Journal of Coastal Research	SI	85	916-920	Coconut Creek, Florida	2018

Fine-resolution Numerical Simulations to Estimate Storm Surge Height and Inundation Vulnerability Considering Future Climate Change Scenario

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ABSTRACT

Yoon, J.J., 2018. Fine-resolution Numerical Simulations to Estimate Storm Surge Height and Inundation Vulnerability Considering Future Climate Change Scenario. *In:* Shim, J.-S.; Chun, I., and Lim, H.S. (eds.), *Proceedings from the International Coastal Symposium (ICS) 2018* (Busan, Republic of Korea). *Journal of Coastal Research*, Special Issue No. 85, pp. 916–920. Coconut Creek (Florida), ISSN 0749-0208.

Typhoons are significant natural disasters in Korea, causing considerable damage to property. Climate change worsens the situation. The most severe loss of life and property in Korea was caused by Typhoon Maemi in September 2003. When storm surges coincide with high tides, they cause even greater damage. Therefore, it is desirable to accurately forecast storm surges, to enable detailed evacuation planning, including hazard mapping. To estimate the maximum probable inundation area while planning a hazard map, it is necessary to consider future climate change scenarios. The simulation of the largest storm surge inundation was successfully carried out with the Typhoon Maemi scenario using the Finite-Volume Coastal Ocean Model (FVCOM). According to the recent IPCC AR5 report, the rate of sea level rise (SLR) could accelerate to 1.4–2.0 m by the end of the 21st century. This estimate should be considered when designing coastal structures in order to prevent coastal disasters. We applied the results of SLR to coastal inundation simulations. We considered the effects of additional future SLR on the traditional storm surge inundation simulation of Typhoon Maemi. Virtual scenarios with additional SLR were simulated to evaluate the maximum probable surge height, and inundation depth and area for each climate change scenario along the southern coast of Korea. The increase in inundation heights and areas at the regional scale was found to be approximately 67–70% and 414–527%, respectively. This study provides a method to determine the maximum probable inundation area due to surge wave propagation.

ADDITIONAL INDEX WORDS: *Coastal inundation, storm surge climate change scenario, Finite-Volume Coastal Ocean Model.*

INTRODUCTION

Sea level rise (SLR), with enhanced intensity and frequency of typhoons due to climate change, has increased the storm surge flood inundation risk of coastal areas. Coastal disasters are not only difficult to predict, but also cause severe damage. Coastal development, such as the reclamation project in Korea, has led to the increased use and spread of the coastal zone, thus increasing the risk of coastal disasters. To minimize the damage, a systematic response against coastal inundation is important.

Typhoon Maemi, which struck Korea in September 2003, caused property damage worth $4 billion, with 131 casualties. Internationally, typhoon Haiyan, which struck the Philippines in November 2013, and Hurricane Irma, which struck Florida, USA, in 2017, caused significant damage. While preventive measures are important, protective infrastructure, such as shore protection and dykes have limited ability to protect from floods. Soft measures include prior evacuation measures through the establishment of a rapid disaster prediction system.

To precisely predict flood inundation in coastal areas, a fine-grid storm surge model, considering various oceanic parameters comprehensively, and a high-resolution climate model, are required. Moreover, a coastal topography database, systematically connecting land altitude and water level, is required. This study designed a numerical model system to predict flood inundation due to typhoons.

USA, which experiences severe damages from hurricanes, uses the SLOSH model in the National Hurricane Center (NHC) under National Oceanographic and Atmospheric Administration (NOAA), to predict the maximum inundation height and area (Glahn et al., 2009). Moreover, it runs a real-time storm surge prediction system using the ADCIRC model (Fleming et al., 2008; Blanton et al., 2012). There is an accurate and immediate storm surge prediction system in Korea, which is in its pilot stage.

This study simulated flood inundation due to a large typhoon that occurred previously, through storm surge numerical modeling. The study combined the results with the predicted value of SLR in the future, in accordance with climate change scenarios, to calculate the maximum inundation height and area for each scenario.

METHOD

Typhoon wind model and storm surge model

When simulating the storm surge caused by typhoons, accurate weather forecast data is essential. For this, a sea-surface wind model that could accurately generate time and space variations of the typhoon wind field must be selected. Moreover, the accurate

DOI: 10.2112/SI85-184.1 received 30 November 2017; accepted in revision 10 February 2018.
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estimation of typhoon parameters is very important. In particular, as estimation data is largely insufficient on the sea, accurate typhoon analysis is required using alternative data sources, such as satellite observation data and numerical model results. In order to calculate the storm surge height, the time and space information on sea surface wind and pressure fields is required.

This study used TC96 sea surface wind model, which is a planetary boundary layer (PBL) model by the U.S. Army Corps of Engineers, to calculate the wind and pressure field during typhoons. The major input parameters of TC96 sea surface wind model include center location, central minimum pressure, and maximum wind radius of the typhoon. The TC96 sea-surface wind model has been introduced in researches by Cardone et al. (1994), Thompson and Cardone (1996) and others.

The estimation of storm surge height uses FVCOM, the 3-dimensional finite volume model (Chen et al., 2006). FVCOM employs the finite-volume method (FVM), combining a numerical calculation flow of the finite-difference method (FDM) and a triangular unstructured grid system of the finite-element method (FEM). FVCOM balances the efficiency of discrete characteristics of FDM with the geometric flexibility of FEM.

The wet/dry treatment method was applied to simulate coastal inundation. Further details of the model are as provided in a previous research (Yoon and Shim, 2013).

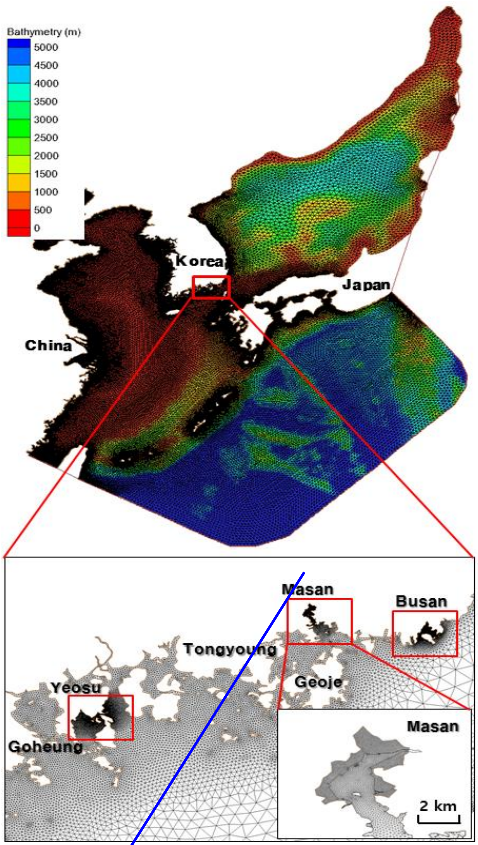

Figure 1. Overview of the model domain, grid composition and bathymetry distribution. Blue line represents the moving track of typhoon Maemi.

Mesh generation and boundary conditions

Storm surges have larger spatial changes due to the regional influence in complicated sea shores like the southern coast of Korea.

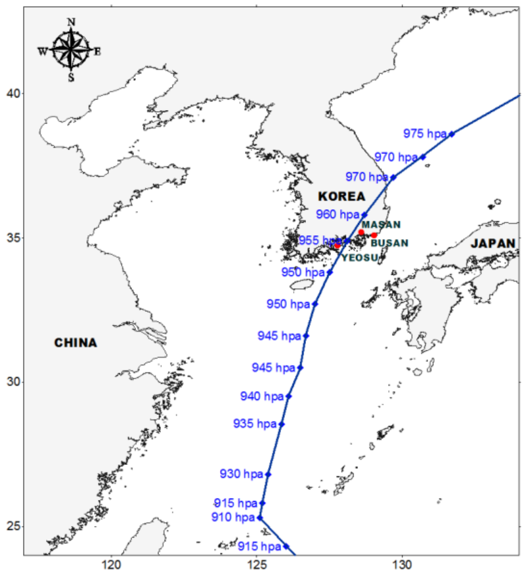

Figure 2. Track of Typhoon Maemi, 2003 (KMA data)

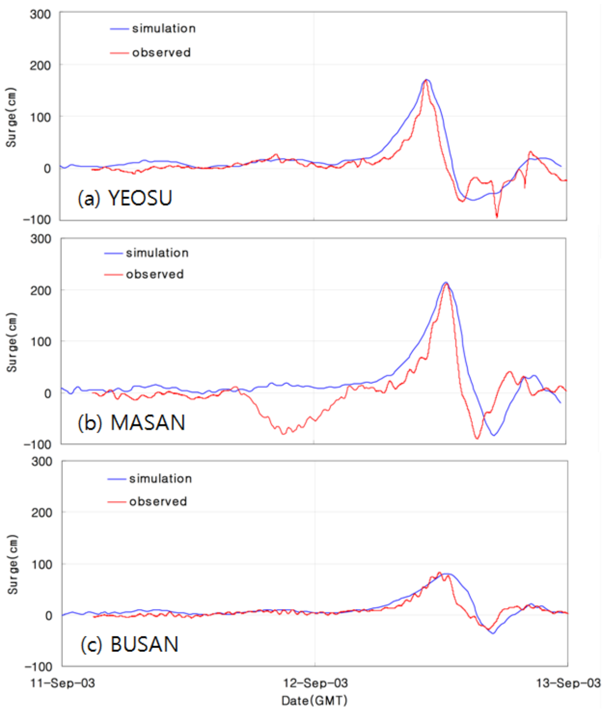

Figure 3. Comparison of the observed (red lines) and simulated (blue lines) storm surge heights at Yeosu, Masan and Busan.

To consider this appropriately, high resolution bathymetry data, with precise grids in the numerical model, are required. For this, it is important to use the available water level information as much as possible to generate accurate water level grid. The grid mesh for the estimation of storm surges covered a broad region, including the Yellow Sea, the East Sea and the East China Sea (Figure 1).

The grid system has an unstructured triangular mesh, whose minimum size (close to the coastal area) is 300–400 m. In some coastal areas such as Yeosu, Masan, and Busan, the calculation grid was expanded to lands with less than 10 m, including details within grids of at least 20–30 m, for the estimation of storm flood inundation. There were a total of 136, 570 nodes and 258,482 elements. The storm-surge height was calculated tridimensionally, with the vertical grid composed of 11 sigma-layers. For the water depth data, data were obtained from the digital nautical chart issued by Korea Hydrographic and Oceanographic Administration (KHOA) for coastal zones and ETOPO1 data (Amante and Eakins, 2008) for regions away from the coastal zone. The study used 8 major tidal components from NAO99jb of 1/12 degree grid as the input data of harmonic constants applied to the open boundary of the model (Matsumoto et al., 2000).

Simulation result for Typhoon Maemi

The storm surge height was simulated as that during Typhoon Maemi in September 2003, which resulted in severe flooding damage by storm surge (2.1 m) in Masan bay.

The maximum observed water level was 3.1 m above MSL, upon overlapping with the highest tide (1.0 m) at this site. The

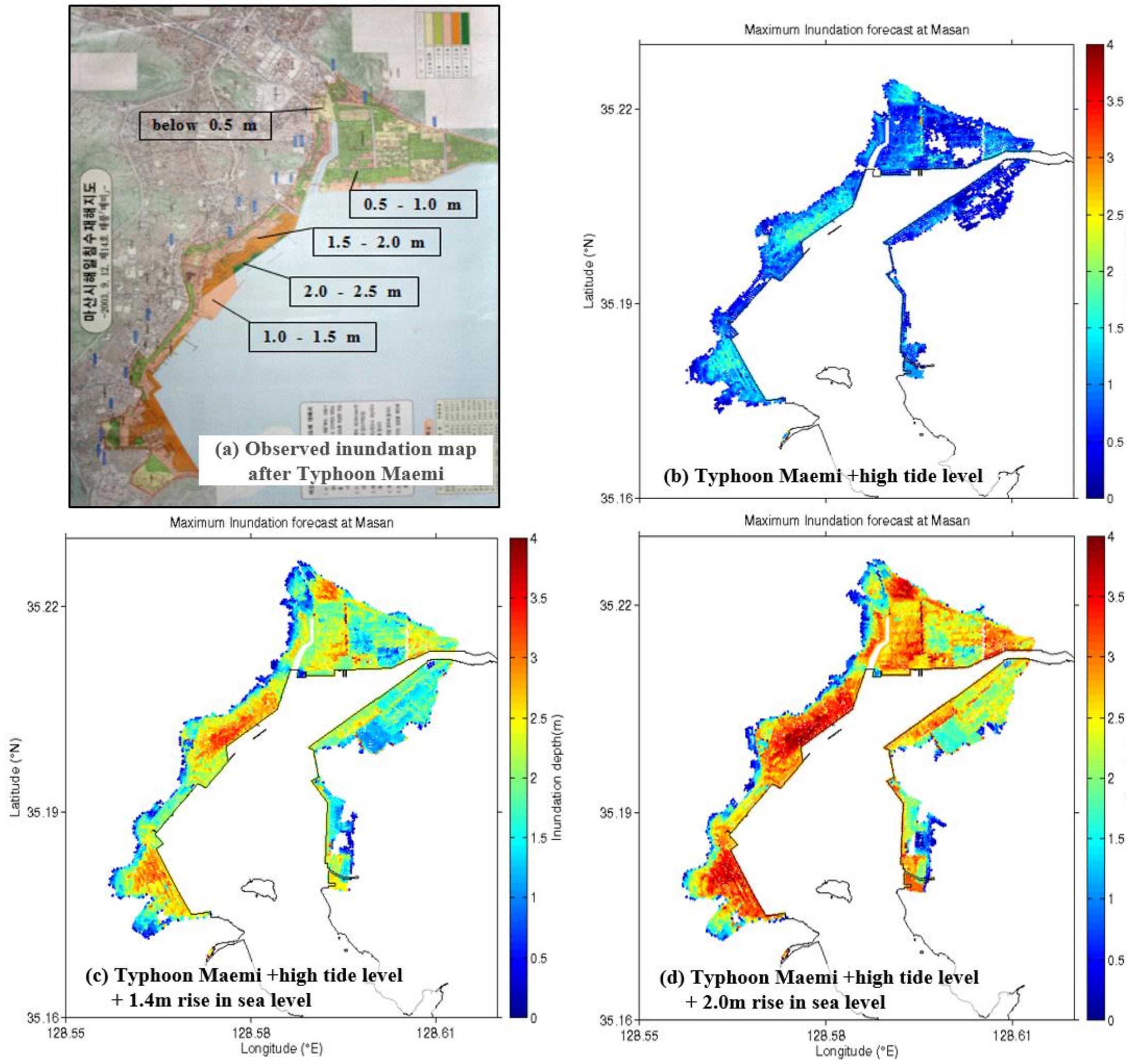

Figure 4. Comparison of observed (a) and simulated (b, c, d) inland flooding distribution for typhoon Maemi in Masan for each scenario.

typhoon passed across the southern coast of Korea, between Yeosu and Masan. For this simulation, the hourly-interpolated meteorological inputs were based on KMA(Korea Meteorological Administration)'s typhoon information (Figure 2).

The FVCOM model's results reproduce the observed data very accurately and appropriately at each station (Figure 3). Simulated maximum surge heights show errors of approximately -2, +2, and -4 cm in Yeosu, Masan, and Busan, respectively. The results of the surge simulation correspond not only with the observed maximum surge height, but also with the particular time phase. Thus, the FVCOM model can accurately reflect the meteorological input forcings by the TC96 wind model. The simulation shows good agreement, despite the complicating influence of many complex narrow channels in the southern coast of Korea. However, in case of Masan, a negative surge occurred before and after the passing of the typhoon. The model results do not follow the observed data in this case, as a negative surge was not observed before the maximum surge. The reason behind this phenomenon remains unknown.

ESTIMATION OF PROBABLE INUNDATION AREA

Selecting the flood inundation scenario

The standard sea level applied to simulate flood inundation was approximately set as the highest high water level, to simulate the scenario of the highest typhoon surge height at the high water level. The parameters of Typhoon Maemi (2003) were selected for the historical typhoon scenario, which recorded the maximum storm surge height in Masan and Busan.

This study applied 1.4 m and 2.0 m as the maximum average potential SLR in accordance with the climate change scenario in AR5 (warming of 2 °C and 5 °C cases under RCP 8.5 with an upper limit of 95%) in order to apply the maximum SLR in 100 years based on future climate changes (Jevrejeva et al., 2016). For simplification, the study processed SLR by adding this value to the mean water level. The 3 final versions of scenarios are listed below (Table 1).

① approximate highest water level + storm surge height of Typhoon Maemi

② approximate highest water level + storm surge height of Typhoon Maemi + 1.4 m SLR

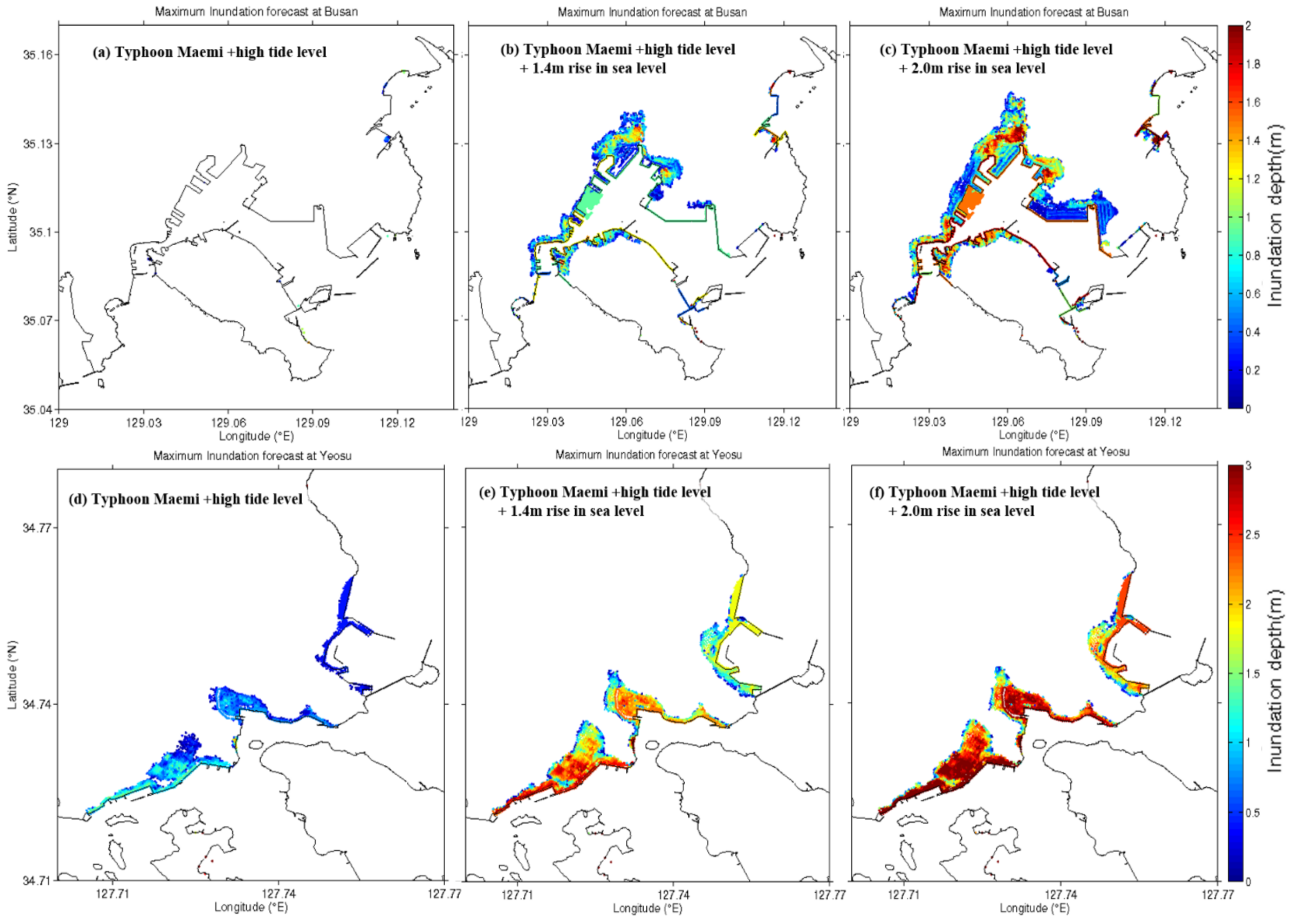

Figure 5. Maximum probable inundation height and area distribution for each scenario, Busan(a, b, c), Yeosu(d, e, f)

③ approximate highest water level + storm surge height of Typhoon Maemi + 2.0 m SLR

In simulations considering SLR in accordance with climate change, the mean water depth was 1.4 m and 2.0 m higher than the scenario without climate change.

Table 1. *List of sea level rise (m) scenario causing flood inundation*

Station	Approximate highest high water level	Max surge height for Typhoon Maemi	Sea level rise in Scenario 1	Sea level rise in Scenario 1
Masan	1.00	2.26	1.4	2.0
Busan	0.65	0.93	1.4	2.0
Yeosu	1.81	1.62	1.4	2.0

DISCUSSION

Simulation result for inundation in each scenario

When simulating the flood inundation of Typhoon Maemi, only Masan and Yeosu showed flood inundation during overlapping with high water level. This simulation calculated the storm surge and inundation due to Typhoon Maemi under the approximately highest water level condition for Yeosu, Masan, and Busan. The simulation result showed that Masan and Yeosu had a maximum inundation damage of 1.5 m (Figure 4b, 5d). The inundation depth and area for Masan are shown in Figure 4(c). Considering 1.4-m SLR, the inundation extent and volume increased by 60.4% and 276.8%, respectively. With 2.0-m SLR, the inundation extent and volume increased by 69.5% and 414.3%, respectively (Figure 4d).

In case of Busan, there was minimal inundation damage in the simulation of Typhoon Maemi (Figure 5a). However, with a 1.4-m SLR, the maximum inundation damage area and depth was significant (Figure 5(b)). Figure 5(c) shows the result for a 2.0-m SLR. As for Yeosu, when simulating the storm surge height with the approximately highest water level condition, a maximum of 1.5 m inundation damage was observed (Figure 5(d)). When considering 1.4-m SLR, the inundation depth and area were as shown in Figure 6(e); the inundation extent and volume increased by 57.4% and 351.2%, respectively. With 2.0-m SLR, the corresponding increases are 67.3% and 526.9%, respectively.

CONCLUSIONS

Due to storm surges every year, Korea has a high possibility of flood inundation in coastal areas. This paper developed a precise mesh expanded to land, while conducting numerical experiments on storm surge height and flood inundation. The 3-dimensional unstructured grid finite volume model, FVCOM, was applied. The simulation results were compared with the observation data from Busan, Masan, Yeosu, to evaluate their accuracy. The experimental results precisely reproduced the observed surge height, inundation range, and inundation depth, confirming its adaptability as a flood inundation model. Using the virtual scenario flood inundation simulation applying SLR in accordance with future climate changes, the study examined the probable flood inundation distribution for each scenario. This scenario considers approximately 140–200 cm SLR compared to Typhoon Maemi, which simulated a maximum potential inland flooding of 4 m (Masan), or 2–3 m (Busan, Yeosu). This is the assumption for SLR based on each scenario. The numerical model system adopted in this study can be expected to be a useful tool for the analysis of storm surges, prediction of coastal inundation, and hazard mapping. In addition, long-term research is necessary to help prepare the structure and policy of disaster prevention.

ACKNWLEDGEMENT

This research was supported by the basic research program of ChungNam Institute.

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