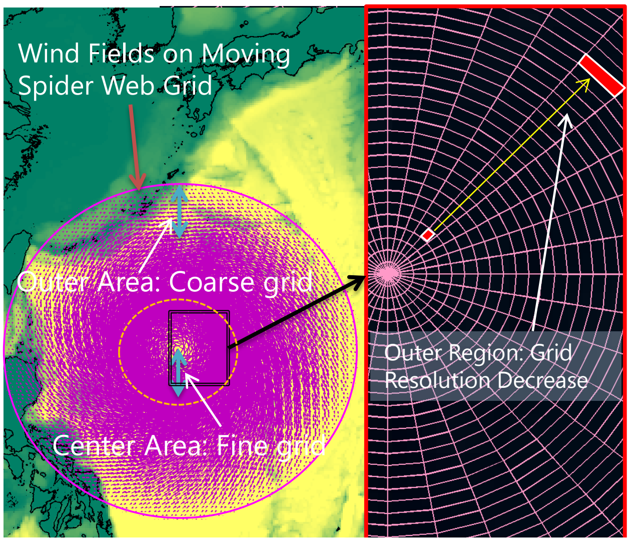

Figure 2. DDB generated Moving Spider Web Grid and comparison of grid resolution in inner and outer areas of the grid system

In Delft3D system, FLOW model, in which calculations are based on the shallow water assumption, was used to simulate the hydrodynamic effects caused by wind, atmospheric pressure changes and tidal forces. TPXO 7.2 Global Tide Model data was input as tidal boundaries of the FLOW model. WAVE model, based on SWAN model (Booij and Holthuijsen 1999), was used to calculate the wind driven waves. FLOW and WAVE models were coupled to exchange the model results between each model at 1 hour communication interval (Fig. 3). Both FLOW and WAVE models were run in a nested grid setup consisted of 3 levels of grids (L1, L2 and L3) (Fig. 1). The grid resolution of L1, L2 and L3 domains of FLOW and WAVE models are 11.10 km, 2.22 km and 0.55 km respectively. By using wind and pressure fields reproduced by MM5 model and DDB Cyclone Tool, Delft3D FLOW and WAVE models were simulated for the period of 5 days from 13th to 18th September, 2012 separately.

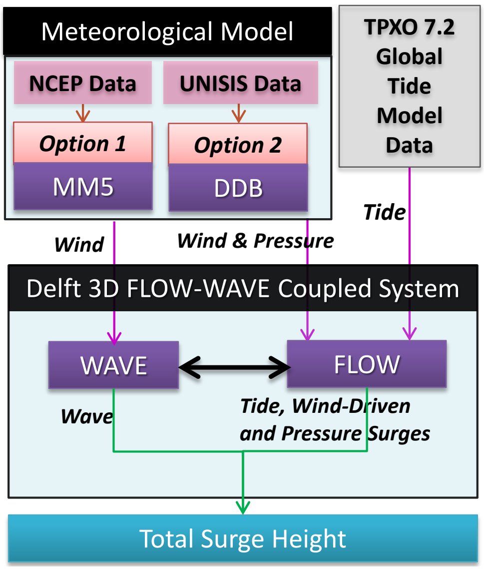

Figure 3. Numerical modeling framework

RESULTS AND DISCUSSION

Wind and pressure fields

MM5 and DDB generated wind fields were validated by using JMA wind observations because assurance of the accuracy of the simulated wind fields are highly important to obtain reliable results. Accordingly, wind observation at N1 (Nomozaki point: 32^0 34.7′ N, 129^0 44.4′ E) was compared with the MM5 and DDB generated wind fields. Fig. 4 shows MM5, DDB generated and measured wind speeds at N1 point for the period from 14^{th} to 18^{th} September. Comparing each, it is clear that the MM5 computed peak value of 29.0 m/s and the DDB generated peak value of 27.6 m/s have almost agreed with the observed peak wind speed of 30.7 m/s. Compared with the underestimated peak wind speed of 1.7 m/s and 3.1 m/s by MM5 and DDB models, discrepancies of these computed peak values are not significant. MM5 model simulated results were obtained from the finest nest level of the model (L3). Hence, as a result of high grid resolution, the accuracy of the wind and pressure fields might have been enhanced. In the case of DDB, 2D wind fields are generated on a moving spider web grid. At the center, this circular grid system has a high grid resolution which enables to capture strong variation of wind and pressure gradients in the center area of the typhoon. However, the influence of the high resolution center area of the circular grid system might not be significant at N1 point since it is located far away from the typhoon center.

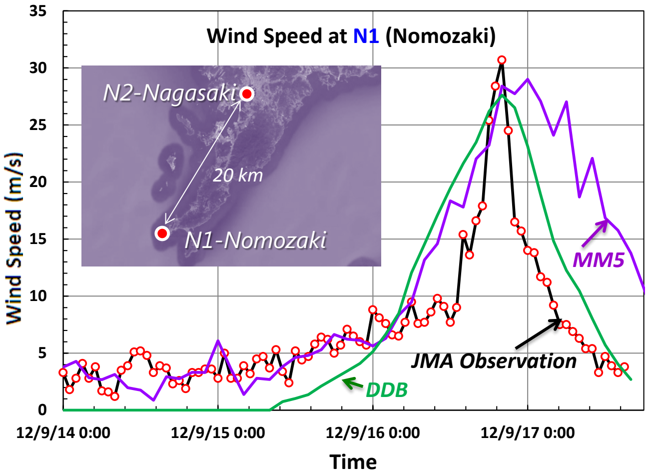

Figure 4. Comparison of calculated (MM5 and DDB) and JMA observed wind speeds at Nomozaki (N1).

For 120 hours of hindcasting period, MM5 and DDB generated spatially varying (2D) wind and atmospheric pressure fields on 13^{th} September at 22.00 (UTC) are shown in Fig. 5. Further, wind speed and atmospheric pressure were extracted along the AB line, which passes through the eye of the typhoon**.** Additionally, wind and pressure values obtained from MM5 model without bogus typhoon effects were also considered for the comparison. From this distribution, lower atmospheric pressure at the eye of typhoon (center of the typhoon) and higher wind speed near the eye wall region of the typhoon can be observed in both MM5 (bogus typhoon included) and DDB generated wind and pressure systems. Since NCEP reanalysis global model data are on 1.0 $\times$1.0 degree grids, input data resolution for MM5 model might be too coarse to represent the realistic typhoon. Specially, there would only be a few data points to represent the strong wind and pressure variation in the center region of the actual typhoon. Hence, to enhance the initial strength and positioning of the typhoon relative to the available background gridded NCEP data, typhoon bogus procedure (Davis and Lownam 2001) was carried out. As a result of adapting bogus procedure, significant improvement of wind and pressure fields in the center area of the typhoon can be observed in Fig.5 (1 a & b). However, the influence of the bogus typhoon parameters is not significant in the outer area of the typhoon. As seen in Fig.5 (1), point X is located 655 km away from the typhoon center. It is clear that both wind and pressure values at point X are almost equal for two MM5 simulations (bogus typhoon included and excluded). With bogus typhoon parameters, MM5 model generated maximum sustained wind speed and minimum atmospheric pressure values on 13^{th} September at 22.00 (UTC) were 45.81 m/s and 936 mbar respectively. Compared with observed maximum wind speed of 56.94 m/s, calculated maximum wind speed has been underestimated. This discrepancy might be caused by the coarse grid resolution (15 km) of L1 outer grid. In the absence of terrain effects, maximum wind speed is spotted near the eye wall region of a typhoon. The lowest pressure might be spotted in the eye (center) of the typhoon. Therefore, grid resolution must be finer enough to resolve and capture these features. In the case of minimum atmospheric pressure also, MM5 simulated value of 936 mbar is higher than the recorded minimum value of 900 mbar. Similar to the wind speed difference, coarse grid resolution might be affected for the pressure difference. However, since our focus area is Nagasaki, the pressure and wind gradients are not so high compared to the center area of the typhoon. Further, accuracy of the meteorological results in Nagasaki area has been enhanced by applying 3 levels of nested grid system for MM5 simulation.

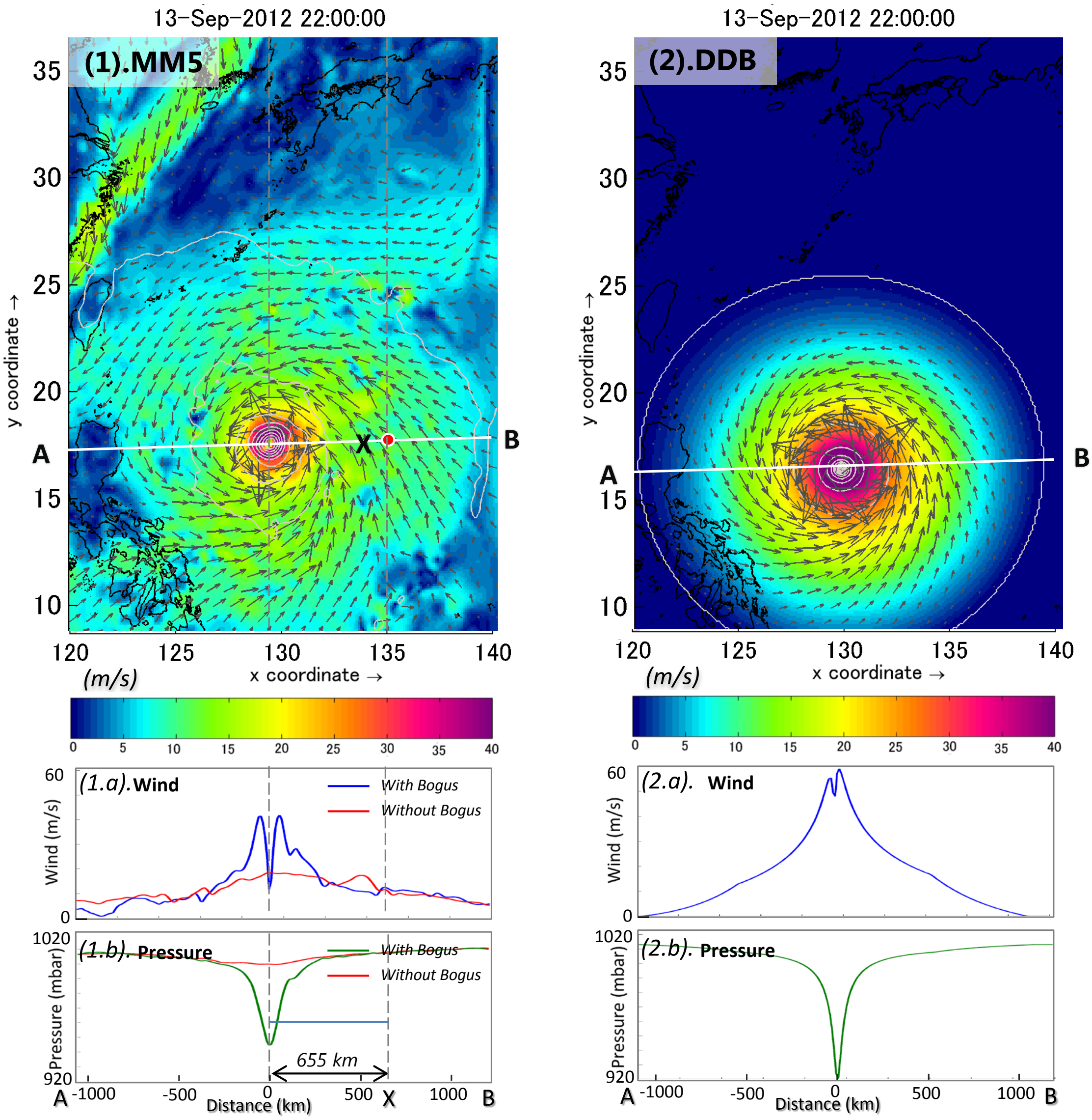

Figure 5. MM5 and DDB systems simulated wind and atmospheric pressure distribution on L1 domain and across AB profile.

The DDB generated maximum sustained wind speed and minimum atmospheric pressure on the moving spider web grid on 13th September at 22:00 (UTC) were 59.05 m/s and 920 mbar respectively. Thus, DDB generated values are in better agreement with JMA observations than the bogus typhoon parameter included MM5 simulated values. This could be caused due to the high grid resolution at the center of spider web grid and resultant capability of capturing the strong wind and pressure gradient at the center area of the typhoon. Therefore, if the point of interest is near to the center area of the typhoon, DDB generated wind and pressure fields give more accurate results than the MM5 results with bogus typhoon parameters. However, compared with spatial distribution of wind and pressure fields of DDB

(Fig. 5), MM5 generated wind and pressure distributions are more realistic in outside region of the typhoon because DDB Wind Enhancement Scheme (WES) model does not consider the asymmetry of the typhoon wind fields induced by the land geometry.

Typhoon track

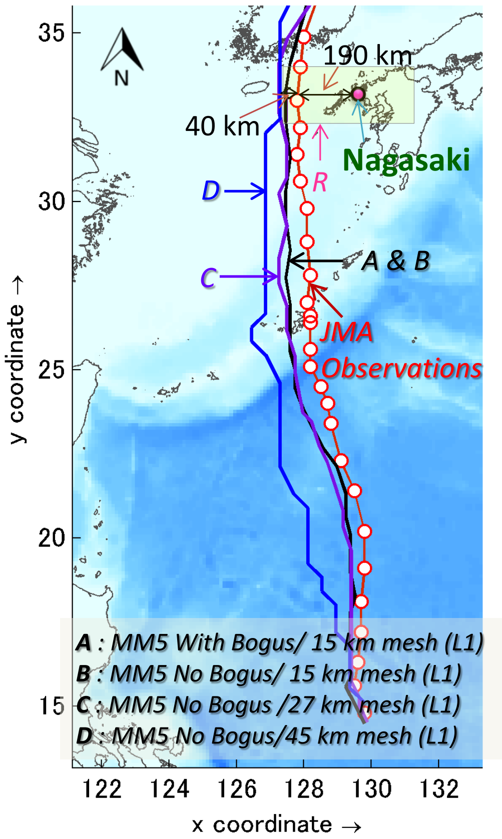

Figure 6. Deviation of typhoon tracks for typhoon bogus and different MM5 grid resolutions (13th - 18th, September 2012)

DDB generated typhoon follows actual track of the typhoon since track of the moving spider web grid is generated by using actual typhoon track coordinates. Therefore, there were no any deviations of DDB generated typhoon track from the real typhoon (Fig. 6). On the other hand, MM5 generated typhoon track and typhoon characteristics mainly depends on the input parameters of the MM5 model. Therefore, more studies were required to identify suitable settings of MM5 model to increase the accuracy of the results. As shown in Fig. 6, the behavior of the typhoon tracks was analyzed for different cases (A, B, C and D), considering the bogus typhoon effect and MM5 model grid resolution. Typhoon SANBA has closely passed 190 km away from Nagasaki point. According to our results, finest gridded cases (A and B) have given nearly correct but similar tracks in spite of bogus typhoon effect. Thus, it is recognized that effect of bogus typhoon has not significantly affected the simulated typhoon tracks. However, it should be kept in mind that influence of bogus typhoon may vary from case to case as its influence depends on many factors such as the size of the typhoon, the strength of the typhoon and the monsoon gyre in the background field. Further, its effect on typhoon intensity has also been studied and will be discussed in section 4. 3. The shift of simulated typhoon tracks from JMA observation for *Case A* (15 km grid resolution L1 domain) along the Nagasaki point is approximately 40 km (Fig. 6 & 7). For more coarse mesh sizes (*Case C*=27 km and *Case D*=45 km) typhoon track has further deviated from JMA observed path as a result of decreased grid resolution. Thus, significant relationship between the typhoon track and MM5 grid resolution was identified. Further, to estimate the effect on typhoon intensity and surge level at N2 point without the track shift of 40 km, simulated wind and pressure fields were shifted by 40 km towards the Nagasaki side.

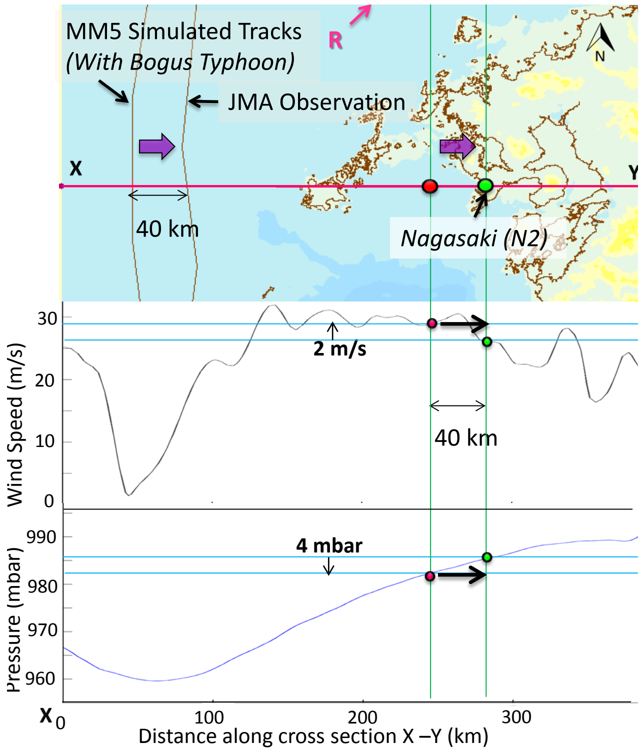

Figure 7. Wind speed and pressure changes after shifting MM5 simulated (Case A) track towards the Nagasaki side.

Fig. 7 shows the distribution of wind and pressure values along the selected XY cross section when typhoon SANBA closely passes N2 point. By shifting typhoon 40 km toward the Nagasaki side, 2 m/s increase of wind speed and 4 mbar decrease of atmospheric pressure were achieved. Since these improvements have minor effect to increase the surge level, effect from track shift error of about 40 km on simulated surge level can be neglected in this study. However, if interested point is near or on the typhoon track, correction for the track shift must be essential because pressure and wind gradient in the center area of the typhoon is high. In overall, MM5 simulation has given successful meteorological output results. To obtain accurate results, selection of correct model physics based on grid resolution, increasing vertical layer numbers, selection of high resolution terrain data and starting simulation at the mature stage of the typhoon were identified as important measures to be carried out.

Storm surge

Time series plots of simulated surge levels from MM5-Delft3D and DDB-Delft3D systems, JMA observed surge levels and astronomical tide levels at the selected station N2 (32^0 44′N, 129^0 52′E) are shown in Fig. 8. Compared with the predicted maximum astronomical tidal level of 1.5 m, it is clear that water level has elevated due to the typhoon effect.

The JMA recorded peak surge level at N2 on 17^{th} September at 00:00 (UTC) was 2.16 m. For the comparison, storm surge levels of *MM5-Case A* simulation were selected. As described in section 4.2, *MM5-Case A* simulation was performed on a finest grid, including bogus typhoon. Thus, from MM5 simulated wind and pressure fields, peak value of 2.09 m was obtained at the corresponding time. In this case, the underestimated peak surge level of 0.07 m is not so significant. The possible cause for this slight discrepancy could be due to the underestimated wind gradients by MM5 models as existing grid resolution of the MM5 model might be not sufficient to capture the actual variation of wind gradients, specially at the typhoon center. However, the coarse grid effect on a distance point is not very important as wind gradient change is weaker in outer area of the typhoon. Therefore, MM5-Delft3D combined modeling system would be more appropriate to simulate the storm surge levels outside the typhoon center. In overall, simulated surge levels obtained from MM5 and Delft3D FLOW-WAVE coupled modeling system (MM5-Delft3D) can be accepted with a reasonable level of accuracy.

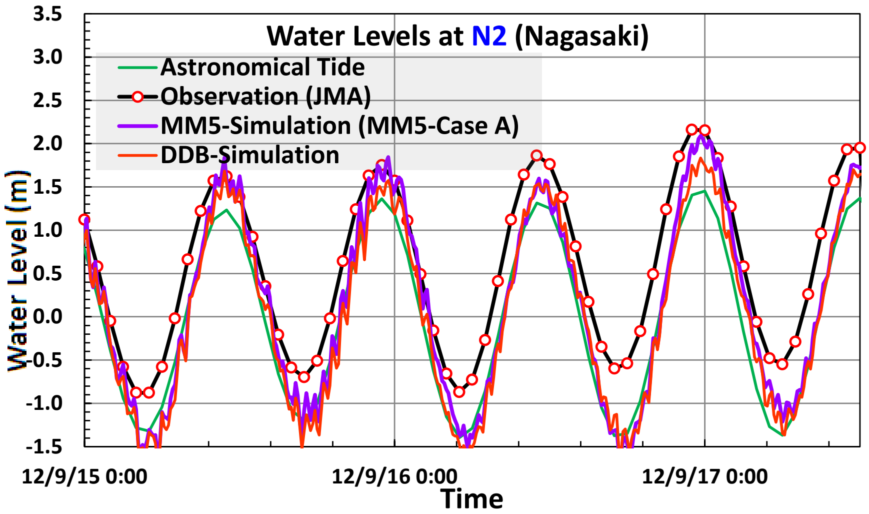

Figure 8. Comparison of water level observation, astronomical tide and computed water levels (MM5 with bogus and DDB) at N2

In the case of DDB-Delft3D system induced storm surge levels, peak value of 1.83 m was obtained at N2 on 17th September at 00:00 (UTC). Even though it is acceptable, the underestimated peak surge level of 0.33 m is slightly higher than the discrepancy of the MM5-Delft3D system generated peak value. Even though grid resolution in the center area of the DDB moving spider web grid is finer to capture the strong wind and pressure variation, the coarser outer grid area might affect to the distance points away from the center of the typhoon. Since N2 point is located far away from the typhoon center, it could be a possible reason for the discrepancy. Moreover, Wind Enhancement Scheme (WES) model of DDB does not consider the change of wind and pressure field symmetries due to the existence of lands. Therefore, it might have an effect on the simulated storm surge level at N2 point, located near the land area. However, if the point of interest is located on or near the typhoon center, DDB wind and pressure fields induced storm surges could have given more accurate results than the outer area of the typhoon.

Hence, during the disaster preparedness and management stages, selection of suitable storm surge simulation methodology could be decided on the basis of the location of the interested point. If it is located far away from the typhoon center, MM5-Delft3D system would give better results. In contrast, if it is located on or near typhoon center, DDB-Delft3D systems might be the better option.

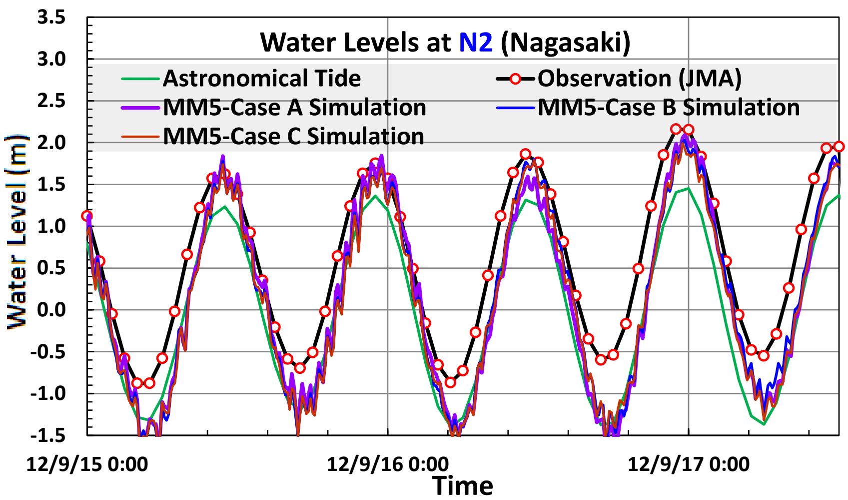

Figure 9. Comparison of observed and computed water levels at N2 for different cases of MM5 simulation

Further, to estimate the effect on surge level due to typhoon bogus and grid resolution of MM5 model, water levels were computed excluding bogus effect *(MM5-Case B)* and decreasing grid resolution *(MM5-Case C)*. Time series plots of 3 simulation cases (*MM5-Case* A, *MM5-Case* B and *MM5-Case* C), JMA observations and astronomical tide levels at station N2 are shown in Fig. 9. After excluding bogus typhoon from *MM5-Case A*, the peak value has decreased only up to 2.03 m since effect of bogus typhoon is not so significant outer area of the typhoon. If point of interest is located in center area, contribution of the bogus typhoon could be identified clearly. Further, for coarse mesh grids *(MM5-Case C)*, peak surge level has decreased further to 1.99 m. Thus, finest grid resolution of MM5 model significantly affected to increase the accuracy of both typhoon tracks as well as storm surge level.

CONCLUSIONS

In this study, applicability of two meteorological simulation techniques; (i) MM5 Mesoscale Model and (ii) Delft Dashboard (DDB) Tropical Cyclone Tool, together with Delft3D FLOW-WAVE coupled modeling system was assessed. By using both systems (i.e. MM5- Delft3D and DDB-Delft3D), storm surge in Nagasaki coast during the passage of 2012 Typhoon SANBA was reproduced. Our results validate the applicability of both MM5-Delft3D and DDB-Delft3D systems to simulate the storm surge heights with a reasonable level of accuracy. Further, compared to the DDB-Delft3D system, MM5-Delft3D system generated storm surge levels were better agreed with the observations at the point of interest (N2), which is located far away from the typhoon center.

In the MM5 simulation, the effect of typhoon bogus was identified as significant in the center area of the typhoon. However, if the interested point is located far away from the typhoon center, bogus typhoon has a minor effect on the induced storm surge. Further, it has minimum effect on the typhoon track too. In this study, grid resolution of the MM5 model also has a minor effect on the induced storm surge level. In contrast, MM5 grid resolution significantly affects to increase the accuracy of typhoon track. Moreover, track shift error of the typhoon on wind and pressure fields were recognized as less significant if the point of interest is far away from the typhoon track.

In the case of DDB generated meteorological field, well resolved wind and pressure fields in the center region of the moving spider web grid enable the simulation of storm surges on or near the typhoon center in higher level of accuracy. However, accuracy of the simulated storm surge levels in outer area of the typhoon has been declined as a result of coarser grid resolution in outer region of the moving spider web. Further, since DDB is incapable to incorporate the asymmetry of the typhoon wind fields due to the land geometry, it might have adversely affected to the results. In overall, applications of DDB-Delft3D system is an easy and fast approach to hindcast the peak storm surge levels with an acceptable level of accuracy. However, in terms of accuracy, MM5-Delft3D system demonstrated much better performance in outer regions of the typhoon compared to DDB-Delft3D system.

ACKNOWLEDGMENTS

The authors wish to acknowledge to The Pennsylvania State University (PSU-USA), University Corporation for Atmospheric Research (UCAR-USA) and Deltaers (The Netherlands) for providing their models for this study. The Japan Meteorology Agency (JMA-Japan) and The Computational and Information Systems Laboratory at the National Center for Atmospheric Research (CISL NCAR-USA) are thanked for providing data for this research.

REFERENCES

Booij, N., Ris, R., Holthuijsen, L. 1999. A third-generation wave model for coastal regions, part I: model description and validation, *Journal of Geophysical Research* 104 (C4), pp. 7649-7666.

Davis, C., and Lownam, S. 2001. The NCAR-AFWA tropical cyclone bogussing scheme, *A report prepared for the Air Force Weather Agency* (AFWA),13p.

Dean, R.G., and Dalrymple, R.A. 2002. *Coastal Processes with Engineering Applications,* Cambridge University Press, 475 pp.

Delft Dashboard Team. 2013. Delft Dashboard, https://publicwiki.deltares.nl/display/OET/DelftDashboard, *(accessed on 10 Jul. 2013).*

Deltaers. 2010. Delft3D - *User Manual*, version 3.14.

Emanuel, K. A. 2005. Increasing destructiveness of tropical cyclones over the past 30 years, *Nature*, Vol. 436, pp. 686-688.

Grell, G.A., Dudhia, J. and Stauffer, D.R. 1994. A description of the fifth-generation Penn State/ NCAR mesoscale model (MM5), *NCAR Tech Note*, NCAR/TN-398+STR, 117.

Holland, G.J. 1980. An Analytic Model of the Wind and Pressure Profiles in Hurricanes, *Monthly Weather Review*, 108-8, pp. 1212-1218.

Low-Nam, S., and Davis, C. 2001. Development of a tropical cyclone bogussing scheme for the MM5 system. Preprint, the Eleventh PSU/NCAR Mesoscale Model Users' Workshop, June 25-27, 2001, Boulder, Colorado, pp. 130-134.

Nordhaus, W. D. 2006. The Economics of Hurricanes in the United States. Boston, Annual Meetings of the American Economic Association.

UNISYS: Hurricane/Tropical Data, http://weather.unisys.com/hurricane/, *(accessed on 10 Jul. 2013).*

Webster, P. J., Holland, G. J., Curry, J. A. and Chang, H. R. 2005. Changes in tropical cyclone number, duration and intensity in a warm environment, *Science*, Vol. 309, pp. 1844-1846.

Wikipedia Contributors. 2013. Typhoon SANBA 2012, Wikipedia, The Free Encyclopedia, *(accessed on 17th May, 2013).*